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INTERPRETING IGNEOUS TEXTURES

A Field Trip to Outcrops in the Cambrian Wichita Mountains Igneous Suite

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INTRODUCTION TO THE GEOLOGY AND PETROLOGY OF THE WICHITA IGNEOUS PROVINCE

The bimodal Cambrian igneous rocks outcropping in the Wichita Mountains of southern and southwestern Oklahoma are the surface expression of the Southern Oklahoma Aulacogen. This rift formed on the southern margin of Laurentia in the Early Cambrian (~525-540 Ma) during the time that, what is now the PreCordillera of Argentina, drifted away, and the supercontinent of Rodinia was breaking up. These rocks include the Carlton Rhyolites and Wichita Granites which are metaluminous. The Carlton, and its equivalent in the eastern Arbuckles, the Colbert Porphyry, is the most widespread unit at the basement surface in southern Oklahoma. The granites are sheet-form A-types crystallized with relatively low H_2O. These Wichita granites all appear to overlie grabbroic units of the Raggedy Mountains Gabbro Group, and to underlie variously aged units of the Carlton Rhyolite Group.

The Glen Mountains Layered Complex of the RMGG is a body at least 65km in long dimension and has an estimated remaining thickness of 3-4km, petrologically similar to the Stillwater and Bushveld complexes. The GMLC is demonstrably older than the granites, and the granites have been intruded along an unconformity that beheads the Complex. Some hydrous gabbros (Roosevelt Gabbros) have intruded the GMLC and abut the overlying granites. There is evidence that some of the Roosevelt Gabbros are very close in age to the Mount Scott Granite, which is the most precisely dated of all the igneous rocks in the Wichitas, 534 +/- 1 ½ Ma (Hogan, Wright, and Gilbert, unpublished). This structural and stratigraphic setting, where gabbro lies below and rhyolite above, has resulted in the formation of a Crustal Magma Trap. Cycles of extrusion-intrusion, that is, rhyolite followed by granite, and finer-grained granite followed by coarser-grained granite, can be related to variations of magma driving pressure, in turn related to variations in rates of extension of the aulacogen. Finally, the whole suite of igneous rocks exposed in the Wichita Mountains can be thought of as a near-surface (low pressure) equivalent of an AMCG complex. The very large positive gravity anomaly association with the Wichita trend shows that most of the crustal column which formed during extension is filled with mafic magmatic rocks.

Because the crustal block that formed in the Cambrian rifting, and its once overlying Early and Middle Paleozoic sedimentary column, was upthrust during Pennsylvanian compression and eroded down to the igneous rocks, the topography now exposed was formed, and then buried, in the Early Permian. The final amazing "fact" is that the surfaces upon which we stand while investigating the SOA rocks have been at or near the Earth's surface at least 4 times previously. This justifies our use of present day geophysics in modeling the Cambrian crustal column.

INTERPRETING TEXTURE IN IGNEOUS ROCKS

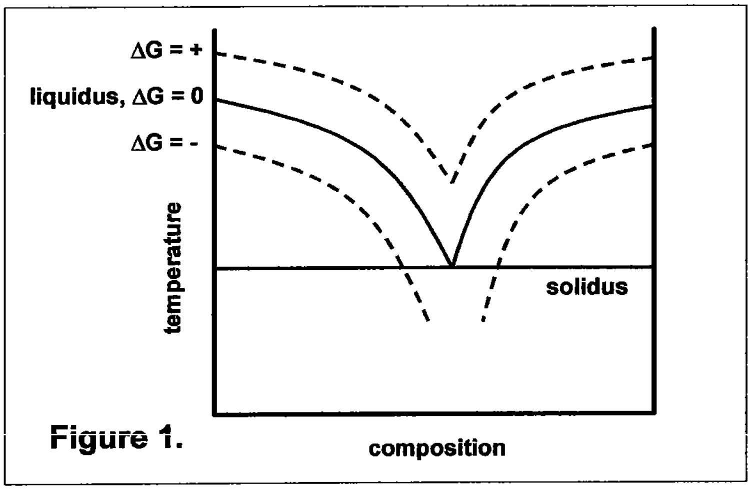


Figure 1.

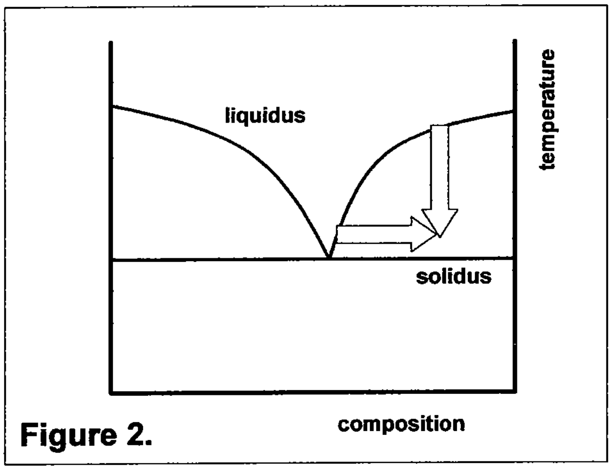


Figure 2.

Crystallization of any liquid proceeds only when and to the extent that the liquid is displaced from the liquidus (where ΔG = 0 for the equilibrium liquid ⇔ crystals) into the field of crystalline phases (where ΔG for the reaction liquid ⇒ crystals becomes negative: Figure 1). Some degree of supersaturation (i.e., a condition in which ΔG for the reaction above becomes negative, and melt persists metastably until crystallization commences) must occur for crystal nuclei to attain to a critical size for survival and growth. A simple schematic binary phase diagram (Figure 2) illustrates two ways in which a melt might be displaced from its liquidus surface into the field of crystals + liquid such that crystallization would ensue. One way is a change of composition, e.g., via assimilation, which could displace the original melt from its liquidus. The other is via cooling, which is a more generally applicable means of stimulating crystallization. Cooling below the liquidus surface without attendant crystallization raises the chemical driving force for the reaction liquid ⇒ crystals sufficiently to overcome the activation energy of diffusion, and it ensures that when crystals nucleate, the driving force is great enough to grow them to the critical size needed for survival.

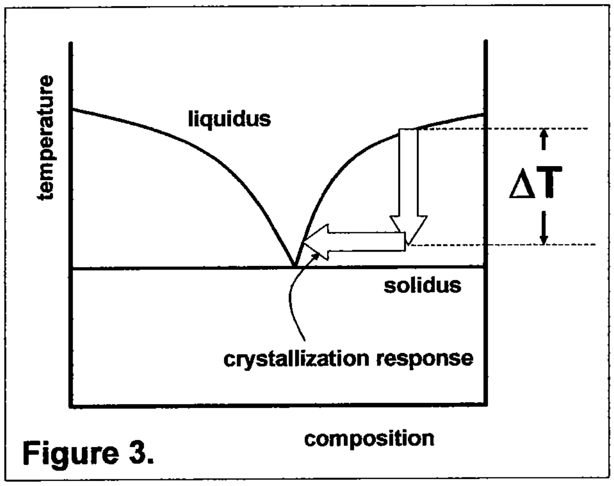
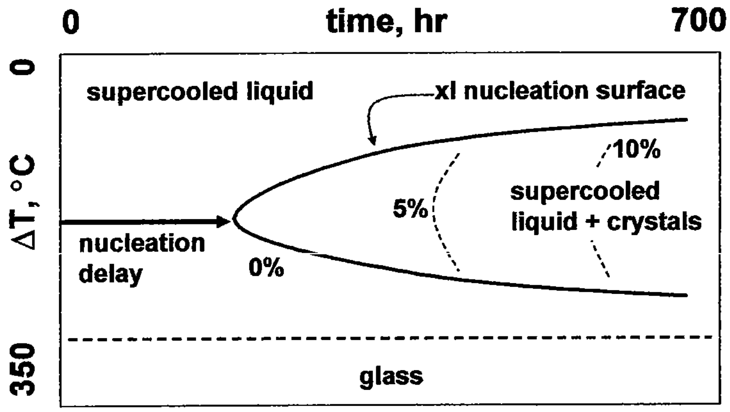


Figure 3.

The magnitude of liquidus undercooling is related to a variable ΔT, where ΔT = 0 at the liquidus, and ΔT increases with decreasing temperature (Figure 3). Silicate liquids in general, and high-silica liquids in particular, are slow to nucleate crystals. This is because nucleation requires diffusion, and diffusion of the T cations (Al, Si) is slow in granitic liquids at magmatic temperatures (their diffusion coefficients are on the order of 10^{-14} m^2/s). Consequently, high-silica melts may experience appreciable undercooling before crystallization commences. The texture of the resultant igneous rock is a primary function of ΔT. It is a secondary function of time, t, insofar as rapid cooling leads melts to experience greater liquidus undercooling before crystallization commences. However, it would not be correct to presume that slow cooling necessarily leads to crystallization at lesser values of ΔT.

Figure 4.



Crystal nucleation in the vapor-saturated haplogranite system has been studied at 200 MPa for the minimum composition $Ab_{38}Or_{28}Qz_{34}$ (Evensen et al., 2001; London et al., 2006). It is important to note that these experiments were vapor-saturated from the start, and that incipient crystallization began in and from the vapor. Hence, the data do not reflect the nucleation properties of melt unless that melt contains vapor surfaces (bubbles) that facilitate nucleation. With these caveats, the nucleation behavior for this composition and pressure is shown in Figure 4. The minimum in nucleation delay (~ 200 hrs) and maximum in nucleation density and growth rate occur at liquidus undercooling (ΔT) of 200°-250°C. Crystallization does not exceed 10% in experiments up to 600 hrs at any value of ΔT, and no crystallization occurs within 50°C of the liquidus up to 700 hrs. Though the melt composition is invariant (minimum), and no compositional gradients are discernable by EMPA in quenched glasses, the crystallization response is sequential: at ΔT = 200°C, coarsely skeletal K-feldspar nucleates and grows first, followed by graphic to spherulitic quartz-sodic alkali feldspar intergrowths, and lastly in some experiments, monophase quartz blebs. Once formed, crystals or clusters tend not to grow larger, but rather, new centers of nucleation and growth appear. The result is a sequential history of uniform crystal texture (size and habit).

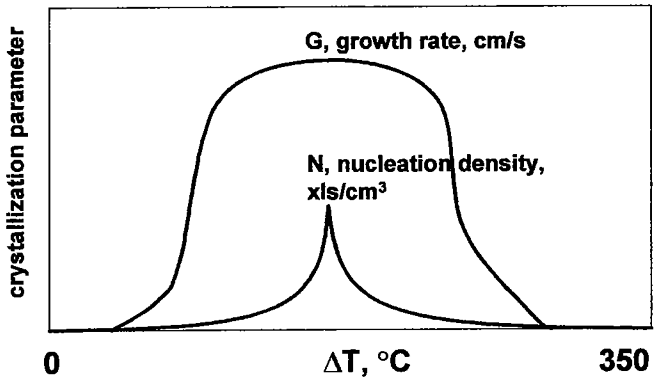


Figure 5.

In an important and so far unique study, Fenn (1977) determined the nucleation and growth characteristics of the alkali feldspars from hydrous silicate melts as functions of bulk composition, total pressure, and H_2O partial pressures. A schematic summary of his results is presented in Figure 5. The important observations from Fenn's work are these: (1) the growth rates are rather high over a wide range of ΔT, whereas the nucleation maxima are sharp and narrow with respect to ΔT; (2) maxima in growth rate and nucleation density occur near ΔT = 200°C; and (3) there is no crystal nucleation and growth within ~ 50°C of the liquidus. Thus, Fenn's (1977) results are fundamentally the same as those in the haplogranite system (Evensen et al., 2001; London et al., 2006). Fenn (1977) did not systematically determine the nucleation delay (the incubation period between the undercooling step, ΔT, and the onset of microscopically observable crystallization), but noted that it was days to weeks in general. Nucleation delays greater than 6 months have been reported in chemically evolved "pegmatitic" melt compositions (e.g., London et al. 1989).

High-silica leucocratic melts crystallize as granites, porphyries, and pegmatites. Each of these textures can be related to a specific region of ΔT-t on Figure 4, and to growth and nucleation rates versus ΔT on Figure 5.

Granite

Granite is characterized by texture uniform in crystal size, shape, and distribution. The conditions that foster this texture are those near the liquidus, but the experimental work done to date suggests that no crystallization of granitic liquids occurs within ~ 50°C of the liquidus temperature, regardless of time or ΔT. The region of ΔT = 50°-75°C has no sharp inflections in N (nucleation density), and so produces fine-grained (ΔT ≈ 50°C) to coarse-grained (ΔT ≈ 75°C) granites (Figure 6a,b).

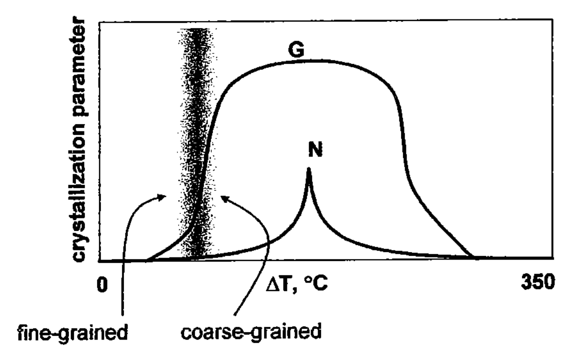


Figure 6a.

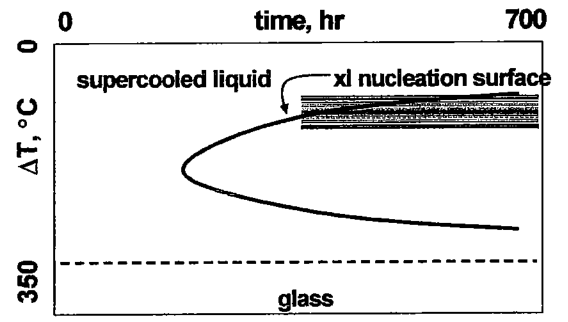


Figure 6b.

The advance of a crystallization front into a large body of melt to produce granite is illustrated schematically in Figure 6c. The key precepts of this diagram are (1) crystallization commences ~ 50°C below the liquidus temperature; (2) the final, complete solidification occurs ~ 50°C below the solidus temperature; (3) the magnitude of ΔT remains constant at a value of ~ 50°C, which requires that crystal nucleation keeps up (advances with) an isotherm. Because crystal nucleation is

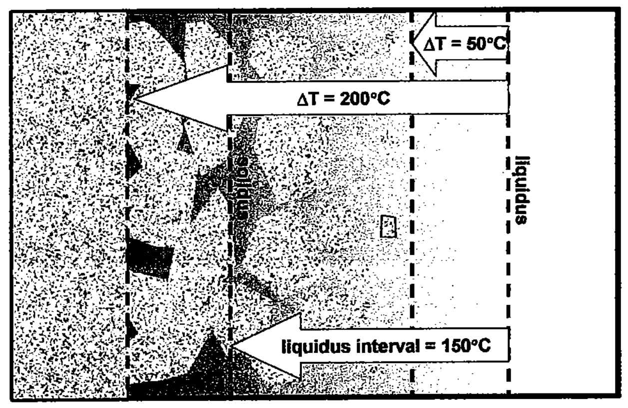


Figure 6c.

sluggish in granitic systems, the advance of the crystallization isotherm must be slower than the nucleation delay. This is why large magma bodies (ignoring restite or other pre-existing crystalline phases) are equigranular and uniform in texture: they are large enough that ***with slow cooling away from the margins***, the nucleation delay is less than the cooling rate. More rapid cooling at the margins of a pluton produces larger values of ΔT, and hence more variable texture. This is why pegmatites (discussed below) are always located along the margins of their source granite plutons.

Porphyry

The classical explanation of porphyritic texture is that two stages occur in the crystallization of the magma: first a deep plutonic environment that fosters slow growth through slow cooling, followed by a change and, in terms of the driving force for crystallization, an increase in ΔT that may be promoted by rapid ascent, by devolatilization of melt, etc.. This change has long been thought to promote fine-grained texture. Though Fenn (1977) suggested that porphyritic texture in granites might result simply from the different nucleation densities for albitic plagioclase (high) and K-feldspar (low), his own experimental data show why, precisely, a fine-grained groundmass should arise when an otherwise slowly cooling melt experiences a sharp increase in ΔT. The growth maximum is broad, but the nucleation density is a sharp spike, which as ΔT approaches that nucleation spike, means that the rock texture will become sharply and distinctly fine-grained compared to the crystal texture that preceded it at lower magnitude of ΔT.

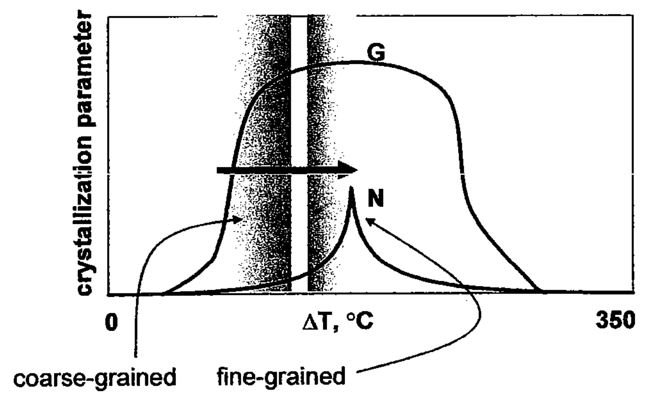


Figure 7.

Pegmatite

Though pegmatite is commonly thought of and defined as exceptionally coarse-grained granite, this definition is neither necessary nor sufficient. Here is a definition of pegmatite (London, monograph in preparation):

pegmatite (pĕg′ mə tīt′) An essentially igneous rock, mostly of granitic composition, that is distinguished from other igneous rocks by its extremely coarse or variable grain size, by sharply bounded zonation of mineral assemblages, by a prevalence of skeletal crystal habits or graphic intergrowths, or by anisotropic fabrics, which are mostly manifested as inwardly directed crystal growth perpendicular to the margins of the body.

Coarse grain size is not requisite for pegmatite. Granophyre, a fine-grained primary intergrowth of quartz and alkali feldspar that is abundant in the Wichita Igneous Province, is pegmatitic texture in subvolcanic felsic igneous rocks. Spinifex texture in komatiite and barred chondrules of olivine or pyroxene in meteorites are all manifestations of pegmatitic texture as well.

Fenn (1986) also provided the defining experimental explanation for the origin of graphic quartz-feldspar intergrowths. The term pegmatite was coined to apply to graphic granite, and that is appropriate: graphic granite is the only textural feature of pegmatites that is unique to pegmatites. All other textural attributes (exceptionally coarse grain size, zoned and monomineralic mineral distributions, banded or layered rocks, and unidirectional growth texture (a.k.a. comb structure) are found in hydrothermal and other metamorphic realms as well as in pegmatites.

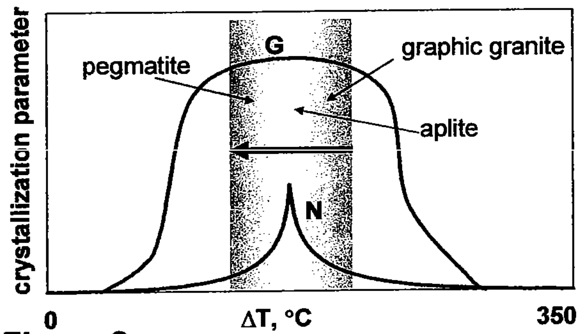


Figure 8a.

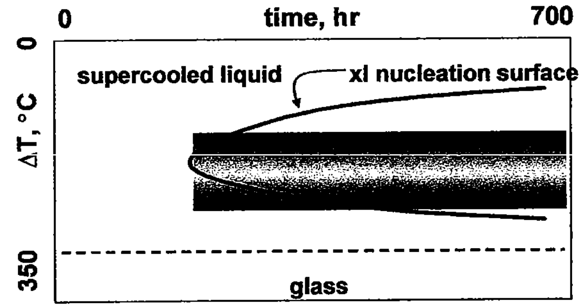


Figure 8b.

Graphic intergrowths of quartz and feldspar arise at values of $\Delta T \geq 200°C$ (Figure 8). This means that pegmatite crystallization must commence at ΔT greater than the "spike" in nucleation density. If this is true, then we might expect that, as pegmatite begins to crystallize, we would see first graphic granite, followed by aplitic (fine-grained) texture at the nucleation maximum, and then a return to exceedingly coarse-grained but non-graphic texture. This is precisely the sequence of textural zones in the famous layered granitic pegmatites of San Diego County, California (Figure 9).

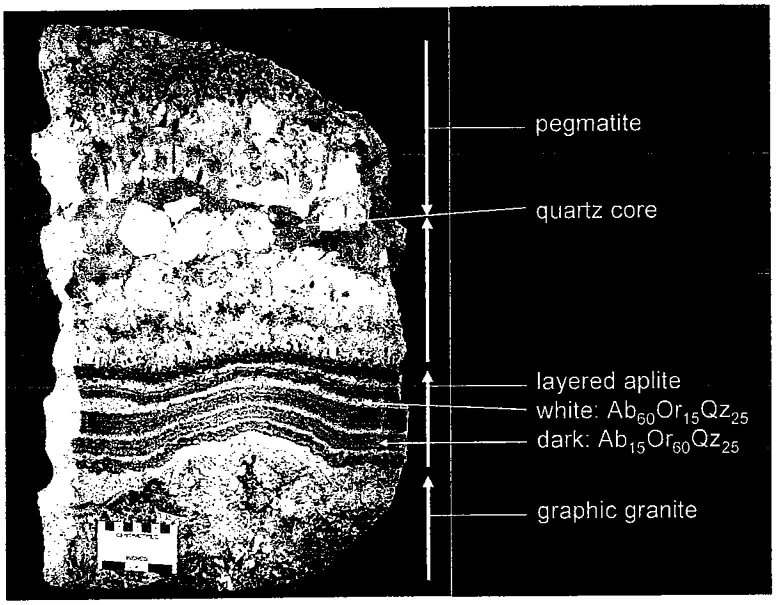


Figure 9.

OVERVIEW OF THE FIELD TRIP

The trip today will make 4 stops all emphasizing questions concerning igneous textures and what they might mean and how they can be interpreted. Ultimately, of course, this does relate to the intensive variables controlling crystallization. In that sense, this trip has general applicability to all intrusive igneous rocks wherever they may be found. The first 2 stops will concentrate on granitic textures and the last 2 stops will focus on gabbroic textures with the hope there will be enough time at each field trip site to be able to discuss each site in depth.

The first stop will be at the Willis Monument Works in Granite, OK. It will take about 3 hours driving time to get to this stop. This stop is the farthest from Norman. From there we will be working our way back toward Norman so that from the 4th and last stop it will only take about 1 ½ hours to get back. The second stop will be along old highway US 62 near Headrick. The third stop will be just east of US 183 south of Roosevelt, OK in the Glen Mountains Layered Complex, the oldest unit exposed in the Wichitas. The fourth stop will be in the Mount Sheridan Gabbro (one of the Roosevelt Gabbros), concentrating on gabbroic pegmatites, just west of OK115 in the Wichita Mountains Wildlife Refuge at the base of Mount Sheridan.

THE STOPS

Stop 1: THE WILLIS GRANITE QUARRY

Sec 26-T6N-R21W on the NW side of the town of Granite, OK.

Geology. The far northwest exposure of the Wichita Mountains (Headquarters Mountain, Walsh Mountain, Brown Mountain, and associated smaller unnamed peaks) displays fascinating outcrops of the older, fine-grained Headquarters Granite intruded by the younger coarse-grained Reformatory Granite. In fact, the Reformatory, named from outcrops located in the Oklahoma State Reformatory on the SE side of the town, is the coarsest granite (up to 1-2 cm) in the Wichita Granite Group. Xenoliths of Carlton Rhyolite are also found in this intrusive mix. Unpublished U-Pb dating of zircons by Hogan shows these rocks are all about 530 Ma.

Texture. The Reformatory Granite has been quarried here for many years and is the best-known and most widely used of Oklahoma granites for tombstones and facing stones. The samples we will see have been assembled, at our request, from their rock piles by the Willis Monument Works for our viewing. The fabrics seen in the polished slabs include granite, granophyre, and pegmatite. We are deeply appreciative of their willingness to accommodate this field trip and help make the stop efficient and illuminating. The slabs we will view, like all of their quarried and manufactured products, are available for purchase (if not already sold at the time of our trip).

The Reformatory Granite at this quarry possesses a strongly patterned fabric. In one slab (Figure 10a) we will see, 33% of the linear clusters of quartz are aligned in the same direction (Figure 10b), parallel to some planes of pure alkali feldspar (red lines, Figure 10b) that extend continuously across the surface of the polished block. Quartz aggregates occur in other directions, and linear to cuspate clusters can bee seen in this rock (e.g., blue lines, Figure 10b). In experiments (e.g., London et al., 1989, 2006), most quartz crystallizes sequentially after alkali feldspar. Thus, the traces of the quartz clusters may delineate the last 10-20% of melt in the rock.

From their pattern, one can reconstruct the size of the crystallization clusters in this granite. You may do so on this slab using grease pencils that will be provided.

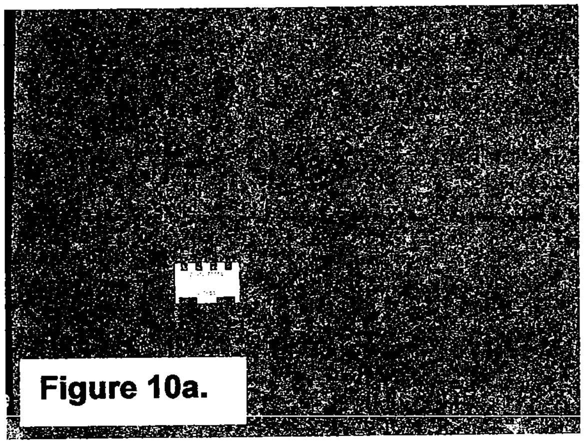


Figure 10a.

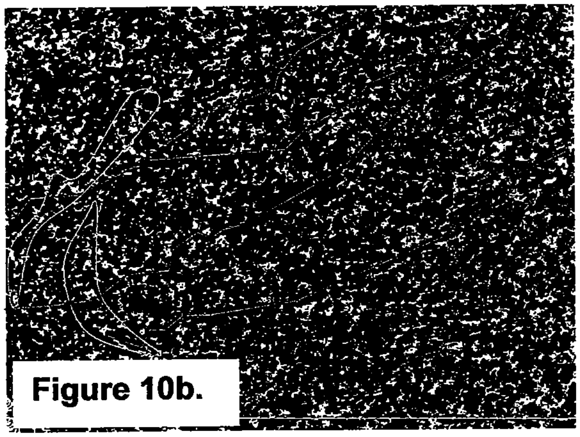


Figure 10b.

Granophyre (Figure 11a) occurs as small segregations and as dikes in the granite. We surmise that the dikes of granophyre represent liquids that were drained from interconnected melt pools. Note that in the polished slabs we'll see, however, the individual feldspars and quartz crystals in the granite appear to have grown into the granophyre (i.e., they are not truncated by it). In a few slabs, the granophyre surrounds small pegmatite bodies that contain all of the salient features of pegmatites: fine-grained aplitic bands, graphic quartz-feldspar intergrowths, quartz cores, some miarolitic, and a halo of hydrothermal alteration in the granite and pegmatite that surround the miarolitic cavities (Figure 11b).

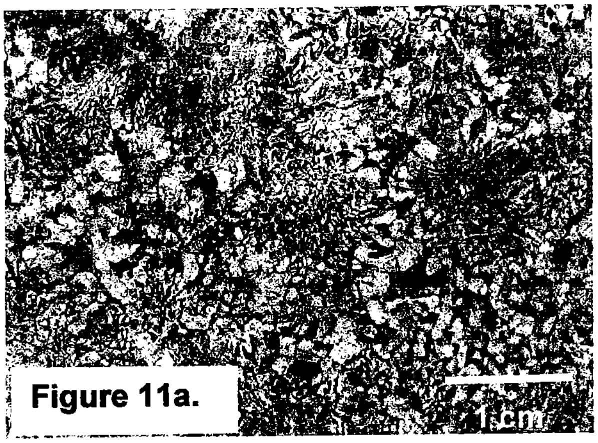


Figure 11a.

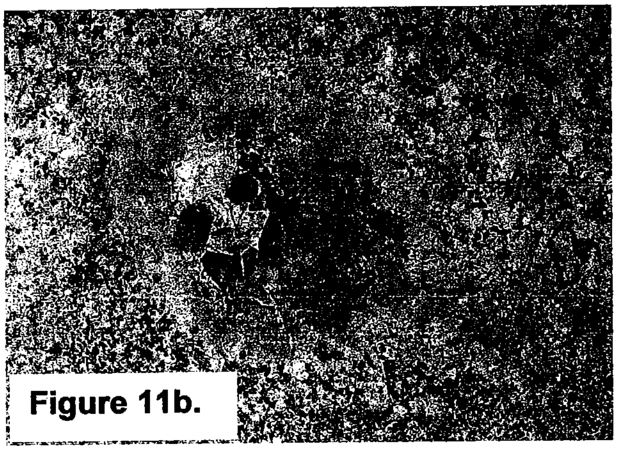


Figure 11b.

Stop 2: MIAROLITIC CAVITIES IN THE LONG MOUNTAIN GRANITE

NW-Sec21-T2N-R18W, along old US highway 62, just W of North Fork Red River

Geology. This outcrop has been tentatively identified as the Long Mountain Granite. The Long Mountain was named for its occurrence in Long Mountain N of US62 and east of the North Fork Red River. This granophyric granite is currently being quarried on the N side of Long Mountain by Meridian for aggregate. The cuts on both sides of the road show abundant miarolitic cavities 1 to 2" in diameter rather evenly spaced. Although the liquid from which this granite crystallized was relatively dry, texture indicates depth of crystallization must have been extremely shallow, and thus the pressure was very low, so that solubility of H_2O was exceeded.

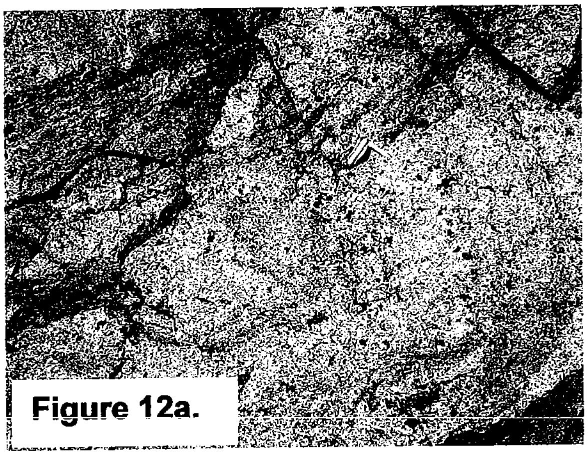


Figure 12a.

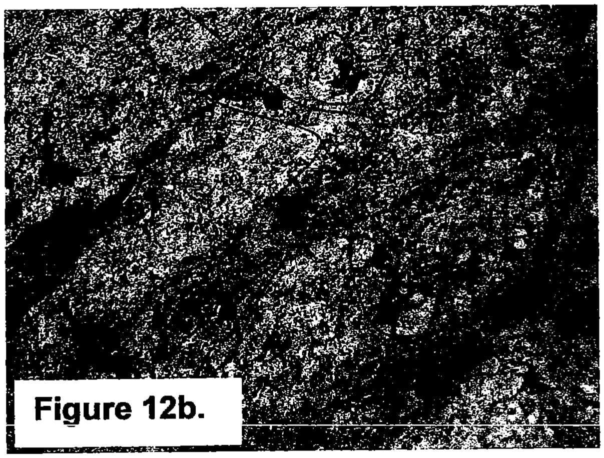


Figure 12b.

Texture. This is a miarolitic texture (Figure 12a,b). The word miarole stems from Italian, *miglio*, for millet grain. Whatever the connection, the term was first applied to the vesicular granites of Baveno and Cuasso al Monte, northern Italy. You will see that the granitic composition and granophyric texture of the rock evolve to predominantly feldspar adjacent to the miaroles, and that the miaroles themselves contain prismatic quartz crystals.

We will provide you with grease pencils so that you can delineate the portions of the rock that contain miaroles and their feldspar-rich selvages. You'll see that you can often trace the feldspar-rich selvages from one miarole to another, and hence, you can delineate the spatial distribution of the last ~ 15-20% of melt in the rock (e.g., red lines, Figure 12b).

Stop 3: L ZONE OF THE GLEN MOUNTAINS LAYERED COMPLEX

NE-Sec 21-T4N-R17W, just south of the section line road E of US183.

Geology. This outcrop is in an anorthositic zone where plagioclase is the cumulate mineral. The largest ophitic clinopyroxenes, up to about 30cm, in the Glen Mountains are known from this area. These pyroxenes are generally elongated in the plane of the layering. Layering is controlled by plagioclase lamination. Typically, plagioclase chadocrysts mimic the layering and, the crystal size to some degree, of plagioclase outside the pyroxene oikocrysts. Thus clinopyroxene nucleation and growth has been taken to be secondary to plagioclase. Adcumulus growth of both plagioclase and clinopyroxene have been taken to occur. Some zones show no mineral chemical zonation, suggesting that "equilibrium" conditions applied during crystallization. Degree of lamination varies from pronounced to indistinct. The textures at this occurrence have generally been described as heteradcumulates (see Powell's analysis in OGS Guidebook 23, 1986, for a more complete discussion)

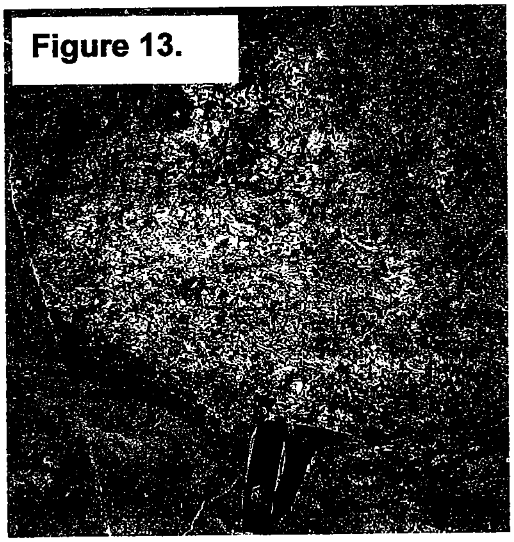


Figure 13.

Texture. The origins of lineated plagioclase and of ophitic texture in anorthositic gabbros are still debated. Ophitic texture exists in mafic plutonic rocks when large clinopyroxene crystals include many plagioclase crystals, whether oriented or not (Figure 13: sunlight reflects off of cleavage surfaces in an ophitic clinopyroxene; dark gray areas within the Cpx are mostly plagioclase). Though the lamination of plagioclase has long been considered a process of sedimentary accumulation (e.g., Wager, 1961, 1962), McBirney and Hunter (1995) challenged this concept on grounds that the layering does not always parallel the margins and likely surfaces within a crystallizing magma chamber. Plagioclase lamination has also been attributed to post-cumulate compaction, but this is not a probable scenario when the oriented plagioclase laths lie in ophitic clinopyroxene crystals: either the plagioclase was oriented upon attachment to the growing pyroxene crystal surface, or, less likely, the pyroxenes have acquired their ophitic texture by recrystallization (e.g., Ostwald ripening) that did not affect the plagioclase.

Stop 4: PEGMATITES IN THE MOUNT SHERIDAN GABBRO

SE Sec 5-T3N-R13W at the base on the SE side of Little Mount Sheridan in the restricted area of the Wichita Mountains Wildlife Refuge

Geology. The Mount Sheridan Gabbro is one of the 5 recognized members of the Roosevelt Gabbros. This gabbro set is distinct for the occurrence of primary biotite (phlogopite) and amphibole signifying hydrous conditions during crystallization. Its field relations are such that it can normally readily be distinguished from the anhydrous Glen Mountains Layered Complex. The Roosevelt Gabbros clearly cross-cut the GMLC and were also thought to be older than the Wichita Granite Group. Two of the Roosevelt Gabbros, the Sandy Creek, and the Mount Sheridan, have inconclusive to problematic contact relations with the overlying Mount Scott Granite. Some evidence indicates a nearly "simultaneous" age for these two rock units and some indicates that the gabbros might be slightly younger.

The Mount Sheridan Gabbro has mineralogic as well as textural layering. Earlier work on this textural layering suggested there had been tilting of the host GMLC layering before intrusion of the RG, which is consistent with an evolving rift setting.

Texture. What you will see here are leucocratic segregations within gabbro (Figure 14a) and dikes of the same leucocratic material that possess hypidomorphic granular texture, and where these dikes widen, the texture evolves sharply to long, hollow, and skeletal pyroxene crystals in a granophyric groundmass (Figure 14b,c).


Figure 14a.

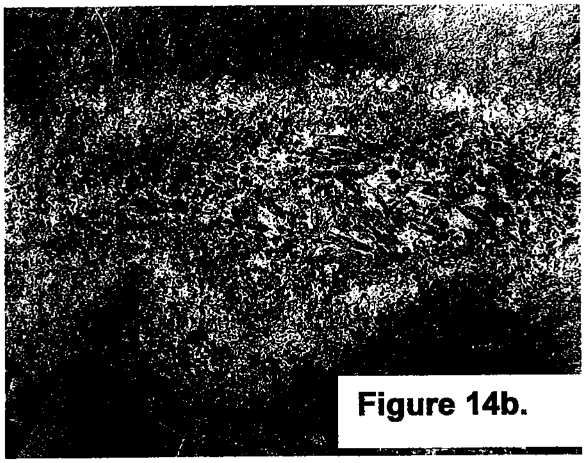


Figure 14b.

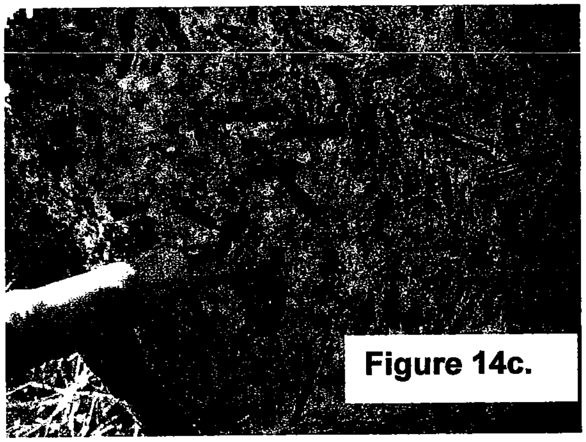


Figure 14c.

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