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Plagioclase-chain networks in slowly cooled basaltic magma

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ABSTRACT

Plagioclase crystals in the slowly cooled interior of the thick Holyoke flood-basalt flow of Connecticut linked to form monomineralic chains at an early crystallization stage. Partial melting experiments reveal that when the quartz tholeiite was only 25% crystallized the chains had already linked to form a continuous 3-D network. At such an early stage of crystallization, the network was weak, highly permeable, and easily deformed. Consequently, the mush of plagioclase-chains and interstitial pyroxene crystals underwent compaction in the lower third of the flow with the expelled liquid rising to the center of the flow where it crystallized to form coarse-grained sheets of fractionated basalt.

Plagioclase chains are most easily seen in the basalt after it has been partly melted and the late crystallizing minerals converted to glass. The chains are several crystals wide. The crystals, which are ~0.5 mm long, are attached together randomly. Normal zoning patterns indicate crystals had a brief period of growth before linking together. The chains branch every few millimeters to form the 3-D network, which was mapped using serial polished sections and X-ray CT scans. The chain frequency measured along vertical and horizontal traverses decreases toward the center of the flow. In the compaction zone, the frequency in the vertical direction is greater than in the horizontal. Making the reasonable assumption that these frequencies were initially the same, the difference is used to calculate the degree of compaction. The resulting pattern through the flow matches almost exactly the pattern indicated by variations in the incompatible elements. Plagioclase chains are also found in some coarser-grained plutonic rocks. If they are common, their fabric may provide a new, direct means of measuring the degree of compaction in crystal mushes.

INTRODUCTION

Many thick flood-basalt flows contain horizontal sheets of rock whose composition indicates that the sheets form from residual liquid that segregates from the host basalt following as little as 30% crystallization of the basalt (Cornwall 1951; Lindsley et al. 1971; Dostal and Greenough 1992; Puffer and Horter 1993; Philpotts et al. 1996). Hawaiian lava lakes contain similar sheets, but their compositions indicate slightly higher degrees of crystallization (Richter and Moore 1966; Moore and Evans 1967; Wright and Okamura 1977; Helz 1980). Although the sheets are generally concordant and horizontal, they can branch or have small transgressive dikes that connect them to overlying and underlying sheets. The host basalt exhibits clear evidence of having been fractured during the emplacement of the segregation sheets. This raises the interesting question of how basalt that is only 30% crystallized can fracture.

Partial-melting experiments on samples from the thick Holyoke flood basalt of Connecticut (Philpotts and Carroll 1996) indicated that this basalt, on cooling slowly, develops a crystal mush when it is no more than 25% crystallized. The experiments further revealed that the mush is held together by a remarkable network of chains of plagioclase crystals (Philpotts et al. 1998). These chains change the physical properties of the magma, making it behave like a semi-brittle material that fails by rupturing during the emplacement of the segregation sheets, despite the large fraction of melt present. Of greater importance, however, is the fact that because the plagioclase chains form at such an early stage of crystallization, the resulting network is sufficiently weak and permeable that it can undergo compaction when the bulk density of the crystals exceeds only slightly the density of the residual liquid. In the Holyoke basalt this led to significant compaction of the crystal mush in the lower third of the flow, with the expelled liquid rising to form the segregation sheets in the central part of the flow (Philpotts and Carroll 1996).

In this paper we describe the nature of the network of plagioclase chains in the Holyoke basalt, and show how the deformation of this network can be analyzed to obtain a direct measure of the degree of compaction within a pile of crystal mush.

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EVIDENCE FOR PLAGIOCLASE CHAINS IN PARTLY CRYSTALLIZED BASALT

The Holyoke basalt is a quartz tholeiite containing 3 to 5% plagioclase phenocrysts in a groundmass of plagioclase, augite, and pigeonite, with a mesostasis of magnetite and granophyre. In the chilled margins of the flow, small olivine crystals are present, but these react out to form pigeonite in the flow's interior. A previous experimental study (Philpotts and Reichenbach 1985) indicates that this basalt was multiply saturated with plagioclase, augite, and pigeonite through out most of its crystallization. In the more rapidly cooled parts of the flow, the mesostasis contains glassy or crystallized iron-rich and silica-rich immiscible liquids (Philpotts 1979; Philpotts and Doyle 1983). The grain size of the basalt remains fine throughout the flow, even where the flow is up to 200 m thick. By contrast, the segregation sheets, which occur in the central part of the flow, typically have a 1 cm grain size, although blades of plagioclase and pyroxene can be up to 10 cm long in pegmatitic patches in these sheets (Emerson 1905). The basalt shows no coarsening of grain size toward the segregation sheets, nor do the segregation sheets show any quenching against the basalt. The grain size difference is interpreted to indicate that many crystal nuclei were distributed throughout the flow at an early stage, perhaps as a result of convection, whereas the segregation sheets formed from liquid that separated from the basaltic mush without bringing with it many crystal nuclei.

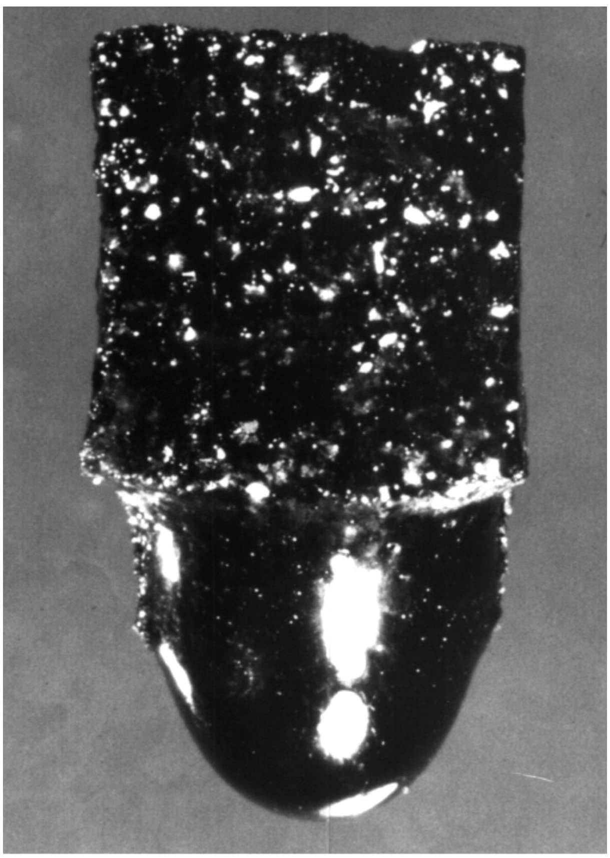

FIGURE 1. A 1 cm cube of basalt from 74 m above the base of the 174 m thick Holyoke flow, which has been heated until 70% melted, retains its shape due to the presence of a plagioclase-chain network. The partial melt is able to flow easily through this open network and form a large lens of liquid on the lower surface of the cube.

The presence of a high-temperature crystal network in the slowly crystallized part of the Holyoke basalt can be demonstrated through simple partial melting experiments (Philpotts et al. 1998). Figure 1, for example, shows a 1 cm cube of basalt from the central part of the flow that was heated until 70% melted. Despite the large degree of melting, the remaining crystals form a network that preserves the shape of the cube while allowing the liquid to drain from it. Furthermore, the network forms an effective filter, because the liquid that drains from the lower side of partly melted cubes rarely contains crystals. Samples of more rapidly cooled basalt from near the base of the flow lack the network of crystals and do not exhibit the same behavior during partial melting. They, instead, collapse into blebs at relatively low melt fractions. The crystal network is therefore characteristic of the more-slowly crystallized parts of the flow.

Although the crystal mush in the partial-melting experiments consists of both plagioclase and pyroxene, the plagioclase crystals provide the mush with its strength by linking together into a network of chains (Fig. 2). Segments of these chains encountered in a normal thin section may consist of as many as several hundred linked crystals. Pyroxene crystals, in contrast, occur as separate individuals or in small clusters of only a few grains. In the partly melted samples, a zone of liquid invariably separates plagioclase from pyroxene. The presence of a single pyroxene crystal in a plagioclase chain would therefore disrupt the chain and weaken the plagioclase crystal network. Thus the chains consist entirely of plagioclase crystals. Near the base of the flow, where chains are absent, most plagioclase and pyroxene crystals are juxtaposed against one another, with the result that most grains become surrounded by liquid during partial-melting experiments, and the crystal mush loses its strength at low melt fractions.

The plagioclase chains are not products of the partial-melting experiments. The chains are present in the unmelted rock, but they are rendered far more visible if the low-melting fraction of the rock is first converted to glass. By heating the basalt at ~1120 °C for 16 hours, all of its mesostasis and late-crystallizing plagioclase and pyroxene are melted. Upon quenching, this liquid forms a dark brown glass, which encloses the refractory plagioclase chains and isolated pyroxene crystals (Fig. 2). It is not implied that the partial-melting experiment reverses the crystallization sequence. The experiments are performed simply to make the plagioclase chains more visible.

DESCRIPTION OF PLAGIOCLASE CHAINS

The refractory plagioclase crystals in the slowly cooled part of the Holyoke basalt are linked together to form chains, not sheets. In a polished or thin section only a small number of the chains will be oriented with their lengths parallel to the plane of sectioning. The following description of the chains is therefore based on the examination of many thin sections and, in particular, of serial polished sections. Serial sectioning was done

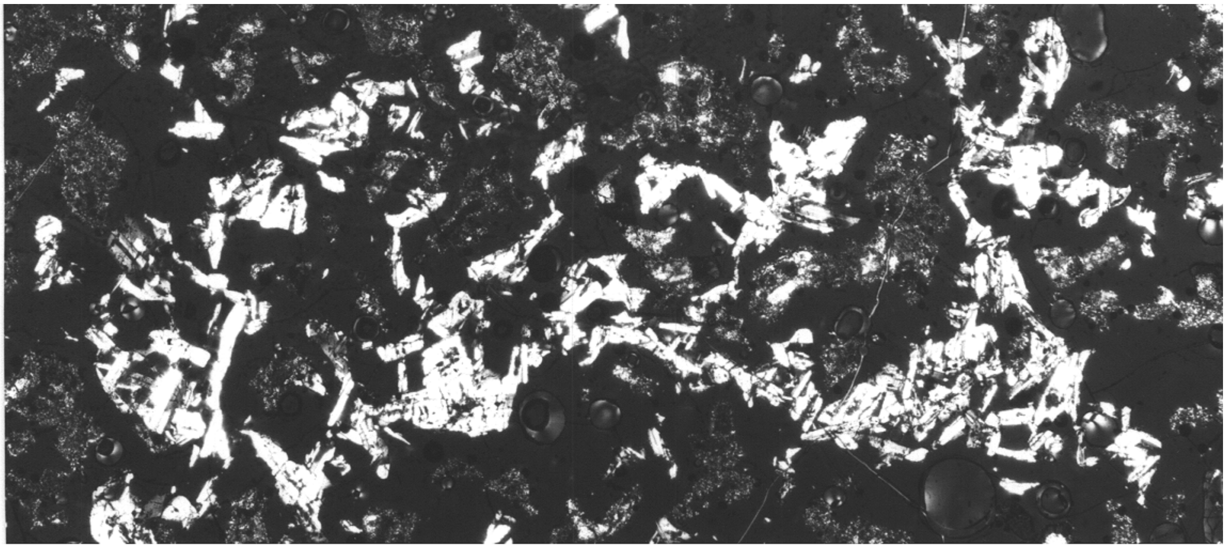

FIGURE 2. Plagioclase-crystal chain in partly melted basalt from 47 m above the base of the Holyoke flow. The refractory plagioclase crystals (white) are everywhere separated from refractory pyroxene crystals by a zone of glass (dark gray). Width of field is 7.7 mm. Partially crossed polarizers.

by first polishing the surface of a partly melted 1 cm cube and then etching it for 5 to 10 seconds in HF fumes, which turns the glass a dark iridescent blue or brown and the plagioclase a light brown, but leaves the pyroxene unaffected. Once the distribution of phases is mapped and stored in a computer, 0.1–0.2 mm is ground away from the surface and the polishing and etching process repeated. With many such sections a 3-D image of the crystal distribution is created (see Bryon et al. 1995, for description of technique).

Plagioclase chains are composed of groundmass crystals that are ~0.5 mm long, although plagioclase phenocrysts may be included. Chains are typically several crystals wide. The crystals appear to be attached to each other in random orientation. In one segment of chain containing 313 linked crystals, the angle between the pole to (010) and the axis of the chain was measured on 213 crystals that fell within the range accessible to the universal stage. The stereographic plot of these poles shows a completely random pattern (Fig. 3). The groundmass crystals constituting the chains in the partly melted samples are normally zoned from cores of An_{65}, but the minimum anorthite content at points of contact between grains is An_{59} (Philpotts et al. 1998). Before linking together to form chains, the crystals must therefore have had a growth period during which they were freely suspended in the magma.

Clustering together of like crystals in magmatic rocks is a common phenomenon for which Vogt (1921) coined the term *synneusis*, or swimming together. The cause of the clustering is uncertain, but because it usually involves like minerals attaching on prominent crystal faces, minimization of surface energies has been considered important (Vance 1969; Dowty 1980; Schwindinger and Anderson 1989). Fluid-mechanical forces acting on crystals in a magma that is flowing or through which the crystals are sinking have also been invoked to bring crystals together (Vance 1969; Schwindinger and Anderson 1989). In addition, resorption of a crystal can lead to a boundary layer of melt that is enriched in the dissolving phase, and if two such crystals were in close proximity, later crystallization from this enriched liquid could result in the crystals becoming bonded together (Hogan 1993). Linkage of crystals could also

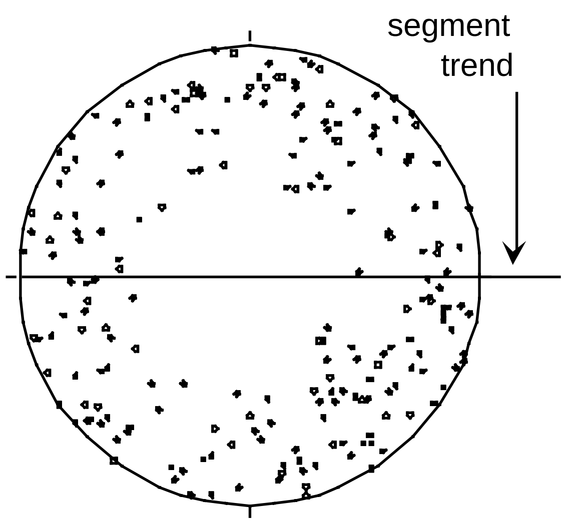

FIGURE 3. Stereographic plot of universal-stage measurements of the orientation of poles to the (010) plane of 213 of 313 continuously linked plagioclase crystals in the chain shown in Figure 2. Measurements are given relative to the local orientation of the chain axis (east-west in plot). One hundred crystals have orientations that fall outside the angular range accessible to the universal stage, thus creating the blind spot in the center of the plot. Crystals that can be measured are randomly oriented with respect to the local chain axis.

result from rapid dendritic diffusion-controlled crystal growth. Roeder et al. (1999) have described strings of chromite octahedra in MORB glasses, which they have been able to reproduce in rapid-crystallization experiments.

The zoning in the groundmass crystals that form the chains in the Holyoke basalt clearly indicate that the crystals grew independently prior to linking to form chains. Consequently, the crystal linkage did not result from rapid dendritic growth, as is also indicated by the lack of chains in the chilled margins. Nor does the zoning in these crystals indicate a period of resorption in the flow, which might have led to clustering. The phenocrysts do have a resorbed core, but these crystals constitute <5% of the rock and are not necessary for chain formation. Although the plagioclase crystals in the Holyoke basalt are linked together in random orientations, lowering of surface energies appears the most likely cause for their adhering to one another. Plagioclase crystals may initially have been brought in close proximity by convective flow, and later the growth of pyroxene crystals may have shepherded or bulldozed the plagioclase crystals together.

The pattern of chains forming the network can be determined only from serial sections and the 3-D models created from them. These models are time consuming to prepare, and unless very thin slices are removed, the linkage of chains from one layer to another is open to interpretation (Bryon et al. 1995). Two samples have been sectioned with considerable care, one from 47 m and the other from 74 m above the base of a 174 m thick section through the Holyoke flow in the Farmington River gorge at Tariffville, Connecticut. The composition of these two rocks indicates that they were formed, respectively, from the most compacted and the most dilated crystal mush in the flow (Philpotts et al. 1996).

The way in which the chains pass through a sample is difficult to illustrate in two dimensions. One of the best ways of visually tracing the chains through multiple layers is to view the serial sections in rapid succession. This can be done in animated mode for the 47 and 74 m samples at http://fermat.geol.uconn.edu/~philpott/. Figure 4, however, attempts to show, in perspective, a small part of the plagioclase-chain network in the 47 m sample; the network in the 74 m sample is similar. In both samples the chains branch every few millimeters. The chains thicken noticeably where they branch due to a larger number of crystals. The most obvious difference between the networks in the 47 m and 74 m samples is that the pore spaces between the chains are more open in the 74 m sample, as would be expected if, as the composition implies, this rock was formed from a dilated crystal mush. As will be discussed below, the chains in the 47 m sample also show a slight horizontal preferred orientation, which is an expression of the compaction the crystal mush underwent during solidification of the magma.

Because 3-D models constructed from serial polished sections take so long to prepare and because some interpolation between layers is still required, it was decided to image the chains using high-resolution X-ray computed tomography (CT) (Carlson and Denison 1992; Denison et al. 1997; Ketcham and Carlson, unpublished manuscript). Two juxtaposed 1 cm diameter cores were drilled from the 47 m sample discussed above. The core axes are parallel to the original vertical direction in the lava flow, and the present true north was marked on each core. The two cores were heated side by side in graphite crucibles at 1120 °C under a CO/CO_2 gas mixture equivalent to the QFM oxygen buffer for 16 hours and then quenched (Fig. 5). Graphite is used because it is not wetted by the silicate melt and therefore does not wick away the liquid. The core on the left in Figure 5 was used for the CT scan, and the one on the right for thin section analysis. The samples underwent 50% melting, but the network of plagioclase chains preserved the shape of the cores, and measurements of their length indicate they experienced no collapse during the experiments.

CT imaging used a microfocal X-ray source operating at 150 kV, 0.16 mA to collect a total of 216 slices, each 60 μm thick and comprising 3600 views. Data for a central slice and

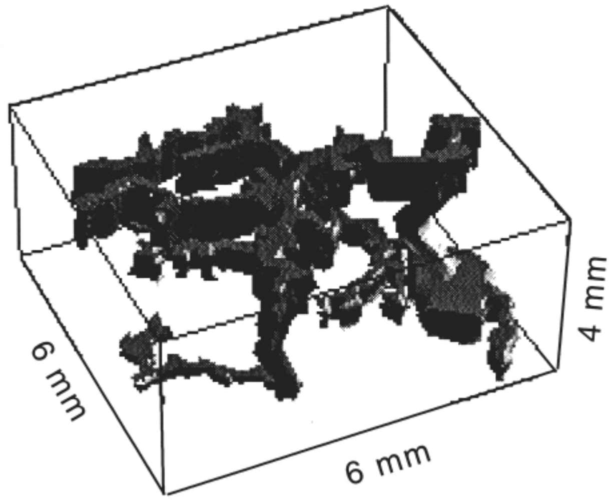

FIGURE 4. Three-dimensional model of plagioclase-chain network constructed from serial sections through partly melted cube of basalt from 47 m above base of Holyoke flow.

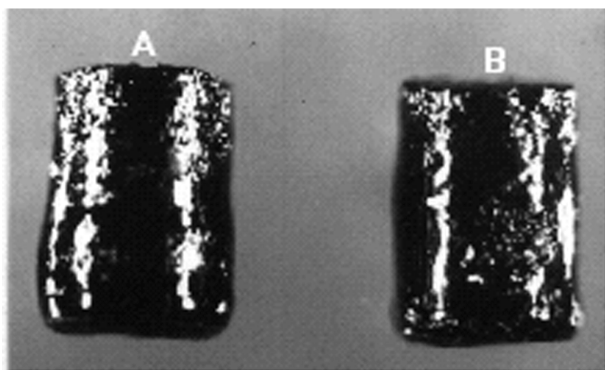

FIGURE 5. Two 1 cm diameter cores of Holyoke basalt after heating for 16 hours at 1120 °C. Both cores were drilled vertically and side by side in the sample from 47 m above the base of the flow. Core A was used for X-ray CT scanning and core B for thin section analysis. The samples were 50% melted.

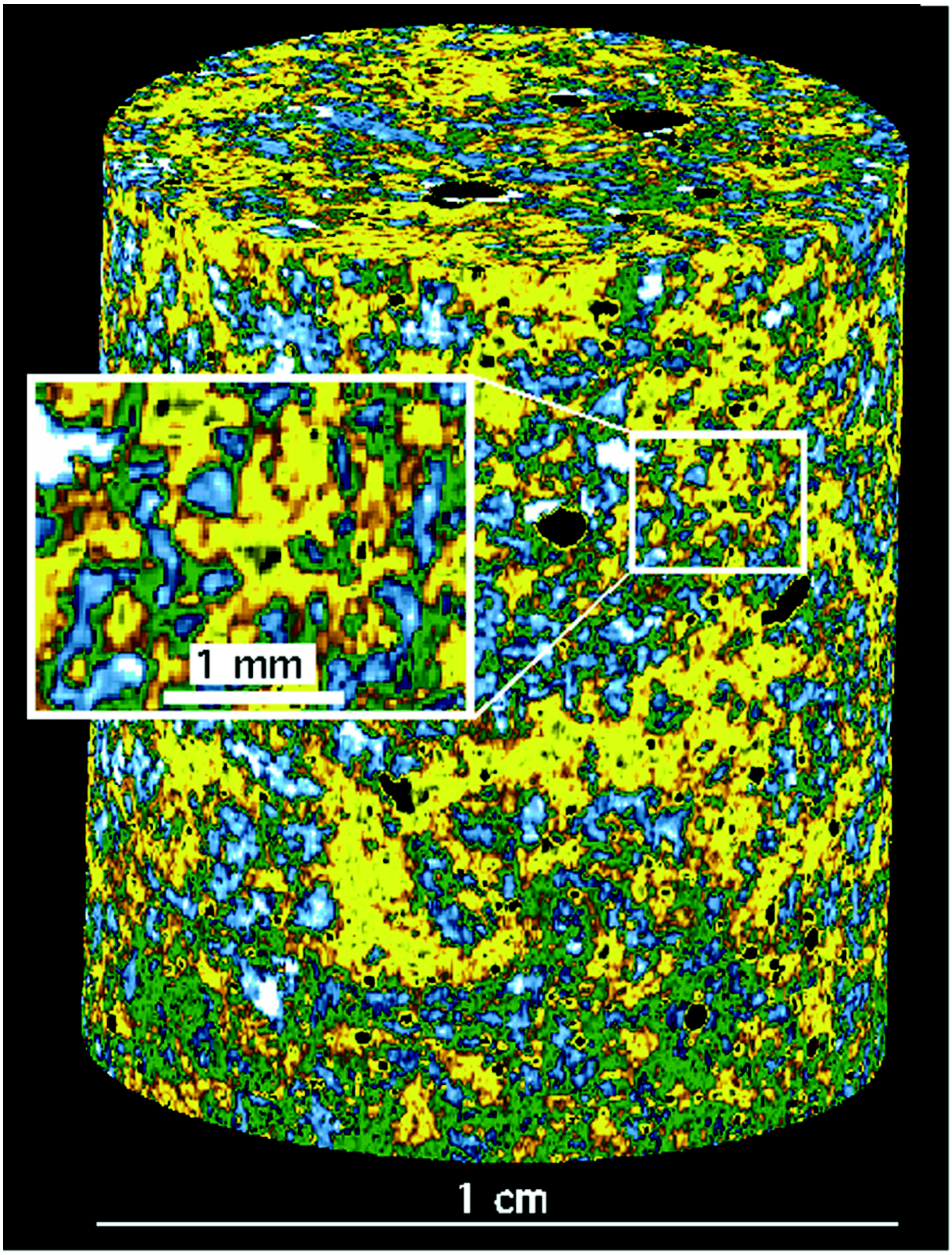

FIGURE 6. X-ray CT image of 50% melted rock cylinder. Plagioclase is rendered yellow, pyroxene light blue with darker halo, glass green, and bubbles black. The plagioclase crystals are linked together into chains that provide the partly melted cylinder with its strength, whereas the pyroxene occurs as separate crystals or small clusters. The inset shows at higher magnification how the narrow zones of melt separating plagioclase and pyroxene grains are clearly resolvable.

adjacent slices above and below it were acquired simultaneously; each set of three slices required 6 minutes of data collection. The experimental charge was enclosed in a small vial filled with powdered garnet, and measured X-ray intensities were corrected by comparison to a scan through the garnet powder alone; these measures optimized image quality by allowing the use of higher X-ray fluxes and minimizing beam-hardening artifacts.

The four phases in the experimental charge have different X-ray attenuation coefficients (from highest to lowest: pyroxene, glass, plagioclase, gas) making it possible to image these phases separately in the CT scans (Fig. 6). The individual plagioclase crystals constituting the chains are small (<0.5 mm long) and the zones of melt separating plagioclase from pyroxene crystals are no more than 0.1 mm wide, yet these zones are clearly resolved in the CT scan (inset, Fig. 6). Although these dimensions approach the limit of resolution for the technique, excellent images were obtained. Figure 6 shows a volume rendering of the CT data for the entire rock cylinder. The glass (green), which contains most of the large gas bubbles (black), everywhere separates the plagioclase crystals (yellow) from the pyroxene crystals (light blue). The plagioclase crystals are clearly linked to form long chains, whereas the pyroxene crystals tend to occur separately or in small clusters.

This difference in the distribution of plagioclase and pyroxene crystals is brought out more clearly in 3-D images showing the plagioclase and pyroxene crystals separately. This is done by rendering as transparent all but the desired phase in the CT image (Fig. 7). To avoid obscuring the distribution with too many superimposed crystals, only a small vertical, rectangular prism through the rock cylinder is shown. The plagioclase crystals are linked to form a network that connects throughout the entire prism, whereas most pyroxene crystals occur as separate grains or in small clusters. These images give a clear impression that a prism consisting of granular pyroxene crystals and melt would not be able to support itself, but one consisting of plagioclase chains and melt could. It should be noted that what is imaged in the plagioclase prism are not the individual crystals, which are quite small (see inset for typical size of crystal), but the plagioclase chains. The 3-D nature of the plagioclase network is more clearly visible when the prism is made to rotate. This animation is available at http://fermat.geol.uconn.edu/~philpott/. The plagioclase network is clearly the structure that preserved the shape of the rock cylinder during the partial melting experiment.

NETWORK MESH SIZE AND SHAPE DISTRIBUTION THROUGH FLOW

Although a single 2-D thin section cannot provide a complete picture of a 3-D network of plagioclase chains, it will intersect a sufficient number of chains to give an indication of what can be referred to qualitatively as the mesh size of the network, that is, the dimension of the smallest region enclosed by a continuous loop of plagioclase crystals. A cursory inspection of a series of partly melted samples from various heights in the flow reveals a significant change in mesh size with height. Figure 8 shows tracings from thin sections of plagioclase chains in partly melted samples that have all been heated at 1120 °C

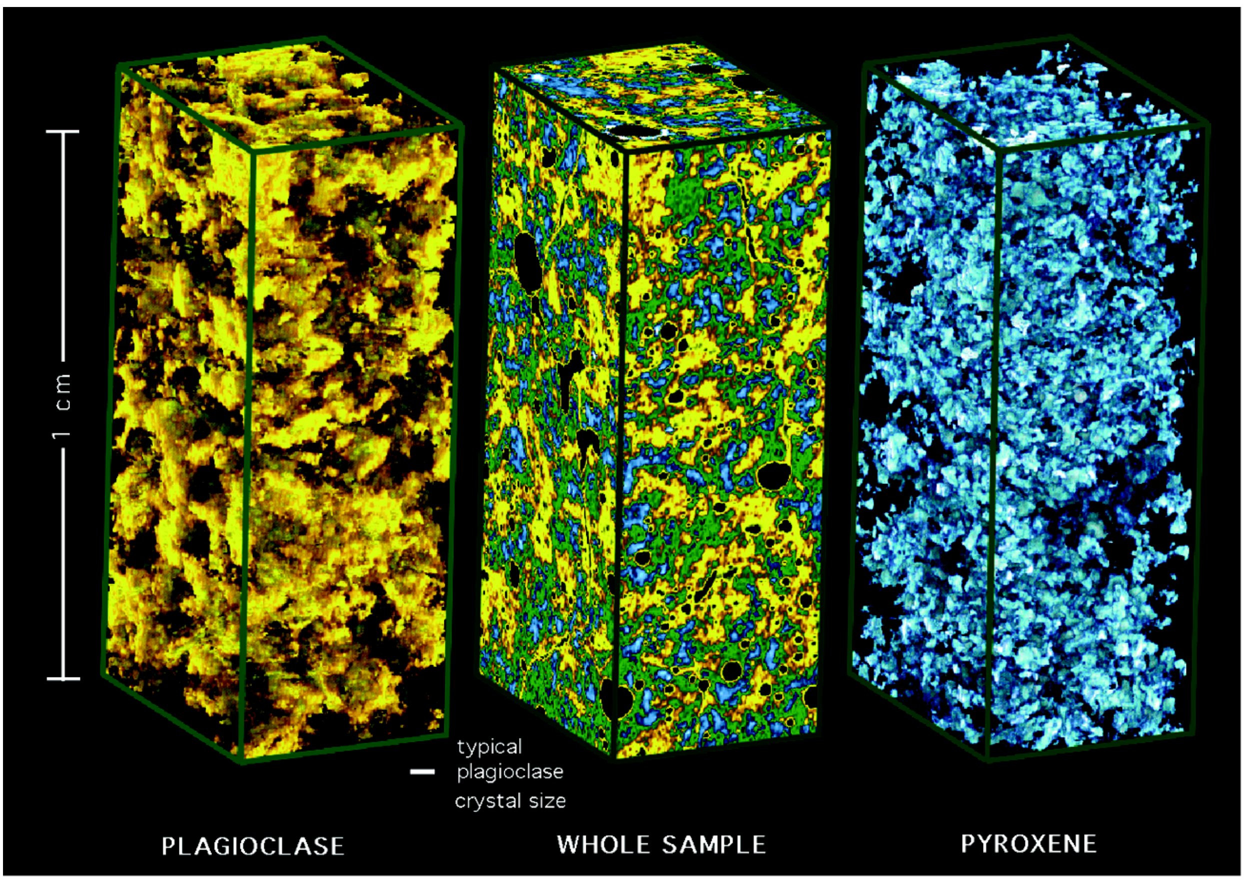

FIGURE 7. Three-dimensional CT images of plagioclase and pyroxene in vertical rectangular prism through the partly melted cylinder of basalt shown in Figure 6. The images of individual minerals are formed by rendering the glass and the other minerals transparent. Plagioclase crystals are linked to form chains that are continuous through the entire prism; pyroxene crystals tend to occur separately or in small clusters, which gives the pyroxene prism a granular appearance. The 3-D nature of the plagioclase network is more evident when the plagioclase prism is rotating. This animation can be viewed at http://fermat.geol.uconn.edu/~philpott.

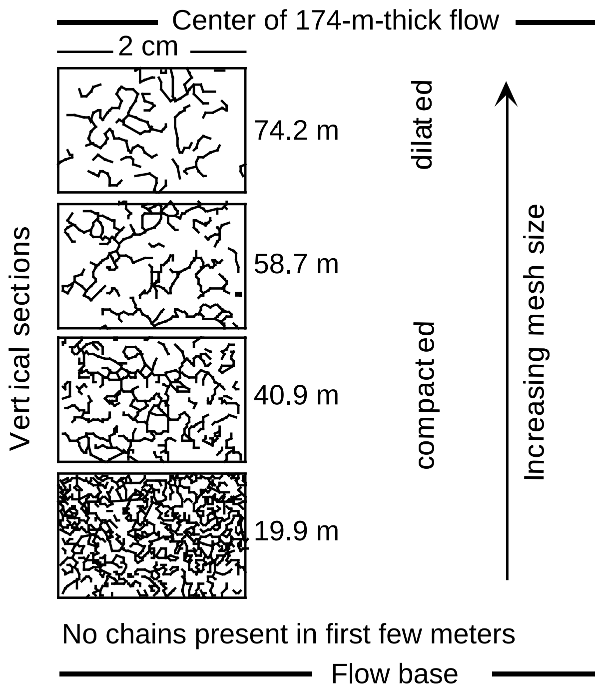

FIGURE 8. Tracings of plagioclase chains in thin sections of partly melted samples from various heights above the base of the 174 m thick section through the Holyoke flow at Tariffville, Connecticut.

for 16 hours. The network mesh size increases significantly with distance from the lower contact of the flow. The grain size of the rock over this same interval, however, remains essentially unchanged. We can draw the important conclusion, therefore, that although the slower cooling rate did not significantly affect grain size, it did affect the way in which the plagioclase chains linked together to form a network.

Variations in the mesh size of the network can be quantified by counting the number of plagioclase chains intersected along traverse lines through thin sections of the partly melted rocks. By traversing in both horizontal and vertical directions, differences in the shape of the mesh can also be quantified. Figure 9 shows the results of such measurements in partly melted samples from the lower half of the flow. To obtain a more representative sample of the network and to reduce subjectivity in the measurement, the following procedure was adopted. From each sample, two 2 × 3 cm petrographic thin sections were prepared. Two individuals then created two independent sets of chain tracings for each thin section. The frequency of chain intersections in these tracings were then counted along traverse lines that were spaced 0.33 mm apart. Each individual therefore counted the number of chains intersected along a total of 1.8 m of traverse in both the horizontal and vertical directions. The values shown in Figure 9 are the averages of the measurements made by the two individuals. The data indicate that the chain frequency in both the horizontal and vertical directions decreases systematically with distance from the lower contact of the flow. At 20 m above the base of the flow, which is where

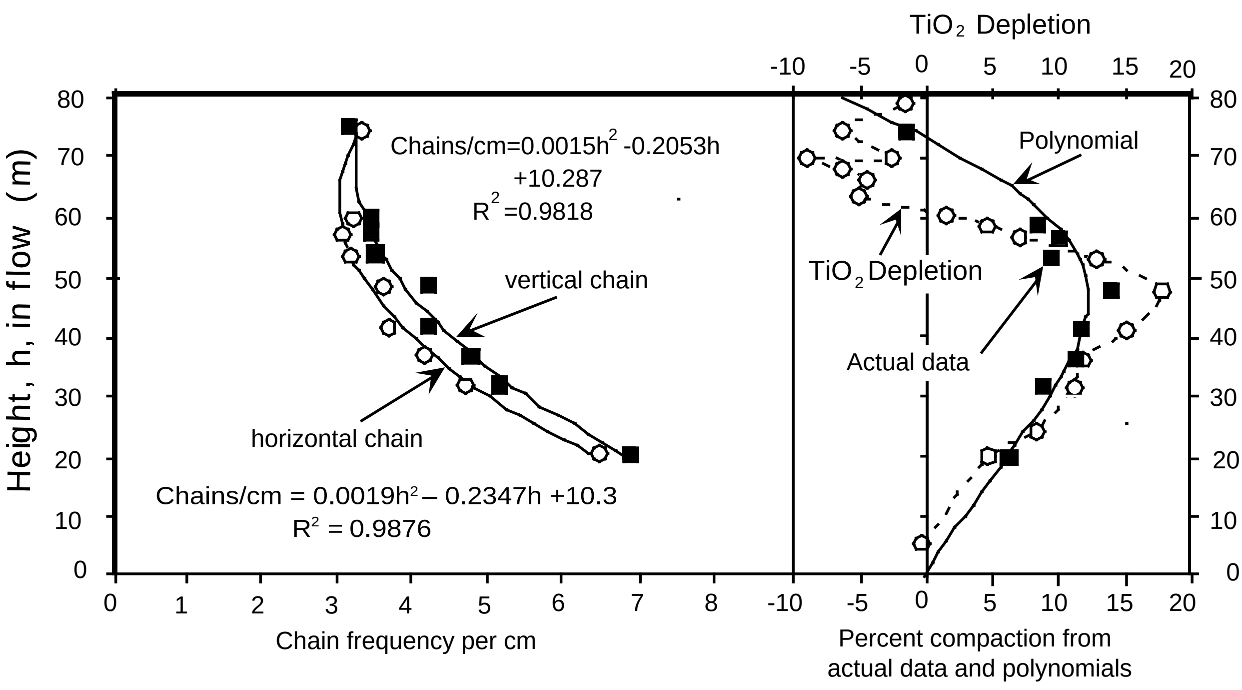

FIGURE 9. Variation in chain frequencies measured in thin section along vertical and horizontal traverses as a function of distance from the lower contact of the flow. The degree of compaction calculated from the difference between these frequencies and the variation in the deviation in TiO_2 from its initial value are also plotted against height in the flow.

we have the lowest sample containing plagioclase chains, 6.5 chains/cm are intersected, whereas at 76 m above the base this number has decreased to 3 chains/cm. The second-order polynomials shown in Figure 9 provide excellent fits ($R^2 > 0.98$) to the data for the vertical and horizontal chain frequencies.

Throughout the lower 60 m of the flow, the number of chains intersected along vertical traverses is slightly greater than along horizontal ones. If the chains initially were oriented randomly, the frequencies in these two directions would have been the same. The higher frequency in the vertical direction therefore implies that the crystal mush underwent compaction and that the degree of compaction can be calculated assuming that the present horizontal frequency is equal to the vertical frequency prior to compaction. The compaction can be calculated from the actual measured chain frequencies or from the polynomial fits to the two data sets. Both are shown in Figure 9. Having spent many hours drawing and counting chains, we realize that the measurements often involve rather subjective calls; for example, is a particular cluster of plagioclase crystals large enough to be considered a chain? Given the uncertainty in the individual measurements, the compaction calculations based on the polynomials may be the more reliable of the two methods, at least up to 60 m; we lack measurements, however, between 60 and 74 m, and so extrapolation is difficult.

The calculations indicate that the lower third of the Holyoke basalt at Tariffville has undergone compaction (Fig. 9), which supports the conclusion drawn previously from the chemistry of the flow (Philpotts et al. 1996). At 20 m above the base of the flow, the degree of compaction is 6%. The compaction increases with height, reaching a maximum of about 14% at 47 m above the base. Above this, the compaction decreases, and at 74 m the network is actually 2% dilated (negative compaction) by the liquid expelled from the compacted zone below.

The chemical variation through this same section of the flow indicates an almost identical pattern of compaction. Titanium is an incompatible element in this basalt and so its concentration is a measure of the amount of liquid present amongst the early crystallizing plagioclase and pyroxene crystals. Mass-balance calculations through the flow (Philpotts et al. 1996) indicate that the enrichment in Ti (and other incompatible elements) relative to the initial magma composition (0.98 wt% TiO_2) in the segregation sheets and dilated crystal mush in the central part of the flow is balanced exactly by the depletion in Ti in the compacted zone in the lower third of the flow. Differences in the TiO_2 content from the initial value indicate depletion or enrichment in residual liquid. The variation in the deviation in TiO_2 from its initial value with height in the flow is almost identical to the variation in the degree of compaction calculated from the chain frequencies. In rising from the base of the flow, TiO_2 shows progressive depletion until it reaches a maximum at 47 m, which is the height where the chain frequencies indicate that compaction reached a maximum. Above 47 m, the TiO_2 depletion steadily decreases, and at 74 m it is slightly negative, which is consistent with 2% dilation of the crystal mush indicated by the chain frequencies.

If the above arguments are correct, the measurement of the plagioclase-chain frequency provides, for the first time, a simple, direct means of measuring the degree of compaction in an igneous crystal mush. Given the importance of such a conclusion, it is worth considering carefully the assumptions involved. First, were the crystals present during the entire compaction process, and second, were the chain frequencies initially the same in all directions, that is, was the network initially isotropic?

Phenocrysts of plagioclase are present in the chilled margins and feeder dike of the flow (Philpotts 1998), and therefore plagioclase must have been crystallizing during the entire period from the initial eruption to the time groundmass crystals linked to form chains. Based on the partial-melting experiments, this linkage occurred when the basalt was only 25% crystallized. The densities of the phenocrysts and groundmass plagioclase range from 2680 to 2710 kg/m^3, which would have made them almost neutrally buoyant in the basaltic liquid, which had a density of 2680 kg/m^3 (Philpotts et al. 1996). This explains why the phenocryst abundance remains almost constant (3–5%) throughout the flow. Moreover, no compaction is likely to have occurred until the later-crystallizing pyroxene caused the density of the bulk solids to exceed significantly the density of the liquid. Based on modal abundances of plagioclase and pyroxene, this density contrast was 320 kg/m^3. Thus compaction would have begun only after a network of crystals was formed and when the bulk density of that network exceeded the density of the interstitial liquid. Because the plagioclase chains provided the interconnection that created the network, they must have been present throughout the period during which compaction occurred.

The second assumption, that the plagioclase-chain network was isotropic prior to compaction, is more difficult to prove. Recent theoretical and experimental work has shown that flow in heterogeneous materials can develop a layered structure (Koenders 1998). However, because the Holyoke flow is so thick, it would have taken many tens of years to solidify and would have been stationary by the time the groundmass crystals linked to form chains. No alignment of chains parallel to the eruptive flow direction is therefore expected. Even if a flow alignment had initially been present, thermal convection or the passage of rising gas bubbles would probably have destroyed it. If it had survived, however, the most likely place to see evidence of it would be in the detailed 3-D image of the rock fabric provided by the CT scans. For this reason we have attempted to quantify the orientation of the plagioclase chains from the CT scans of the 47 m sample.

The 3-D model of the 47 m sample, shown in Figure 6, was constructed from 216 horizontal CT scans. Serial sections were created through this model parallel to the vertical planes in both the north-south and east-west directions and in the horizontal plane. Although 256 serial sections were created in each direction, the differences between adjacent sections are very small. We therefore chose to map the chains in only every fourth layer, which was considered adequate to determine the "apparent" orientation and length of chain segments in these three directions. Most chains, of course, do not lie in the plane of sectioning, but pierce it. Chains that are normal to the section appear as equidimensional clusters and may be difficult to identify as chains. Most, however, exhibit an elongation (due to the finite thickness of the chains), which can be measured relative to a reference direction (horizontal or north). Unless a chain lies in the plane of sectioning, however, the angle and the length of the chain segment can be considered only as apparent, because they will also depend on the angle at which the chain pierces the plane of sectioning. However, if the network of chains is random or nearly so, the apparent measurements should affect all directions equally. Consequently, we have measured the orientation and length of all chain segments in the serial sections in the three mutually perpendicular directions. To obtain an overall measure of the network, we have weighted each angular measurement by the length of chain segment it represents. If the network is random, all directions should be represented equally. If they are not, the network exhibits a preferred orientation.

Each CT section was first imported into a layer in the Deneba *Canvas* drawing program. In a second layer the individual plagioclase chains were traced using the polyline drawing tool. The layer containing the polylines was then saved as a DXF file (Drawing Interchange Format). This file, when opened in Microsoft *Word*, appears as a list of numbers, in which the x and y coordinates of the end of each line segment can be extracted from a list of encoded data. These coordinates were imported into Microsoft *Excel*, where the length and the angle of each chain segment relative to the reference direction (horizontal in the vertical sections, and north in the horizontal sections) were calculated from the coordinates. The total chain length falling within ten-degree increments was then calculated. These lengths were plotted as percentages of the total chain length against the angle at the midpoint of each angular interval (Fig. 10). If chains are randomly oriented, each ten-degree segment should contain one-eighteenth (5.56%) of the total length of chains. The actual cumulative length of the chains within each ten-degree interval is plotted in Figure 10 as a deviation from this expected random percentage.

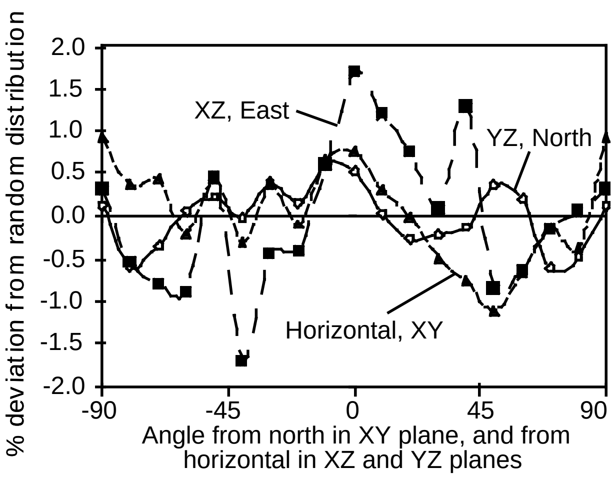

FIGURE 10. Percent deviations of the fractions of the total length of plagioclase chains in the CT-scanned rock cylinder falling within ten-degree intervals relative to the north direction in horizontal sections and to horizontal in vertical east-west (XZ) and north-south (YZ) planes. If chains were random, each ten-degree interval would contain one-eighteenth of the total length of chains. The distribution is very nearly random.

Figure 10 reveals that in all three directions, the chains are very nearly randomly oriented. In both the horizontal and the north-south vertical planes, the cumulative chain lengths falling within each angular interval are within about 0.5% of the random distribution. Only in the east-west vertical plane is there possibly a slight horizontal preferred orientation, but the maximum here is only 1.7% above what would be expected for a random distribution. Given the small sample size of the rock cylinder used for the CT scans, such a deviation from randomness cannot be considered significant, and thus we conclude that the network preserves no detectable flow orientation.

The lack of a significant alignment of plagioclase chains parallel to the horizontal plane, however, is surprising given that the 47 m sample underwent the maximum amount of compaction of all the rocks in the flow, as indicated by the difference in vertical and horizontal chain frequencies measured in thin sections and the whole-rock chemical compositions. The difference could be due to differences in the samples used for the thin-section and CT analyses, or to the method of imaging, i.e., thin section vs. CT scan.

The first two of these possible explanations can be tested by performing chain-frequency measurements on the tracings of plagioclase chains in the CT sections that were used for the angular measurements given in Figure 10. Each CT section samples a rather small area of rock, and so the number of chains intersected in each section varies considerably, but in every case the chain frequency in the vertical direction is greater than in the horizontal direction. The compaction calculated from these frequencies in ten CT sections ranges from 0 to 23.5% and averages 11.8%, which is the value obtained from the polynomial fits to the chain measurements made on the thin sections. Given the small sample size of the cylinder of rock used for the CT analysis, this is a remarkable fit.

The fact that 11.8% compaction did not produce a measurable preferred orientation of the chains suggests that, either chain rotation is a less sensitive means of detecting compaction than is the difference in horizontal and vertical chain frequencies, or compaction takes place by some process that does not involve chain rotation. Higgins (1991), for example, calculated that free rotation of crystals during compaction produces no significant alignment unless the compaction is extreme, which was certainly not the case in the Holyoke basalt. His analysis, however, applies to crystals that do not interact (see, for example, March 1932). Clearly the plagioclase-crystal chains in the Holyoke basalt are linked in a 3-D network, which might cause interactions that would bring about alignments (Meurer and Boudreau 1998). The network, however, could undergo compaction as a result of chains simply breaking. This could increase the vertical chain frequency relative to the horizontal frequency while causing no angular change. Until the compaction mechanism is identified, we are unable to decide between these two possibilities.

Although the chain-orientation measurements indicate a random network, they do not prove that the vertical and horizontal chain frequencies were the same prior to compaction, but it is the simplest interpretation. The fact that the calculated compaction matches so well the chemical data strongly supports this assertion. We thus chose to apply Occam's razor and conclude that the plagioclase-chain network was initially isotropic, and that during compaction the chains were moved closer together in the vertical direction without causing significant rotation of the chains. And, because the chains were present during the entire compaction process, the difference between the vertical and horizontal chain frequencies records the complete compaction history of the crystal mush.

PLAGIOCLASE CHAINS IN INTRUSIVE BASALTIC ROCKS

Plagioclase chains in flood-basalt flows form only in the slowly cooled interiors of thick parts of these flows. Slow cooling appears essential to their formation. Large intrusive bodies may, therefore, provide ideal conditions for their development, and if present, they may play a role in the differentiation of such bodies. We have made a cursory survey of the petrographic collections at the University of Connecticut and have found several examples of plagioclase chains in intrusive rocks that appear similar to the chains in the Holyoke basalt.

The intrusive bodies that come closest in composition and dimensions to thick flood-basalt flows are diabase sills. They also exhibit evidence of compaction of crystal mush in their lower parts, with segregation liquids forming lenses in their upper part (e.g., Shirley 1987). Clear examples of plagioclase chains are seen in samples from the Palisades Sill and Karoo dolerites. The sample from the Birds River, South Africa, shown in Figure 11 illustrates a well-developed ophitic texture, but the plagioclase crystals are linked together to form chains.

When rocks are coarse grained, a normal petrographic thin section is not likely to reveal enough of a network to make plagioclase chains readily visible. In such rocks it may be necessary to resort to examining polished slabs for evidence of chains. One of the coarsest grained igneous rocks, which is also widely used as a facing stone on buildings and thus is available in large polished slabs, is the Precambrian massif-type noritic anorthosite from St. Gedion near Lac St. Jean, Quebec. This rock exhibits a texture that is common in many massif-type anorthosites. Regions of pure anorthosite separate decimeter-sized ophitic patches of plagioclase and orthopyroxene (plus magnetite and ilmenite). The plagioclase crystals in the anorthositic part of the rock are several centimeters long and are randomly oriented, whereas those in the ophitic patches are ~1 cm long and have a sub-horizontal alignment. The larger crystals appear to play the same role as the plagioclase chains in the Holyoke basalt, and the ophitic patches are equivalent to the patches of mesostasis in the basalt. Compaction in the anorthosite results in the flattening of the ophitic patches and the alignment of the enclosed plagioclase crystals, but the plagioclase crystals in the intervening anorthosite remain randomly oriented because they are linked together in chains. Compaction in this rock could possibly be studied at the outcrop scale using the same chain-frequency measurements used at the thin-section scale on the Holyoke basalt.

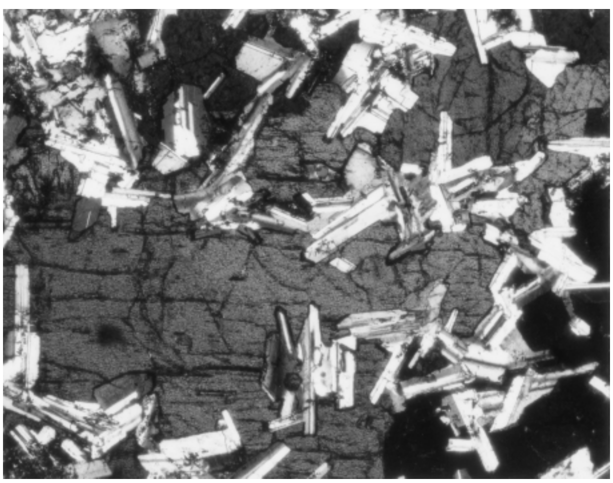

FIGURE 11. Karoo dolerite from the Birds River, South Africa. The plagioclase crystals, which are ophitically intergrown with pyroxene, are linked together to form chains. Width of field is 3.2 mm. Crossed polarizers.

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