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1990, pp. 201-206. https://doi.org/10.56577/FFC-41.201

in:

Tectonic Development of the Southern Sangre de Cristo Mountains, New Mexico, Bauer, P. W.; Lucas, S. G.; Mawer, C. K.; McIntosh, W. C.; [eds.], New Mexico Geological Society 41st Annual Fall Field Conference Guidebook, 450 p. https://doi.org/10.56577/FFC-41

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SYNTECTONIC EMPLACEMENT OF THE HARDING PEGMATITE, TAOS COUNTY, NEW MEXICO

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Abstract—The Harding pegmatite of Taos County, New Mexico, displays evidence of internal and marginal deformation. Within the pegmatite, quartz exhibits undulose extinction and contains well-developed subgrains. Lath-shaped spodumene crystals are broken, kinked and folded. Both the hanging-wall contact of the pegmatite against strongly foliated and lineated amphibolite, and the internal contact between the quartz and quartz-lath spodumene zones, show cuspate-lobate folds. The folds display a range of amplitudes (up to 2 m) and variable wavelengths; fold hinges are parallel to the intersection of a foliation developed by shearing in the amphibolite with the pegmatite/amphibolite contact. The foliation fans divergently around the lobate hinges and into the cuspate hinges of the folds along the upper contact of the pegmatite. The morphology and orientation of the Harding pegmatite bodies with respect to the orientation and tectonic transport direction of shearing in the amphibolite are similar to those of extension fractures developed in brittle-ductile shear zones.

INTRODUCTION

The Harding pegmatite is located in the southwestern part of the Picuris Mountains of north-central New Mexico, roughly 35 km southwest of Taos (sec. 29, T23N, R11E). The pegmatite is accessible from NM State Highway 75, between Dixon and Peñasco (Fig. 1).

The pegmatite is emplaced in a heterogeneous, tectonically juxtaposed sequence of Proterozoic metasedimentary and metavolcanic rocks, the younger felsic-dominated Vadito Group and the older mafic-dominated Pecos Complex (Bauer and Williams, 1989). In the southwestern Picuris Mountains, inverted Vadito Group rocks are juxtaposed against younger, right-side-up metasediments of the Hondo Group along a south-dipping ductile shear zone 2 km north of the pegmatite (Bauer, 1988; Bauer and Williams, 1989; Mawer et al., 1990).

The Harding pegmatite consists of a series of complex, well-zoned pegmatite bodies that crop out in a broad, west-trending belt 800 m in length (Jahns and Ewing, 1976). Figure 2 shows the distribution of pegmatite cropping out in the area of the Harding mine. The bodies are generally flattened and tabular, with thicknesses ranging from less than 10 cm up to a maximum of 25 m in the thickest portion of the main pegmatite body. The bodies trend west and dip 10° to 15° to the south. The main pegmatite body has an explored length of 500 m down dip.

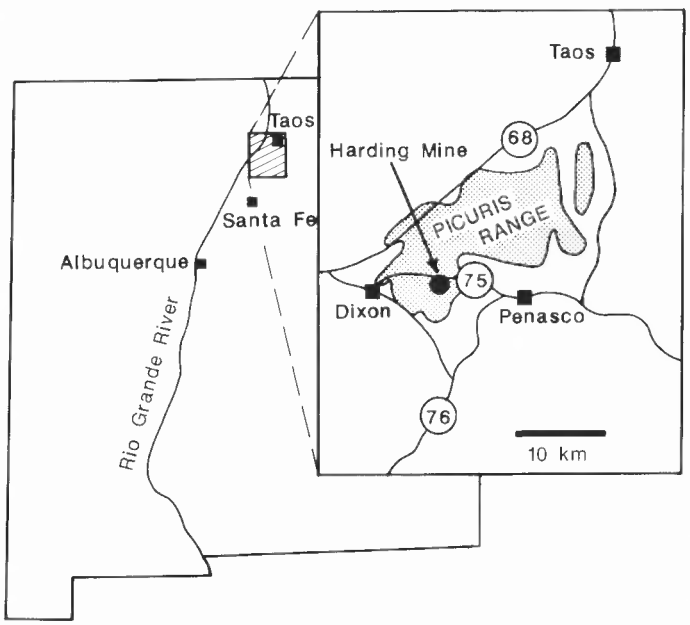


FIGURE 1. The location of the Harding pegmatite (after Bauer, 1988).

The main body of Harding pegmatite appears to be emplaced along the contact between quartz-muscovite-biotite schist outcropping to the north of the pegmatite exposure, and amphibolite outcropping to the south (Jahns and Ewing, 1976). However, examination of drill core from exploration drilling conducted in the early 1960's(?) reveals that the pegmatite lies at this contact only near the present erosional surface; the majority of the body south and east of the surface outcrop is hosted solely by amphibolite. The drill cores only extend a few meters below the lower contact of the main pegmatite body. Therefore, the depth beneath the pegmatite to the quartz-muscovite-biotite schist, and its extent southward beneath the amphibolite, are not known. Several of the smaller bodies of pegmatite cropping out in the mine-area have similar morphology and orientation to the main body, and are located almost entirely within the amphibolite; a few are located entirely within the quartz-muscovite-biotite schist.

The crystallization history, internal lithologic structure and mineralogy of the Harding pegmatite are well-documented (Jahns and Ewing, 1976; Brookins et al., 1979). This discussion focuses on the structural setting and relative timing of emplacement of the Harding pegmatite bodies with respect to the shearing deformation of the amphibolite host rock. The pegmatite bodies have previously been interpreted as products of the forceful injection of a highly differentiated melt into the already-deformed country rock, with little deformation of the pegmatite during or after crystallization (Jahns and Ewing, 1976). The pegmatite has been considered to crosscut the deformational fabrics in the country rock and, therefore, to be later and unrelated. We present evidence showing that considerable internal deformation of the Harding pegmatite has occurred. Furthermore, we suggest that the deformation, morphology and orientation of the pegmatite bodies are consistent with their syntectonic emplacement and crystallization in extension fractures developed during brittle-ductile shearing of the amphibolite host.

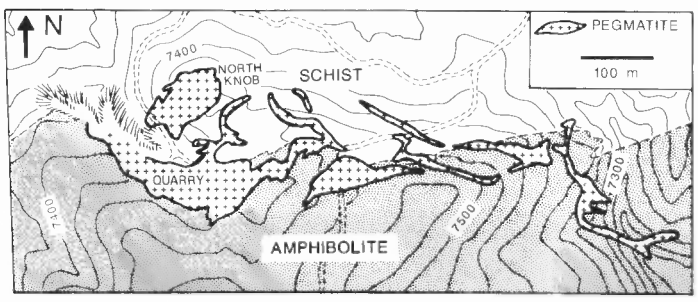


FIGURE 2. Distribution of pegmatite exposures in the area of the Harding mine (modified from Jahns and Ewing, 1976).

EVIDENCE FOR INTERNAL DEFORMATION OF THE PEGMATITE

Both microscopic and outcrop-scale evidence suggest that the pegmatite is deformed. Petrographic examination of quartz from the quartz zone reveals microstructures consistent with crystal-plastic deformation. The quartz has undulose extinction and contains many well-developed subgrains and deformation bands. New, small, dynamically recrystallized quartz grains have been produced at pre-existing grain boundaries by the crystal-plastic dynamic recrystallization process of grain-boundary migration and bulge rotation. Figure 3 is a photomicrograph showing these microstructures in quartz from the Harding pegmatite.

At the outcrop scale, in the quartz-lath spodumene zone, broken and folded spodumene crystals imply deformation of the pegmatite. Quartz fills fractures that separate broken pieces of individual spodumene crystals. The lath-like spodumene crystals are often kinked and folded, sometimes to interlimb angles of nearly 90°. Figure 4 shows a spectacularly folded group of spodumene crystals located just within the main entrance of the underground workings. Individual crystals of spodumene are folded into an "S" shape against a block of quartz ± lepidolite. It is unlikely that the bent spodumene crystals originally grew with this geometry; their shape strongly advocates internal deformation of the pegmatite.

Another outcrop-scale feature indicating that the pegmatite is deformed is the cuspate-lobate folding of the hanging-wall contact and the internal contact between the quartz and quartz-lath spodumene zones. The folds have a range of amplitudes (up to 2 m) and variable wavelengths. Fold hinges trend southeast, parallel to the intersection lineation between a foliation developed by shearing in the amphibolite and the amphibolite/pegmatite contact. The cuspate-lobate fold geometry, characterized by alternating rounded and pointed hinges, has produced mullions on the upper surface of the pegmatite and on the lower surface of a portion of the quartz zone. This style of folding occurs when materials of slightly differing competence are compressed parallel to their mutual contact; the stronger materials form the mullion structures (Ramsay and Huber, 1987, p. 397). Figure 5 shows such folding exposed in the quarry face. The geometry and orientation of the cuspate-lobate folds in the Harding pegmatite imply that the upper portion of the pegmatite was more competent than either the overlying amphibolite or the underlying quartz-lath spodumene zone during southeast-northwest-directed shortening. In addition to being folded, pieces of the border rind are locally broken and displaced near the sharply pointed, cuspate fold hinges.

Apophyses of pegmatite extending up from the main pegmatite body into the host rock also show evidence of deformation. Figure 6 is a

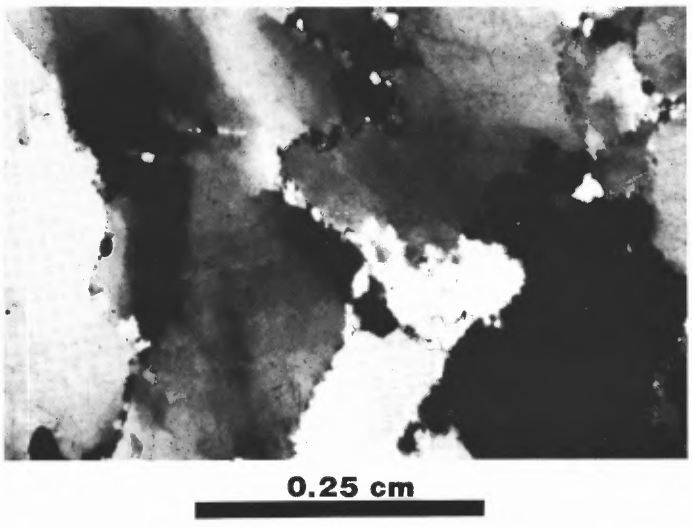


FIGURE 3. Photomicrograph of quartz from the quartz zone of the Harding pegmatite viewed under cross polarized light. Note the undulose extinction, well developed subgrains, approximately horizontal deformation bands and the new, dynamically recrystallized grains generated at pre-existing grain boundaries.

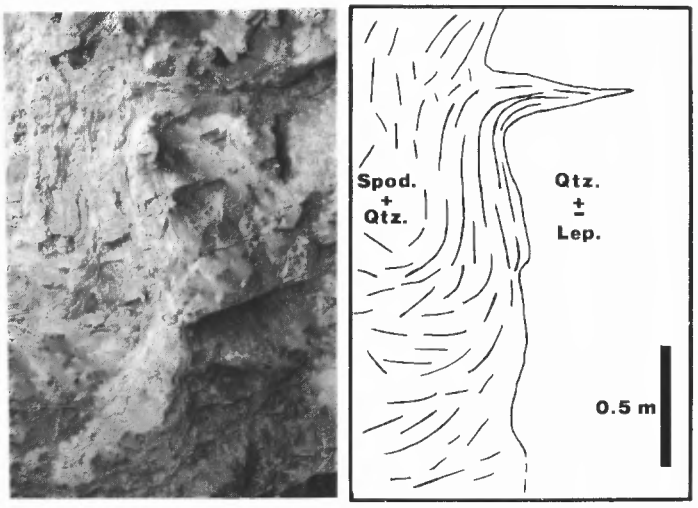
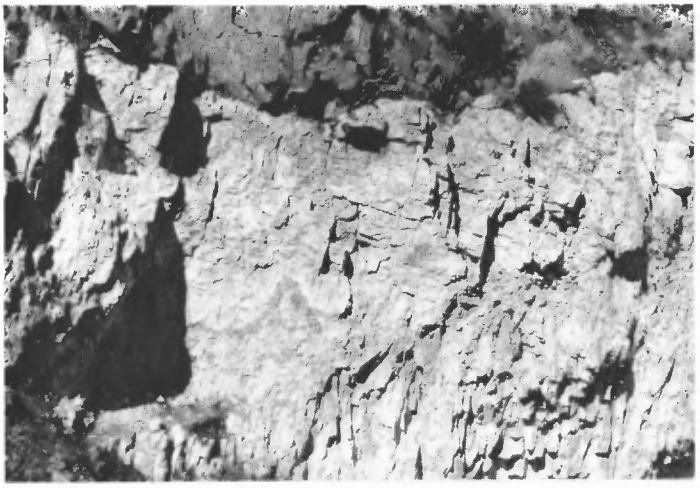


FIGURE 4. Photograph of lath-shaped spodumene crystals folded into an "S" shape against a competent block of quartz ± lepidolite. The view is looking to the northeast from just within the main entrance to the underground workings.



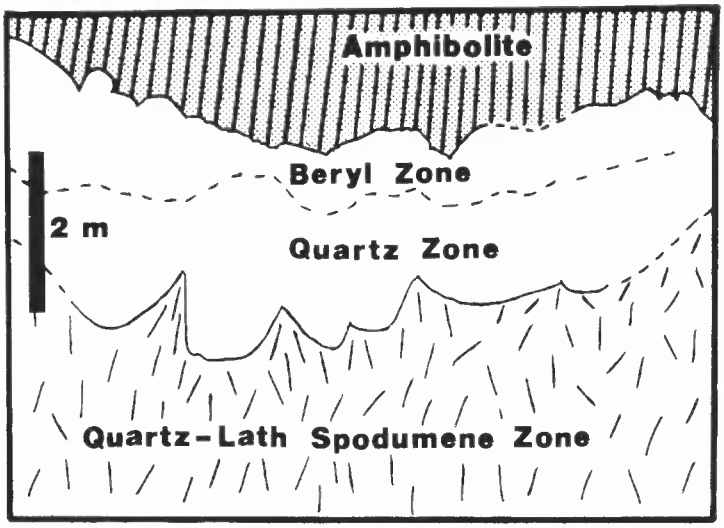


FIGURE 5. Photograph of a portion of the quarry face in the Harding mine, showing the cuspate-lobate fold geometry of the hanging-wall amphibolite/pegmatite contact and a portion of the internal quartz zone/quartz-lath spodumene zone contact. The view is to the south-southwest.

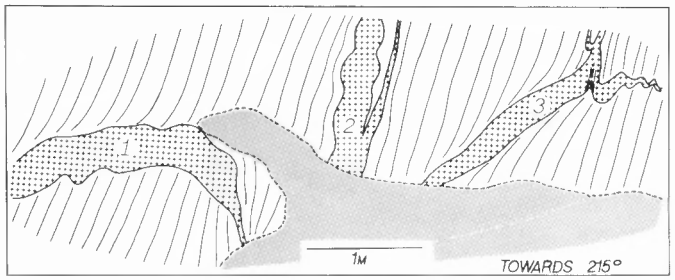


FIGURE 6. Field sketch of part of the southern quarry wall, showing three small deformed pegmatite apophyses (numbered, with cross pattern) less than 1 m above the upper main body contact. Foliation trends in the host amphibolite are shown by the thin, southeast-dipping lines. Shaded area is covered by talus. View looks towards 215° and was sketched on 19 August 1988.

sketch of three thin apophyses of pegmatite within the hanging-wall amphibolite, less than 1 m above the upper Harding pegmatite contact. These are probably contemporaneous with the injection of the Harding main body; the branching pattern of pegmatites 2 and 3 show that they were injected upwards. All three thin pegmatites are deformed. Pegmatite 1 (left) is folded, with characteristic deflection of the amphibolite foliation at the upper and lower contacts (i.e., divergent fanning about the rounded outer arc of the fold, and converging into the inner arc of the folds). Pegmatite 2 (center), intruded roughly parallel to the host amphibolite foliation, is extended and shows characteristic pinch-and-swell structures. Pegmatite 3 (right) shows complex deformation behavior. Its lower limb shows extension and deflection of the amphibolite foliation along its margin consistent with overall northwest-directed shearing; the central vertical, foliation-parallel limb is thinned; and the right-hand, foliation-orthogonal limb is folded (see pegmatite 1). Note that an axial-surface foliation is developed at the join between left-hand and right-hand limbs (thin vertical lines in figure).

DEFORMATION IN THE HOST AMPHIBOLITE

The prominent foliation (S_1) in the amphibolite country rock strikes northeast (N45°–55°E) and dips steeply southeast (55°–75°SE). This foliation intersects the shallowly dipping pegmatite bodies at a 40° to 65° angle. Near the contact with the pegmatite, the S_1 foliation is deflected. As the steeply dipping foliation approaches the pegmatite, its dip shallows. Just above the contact, the foliation divergently fans about the rounded, lobate fold hinges and converges into the pointed, cuspate hinges of the folds in the upper surface of the pegmatite. Figure 7 illustrates the behavior of the S_1 foliation in the amphibolite near the upper surface of the pegmatite. An extension lineation runs down dip or rakes steeply to the northeast on the S_1 foliation. The lineation in the hornblende-rich portions of the amphibolite is moderately well developed and is defined by the alignment of elongate hornblende crystals. In quartz-rich mylonite zones that parallel the S_1 foliation, the extension lineation is well developed, and is defined by ribboned quartz grains.

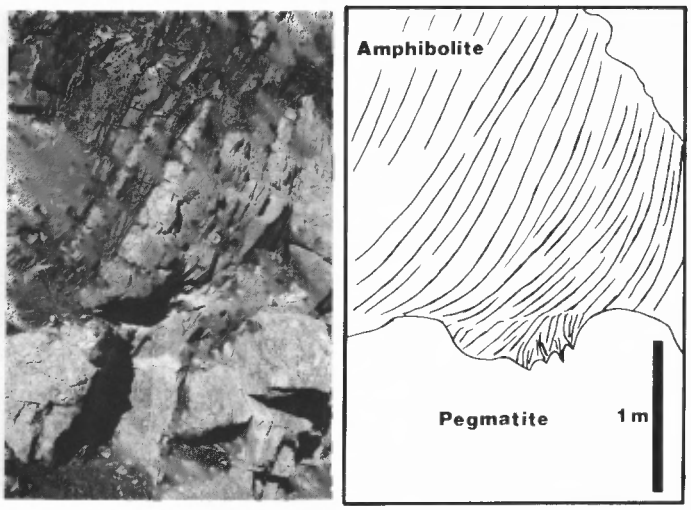


FIGURE 7. Photograph showing the deflection of the S_1 foliation in the amphibolite near the pegmatite contact. The view is looking southwest near the west end of the quarry. The dip of the foliation shallows; then it diverges about the rounded, lobate fold hinges and converges into the pointed, cuspate hinges in the folded pegmatite contact.

A second foliation (S_2) is locally present near the pegmatite contact. This foliation is defined by the alignment of biotite in the narrow biotite-plagioclase alteration zone surrounding the pegmatite. The biotite aureole was produced by the reaction of hornblende in the amphibolite with alkali-rich fluids exsolved from the pegmatite during crystallization (Jahns and Ewing, 1976). Where present, S_2 is subparallel to the contact and is folded along with the contact into the cuspate-lobate folds. The biotite-plagioclase alteration and S_2 foliation obliterate or crosscut the primary (S_1) foliation in the amphibolite near the pegmatite contact.

Mylonite zones ranging in thickness from less than 1 cm to greater than 1 m occur in the amphibolite and are oriented parallel to the S_1 foliation. Figure 8 is a photomicrograph of a thin section made from an oriented sample of a 0.5-m-thick mylonite zone that crops out 0.5 km southwest of the pegmatite. Larger quartz grains are ribboned. Small, dynamically recrystallized quartz grains with a well-developed crystallographic preferred orientation (based on flat-stage study with a first-order red plate) and left vergence (based on alignment of asymmetric grains) comprise the fine-grained mylonite between the ribboned quartz. The shear sense indicated by the microstructures in the photomicrograph is sinistral, which suggests top-to-the-northwest tectonic transport.

The hornblende-rich amphibolite betwen mylonite zones also preserves evidence of shear strain. Broken and displaced porphyroclasts as well as shear bands are found at the microscopic and outcrop scales. Figure 9 is a photomicrograph of a broken and displaced porphyroclast of quartz and hornblende from an oriented sample of amphibolite 2 m above the pegmatite contact. The porphyroclast is sheared; the two

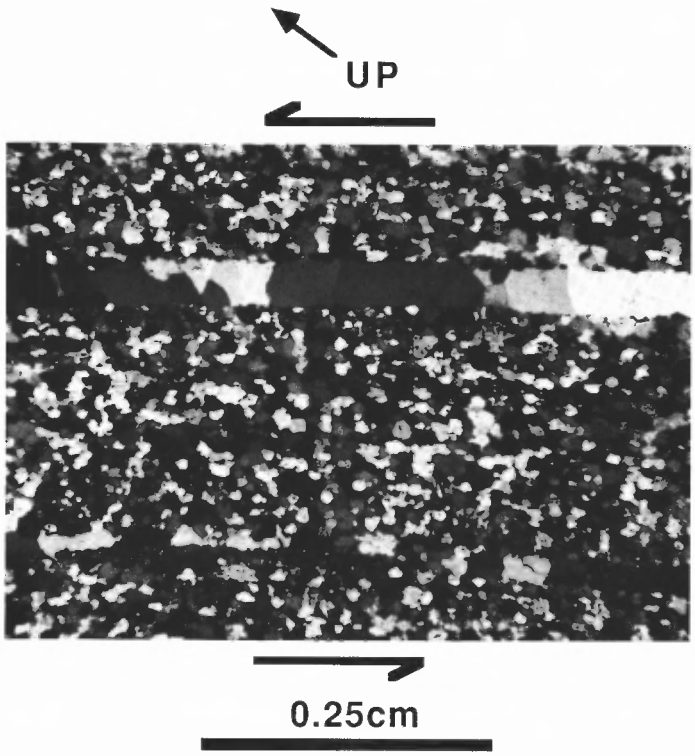


FIGURE 8. Photomicrograph of mylonite from within the amphibolite viewed under cross polarized light. The thin section is cut perpendicular to the northeast-striking S_1 foliation and parallel to the extension lineation which rakes steeply northeast on the S_1 foliation at this location. Northwest is to the left. Larger quartz grains are ribboned; the multitude of small mylonite grains display a well-developed crystallographic preferred orientation and left vergence. The sense of shear indicated is sinistral (top-to-the-northwest).

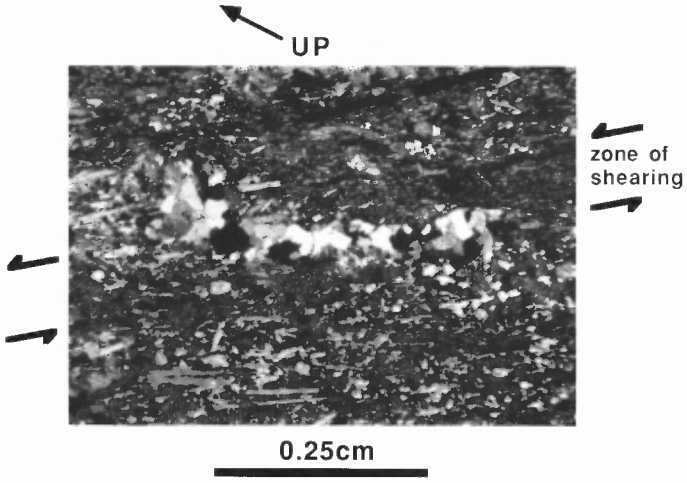


FIGURE 9. Photomicrograph of a sheared and displaced porphyroclast of quartz and hornblende in the amphibolite. The section is cut perpendicular to the S_1 foliation and parallel to the down-dip extension lineation, and is shown under cross polarized light. Northwest is to the left. The shear sense indicated is sinistral (top-to-the-northwest).

pieces are displaced parallel to the shear foliation (S_1) in a top-to-the-northwest sense. Recrystallized material from the porphyroclast is located along the narrow zone of shearing.

DISCUSSION

Structural setting

The Harding pegmatite bodies are emplaced near the northern margin of a broad zone of brittle-ductile shearing within the amphibolite. The prominent S_1 tectonic foliation roughly parallels the shear-zone boundries, and was apparently produced during the shearing deformation. Most shear strain concentrated in discrete, quartz-rich mylonite zones within the generally strained amphibolite. Sense-of-shear indicators in amphibolite, including asymmetric porphyroclasts, broken and displaced porphyroclasts, shear bands and preferred alignment of mylonite grains, indicate that the southeast side moved up with respect to the northwest. The top-to-the-northwest transport direction indicated by the microfabrics is consistent with a reverse sense of shear along the broad, southeast-dipping shear zone. A component of right-lateral shear may also be present, as indicated by the steep, northeast rake of the extension lineation in some locations. The magnitude of displacement along the shear zone is unknown, but may be relatively small. The orientation and tectonic transport direction of this shear zone are similar to those of the shear zone which juxtaposes the Vadito Group against the younger Hondo Group 2 km north of the pegmatite (Bauer, 1988; Bauer and Williams, 1989; Mawer et al., 1990).

Relative timing of pegamtite emplacement

The emplacement and crystallization of the Harding pegmatite have previously been interpreted as post-tectonic, resulting from forceful intrusion of a highly differentiated melt into the already-deformed country rock (Jahns and Ewing, 1976). However, it is unlikely that the forceful intrusion of a fluid into a strongly foliated host would result in large, flattened, tabular bodies that cut across the prominent foliation at a high angle. Forceful intrusion would more likely take advantage of the steeply dipping structural planes of weakness provided by the foliation, and result in pegmatite bodies with contacts that parallel the foliation. Alternatively, the angular relationship between the Harding pegmatite and the shear foliation, and the internal and marginal deformation of the Harding pegmatite, might be explained by either pretectonic or syntectonic emplacement and crystallization of the pegmatite with respect to the shearing deformation in the amphibolite.

A pretectonic model

In a pretectonic model, the already-crystallized, quartz-rich pegmatite must behave as a relatively competent block surrounded by less competent amphibolite during the shear deformation which formed the prominent (S_1) tectonic foliation in the amphibolite. However, several features of the pegmatite are not consistent with pretectonic emplacement and crystallization.

First, if the pegmatite were pretectonic, then the shear strain in the amphibolite might be expected to rotate significantly the pegmatite out of its original orientation. Yet, noticeable rotation of the Harding pegmatite has not occurred. The internal lithologic structure of complex, well-zoned pegmatite is often predictably related to the gravitational field at the time of crystallization (Jahns and Burnham, 1969; Jahns, 1982). The well-developed, sub-horizontal zonation of the lithologic units in the Harding pegmatite suggests that it is right-side-up, and that it crystallized in close to its present orientation. Second, the narrow biotite-plagioclase alteration zone surrounding the pegmatite, and the S_2 foliation locally defined by biotite in the alteration zone, obliterate or crosscut the shear-parallel foliation (S_1) in the amphibolite. From these observations, one may infer that pegmatite emplacement and crystallization post-dated the development of S_1 foliation. Therefore, the pegmatite is not pretectonic with respect to the deformation which produced S_1.

A syntectonic model

During the evolution of a brittle-ductile shear zone, and especially near the margins of the zone, locally dilatant extension fractures or tension gashes commonly develop (Ramsay and Huber, 1987; Hodgson, 1989). These essentially planar features are typically oriented perpendicular to the direction of maximum extension and contain the direction of maximum shortening of the bulk incremental strain ellipse. Shear zones are commonly oriented 45°–60° from the direction of maximum shortening, and the shear-parallel foliation intersects the extension fractures at high angles approaching approximately 60° (Hodgson, 1989). Figure 10 illustrates angular relationships typically observed between principal stress directions, shear zones and extension fractures.

If the melt were emplaced somewhat passively in locally dilatant extensional sites developed late in the shearing which produced the S_1 foliation in the amphibolite host, then the high angle between the pegmatite bodies and the shear-parallel foliation is not only acceptable, but predictable. If the maximum extension direction during the deformation was nearly vertical, then the orientation of extension fractures developed would be nearly horizontal—similar to the orientation of the Harding pegmatite bodies.

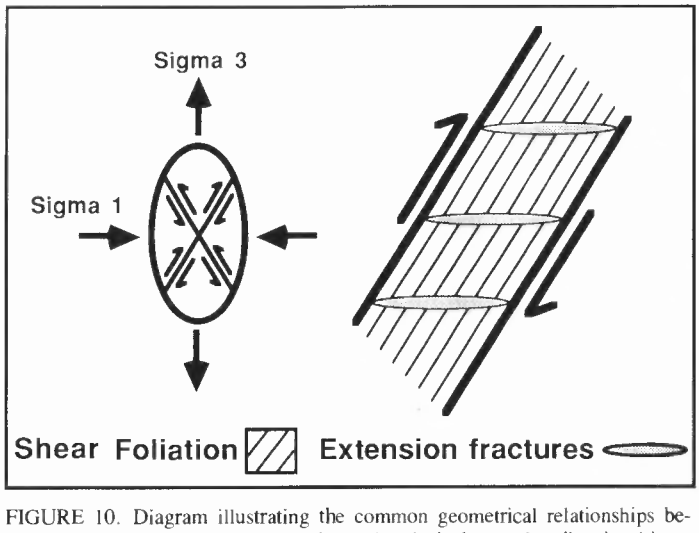


FIGURE 10. Diagram illustrating the common geometrical relationships between principal compressive stress (sigma 1), principal extension direction (sigma 3), shear zones developed in response to the stress, and extension fractures occurring in and near the shear zones.

Little of the internal and marginal deformation of the pegmatite need occur during the emplacement and crystallization of the pegmatite, even in a syntectonic model. Using cooling models for a finite sheet, Chakoumakos and Lumpkin (unpubl. 1989) have estimated that the time required for magmatic crystallization of the pegmatite was 100 to 1000 years, depending on the temperature of the host rocks at the time of emplacement. While little constraint exists on the length of the shortening event associated with shearing in the amphibolite, it was almost certainly several orders of magnitude longer than the time required for pegmatite crystallization, based on typical tectonic strain rates in shear zones (e.g., White and Mawer, 1988). Therefore, crystallization of the pegmatite may have been geologically instantaneous compared to the deformation event.

Southeast-northwest directed shortening that continued after emplacement and crystallization of the pegmatite in extension fractures would produce the internal deformation, the cuspate-lobate folding of the pegmatite and its apophyses, and the deflection of the S_1 foliation in the amphibolite near the pegmatite. The contact-parallel S_2 foliation defined by biotite in the alteration zone can also be accounted for by continued shortening. The local compression direction near a contact between materials with contrasting rheology becomes reoriented to a high angle to the contact of the more competent material (e.g., Dieterich and Carter, 1969). Since the stress field becoomes locally reoriented, and perhaps even intensified, local fabric development may result with its orientation largely controlled by the local stress directions. It should be emphasized that this effect occurs at a limited scale. At the Harding pegmatite, the S_2 foliation is not pervasive; it typically occurs only at distances less than 10 cm from the pegmatite contact. Reorientation of the stress field within a few cm of the pegmatite so that the compression direction was at a high angle to the contact, and minor local deformation, could have generated the contact-parallel alignment of biotite which defines S_2 in the narrow alteration zone.

Other general morphological features of the Harding-pegmatite bodies are consistent with syntectonic emplacement in late extension fractures developed in a broad zone of shearing. The pegmatite bodies crop out in a west-trending belt 800 m in length. The bodies range in size, but generally have similar orientation (Jahns and Ewing, 1976). The outcrop pattern and relatively consistent orientation of the pegmatite bodies are suggestive of the en echelon geometry observed in a series of extension fractures developed in zones of shearing. Figure 11 summarizes the generalized geometric relationships observed between the Harding pegmatite bodies, the shearing-parallel S_1 foliation in the amphibolite and the inferred directions of maximum shortening and extension. Note the close similarity of these relationships to those ideal relationshps shown in Figure 10.

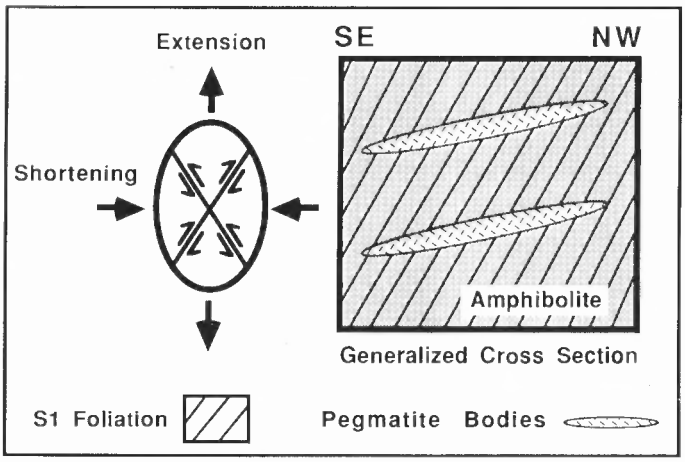


FIGURE 11. Diagram illustrating the generalized geometrical relationships observed between the prominent S_1 foliation in the sheared amphibolite, the Harding pegmatite bodies and the inferred directions of maximum shortening and extension. Note the close similarity of these relationships to those in Figure 10.

Alternatively, the internal and marginal deformation of the pegmatite might have been generated by a later, southeast-northwest shortening event. In this scenario, the pegmatite emplaced and crystallized, with little internal deformation, sometime after the development of S_1 foliation in the amphibolite. Even later, another southeast-northwest directed shortening event produced the internal and marginal deformation in the pegmatite. However, no pervasive flattening foliation or other fabric elements, which one might expect to be produced during a later shortening event, have been seen overprinting the S_1 shear foliation in the amphibolite away from the pegmatite. Therefore, the single-event, syntectonic model seems favorable.

Speculations

If pegmatite emplacement and crystallization was syntectonic, then the age of the pegmatite is also the age of a component of the deformational event. Unfortuantely, the age of the pegmatite is not well-constrained. Aldrich et al. (1958) reported K-Ar and Rb-Sr age determinations of 1260 Ma for Harding muscovite and 1350 Ma for Harding lepidolite. Brookins et al. (1979) reported the average age of the Harding pegmatite as 1366 Ma, based on Rb-Sr isotopic geochronology of whole-rock samples and mineral separates from various lithologic units within the pegmatite. However, Rb-Sr age determinations must be viewed with caution since the isotopic equilibrium in the pegmatite has been disturbed by late redistribution of Rb and Sr (Brookins et al., 1979). If the pegmatite is syntectonic, and if an age of 1366 Ma is accepted for the crystallization of the pegmatite, then northwest-directed crustal shortening was occurring in northern New Mexico at this time.

SUMMARY

The Harding pegmatite of Taos County, New Mexico, is internally deformed. Evidence in support of this includes: (1) quartz with undulose extinction and well-developed subgrains, deformation bands and dynamic recrystallization; (2) broken, kinked and folded spodumene crystals; and (3) cuspate-lobate folding of the hanging-wall contact between pegmatite and amphibolite and the internal contact between the quartz and quartz-lath spodumene zones.

Strongly foliated and lineated amphibolite with a prominent northeast-striking, southeast-dipping foliation hosts the pegmatite. Sense-of-shear indicators in the amphibolite, including asymmetric porphyroclasts, sheared and displaced porphyroclasts, shear bands and preferred alignment of mylonite grains, together with the down-dip extension lineation, suggest a northwest-directed sense of displacement during shearing of the amphibolite. In general, the deformation, morphology and orientation of the pegmatite bodies might be explained by either pretectonic or syntectonic emplacement of the pegmatite; however, the syntectonic model is favored since the pegmatite shows little evidence of rotation since crystallization, and since the narrow, biotite-plagioclase alteration zone surrounding the pegmatite overprints the shearing-parallel S_1 foliation in the amphibolite. The pegmatite probably emplaced as a highly differentiated melt in locally dilatant extension fractures that were produced late in the brittle-ductile shearing of the host rock. The age of the pegmatite is poorly constrained. Rb-Sr isotope geochronology on various lithologic units within the pegmatite gives an average age of 1366 Ma (Brookins et al., 1979). If the pegmatite is syntectonic, and if this age is reliable, then this is the age of at least the last stages of the deformation event.

ACKNOWLEDGMENTS

We thank P. W. Bauer (NMBMMR) and J. A. Grambling (UNM) for their careful critical reviews. Part of this work is from the senior thesis of C.J.N., performed under the supervision of R. C. Ewing. C.K.M. acknowledges support from the NSF (Grant EAR-8816402 to J. A. Grambling and C. K. Mawer) and Sandia National Laboratories (via SURP 06-5629, Task 7).

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The St. James Hotel in Cimarron, May 1990. Henry Lambert began construction of a small, six-bedroom adobe hotel here on the Santa Fe Trail in 1872. Business was so good that in 1880 he built and furnished a large addition that was reputed to make it one of the finest hotels west of the Missouri River. The adobe walls were more than two feet thick; each room contained a fireplace, marble lavatories, high poster beds, marble-top dressers and fine artwork. A second-story balcony originally extended around two sides of the hotel. After Lambert died, the hotel was renamed the Don Diego Hotel. Subsequently, the interior of the hotel has been restored to original style and renamed the St. James. Photo by P. W. Bauer.