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On the cover—

Folded Flow Banding in the Carlton Rhyolite, Slick Hills, Southwestern Oklahoma

The view shows a tight, nearly recumbent flow fold of well-preserved flow banding in a rhyolite lava within the Carlton Rhyolite Group (Cambrian). The photo is from a thick lava flow exposed in the Blue Creek Canyon area of the Slick Hills, located on the northern side of the Wichita Mountains in Comanche County. In thin section, flow banding in the lava is visible on a microscopic scale but is overprinted by perlitic texture, formed during low-temperature hydration of silicic glass, and by a series of devitrification textures. For further discussion, see paper by Bigger and Hanson in this issue (p. 124–142); location of the flow fold with respect to other features of the lava flow is shown in figure 3 of that paper.

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DEVITRIFICATION TEXTURES AND RELATED FEATURES IN THE CARLTON RHYOLITE IN THE BLUE CREEK CANYON AREA, WICHITA MOUNTAINS, SOUTHWESTERN OKLAHOMA

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Abstract

The Carlton Rhyolite Group forms a widespread silicic volcanic sequence of Cambrian age in southern Oklahoma. Where the rhyolite is exposed in the Blue Creek Canyon area on the northern side of the Wichita Mountains, southwestern Oklahoma, it consists of a single, thick, flow-banded, porphyritic lava flow that was originally emplaced as glass. Primary textures are well preserved in the rhyolite on thin-section scales and can be used to construct a relative sequence of events related to the emplacement, degassing, and devitrification of the glassy lava. Degassing and vesiculation occurred both during and after emplacement, and large lithophysal cavities developed in certain horizons where high-temperature volatiles collected in pockets while the glass was still plastic. Small euhedral crystals on the walls of the cavities, now replaced by microcrystalline quartz, have shapes suggesting that they were originally β-cristobalite and β-tridymite; these high-temperature silica polymorphs were precipitated directly from magmatic vapors in the cavities.

Devitrification textures overprint delicate flow banding in the lava and developed in two stages. Primary devitrification occurred during initial cooling from magmatic temperatures and formed complex spherulitic intergrowths in distinct areas bound by sharp devitrification fronts. In places, coalescing spherulites grew out from a central point to produce large, spheroidal masses as much as 30 cm across that weather out preferentially from the host lava. Snowflake texture (micropoikilitic quartz surrounding feldspar microlites) formed in the spheroids after initial spherulitic crystallization. Rhyolite outside of the devitrification fronts initially remained glassy but underwent later, low-temperature hydration to form perlitic texture, which was followed by prolonged secondary devitrification, producing extremely fine-grained quartzo-feldspathic mosaics. Development of the devitrification textures can be explained by variations in the rates of crystal growth and nucleation within the glass, which were controlled by variations in volatile content and temperature during post-emplacement cooling.

Introduction

Cambrian rifting in the southern Oklahoma aulacogen was associated with the generation of large volumes of silicic magma, which formed the Wichita Granite and Carlton Rhyolite Groups. The granites and rhyolites chemically are A-type, or anorogenic, in affinity and have isotopic ages of ca. 525 Ma (Ham and others, 1964; Gilbert, 1983; McConnell and Gilbert, 1990). The Carlton Rhyolite is widespread

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in the subsurface of southern Oklahoma (Ham and others, 1964) and crops out in both the Arbuckle and Wichita Mountains. Although the rhyolites represent a major part of the silicic igneous activity related to the aulacogen, they have received relatively little detailed study. Ham and others (1964) showed that the Carlton Rhyolite Group is a thick sequence of lava flows, ignimbrites, and bedded tuffs. Anderson (1970) and Hanson (1977) provided additional petrographic details, and the chemistry and petrogenesis of the rhyolites have been discussed by Hanson and Al-Shaieb (1980), Gilbert (1982), and Weaver and Gilbert (1986).

As would be expected, there is abundant petrographic evidence that the rhyolites were originally glassy and have undergone pervasive devitrification. On the one hand, this is unfortunate, because it has tended to obscure some of the primary volcanic features in the Carlton Rhyolite. On the other hand, the widespread development of devitrification textures in the rhyolites makes them an excellent subject for the study of devitrification phenomena in silicic volcanic glasses. This is a topic that was pursued assiduously by the early petrographers but has received less attention in recent years.

The purpose of this paper is to describe a series of devitrification textures and related features present in a well-exposed part of a lava flow within the Carlton Rhyolite in the Slick Hills on the northern side of the Wichita Mountains. In spite of the antiquity of these rocks, the textures are remarkably well preserved on a thin-section scale, and it is possible to recognize a progressive sequence of events involved in the emplacement, degassing, and devitrification of the Cambrian lava. A more detailed discussion of the results presented here may be found in Bigger (1991).

Geologic Setting

The Slick Hills form a structurally complicated area north of the Meers fault, which separates them from the main mass of the Wichita Mountains to the south (Fig. 1). The hills consist primarily of folded and faulted sedimentary rocks of the Upper Cambrian Timbered Hills Group (Reagan Sandstone and Honey Creek Limestone) and the Cambrian–Ordovician Arbuckle Group (Donovan, 1986). These strata rest unconformably on the Carlton Rhyolite, which is exposed in two main areas in the Slick Hills. The most extensive rhyolite exposure is located in the Blue Creek Canyon area. Additional outcrops of rhyolite occur on Bally and Zodletone Mountains, to the northwest along strike (Fig. 1).

The study area is located near Blue Creek Canyon, where a large expanse of rhyolite is present to the east of Highway 58 (Fig. 2). On the west side of the road, the rhyolite has been juxtaposed against part of the Arbuckle Group along the Blue Creek Canyon fault (Donovan, 1982). The rhyolite there is directly overlain by the Honey Creek Limestone; absence of the Reagan Sandstone reflects paleotopography on the rhyolite surface during Reagan deposition (Donovan and others, 1986). Just east of the Blue Creek Canyon fault, the road partly follows a second fault that cuts the rhyolite and is a splay from the main fault (Fig. 2); rhyolite along the second fault shows outcrop and thin-section evidence of brittle shearing.

Rhyolite east of the road is overlain by strata of the Timbered Hills Group that dip to the northeast at about 10–15°. The rhyolite beneath the unconformity in that area is part of a single, thick, porphyritic lava flow characterized by a uniform phenocryst content. The lower part of the flow is cut by the fault running along the road, but the unit has a minimum thickness of 300 m. Flow banding is common and typically is roughly conformable with bedding in the overlying strata. The flow banding in many cases is deformed into variably oriented, tight to isoclinal flow folds with amplitudes as much as 4 m (see cover photo). The local complexity of the flow

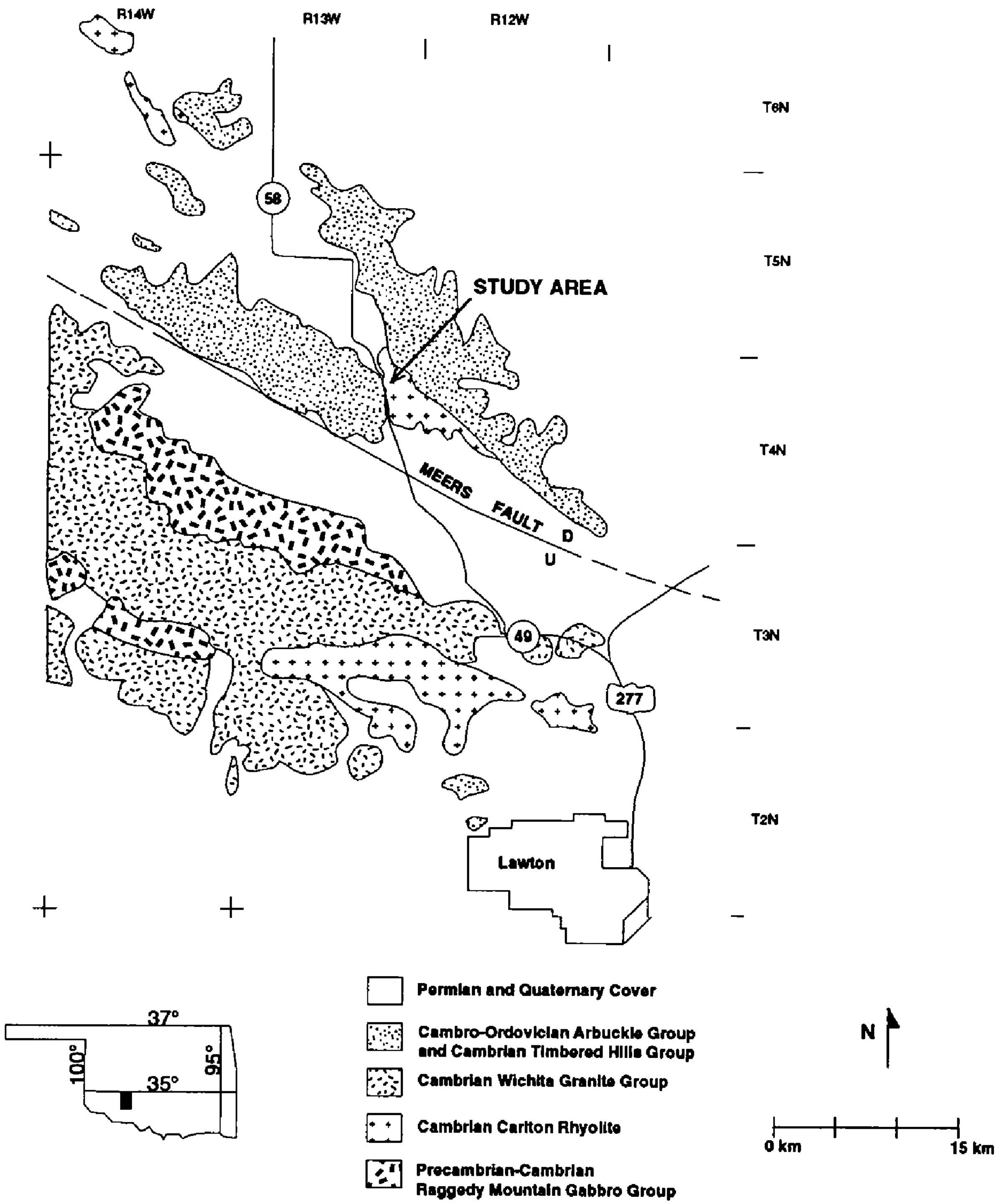

Figure 1. Geologic map of the eastern part of the Wichita Mountains and the Slick Hills. Location of study area is indicated. Offset on Meers fault refers to Pennsylvanian movement. Modified from Myers and others (1981).

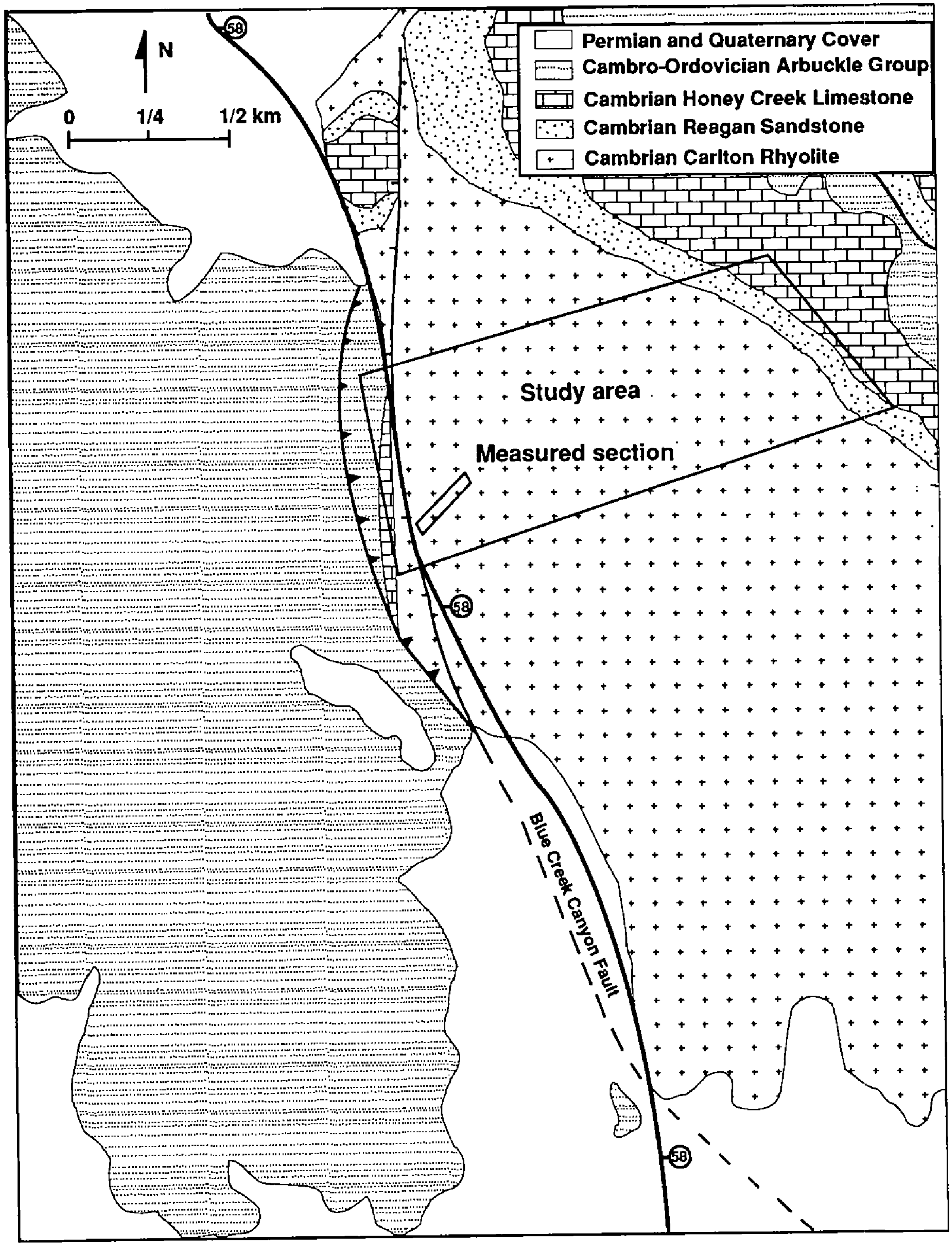

Figure 2. Geologic map of the Blue Creek Canyon area, showing the location of the studied rhyolite. Modified from Donovan and others (1986).

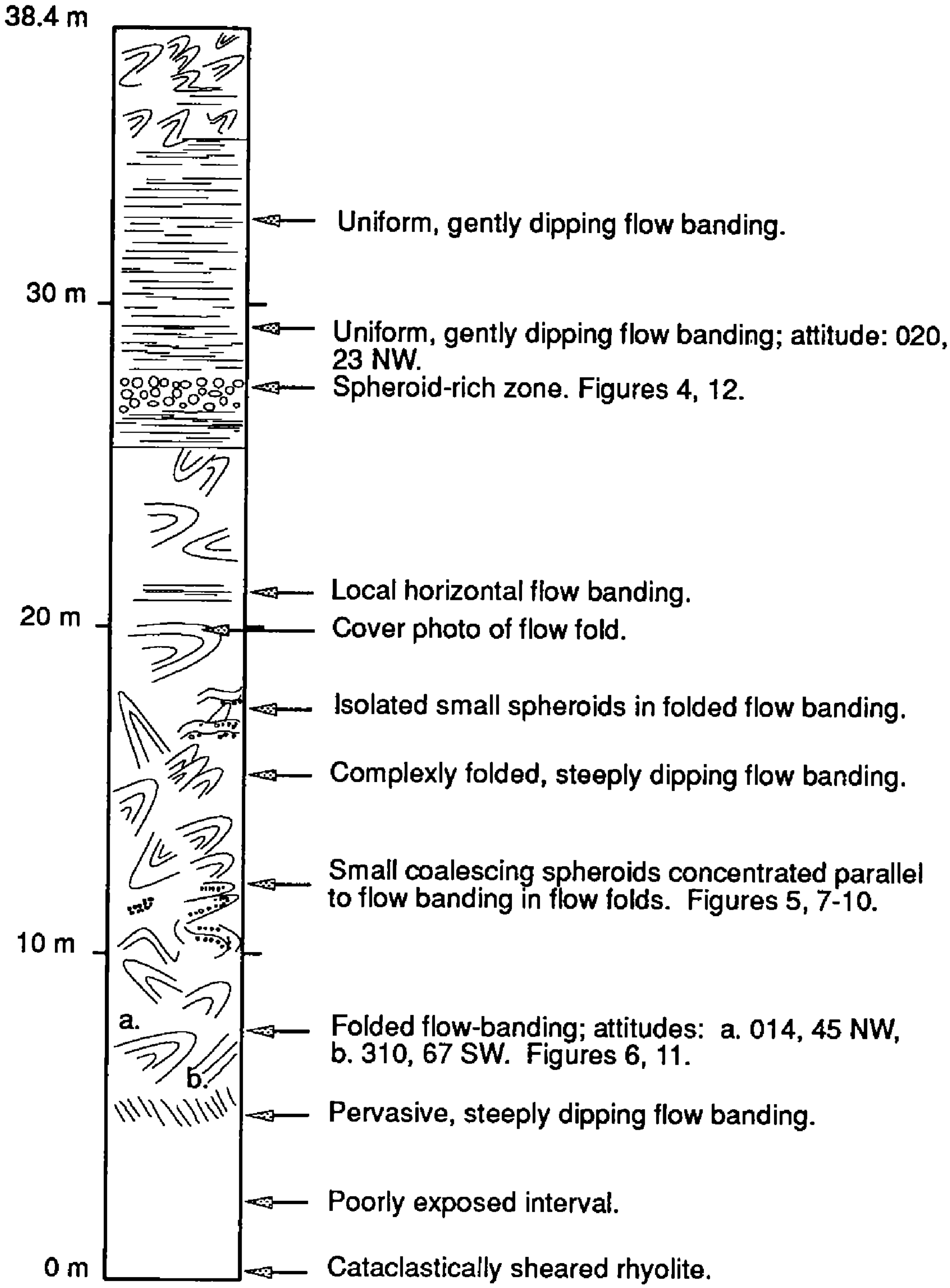

Figure 3. Measured section of part of the rhyolite lava flow (for location see Fig. 2). Flow banding and flow folds are shown schematically, and positions of photographs shown in text are indicated. The section is exposed in a stream valley that extends east from Highway 58 in sec. 11, T. 4 N., R. 13 W., 300 m south of the point where the road crosses the northern boundary of sec. 11.

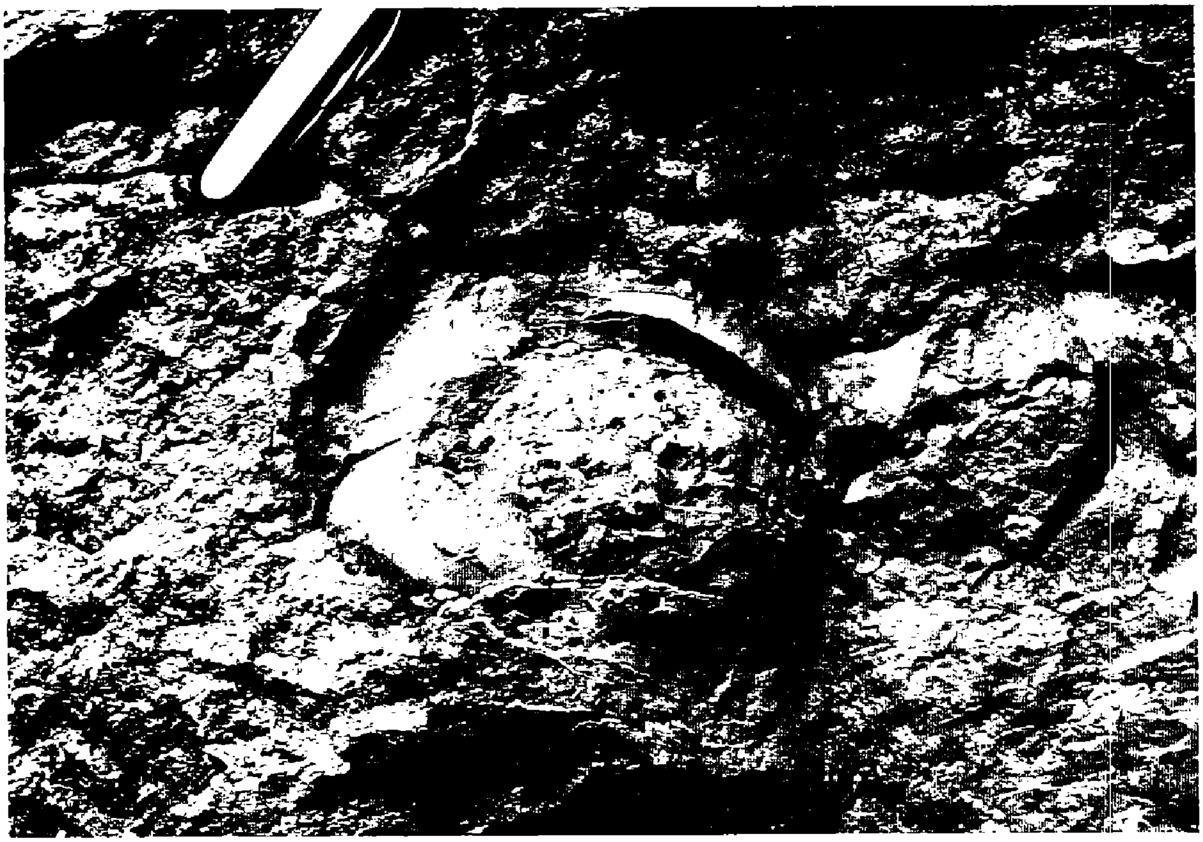

Figure 4. Spheroid weathering out preferentially from rhyolite. The spheroid is crossed by several subhorizontal quartz veinlets. Note the two-part concentric structure (see text for further discussion).

folding is illustrated in Figure 3, which is a measured section of a particularly well-exposed part of the lava flow in a steep-walled stream valley that extends northeast from the road (Fig. 2). Most of the petrographic observations discussed in this paper are from samples collected from the measured section.

A striking feature of the rhyolite in the measured section is the presence of spheroidal masses that weather out preferentially from the adjacent rhyolite and are as much as 30 cm in diameter (Fig. 4). The spheroids occur in abundance in three separate horizons within the flow (Fig. 3). In the lower two horizons, they are ≤5 cm in diameter and are aligned in bands that are affected by flow folds. The larger spheroids are present in the uppermost horizon, where they occur in a distinct, laterally continuous zone 1.5 m thick in part of the flow showing uniform, gently dipping flow banding. The spheroids in all three horizons commonly coalesce with nearby spheroids and have sharp contacts against the adjacent matrix. They cut directly across the flow banding, showing that they developed after flow of the lava had ceased. A concentric structure is visible in hand sample and appears to reflect a two-stage growth process, with an inner core having a hummocky surface, surrounded by a featureless outer rim (Fig. 4).

Lithophysal cavities partly or completely filled with microcrystalline quartz occur within many of the spheroids; where these cavities are only partly filled, they are lined with drusy quartz crystals. The smaller spheroids have small, relatively spherical cavities near their centers. In the large spheroids, the cavities are as much as 10 cm in length and tend to be more irregular and lenticular in shape; two or more cavities may occur within a single spheroid. Lithophysal cavities form during the primary cooling of silicic lava after flow has ceased but while the glass is still plastic (i.e., at temperatures above the softening point for glass). They develop in response to continued exsolution of gas from the cooling flow, coupled with the volume decrease attendant upon magma solidification (Wright, 1915; Ross, 1941; Westrich and others, 1988). In the present case, the restriction of the lithophysal cavities and the associated spheroids to certain horizons suggests that these features developed in parts of the flow in which volatiles had preferentially concentrated during emplacement.

General Petrography

The rhyolite contains 10–15% phenocrysts and glomerophenocrysts as much as 4.5 mm in length set in an aphanitic groundmass that in thin section is seen to consist primarily of very fine-grained, intergrown quartz and feldspar. Phenocrysts are predominantly plagioclase and microperthitic microcline, with small amounts of iron-titanium oxide. Crystals of a primary ferromagnesian mineral, probably pyroxene, have been completely replaced by chlorite ± leucoxene. Zircon is a common accessory phase. Quartz phenocrysts are absent, which is typical of the Carlton Rhyolite in this area (Hanson, 1977).

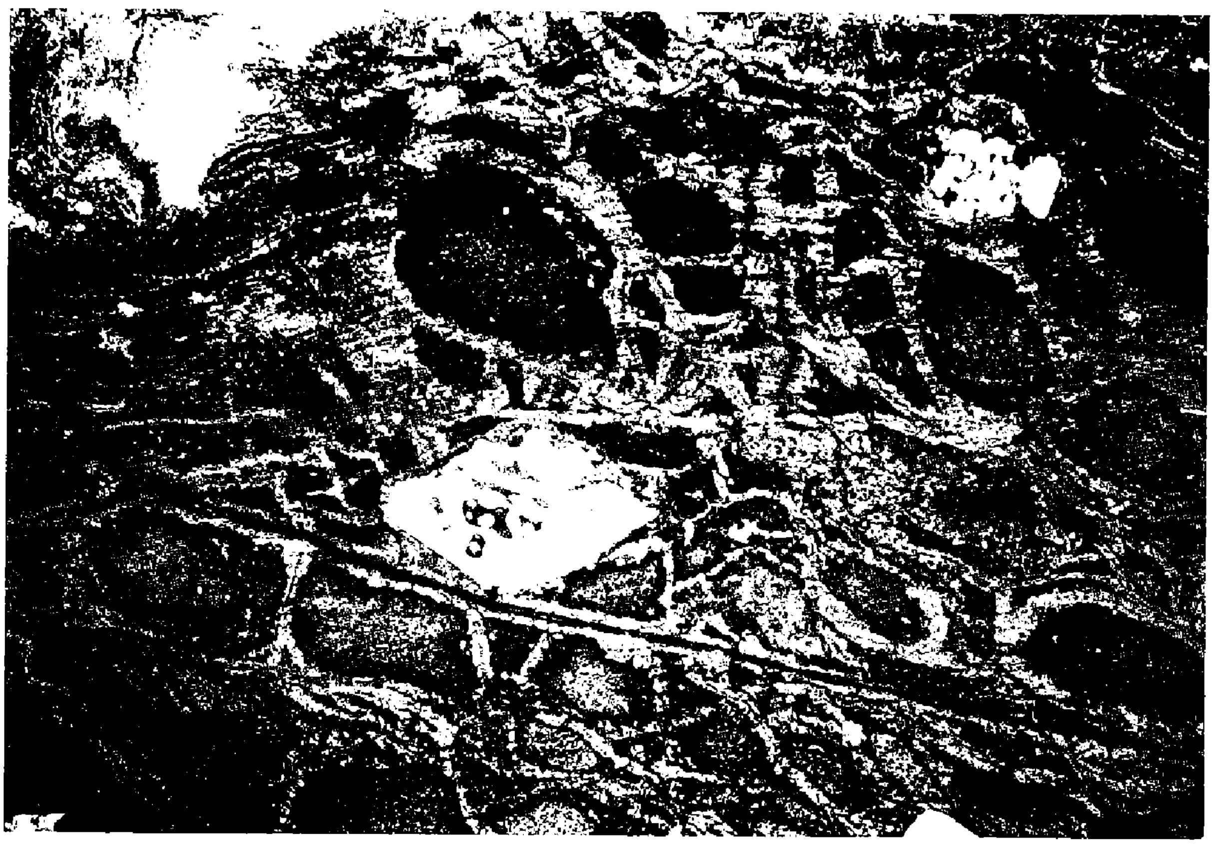

Figure 5. Photomicrograph of delicate flow banding overprinted by perlitic texture. Two partly resorbed feldspar phenocrysts are visible. Plane light; length of field of view is 9 mm.

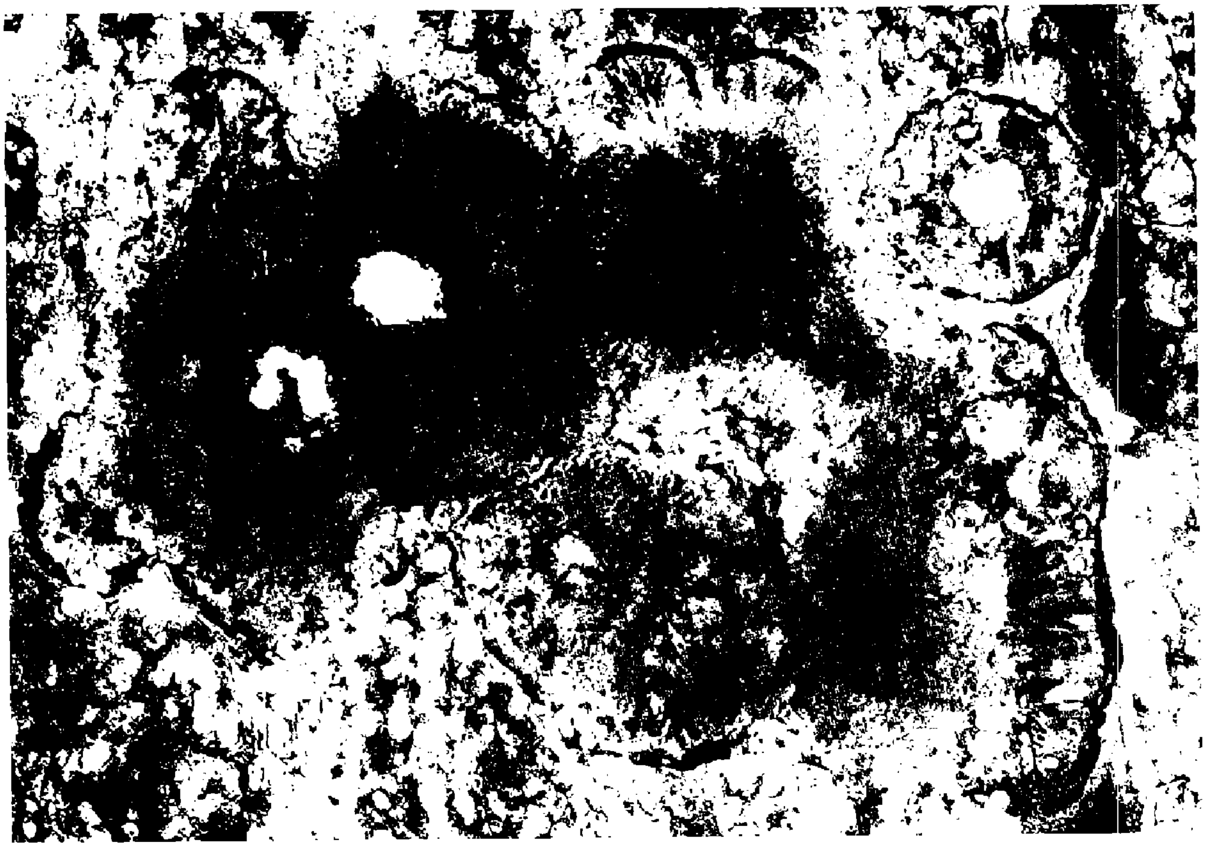

Figure 6. Vesicles and spherulites in rhyolite groundmass. Three of the spherulites have nucleated on small, spherical vesicles filled with quartz. The rims of the spherulites are outlined by oxide dust. Two of the vesicles to the left of center are close together, so that the associated spherulites have partly coalesced. Smaller, lighter colored spherulites have nucleated on the rims of some of the larger spherulites; a particularly good example is visible just to the right of upper center. Plane light; length of field of view is 1.75 mm.

Low-temperature alteration products are prevalent in the rhyolite. Hematite is common as a lining of fractures and as dust in the groundmass, and parts of the groundmass are rich in very fine-grained, disseminated flakes of chlorite. The chlorite has a somewhat higher birefringence than usual, possibly reflecting a high iron content (Deer and others, 1966, p. 238), and its identification has been confirmed by X-ray diffraction.

A very delicate flow banding generally is visible in thin section in plane light and is defined by thin laminae of differing color (Fig. 5), which are affected by numerous isoclinal microfolds. Relations of other microscopic textures to the flow banding help define a relative sequence of events. Small vesicles, now filled with quartz and/or chlorite, are present in some thin sections and represent two stages of degassing of the lava. Irregular, highly elongate vesicles are aligned in the flow banding and formed while the lava was still flowing. Other vesicles, in contrast, are nearly perfectly spherical (Fig. 6) and cut directly across the flow banding, indicating that they formed after flow had ceased.

In many parts of the groundmass, the quartz and feldspar form spherulitic devitrification products, which are described below. Where these delicate and complex spherulitic textures are absent, the groundmass exhibits a well-developed relict per-

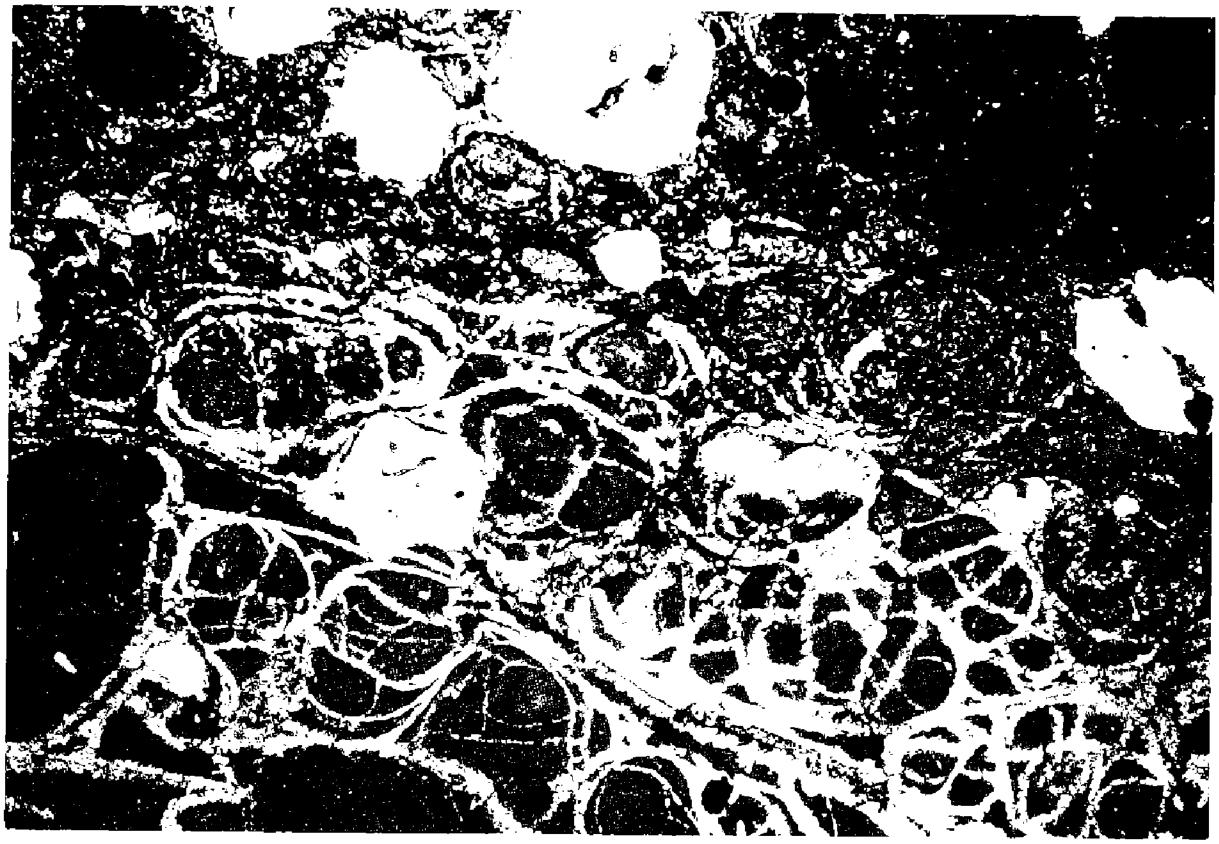

Figure 7. Typical perlitic texture, which in this case has completely obliterated the original flow banding. Several feldspar phenocrysts are visible. Plane light; length of field of view is 9 mm.

litic texture, which is defined by a series of concentric cracks. The perlitic cracks are outlined by light-colored, very fine-grained quartzo-feldspathic material and surround cores richer in secondary chlorite. The perlitic texture cuts directly across the flow banding (Fig. 5) and, in many cases, partly to completely obliterates the delicate flow bands (Fig. 7). Perlitic texture is a common feature of glassy silicic lavas and develops by slow, low-temperature hydration of the glass; the cracks form due to the increase in volume that occurs during hydration (Ross and Smith, 1955; Friedman and others, 1966).

Tiny, acicular microlites with relatively high relief are abundant in some parts of the groundmass. These crystals are too small to be identified with certainty, but they are similar in form to the pyroxene microlites that are common in many silicic glasses and have been described by Ross (1962). Some have curved shapes and resemble thin hairs; these may be termed trichites (Ross, 1962). They appear to be partly oxidized to extremely fine-grained granules of opaque material. In some places, the microlites are aligned in the flow planes and therefore must represent an early period of nucleation and limited crystal growth during emplacement of the flow. In most cases, they are randomly arranged and must have crystallized after flow had ceased.

Lithophysal cavities have sharp contacts with the adjacent groundmass in thin section, and small bodies with spherical to isometric shapes are present on cavity

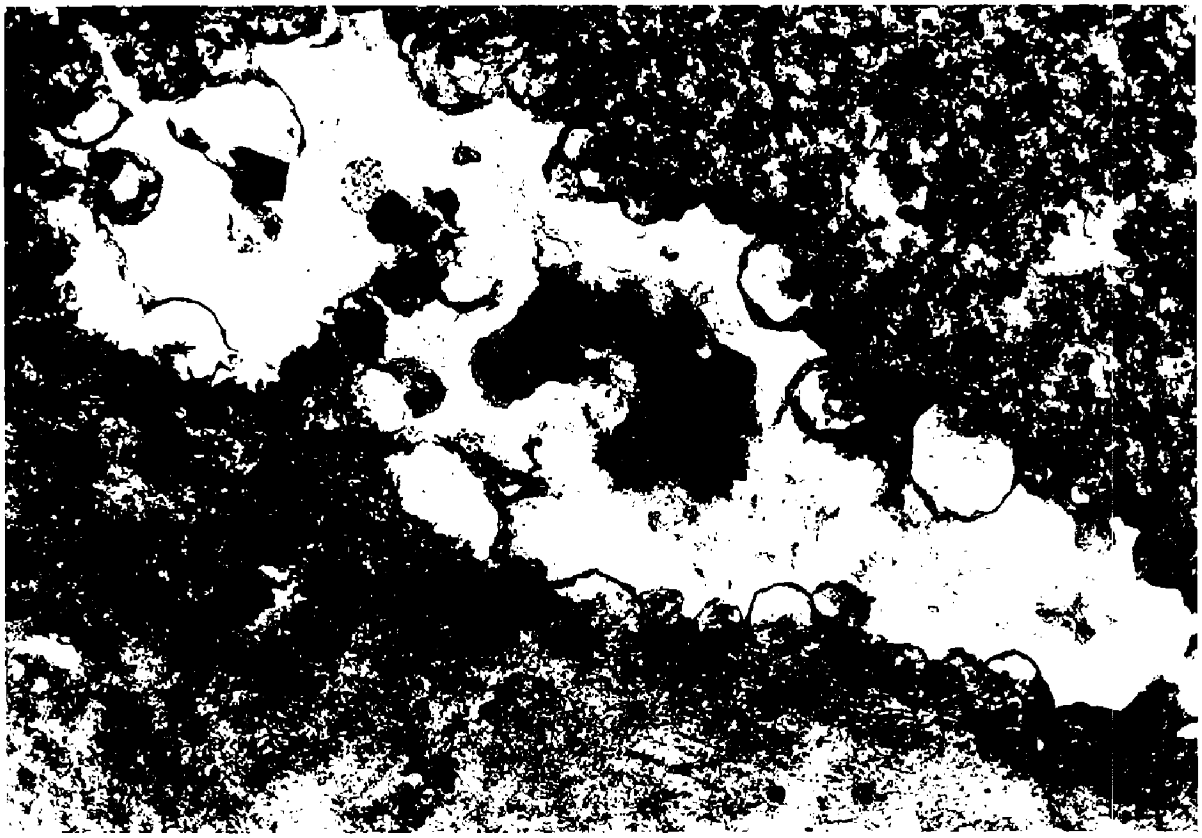

Figure 8. Spherical and isometric crystals, probably originally β-cristobalite, growing from the wall of a lithophysal cavity and replaced by microcrystalline quartz. The cavity is filled primarily by microcrystalline quartz, with a patch of chlorite in the center. Plane light; length of field of view is 1.75 mm.

walls (Fig. 8). These are replaced by microcrystalline quartz, but their original shapes have been outlined by a coating of hematite dust that separates them from the quartz filling the remainder of the cavity. The shapes suggest that these bodies were originally crystals of β-cristobalite, which develops habits of this type when it grows in open spaces in volcanic rocks (e.g., Rogers, 1922; Moehlman, 1935; Larsen and others, 1936). Less commonly, small, wedge-shaped crystals replaced by microcrystalline quartz line the cavity walls (Fig. 9). These probably represent quartz pseudomorphs of original β-tridymite crystals. Both of these high-temperature silica polymorphs typically develop in lithophysal cavities in silicic lavas, where they are precipitated directly from the vapor phase (Ross and Smith, 1961; Frondel, 1962). To our knowledge, this represents the first report of the original presence of these silica polymorphs in the Carlton Rhyolite.

Devitrification Textures

Glass is thermodynamically unstable and will spontaneously devitrify with time. Conversion of glass to a fine-grained crystalline aggregate produces a distinctive suite of devitrification textures, which reflect the interactions between the processes of crystal nucleation and crystal growth (Marshall, 1961; Lofgren, 1970). Crystal growth occurs after a nucleation point has been established in the glass.

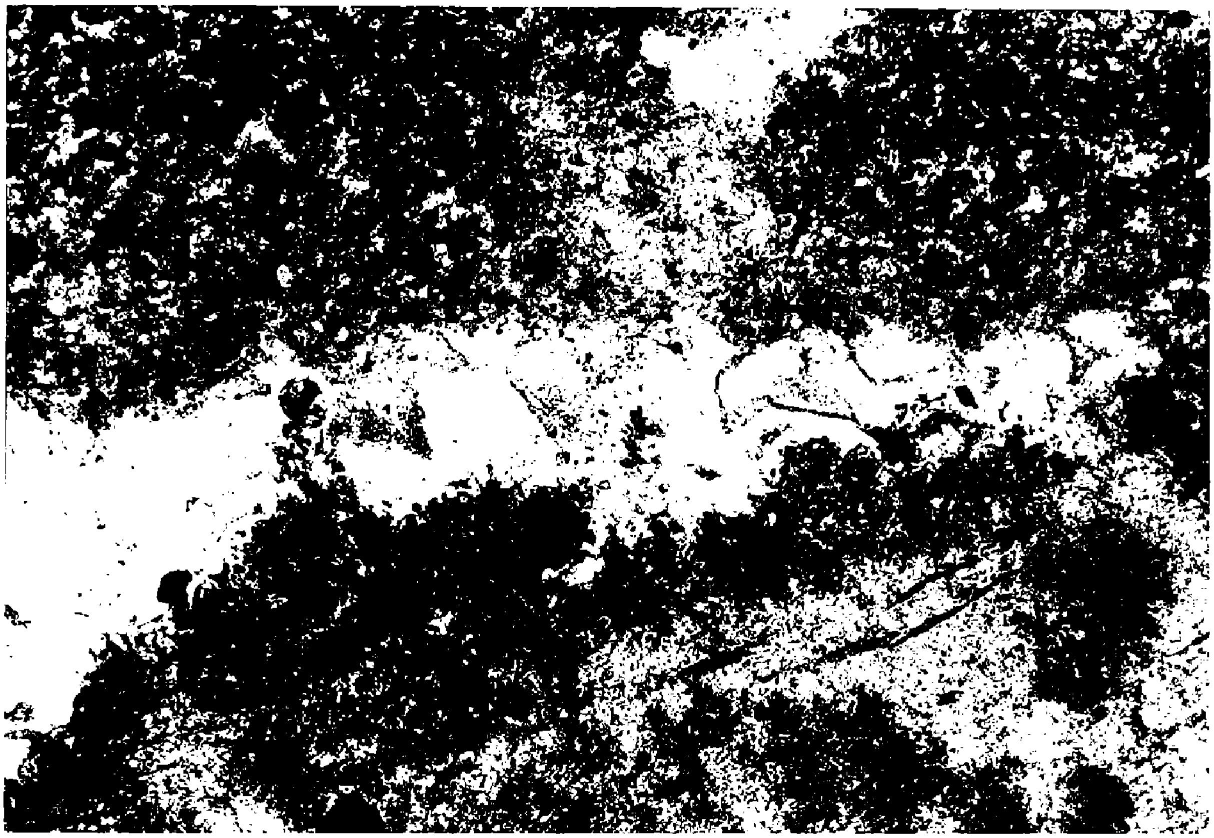

Figure 9. Small, wedge-shaped crystals, probably originally β-tridymite, growing from the wall of a lithophysal cavity and replaced by microcrystalline quartz, which also fills the remainder of the cavity. Plane light; length of field of view is 1.75 mm.

The most complicated quartzo-feldspathic intergrowths produced by devitrification in the Blue Creek Canyon rhyolite occur in areas showing spherulitic texture. In contrast, areas characterized by relict perlitic texture generally have devitrified to rather featureless mosaics of very fine-grained, randomly arranged, equigranular quartz and feldspar. A third type of intergrowth between quartz and feldspar, known as snowflake texture, also locally is present in some parts of the groundmass.

Spherulitic Textures

Spherulites in silicic glass typically develop as aggregates of radially oriented, acicular microlites of alkali feldspar, often intergrown with a silica polymorph (Lofgren, 1971a,b; Cas and Wright, 1987); the silica may show evidence of subsequent recrystallization between and around the feldspar laths. The radial structure is the result of fibrous crystal growth extending from a single, discrete nucleation point within the glass.

In the Blue Creek Canyon rhyolite, areas of spherulitic crystallization are separated from areas showing perlitic texture by sharp boundaries (Fig. 10). These boundaries are analogous to the contacts between primary devitrification products and residual glass produced experimentally by Lofgren (1971a), which he termed devitrification fronts. Not only do these devitrification fronts separate areas of spherulitic texture from areas showing perlitic cracking, they also control the presence of the tiny, randomly arranged pyroxene(?) microlites described above. The

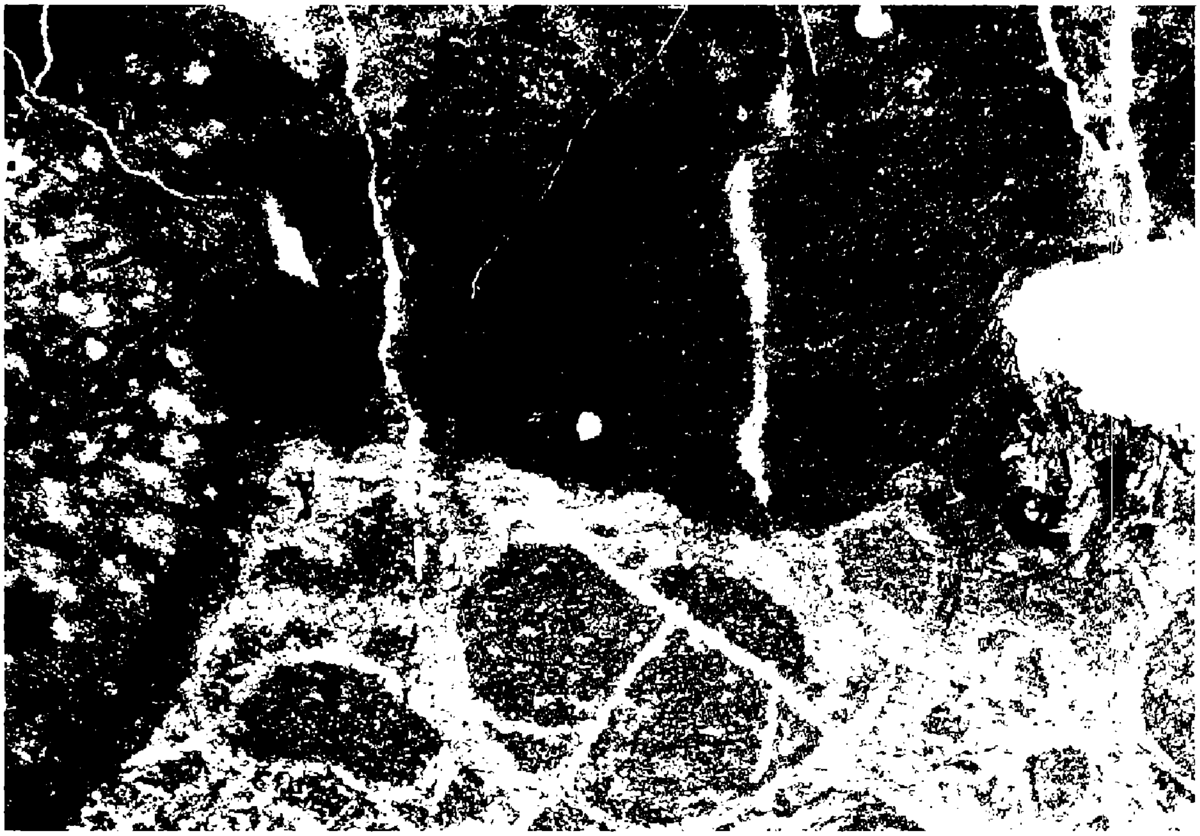

Figure 10. Sharp devitrification front between area showing perlitic texture (lower part of view) and area with spherulitic texture (darker colored). Plane light; length of field of view is 4.5 mm.

microlites commonly are abundant in the areas showing spherulitic texture, but they are completely absent on the other side of the devitrification fronts.

Individual crystal fibers within the spherulites grow directly across the pyroxene(?) microlites without displacing them in any way. The spherulites also transect flow banding in the lava, but in plane light the delicate flow bands are still visible in the areas of spherulitic crystallization and can be seen to continue in an uninterrupted fashion across the devitrification fronts. Areas of spherulitic crystallization tend to follow flow banding in a somewhat irregular fashion, and linear zones up to a few cm across of dense spherulitic development alternate with zones showing well-preserved perlitic texture. In such cases, the spherulites have relatively simple, circular outlines typically ≤1 mm in diameter and tend to coalesce to various degrees.

In many cases, the spherulites did not begin growth from an indeterminate point within the glass, but instead nucleated on a physical boundary within the lava. For example, delicate spherulites in some cases extend from the corners of phenocrysts (Fig. 11). In other cases, the spherulites have grown from small, spherical vesicles (Fig. 6) or from flow bands within the lava. This is analogous to the phenomenon of heterogeneous nucleation well known to chemists, in which crystals that have difficulty in nucleating spontaneously will tend to grow from mechanical discontinuities, such as scratches on the side of a beaker.

Many spherulites exhibit a concentric banding defined by distinct differences in color (Fig. 11), which are caused by variations in the amount of minute iron oxide

Figure 11. Several spherulites nucleated on the edge of a feldspar glomerophenocryst. Note the concentric color banding in the largest spherulite. In the lower left, a small, symmetrical spherulite has nucleated on a tiny spherical vesicle. Perlitic cracks are visible in the dark-colored part of the groundmass, beyond the spherulites. Plane light; length of field of view is 4.5 mm.

particles included between individual crystal fibers within the spherulite. The color bands presumably record variations in the rate at which impurities were expelled from the advancing spherulite versus the rate of crystal growth. Multiple episodes of spherulitic development are evidenced by the nucleation of small spherulites on the edges of larger spherulites (Fig. 6).

Spherulitic Textures in the Spheroids

Thin sections show that the large spheroidal masses present in certain horizons in the flow are made of dense masses of feathery, coalescing spherulites (Fig. 12). As in other parts of the rhyolite, the spherulites occur behind a sharp devitrification front that separates them from areas showing perlitic texture; margins of the spheroids visible in outcrop (Fig. 4) are, in fact, hand-sample examples of such fronts. Flow banding is well preserved inside the spheroids and is crossed at various angles by the spherulitic fibers. There is no direct relation between the external form of the spheroids and the internal arrangement of the spherulites, which have grown from a great number of separate nucleation points within each spheroid. The shape of the spheroids apparently simply reflects their formation as domains within the glassy

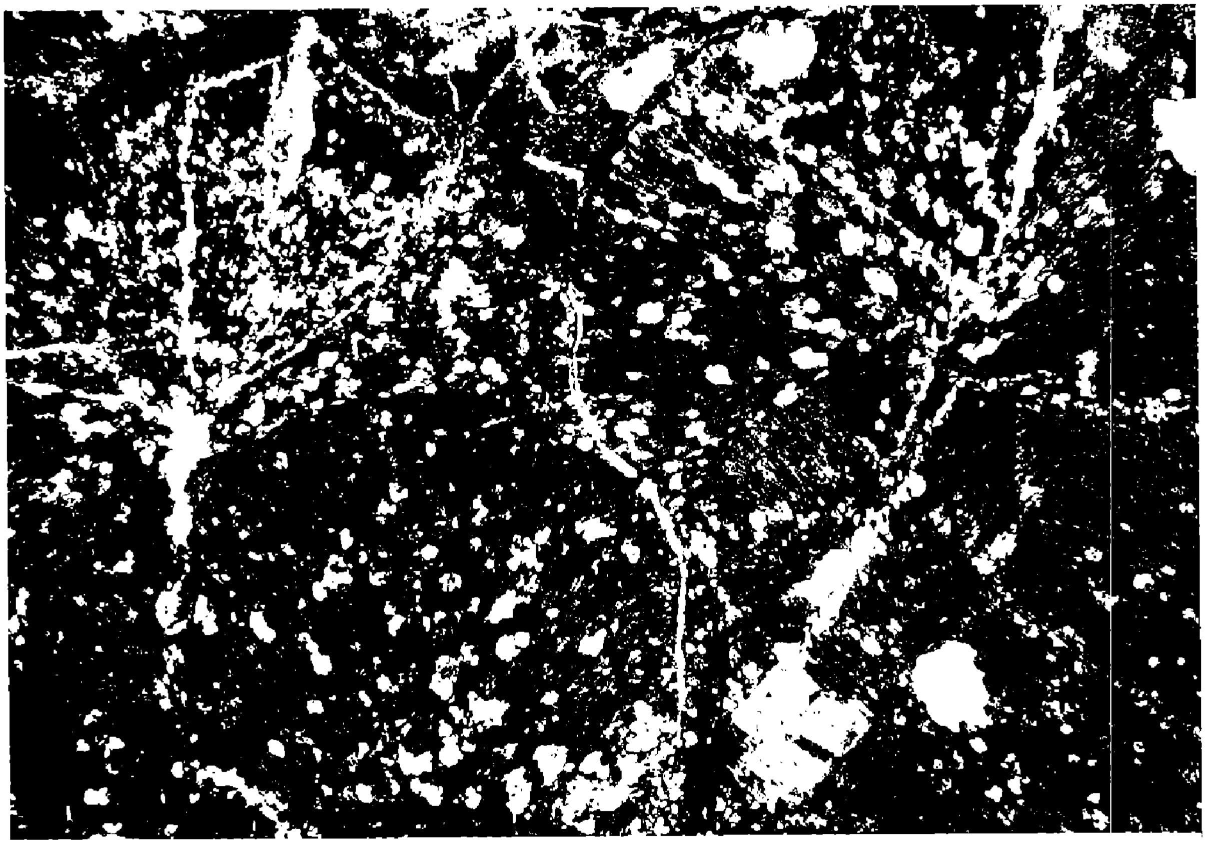

Figure 12. Several relatively large, coalescing spherulites within a spheroid. Feldspar phenocrysts are visible in the lower right. The numerous small, bright patches within the spherulites are irregular, poikilitic quartz crystals that have grown around the radiating, fibrous feldspar crystals (snowflake texture). Crossed polars; length of field of view is 4.5 mm.

rhyolite that underwent intense spherulitic devitrification proceeding outward in all directions from a central point in the glass.

The spherulites within the spheroids commonly are larger than in other parts of the lava flow. In some cases, there is a decrease in diameter of the spherulites from the center to the edge of a spheroid. Near the center, relatively large spherulites as much as ≥5 mm in diameter have grown from a limited number of nucleation points; closer to the edge, many small, coalescing spherulites (~0.25 mm in diameter) are completely intergrown together. A thin section is not available from the spheroid in Figure 4, but the zonation seen in that example probably results from a similar outward decrease in the size of the spherulites. The hummocky nature of the inner core of the spheroid presumably reflects the presence of spherulites with considerably larger diameters than those in the featureless outer rim.

Snowflake Texture

In some parts of the groundmass, randomly or radially arranged feldspar microlites are poikilitically enclosed by small, irregular patches of optically continuous quartz (Fig. 12). Each patch of quartz typically surrounds a number of feldspar microlites, and the presence of the micropoikilitic quartz gives the groundmass a distinctive, patchy extinction as the stage is rotated. This corresponds to the snowflake texture recognized by Anderson (1969) in the devitrified parts of certain densely welded ash-flow tuffs. The same texture was duplicated by Lofgren (1971a) in experimentally devitrified silicic glass.

Snowflake texture is best developed in the large spheroids. In these cases, individual, radiating fibers of feldspar within spherulites are surrounded by micropoikilitic quartz crystals that have irregular outlines against one another (Fig. 12). Snowflake texture also is sporadically present in parts of the groundmass that show perlitic cracking. In this case, it clearly postdates formation of the perlite, because the "snowflakes" extend directly across the perlitic cracks.

Interpretation

Relative Timing of Events and Controls on Devitrification Textures

Figure 13 illustrates the relative timing of development of devitrification textures and related phenomena in the Blue Creek Canyon rhyolite, during and after emplacement of the flow. Flow banding and orientation of early-formed pyroxene(?) microlites record laminar flow of molten lava. Degassing of the lava occurred both during flow, as evidenced by vesicles elongated parallel to flow banding, and after flow ceased, as evidenced by spherical vesicles. Lithophysal cavities clearly must have formed at high temperatures, while the glass was still plastic enough to adjust around expanding gas cavities.

Following emplacement of the lava, devitrification of the glass began. In such a situation, there are two possible thermal regimes within which devitrification may occur (e.g., Bonney and Parkinson, 1903). Primary devitrification occurs during the initial cooling of glass after extrusion, when relatively high temperatures favor rapid crystal growth. Secondary devitrification occurs in glass that has cooled to ambient temperatures and results in the gradual conversion of the glass to fine-grained crystalline material long after the volcanic activity has ceased. This low-temperature devitrification generally is preceded by slow hydration of the glass.

General restriction of spherulitic textures in the rhyolite to areas behind sharp devitrification fronts (e.g., Fig. 10) implies that the spherulites developed during primary devitrification at high temperatures. The fronts reflect the cessation of spherulitic growth as temperature decreased below some critical value necessary for continued growth of these delicate crystal forms in the cooling glass. There are two other lines of evidence that the spherulitic textures formed during initial cooling. Firstly, the large spheroids, which consist of a complex intergrowth of coalescing spherulites, in many cases are closely associated with lithophysal cavities. This suggests that spherulitic crystallization occurred at the same time the cavities were forming by exsolution of high-temperature volatiles from the still plastic lava. Secondly, the textural relations show that the spherulites formed *before* the development of perlitic texture in the remaining glass. The distinctive perlitic cracks are present only outside of the devitrification fronts. Thus, the fronts separate areas that underwent early, spherulitic devitrification from areas that remained glassy for long time periods and experienced gradual, low-temperature hydration to form perlitic texture. Similar age relations between early-formed spherulites and later perlitic

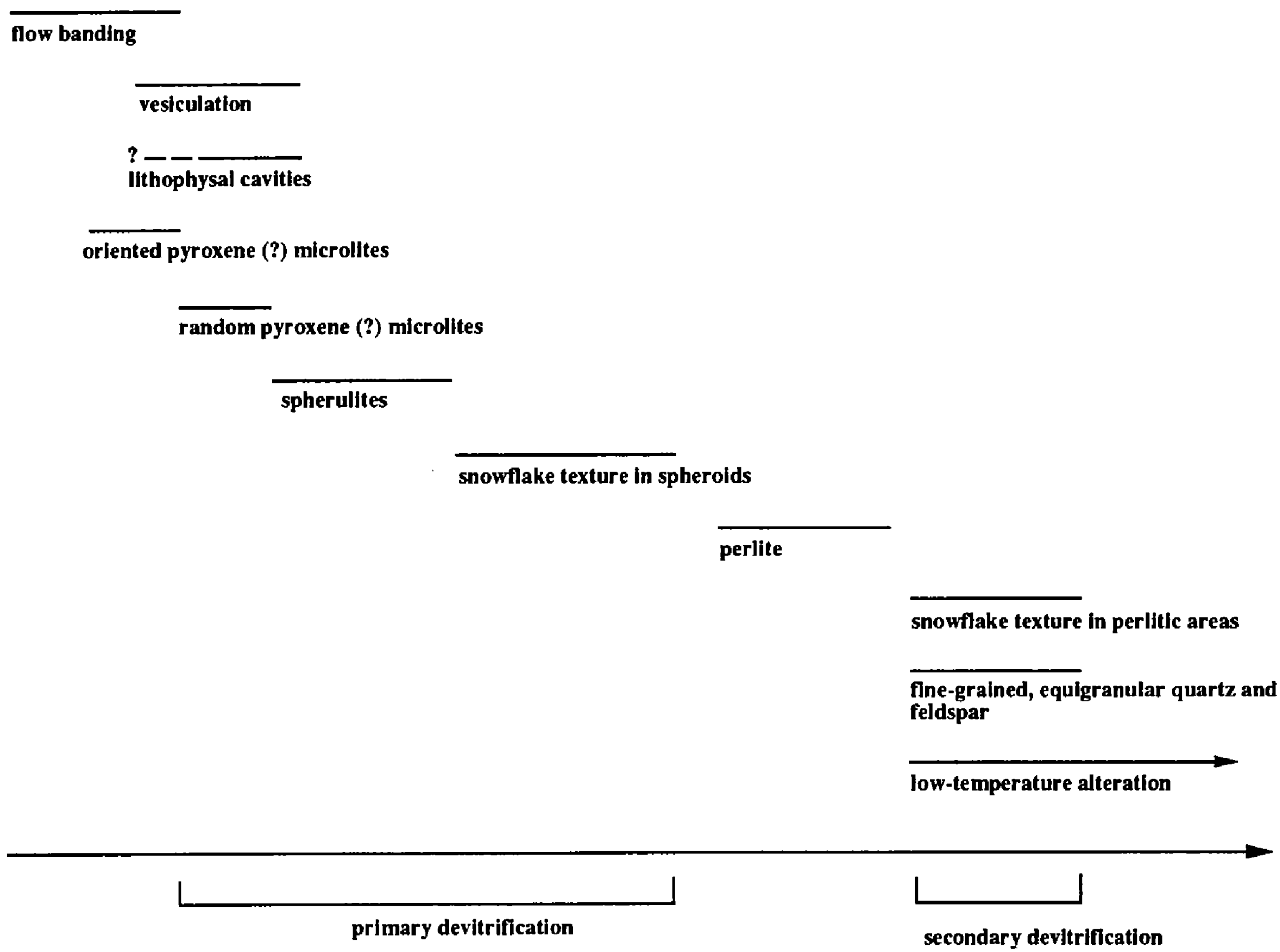

Figure 13. Schematic time relations of textures produced during emplacement, degassing, and primary and secondary devitrification of the rhyolite lava. Relative age decreases to the right; no scale is implied.

texture have been described from other rhyolites (e.g., Colony and Howard, 1934; Mourant, 1934).

The earliest stage in primary devitrification behind the advancing fronts was the crystallization of randomly arranged pyroxene(?) microlites. These reflect early, post-emplacement nucleation and segregation of ferromagnesian components from the silicic glass, which was followed by crystallization of the quartzo-feldspathic components to produce the spherulites. Spherulitic crystallization occurred along specific bands in the rhyolite or developed outward from distinct centers, forming the spheroids visible on outcrop. It is likely that spherulitic crystallization was favored in those parts of the cooling lava that had higher volatile contents after emplacement. Volatiles, especially H_2O, increase the rate of devitrification because they depolymerize the random silicate structure of the amorphous glass, making it easier for crystals to nucleate and grow (Marshall, 1961; Lofgren, 1970; Swanson and others, 1989). Close association between the spheroids and large lithophysal cavities supports a direct relation between higher volatile concentrations and development of spherulites during primary devitrification.

The outward decrease in size of the spherulites within the spheroids is consistent with crystallization during primary cooling of the glass. Experimental studies of the kinetics of quartz and feldspar crystal growth in silicic melts and glasses show that the rate of crystal growth reaches a maximum and then decreases during progressive cooling, whereas the rate of nucleation continues to increase with decreasing temperature (Swanson and others, 1989). Thus, the largest spherulites formed first at the centers of the spheroids when nucleation rates were relatively low and crystal growth rates were high. With continued cooling, smaller and more numerous spherulites developed at the rims, where nucleation sites appeared more rapidly in the glass at the same time that crystal growth was slowed.

Following the end of primary devitrification, gradual, low-temperature hydration of the remaining glass occurred, forming perlitic texture in areas beyond the primary devitrification fronts. Long-term secondary devitrification of the hydrated glass then ensued. The texture of the secondary devitrification products reflects their development under temperature conditions where high nucleation densities were coupled with low rates of crystal growth, producing an extremely fine-grained, equigranular, quartzo-feldspathic mosaic.

Significance of Snowflake Texture

Snowflake texture is interpreted to have formed in two stages in Figure 13. The abundance of snowflake texture in the large spheroids suggests that it developed there as part of the primary devitrification history, after formation of the spherulitic fibers. Sporadic occurrence of the texture beyond the primary devitrification fronts, in perlitic areas that underwent long-term hydration before devitrification, indicates that snowflake texture also developed in some cases during later, low-temperature, secondary devitrification.

Anderson (1969,1970) suggested that snowflake texture is restricted to devitrified, densely welded tuffs and thus could be used to prove an ash-flow origin when found in sequences of ancient silicic volcanic rock, such as the Carlton Rhyolite. Green (1970), however, argued that the texture also may develop during devitrification of glassy lava flows. Recognition of snowflake texture in the Blue Creek

Canyon rhyolite lava emphasizes the fact that the texture is not restricted to welded tuffs and by itself cannot be used as a criterion for ash-flow origin in the Carlton Rhyolite Group.

Acknowledgments

Nowell Donovan pointed out the well-exposed section of rhyolite that is the basis for this paper. We are grateful to him for introducing us to the study area and for providing funds for the research. Jim Underwood, manager of the Kimbell Ranch, kindly permitted access to the study area. We thank Arthur Ehlmann for identification of the chlorite by X-ray diffraction and Arthur Busbey for assistance in computer production of the figures. Van Lohuizen prepared the thin sections with particular care. The manuscript benefited from thoughtful reviews by John Hogan and Charles Gilbert.

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NEW OGS PUBLICATION

CIRCULAR 93. *Source Rocks in the Southern Midcontinent, 1990 Symposium,* edited by Kenneth S. Johnson and Brian J. Cardott. 352 pages, 33 contributions. Price: Paperbound, $12.

From the editors' preface:

This is the third symposium in as many years dealing with topics of major concern to geologists and others involved in petroleum-resource development in Oklahoma and adjacent states. These symposia are intended to foster the exchange of information that will improve our ability to recover our Nation's oil and gas resources. Proceedings of the first symposium (on the Anadarko basin) were published as OGS Circular 90, and proceedings of the second symposium (Late Cambrian–Ordovician geology of the southern Midcontinent) were published as OGS Circular 92.

Hydrocarbon source rocks consist of organic-rich sediments that contain kerogen (disseminated insoluble organic matter) that can be converted to oil and/or gas through thermal maturation. Oklahoma and adjacent states are underlain by thousands to tens of thousands of feet of marine sedimentary rocks that contain known or potential hydrocarbon source rocks. Understanding the distribution, character, and thermal history of these source rocks can provide valuable insight into the occurrence, distribution, and character of oil and gas contained in petroleum reservoirs.

To facilitate the exchange of information on source rocks, petroleum occurrence, and petroleum recovery, the Oklahoma Geological Survey (OGS) and the Bartlesville Project Office of the U.S. Department of Energy (BPO–DOE) co-sponsored this symposium dealing with source rocks and the generation and migration of hydrocarbons in the southern Midcontinent. The symposium was held on February 6–7, 1990, at the Oklahoma Center for Continuing Education, The University of Oklahoma, in Norman. This volume contains the proceedings of the symposium.

Research reported upon at the symposium focused on the organic geochemistry, diagenesis, and thermal history of the major source rocks in the region, with special emphasis on the Woodford–Chattanooga Shale, on various Pennsylvanian shales, and on carbonate units such as the Arbuckle and Viola Groups. Other research includes characterization of oil types, deep pressure compartments, diagenetic aureoles, and the hydrodynamics of fluid migration to reservoirs. We hope that the symposium and these proceedings will bring such research to the attention of the geoscience and energy-research community, and will help foster exchange of information and increased research interest by industry, university, and government workers.

Twenty-two papers were presented orally at the symposium, and they are presented as full papers or abstracts. An additional 11 reports were given as posters, and they are presented as short reports or abstracts. About 200 persons attended the symposium.

Circular 93 can be obtained over the counter or by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031. Add 10% to the cost of publication(s) for mail orders, with a minimum of 50¢ per order.

INDUSTRY SUPPORTS OU PROGRAMS

- **Amoco Foundation Inc. of Chicago** has pledged $100,000 to establish the Amoco Center for Excellence in Business at OU's College of Business Administration. The center provides a 30-unit computer laboratory, linked to the University's major computer systems.

- **Exxon Corp.** recently awarded grants totaling $43,000 to chemical engineering, mechanical engineering, electrical engineering, civil engineering, petroleum engineering, geology, accounting, business administration, and computer science. The departments can use the funds for any educational purpose they choose. Past grants have supported scholarships, field trips, visiting speakers, equipment purchases, student and faculty travel to professional meetings, and other academic projects.

- **Shell Oil Co. Foundation** presented $28,800 to the University of Oklahoma to supplement funding in both graduate and undergraduate areas. Two $10,000 graduate grants are being provided to the School of Petroleum and Geological Engineering, and four Shell Assists support chemical engineering, management information systems, mechanical engineering, and the College of Business Administration. The assists are used to strengthen activities at the undergraduate level in specified academic areas and enhance career counseling and placement activities. Shell also contributed $800 to Career Planning and Placement Services at OU.

- **Halliburton Foundation** has awarded OU a $25,000 grant for faculty development. The College of Engineering was presented $20,000, and the Department of Chemistry received $5,000.

- **CITGO Petroleum Corp. of Tulsa** donated $15,000 to fund five $3,000 scholarships for academically promising incoming freshmen who plan to major in petroleum or geological engineering at OU. The contribution is part of a new scholarship program called PGE Excellence in Engineering Scholarships for Freshmen.

SEPM ELECTS NEW OFFICERS

Officers of the Society of Economic Paleontologists and Mineralogists for the 1992–93 term are:

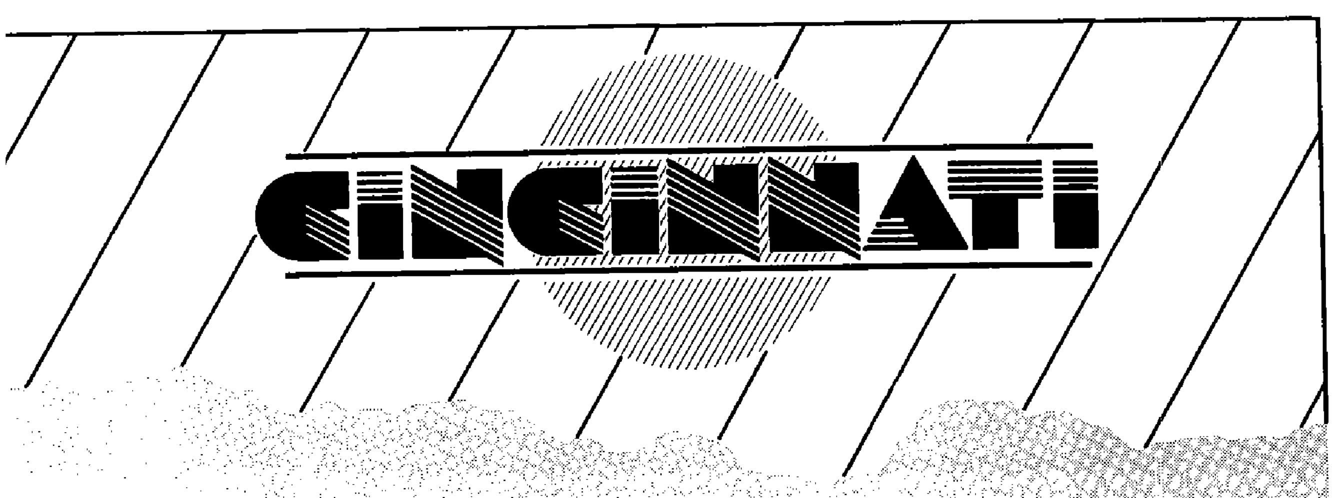
President: Harry E. Cook, U.S. Geological Survey, Menlo Park, California
President-Elect: Sherwood W. Wise, Jr., Florida State University
Paleontology Councilor: Gregory H. Blake, UNOCAL
Sedimentology Councilor: Stephan A. Graham, Stanford University
Secretary-Treasurer: Emily L. Stoudt, Texaco Exploration and Production Research Dept., Houston
Councilor for Research Activities: S. J. Mazzullo, Wichita State University
Editor, *Journal of Sedimentary Petrology:* Harvey Blatt, University of Oklahoma
Editor, *PALAIOS:* David J. Bottjer, University of Southern California
Editor, Special Publications: Barbara H. Lidz, U.S. Geological Survey

GSA ANNUAL MEETING
Cincinnati, Ohio, October 26–29, 1992

The Geological Society of America will hold its Annual Meeting in Cincinnati from October 26 through 29. The meeting will take place in the newly remodeled and enlarged downtown convention center, which is connected by skywalks to almost all of the downtown hotels. Join us in a celebration of new discoveries in the geological sciences on the quincentenary of Columbus landing in the Bahamas, which revealed to Europe the existence of another, unexpected world. In the same spirit, the Cincinnati meeting will present images of unexpected new worlds from the surface of Venus to the subsurface of Ohio. Come to examine the new discoveries ranging from those made by the Magellan spacecraft to the detection of a large rift basin a mile beneath Cincinnati.

Field trips will not visit either of these two localities, but you will be able to visit San Salvador to see Columbus' landing site as well as the spectacular modern carbonates of the Bahamas. Ancient carbonates will be on display in several trips around Cincinnati, and you will be able to visit, in upper Michigan, a well-exposed rift sequence of an age similar to that of the one beneath Cincinnati. Technical sessions will feature new discoveries in the Neoproterozoic history of Earth, K–T boundary sequences in the Caribbean, the effects of melting glaciers on the oceans, the structures of minerals using transmission electron microscopy (TEM), and the newly appreciated extent of a giant Ordovician volcanic eruption that can be followed from Estonia to the U.S. Midcontinent. And don't miss our Keynote Symposium, "From Columbus to Magellan—Discovery," that explores some of the latest concepts in earth and planetary geoscience.

— J. Barry Maynard
1992 Co-Chairman



GSA Annual Meeting Agenda

THE VOYAGE CONTINUES
From Columbus to Magellan

Technical Program

Symposia

From Columbus to Magellan—Discovery
History of Late Glacial Runoff from the Southern Laurentide Ice Sheet
The History of the Use of Art and Photography in Geological Literature
Preserving Geoscience Imagery
Frontiers of Chemical Mass Transport in Contaminant Systems
Reform in Science Education
Mineralization Related to Continental Rifts
Black Shales and Related Ore Deposits
Ground Truth: Geology of the Earth and Planets from Rocks and Analogs
Applications of Stable Isotope Geochemistry to Problems in High-Temperature Petrogenesis
Geologic Aspects of Development Projects in Latin America and the Caribbean Basin
Instability on Clay and Shale Hillslopes
Physical and Chemical Responses to Allocyclic Processes in Carboniferous Coal-Bearing Strata
Controls on Carbon Preservation
The Role of Fluids in Crustal Deformation
Synergism: Archaeological and Geological Sciences
Paleosols: Their Geologic Applications

Theme Sessions

Tectonic Settings and Paleoenvironments of the Paleo-Pacific Margin—Antarctic and Related Gondwana Sequences
New Discoveries in Neoproterozoic Earth History
Intraplate Neotectonics
Hydrogeochemistry and Isotope Hydrology of Regional Aquifer Systems
Hydrogeology, Hydrogeochemistry, and Ground-Water Contamination in the Midwest Basin and Arches Region
Environmental Geology: The Voice of Warning
Environmental Geology: The Voice of Reason
Gulf Coast Cretaceous Project: Biostratigraphy and Correlation; Sea-Level Change and Paleogeography; Depositional Environments and Diagenesis
Discovery in Hydrogeology—Heritage, Wisdom, and Vision
Transmission Electron Microscopy in Mineralogy and Petrology
Paleozoic Depositional Sequences; Contrasts in Environments and Fossil Diversity
Origin and Nature of Meltwater Release from the Laurentide Ice Sheet and Its Impact on Late Glacial Oceans

Environmental Issues in Urban Settings
Consultants/Industries Innovative Applications in Environmental Investigations
Magellan, Galileo, and Planetary Frontiers: The Discovery of New Worlds Continues
Paleosols: Their Geologic Applications
Thrust Fault Sesquicentennial
Quantitative Chemical Hydrogeology: Calculation of Solute Transport and Water Rock Interaction in Geochemical Processes
Orodvician K-Bentonites
Biotic Responses to Allocyclic Processes in Carboniferous Coal-Bearing Strata
Time and Place of Compressional Events in the Appalachian Orogen
Formation of Fault Systems
Advances in Investigation, Characterization, and Monitoring of the Geologic Environment for Waste Disposal
Metamorphism in North and Central America: Regional Studies and Digital Compilation Techniques
Late Proterozoic Rifting of the North American Craton
New Cretaceous–Tertiary Boundary Discoveries—Caribbean and High Latitudes

Field Trips

Premeeting Trips

Paleoclimate Controls on Carboniferous Sedimentation and Cyclic Stratigraphy in the Appalachian Basin, *Oct. 22–25*
The Geology of Columbus' Landfall, *Oct. 22–25*
Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the "Type Cincinnatian," *Oct. 23–24*
Karst and Cave Systems in the Stones River Group, Central Tennessee, *Oct. 23–24*
Regional Aspects of Pottsville and Allegheny Stratigraphy and Depositional Environments, Ohio and Kentucky, *Oct. 24–25*
Geology of Key Archaeological Sites in Northern Kentucky and Southern Ohio, *Oct. 24–25*
Orodvician, Silurian, and Middle Devonian Stratigraphy in Northwestern Kentucky and Southern Indiana—Some Reinterpretations, *Oct. 24–25*
The Sangamonian–Wisconsin Transition in Southwestern Ohio and Southeastern Indiana, *Oct. 25*
Cincinnati's Geologic Envirommment: A Trip for Secondary School Science Teachers, *Oct. 25*

Half-Day Mini Trips (held during the meeting)

Geologic Glimpses from Around the World: The Geology of Monuments in Woodland Cemetery and Arboretum, Dayton, Ohio, *Oct. 26*
Excursion to Caesar Creek State Park in Warren County, Ohio: A Classic Upper Ordovician Fossil Collecting Locality, *Oct. 28*

Postmeeting Trips

Changing Interpretations of Kentucky Geology: Layer-Cake, Facies, Flexure, and Eustacy, *Oct. 29–31*
Building Stone in Three Ohio Cities: Cincinnati, Columbus, and Cleveland, *Oct. 29–31*
The Sangamonian–Wisconsin Transition in Southwestern Ohio and Southeastern Indiana, *Oct. 30*
Mississippian Paleosols, Paleokarst, and Eolian Carbonates in Indiana, *Oct. 30–31*
Fort Payne Carbonate Buildups of South-Central Kentucky, *Oct. 30–31*
Structure and Tectonics of the Rough Creek Graben, Western Kentucky and Southeastern Illinois, *Oct. 30–31*

Other Field Trips

Keweenawan Copper Deposits of Western Upper Michigan, *Oct. 20–23*
Cyclic Sedimentation and Sequence Stratigraphy of a Storm-Dominated Carbonate Ramp: Kope and Fairview Formations of the Cincinnati Region, *Oct. 25*
Zinc Deposits in East Tennessee, *Oct. 29–Nov. 1*

Short Courses/Workshops/Forums

Geographic Information System Software: Facts and Fiction, *Oct. 23–25*
High-Resolution TEM, *Oct. 23–25*
Introductory Rock and Paleomagnetism, *Oct. 24–25*
How To Do Anything with Mohr Circles: A Short Course About Tensors for Structural Geologists, *Oct. 24–25*
Paleosols for Sedimentologists, *Oct. 25*
Phase I—Preliminary Site Assessments, *Oct. 25*
Practical Tracing of Ground Water, with Emphasis on Karst Terranes, *Oct. 25*
Teaching Introductory Geology with Video as a Partner, *Oct. 25*
Organic Geochemistry of Sediments and Sedimentary Rocks, *Oct. 25*
Trace Fossils, *Oct. 25*
DataBase Forum, *Oct. 25*
GeoRef Workshop, *Oct. 26*
Our Common Future: The Concerns of Earth Science Students, *Oct. 27*
Environmental Applications of Shallow Seismic Reflection, *Oct. 30*

For further information about the annual meeting, contact GSA, Meetings Dept., P.O. Box 9140, Boulder, CO 80301; (303) 447-2020 or 1-800-472-1988. The preregistration deadline is September 25.

THE VOYAGE CONTINUES
From Columbus to Magellan

UPCOMING MEETINGS

GSA Penrose Conference: Late Precambrian Tectonics and the Dawn of the Phanerozoic, October 18–23, 1992, Death Valley, California. Information: Ian Dalziel, Institute for Geophysics, University of Texas, Austin, TX 78759; (512) 471-6156, fax 512-471-8844.

American Association of Stratigraphic Palynologists, Annual Meeting, October 21–23, 1992, San Diego, California. Information: Roger J. Witmer, UNOCAL Science and Technology Center, 376 S. Valencia Ave., Brea, CA 92621; (714) 528-7201, ext. 2403, fax 714-528-3520.

Water Resources During Global Change, International Meeting, November 1–5, 1992, Reno, Nevada. Information: American Water Resources Association, 5410 Grosvenor Lane, Suite 220, Bethesda, MD 20814; (301) 493-8600.

Clay Minerals Society Meeting, November 1–6, 1992, Minneapolis, Minnesota. Information: Wayne Hudnall, Dept. of Agronomy, Louisiana State University, Baton Rouge, LA 70803; (504) 388-1344.

Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration—A Conference and Exposition, November 4–6, 1992, Houston, Texas. Information: National Ground Water Association, 6375 Riverside Dr., Dublin, OH 43017; (614) 761-1711, fax 614-761-3446.

Industrial Minerals Development in Oklahoma, A Workshop, November 10–11, 1992, Norman, Oklahoma. Information: Kenneth S. Johnson, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031, fax 405-325-7069.

NOTES ON NEW PUBLICATIONS

Strategic and Critical Minerals in the Midcontinent Region, United States

Edited by W. C. Day and D. E. Lane, this 42-page USGS bulletin reports results of studies conducted as part of the U.S. Geological Survey Midcontinent Strategic and Critical Minerals Project. Chapters A–C are issued in this single volume and are not available separately. Chapter A is "Geology and Mineral Paragenesis of the Pea Ridge Iron Ore Mine, Washington County, Missouri; Origin of the Rare-Earth-Element- and Gold-Bearing Breccia Pipes," by L. M. Nuelle, W. C. Day, G. B. Sidder, and C. M. Seeger. Chapter B is "Some Mineralogical and Geochemical Aspects of Middle and Upper Pennsylvanian Marine Black Shales in Part of the Midcontinent Region," by G. A. Desborough, J. R. Hatch, and J. S. Leventhal. Chapter C is "Mineralogical and Geochemical Analysis of the Metal- and Organic-Rich Grassy Creek Shale of the New Albany Group (Upper Devonian and Lower Mississippian) in Hardin County, southern Illinois," by G. A. Desborough.

Order B 1989-A–C from: U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $3; add 25% to the price for foreign shipment.

OKLAHOMA ABSTRACTS

The Oklahoma Geological Survey thanks the Oklahoma Archeological Survey, the Geological Society of America, and the authors for permission to reprint the following abstracts of interest to Oklahoma geologists.

Interdisciplinary Studies of the Hajny Mammoth Site, Dewey County, Oklahoma

DON G. WYCKOFF, Oklahoma Archeological Survey, University of Oklahoma, Norman, OK; BRIAN J. CARTER, Dept. of Agronomy, Oklahoma State University, Stillwater, OK; PEGGY FLYNN, Edmond, OK; LARRY D. MARTIN, Kansas Museum of Natural History, University of Kansas, Lawrence, KS; BRANLEY A. BRANSON, College of Natural and Mathematical Sciences, Eastern Kentucky University, Richmond, KY; and JAMES L. THELER, Dept. of Sociology/Anthropology, University of Wisconsin, LaCrosse, WI

When gravel quarrying exposed mammoth bones buried deeply in a prominent terrace of the Canadian River in Dewey County, Oklahoma, controlled archeological excavations were undertaken to ascertain if the animals had been killed by Paleoindian hunters. Although no traces of humans were found, the site did yield a small, but intriguing, array of Pleistocene animals in an interesting geologic setting.

Manual stripping and extensive backhoe trenching revealed the presence of five ancient spring deposits. Located at similar elevations above the Canadian's modern course and embedded within fluvial sands and gravels, these springs formed by upwelling ground water when the river was aggrading a terrace 35 meters higher than its modern flood plain. Two springs contained bones of Pleistocene elephants, but only those around Spring #2 were uncovered and studied in detail. Portions of two mammoths and scattered bones of turtles, frogs, a water rat, a wood duck, a pocket gopher, a horse, and a pronghorn were recovered there. Along with nearly a dozen taxa of aquatic and terrestrial gastropods, these fauna attest to a marshy setting and adjacent grasslands. A few species of gastropods and the water rat are indicators of cooler summers and warmer winters than today.

The mammoth bones were arranged and damaged by large animals and subsequent chemical and fluvial processes. The springs apparently existed temporarily during a period of floodplain stability before being covered with several meters of interbedded sand and gravel, after which nearly three meters of soil accumulated. Subsequently, soil and some underlying fluvial sediments were eroded away and mass-wasting of the hillside occurred.

Dating of the site remains problematic. The mammoth molars share attributes with both *Mammuthus imperator* and *M. columbi*. Experimental uranium series dating of the teeth enamel yielded results ranging from roughly 140,000 to 165,000

years ago, but radiocarbon dated samples of gastropod shells from two different springs indicate a Wisconsinan age of some 21,500 to 34,000 years ago. The form of water rat and the elevation of the terrace seem more congruent with the late Illinoian or early Sangamon age. Resolution of the site's age awaits continued study of Pleistocene settings and fauna along western Oklahoma's Canadian River watershed.

Reprinted as published in the Oklahoma Archeological Survey, *Studies of Oklahoma's Past*, no. 17, February 1992.

How Shallow Drilling Would Clarify Relations within the Southern Oklahoma Aulacogen

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Shallow holes proposed to be drilled immediately south of the Wichita Mountains in northern Tillman county, Oklahoma are critical to deciphering the geologic history of the early stages of the Cambrian Southern Oklahoma Aulacogen. The earliest known unit of the aulacogen is the Glen Mountains Layered Complex (GMLC), a part of the Raggedy Mountain Gabbro Group. However, the country rock into which the GMLC intruded is not known. The relation of the GMLC to the subsurface Navajoe Mountain Basalt/Spilite Group and Tillman Metasedimentary Group, possible host rocks, is not established. Both of these latter rock units occur in apparent contact/juxtaposition with the Raggedy Mountain Gabbro in the subsurface in the targeted area at depths of about 500 meters. A shallow drilling project in which several hundred meters of core is obtained from each of the main subsurfaces bodies and their contact zones will establish the age and geochemical characteristics of the rock units and their structural and stratigraphic relationships. It should also be possible to determine if any of this set of rocks is part of the aulacogen or part of an earlier Proterozoic geosynclinal sequence.

Proposed drilling sites are in T1N R16W on the up side of the Burch fault zone that marks the approximate southern boundary of the aulacogen and may be near the presumed Grenville suture. The sites also occur in proximity to several COCORP seismic lines and to the UTD–UTEP large-aperture seismic experiment. Systematic sampling should provide further insights into the nature of these major crustal boundaries and possibly to the origin of the deep horizontal layering.

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Southerly Vergence Associated with Northerly Directed Thrusts of the Ouachita Mountains of Oklahoma

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Regional stratigraphy, structure, and geophysical surveys outline large scale northerly directed thrusts characterizing the late Carboniferous deformation of the Ouachita Mountains in Oklahoma. Yet within the oldest rocks of the Broken Bow uplift southerly verging structures dominate. The Broken Bow uplift has been subdivided into four structural domains: Hochatown Dome, Carter Mountain anticlinorium, Linson Creek synclinorium, and Cross Mountain anticlinorium. Detailed mapping indicates a history of progressive deformation in which four phases have been described. The earliest folds are tight, overturned, southerly verging and associated with a well developed slaty cleavage. These folds are documented as far north as the Linson Creek synclinorium. Second generation folds are best preserved in the southern part of the uplift where the folded slaty cleavage is apparent. These folds are coaxial with the first generation, are open to tight, are inclined revealing southerly vergence. Faults are also associated with the second generation folds. In the south these faults dip toward the north and in the north they dip toward the south, forming a fan like distribution. Third phase structures are interpreted to be related to flattening of the succession, producing recumbent buckles, pencil structures, and a rough cleavage. The fourth phase is associated with a crenulation cleavage development and a family of open, nearly upright northeast-trending folds. A model involving initial basin shortening is proposed to explain the first generation folds. Subsequent detachment and translation of this deformed sequence is believed to have produced the second and third generation structures. The structural fan is interpreted to be associated with the emplacement of the Boktukola fault to the north and consequently associated with the regional northerly directed thrusting.

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The Dyer Mountain Fault Zone, Broken Bow Uplift, Southeastern Oklahoma

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The Dryer Mountain fault zone (DMFZ) separates the Hochatown dome to the south from the Carter Mountain anticlinorium to the north. The DMFZ has been traced from the western flank of the uplift to the Broken Bow Reservoir (10 km). The DMFZ is characterized by a complex pattern of faults, imbricate slices, and rootless folds. The faults are dipping steeply to the north but slip is difficult to interpret. Locally normal separation has been proposed to explain map offsets. Refolded mesoscopic first generation folds in the footwall of the DMFZ indicate southerly

directed thrusting associated with the second stage of folding. The first generation folds are tight to isoclinal, subhorizontal with sharp hinges and planar limbs. The second generation folds are coaxial with the first and are open to tight, inclined, and southerly verging. Northerly dipping faults truncate the limbs of these second generation folds. A megascopic syncline (wavelength 2 km) has been outlined just south of the DMFZ in the Arkansas Novaculite. First generation folds which trend east–west and are subhorizontal in the footwall plunge moderately (30) toward the northwest in the hanging wall of the DMFZ, suggesting rotation associated with simple shear. Flattening associated with these faults modifies both the first and second generation folds. Steeply dipping limbs are folded into recumbent buckles while gently dipping limbs are thinned. The early slaty cleavage is rotated and a new locally developed rough cleavage with associated pencil structures are documented. These mesoscopic data suggest initial southerly directed thrusting along the DMFZ. Subsequent deformation associated with the development of the uplift probably reactivated this fault system generating components of right lateral and normal slip.

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Evolution of a Mixed Carbonate-Siliciclastic Shelf During Sea-Level Rise, Lower Morrowan (Pennsylvanian) of Northwest Arkansas

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Early Morrowan strata on the northern margin of the Arkoma Basin in northwest Arkansas record a transition from a high energy, tide dominated shelf on which mixed skeletal and quartz sands accumulated to a lower energy shelf on which quartz and skeletal sands were deposited in an association with terrigenous mud.

The transgressive Prairie Grove Member of the Hale Formation unconformably overlies the Cane Hill Member and is dominantly composed of skeletal fragments and quartz sand. Sets of large scale trough and tabular cross strata characterize most of the unit. Small mounds of carbonate mudstone stabilized by red algae occur at the base of the unit. They are overlain by and grade laterally into the mixed, cross stratified sands. Skeletal grains were generated in and around the mounds in low energy settings and were entrained by tidal currents already transporting quartz sand. The Brentwood Member of the Bloyd Formation conformably succeeds the Prairie Grove Member. The unit is dominantly composed of shale and contains lenticular bodies of quartz sand and skeletal fragments. The bodies range to 15 meters in thickness and in cross section are several hundred meters wide. Medium to large scale sets of cross strata are abundant. Brentwood sediments accumulated on a slightly deeper shelf seaward of the shallower and tidally dominated setting in which Prairie Grove sands accumulated. Tidal currents created shallow shelf to basin channels in which skeletal and quartz sands were deposited.

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Comparative Spring Water Chemistry, Ozark and Ouachita Provinces, Arkansas

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The Paleozoic region of western and northern Arkansas consists of the Ozark Plateaus and Ouachita Mountains separated by the Arkoma Basin. The Salem and Springfield plateau surfaces of the Ozarks are formed by carbonates of Ordovician and Mississippian age respectively, while the Boston Mountains Plateau is formed by mixed terrigenous clastics and carbonates of Pennsylvanian age. Most of the Ozark sequence represents deposition under shallow shelf conditions. In contrast, coeval rocks if the Ouachitas are dominated by terrigenous clastics representing either starved basin or flysch deposition in deep ocean setting.

The chemistry of spring water reflects the different geological setting of the Ozarks and Ouachitas. Abundance of carbonate aquifer systems in the Ozarks is shown by median values of 66 mg/L for calcium, 324 uohmos/cm for specific conductance and 194 mg/L total alkalinity as calcium carbonate. Comparable values for the Ouachita spring waters are 2.1 mg/L, 40 uohmos/cm and 14 mg/L, respectively. Influence of the Ozark carbonate aquifers on spring water chemistry is reflected further by a median pH value of 7.5 versus a median pH value 5.7 for Ouachita spring waters. Graphical representation of ion chemistry, particularly iron and manganese, illustrates the contribution of those elements by shales to spring water in the Ouachita aquifer systems, and their comparatively low values in the carbonate dominated systems in the Ozarks.

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Comparison of the Ouachita and Carpathian Thrust-Fold Belts and their Back-Arc Basins: Gulf of Mexico and Pannonian Basin

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The Late Paleozoic Ouachita orogenic belt is a north-vergent thrust-fold belt, related to an A-type subduction of the passive margin of North America. The thin-skinned Ouachitas and their deep foredeep basins were formed during this southward directed subduction. Synchronously with compression in the thrust-fold belt, thick Pennsylvanian to Permian marine sediments were deposited to the south of the Ouachita belt, in the Paleozoic Gulf of Mexico. Although this sedimentary succession typically lacks apparent extensional features, its position on the concave side of an orogen associated with A-subduction points to its back-arc origin. The

Pannonian basin of Hungary provides a well-documented analogy for this specific basin setting.

The Pannonian basin of Central Europe is one of the Mediterranean, extensional back-arc basins, characterized distinctly by attenuated continental crust. Very thick (locally >8 km) sedimentary successions formed during the syn-rift (middle Miocene) and post-rift (late Miocene to Recent) period. The style and magnitude of extension is well documented based on reflection seismic and well log data. The loop of the Carpathians surrounds the Pannonian basin and forms a continuous, thin-skinned thrust-fold belt which is coeval with the extension on its concave side. The Neogene evolution of the Carpathians is dominated by the formation of thick flysch nappes toward the foreland and a deep foredeep basin.

Beyond these broad similarities between these thrust-fold and back-arc basin couples (Ouachita–Gulf of Mexico and the Carpathians–Pannonian basin, respectively), other specific details, such as foreland basement promontories of comparable size and kinematic role, such as the Llano Uplift and the Bohemian Massif make this comparison even more viable.

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Precambrian and Paleozoic Crustal Structure and Tectonic History of the Northern Rim of the Gulf of Mexico

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Mesozoic opening of the Gulf of Mexico along the southern margin of North America was superimposed on rock fabrics that record both late Precambrian–Cambrian rifting (Iapetus Ocean) and late Paleozoic convergence (Appalachian–Ouachita orogen). Along the late Precambrian–Cambrian rifted continental margin, northeast-striking rift segments and northwest-striking transform faults outlined the Alabama promontory, Ouachita embayment, Texas promontory, and marathon embayment. Intracratonic faults include the rift-parallel Mississippi Valley and Birmingham systems and the transform-parallel Southern Oklahoma system. Rifting began along the Appalachian Blue Ridge margin in the late Precambrian and shifted to the Ouachita margin in the earliest Cambrian. Most Ouachita-rift extension was transformed (Alabama–Oklahoma transform) to the Mid-Iapetus Ridge outboard from the Blue Ridge margin, but the intracratonic Mississippi Valley and Birmingham fault systems reflect minor extension northeast of the transform. A passive margin persisted around southern North America from Late Cambrian into Early Mississippian. Structure of the diachronous, late Paleozoic Appalachian–Ouachita orogenic belt varies along strike. Arc-continent collision began on the southwest side of the Alabama promontory during the middle Mississippian and progressed westward to close a remnant ocean basin in the Ouachita embayment during the Middle Pennsylvanian. In the Ouachita embayment, the arc, forearc basin, and subduction complex are preserved in the allochthon, and the older passive-margin shelf is preserved in the autochthon as the floor of a peripheral foreland basin. To the east, along the southwest (Ouachita) side of the Alabama promontory, the arc

and forearc were imbricated and thrust over the passive-margin shelf. In contrast, in the later Pennsylvanian, continent-continent collision along the southeast (Appalachian) side of the Alabama promontory resulted in imbrication of the passive-margin shelf (Appalachian thrust belt), tectonic replacement of the passive-margin cover of continental crust by accreted terranes, and accretion of African continental crust and cover (Suwannee terrane) to the margin of North America. Mesozoic rift and post-rift structures suggest re-use of the older structural fabrics; for example, (1) a Mesozoic transform (Alabama–Arkansas fault system/Bahamas fracture zone) coincides with the Cambrian Alabama–Oklahoma transform, and (2) a Mesozoic extensional fault-bounded basin (South Georgia basin) overlies the late Paleozoic Suwannee–Wiggins suture.

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The Appalachian–Ouachita Orogen, Southeastern North America

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The late Paleozoic Appalachian–Ouachita orogenic belt is exposed in the Appalachian and Ouachita Mountains, but large parts are covered by post-orogenic strata of the Gulf Coastal Plain. Large, sinuous curves of the orogenic belt (Alabama recess, Ouachita salient) mimic the shape of a late Precambrian–Cambrian rifted margin, along which the Alabama promontory and Ouachita embayment were framed by northeast-striking rift segments offset by a northwest-striking transform fault. Stratigraphy of the Appalachian–Ouachita foreland, as well as the Appalachian thrust belt in the Alabama recess, includes a Cambrian to Lower Mississippian shallow-marine, passive-margin shelf succession and an Upper Mississippian and Pennsylvanian shallow-marine to deltaic, synorogenic clastic wedge derived from the Ouachita orogen. The Appalachian thrust belt consists of large-scale, internally coherent thrust sheets, the structural style of which is controlled by a thick unit of Cambrian–Ordovician carbonate rocks of the passive-margin succession. In contrast, the Ouachita thrust belt consists of deep-water facies that record a Cambrian to Early Mississippian passive margin and a Late Mississippian to Pennsylvanian arc-continent collision orogen. Internally complex thrust sheets and disharmonic structures in the Ouachitas contrast with Appalachian structures, reflecting the lack of a stiff layer like that in the Appalachians. A north-to-south profile of the Ouachita orogen includes (1) a peripheral foreland basin, the southern part of which is deformed by north-directed thrust faults; (2) a subduction complex, including a forearc ridge; (3) a thrust-imbricated forearc basin, which has a late orogenic to post-orogenic fill of Desmoinesian to Permian age; and (4) remnants of an arc. Diachronous arc-continent collision began on the east in the middle Mississippian and progressed westward to close a remnant ocean basin in the Ouachita embayment by Desmoinesian time. The subduction complex was emplaced over autochthonous passive-margin cover on North American continental crust. Northwest-directed Appalachian thrusting post-dated Ouachita thrusting, dismembered the southeastern

part of the Ouachita foreland basin, and overrode the eastern part of the Ouachita thrust belt. A northwest-to-southeast profile of the Appalachian orogen includes (1) thrust-imbricated, passive-margin shelf facies and synorogenic clastic rocks of the Ouachita foreland basin; (2) accreted metamorphic terranes that tectonically replaced the passive-margin cover strata on North American continental crust; and (3) African crust and cover accreted to North America.

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Lithospheric Structure of the South-Central United States

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Recent seismic data in the Ouachita Mountains area and the Gulf of Mexico make it possible to construct a lithospheric-scale cross section (transect) from the midcontinent region to the gulf. We constructed a transect in the form of a gravity model, but it incorporates all available seismic, drill hole, and geologic data as constraints. The thrust sheets of the Ouachita orogenic belt appear as a thin veneer covering the southern part of the Arkoma basin and the preserved Paleozoic continental margin. Mesozoic rifting is evident in three areas: (1) southern Arkansas and northern Louisiana where extension was minor, (2) the vicinity of the Texas–Louisiana coastline where modification of the lithosphere and subsidence were considerable, and (3) the deep Gulf of Mexico where rifting was successful. A significant variation in the average density of the mantle, which could delineate the North American craton as a lithospheric feature, was detected near the Paleozoic continental margin.

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The Expression of Convergence Rate and Slab Pull in Foreland Basins

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Cenozoic orogenic belts of the Mediterranean region display different structural and morphological characteristics that are predominantly controlled by the dynamic environment in which each belt evolved. Belts that formed in environments dominated by convergence due to external plate motions generally have high topography, marginal thrust belts consisting of shallow water passive margin sediments and molasse, cores of high-grade metamorphic rocks, significant involvement of crystalline basement, extensive post-collisional convergence, and commonly develop antithetic thrust belts. Those belts that form in environments dominated by slab pull generally have low topography, marginal thrust belts dominated by flysch,

low-grade metamorphism, lack significant involvement of continental crystalline basement, lack antithetic thrust belts, lack significant post-collisional convergence, and commonly display extensional deformation in the back-arc to inter-arc region. The forces operating in these two different dynamic settings are clearly expressed in the deflection of the foreland lithosphere adjacent to the thrust belts. In settings where deformation is driven by large-scale plate convergence and where plate convergence is occurring more rapidly than subduction, flexural bending of the foreland lithosphere occurs primarily in response to loading of the lithosphere by thrust sheets; the depth and geometry of these foreland basins are roughly consistent with the size of the adjacent mountain belt. In settings where deformation is driven by forces acting on the subducted slab (probably largely related to the negative buoyancy of the subducted slab) and subduction is occurring more rapidly than large-scale plate convergence, flexural bending of the foreland lithosphere occurs primarily in response to forces transmitted to the foreland from the subduction zone. In these settings loading of the foreland lithosphere by thrust sheets contributes to the loading of the foreland in only a minor way (or in some cases not at all) and the foreland basin is typically much deeper and sits much farther in front of the adjacent mountain belt than would be expected from the size of the mountain belt itself. This systematic pairing of topographically high mountains with relatively shallow foreland basins in tectonic settings dominated by large-scale plate convergence is conducive to the protracted history of molasse deposition observed in these belts, as sufficient material is usually available to keep the foreland basins filled with coarse clastic material. In contrast, the systematic pairing of topographically low mountains with relatively deep foreland basins in tectonic settings dominated by slab-pull is conducive to the protracted history of flysch deposition observed in these belts, as the sediment source is commonly insufficient to fill the adjacent foreland basin, resulting in deposition of predominantly fine-grained material in deep water conditions via submarine fan development. The Late Paleozoic Ouachita thrust belt of the south-central U.S., and its associated foreland basin, displays most if not all of the characteristics of more recent thrust belts that formed in an environment dominated by slab pull.

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Fluid-Inclusion Studies of Regionally Extensive Epigenetic Dolomites, Bonneterre Dolomite (Cambrian), Southeast Missouri: Evidence of Multiple Fluids During Dolomitization and Lead–Zinc Mineralization

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Sources of basinal fluids that precipitated the dolomite-hosted Mississippi Valley-type orebodies of southeast Missouri historically have been a subject of debate. This study presents microthermometric data for fluid inclusions in the regionally exten-

sive epigenetic dolomite at the base of the ore-hosting Bonneterre Dolomite and in gangue dolomite of the Viburnum Trend Pb–Zn district. Samples of epigenetic dolomite cover an area of more than 25,000 km^2 west of the St. Francois Mountains and permit determination of regional variations of temperature and composition of the mineralizing fluids and possible fluid interactions.

Homogenization temperature–ice-melting relationships (temperature-salinity) among these inclusions document at least two end-member fluid components: a warmer, less saline fluid (120 to 187°C; 5 wt% equiv. NaCl) and a cooler, more saline fluid (60 to 80°C; >30 wt% equiv. NaCl). Intermediate temperatures and fluid compositions indicate that the end-member fluids likely mixed as they flowed through the region. Mixing was not confined to a stationary front but occurred throughout the study area. Comparison of homogenization temperatures to distance from possible basinal fluid sources indicates *no* discernible temperature gradient over the >25,000 km^2 study area. The data are interpreted to indicate multiple basinal-fluid interactions coeval with dolomitization and associated Pb–Zn ore formation.

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