with no evidence for interaction between wallrocks and pegmatite-derived aqueous fluids earlier in the crystallization history of the pegmatite.

THE HARDING MINE, NEW MEXICO

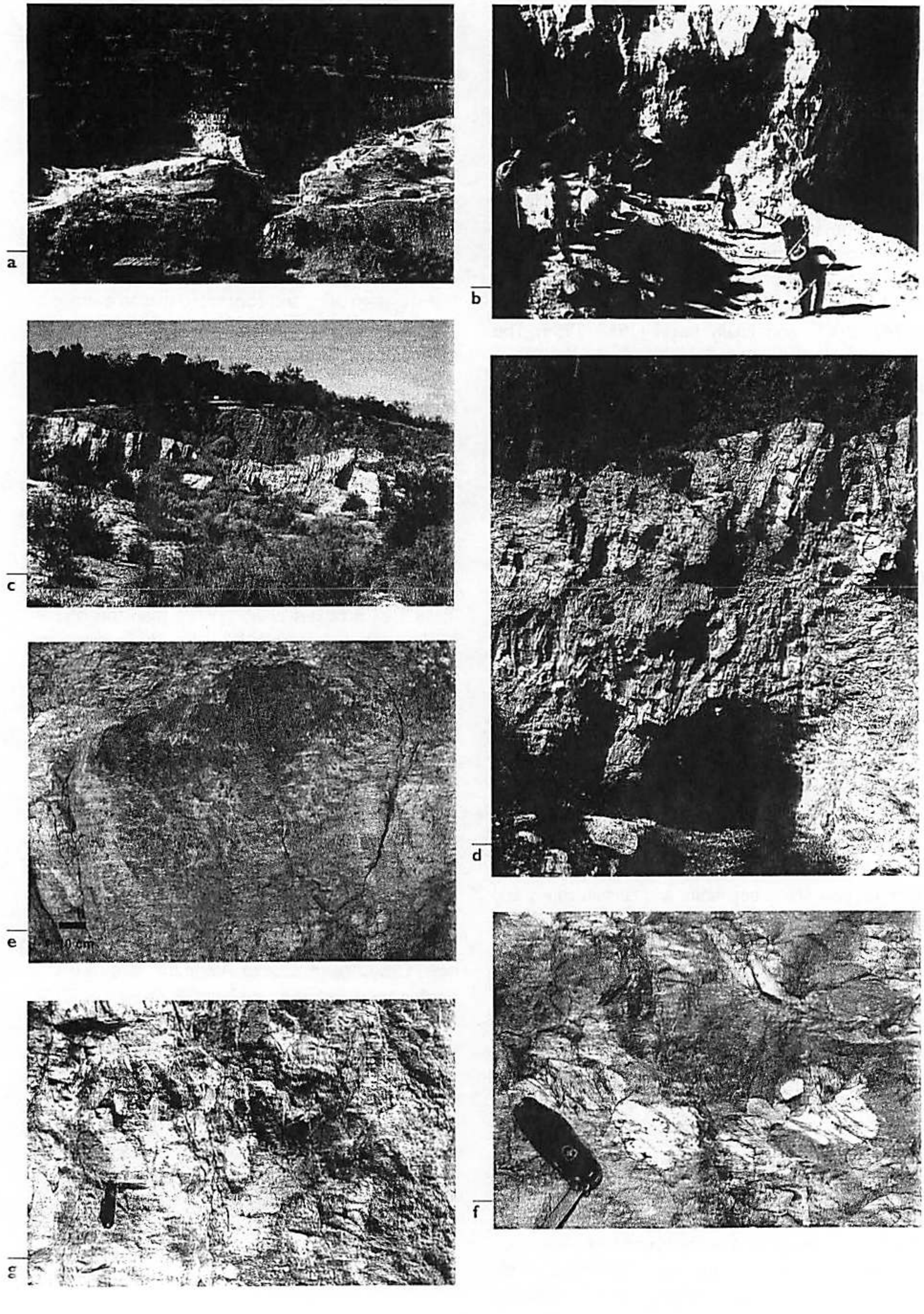
The Harding mine near Dixon, Taos County, northern New Mexico, was an economic source of beryl, spodumene, and microlite (Na–Ca tantalate) through the first half of the 20th century. As summarized by Jahns & Ewing (1977), the history of mining began with lepidolite for glass manufacture (1919–1930), and then microlite, and spodumene (1942–1947), and finally beryl (1950–1958). The pegmatite was well exposed by open cuts and short inclined adits (Fig. 7–10), and it was explored by core drilling conducted by the U.S. Bureau of Mines (Soulé 1946). Personnel of the U.S. Geological Survey logged the U.S.B.M. core, and ore reserves were calculated that remain in place today (Jahns & Ewing 1977). Of importance to science, the "Harding composite" based on that core log (Table 7–1) became the scientific standard for a Li-rich rare-metal pegmatite, and that composite or its equivalent composition was utilized by Jahns & Burnham (1957, Burnham & Nekvasil 1986) and Fenn (1986) in their studies of phase equilibria in evolved pegmatite systems.

Information on the geology, geochronology, fluid inclusions, and especially the mineralogy and composition of microlite at the Harding mine is available in print, though little of it is in readily accessible international journals or other monographs. Jahns & Ewing (1977) presented the general geology of the pegmatite, including a list of minerals, the estimated bulk-composition of the pegmatite and certain zones, and some data on the composition of micas. Brookins *et al.* (1979) provided updates on the selected topics of geochronology, fluid-inclusion microthermometry, and the crystal chemistry of microlite (also see Lumpkin *et al.* 1986, Lumpkin & Chakoumakos 1988, Lumpkin 1998). Shmakin *et al.* (2000) outlined the compositions and some aspects of crystal structure of the alkali feldspars and micas, and Northrup *et al.* (1989) presented an overview of the compositions of beryl and apatite.

Geology

The pegmatite forms a subhorizontal lens-like body that dips gently to the southwest. It transects a northeast-striking and steeply dipping contact between muscovite-rich schist to the north and amphibolite to the south with little change in form, attitude, or mineralogy except in the nature of wallrock alteration, as described below. Though numerous granitic bodies occur in the region, several different textural types of pegmatite cut all of the granites, and the pegmatites cut hydrothermal quartz veins as well (Long 1974). For these and other reasons, Long (1974) suggested that the pegmatites are younger than any of the exposed granites, and hence that none of the exposed granites represents a source of the pegmatites. Brookins *et al.* (1979) determined the Rb–Sr age of various mica and feldspar separates from the Harding pegmatite, and concluded that an average of 1366 ± ~100 Ma represents a probable age of the emplacement. Brookins *et al.* (1979) suggested that variations in radiometric ages of micas and feldspars from different pegmatite units (margin to core, early to late) might delineate the cooling history of the pegmatite (from oldest to youngest Rb–Sr date). The total range in Rb–Sr isochrons reported by Brookins *et al.* (1979, their Table 1), however, spans 4,535 Ma (that's 4,535,000,000 years, older than the age of the Earth!). If an anomalously high (5,253 Ma) and low (718 Ma) Rb–Sr age are removed from the data in Table 1 of Brookins *et al.* (1979), then the crystallization history as implied by the Rb–Sr dates still covers 408 Ma (nearly half a billion years). In marked contrast, a conductive cooling model for the Harding pegmatite shortens the entire crystallization event to a few years (Chakoumakos & Lumpkin 1990).

Jahns & Ewing (1977) identified eight zones that comprise a more or less continuous layered sequence in the pegmatite (Fig. 7–11). Up from the footwall, the pegmatite evolves through three zones dominated by sodic plagioclase: from footwall aplite to bladed albite + muscovite followed by bladed albite + "rose" muscovite, a bright pink (*colored by manganese*) Li-bearing muscovite. Along the hanging wall, a border zone described by Jahns & Ewing (1977) as quartz – albite – muscovite – perthite was subdivided by Chakoumakos & Lumpkin (1990) into a thin (1–3 cm) fine-grained border zone succeeded inwardly by a mineralogically similar but much coarser-grained wall zone. The wall zone at the Harding mine is unlike most others in that it is locally rich in coarse-grained beryl, apatite, and columbite–tantalite, so much so that meter-sized portions of the border zone are comprised almost entirely of beryl + apatite with subordinate Li-mica, albite, and quartz. The wall zone is also termed the "beryl zone" (Chakoumakos &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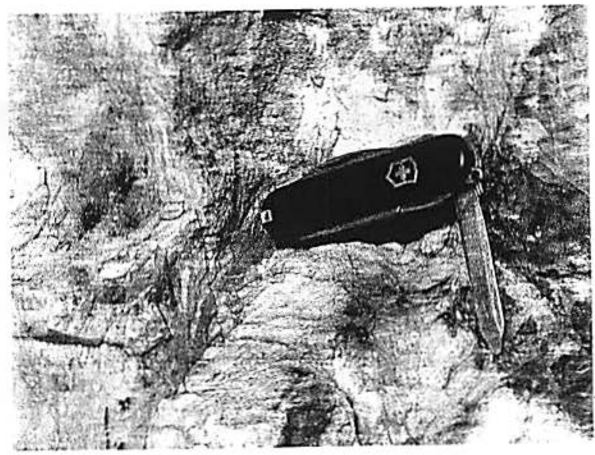

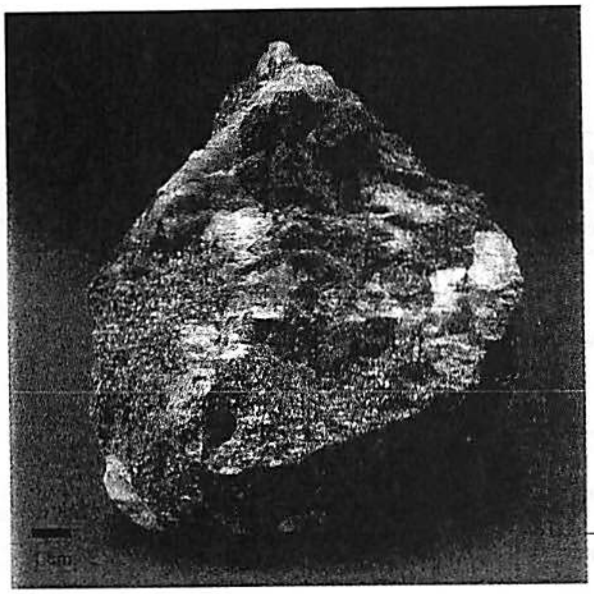

Fig. 7-10.

Views of the Harding pegmatite, New Mexico. (a) The pegmatite working surface and its environs looking southwest toward the main quarry face, circa 1960, used by permission of the University of New Mexico Archives. (b) A portion of the lath spodumene zone as it appeared circa 1960, used by permission of the University of New Mexico Archives. (c) The main quarry face and (d) a portal to an underground adit as they appear today. (e) Microcline altered to lepidolite with remnant albite. (f) The spotted rock zone shows ovoid relics of spodumene in massive lepidolite containing microlite and minor smoky quartz. (g) Detail of the core unit, showing fine-grained spodumene laths in a matrix of mostly rose muscovite or lepidolite. (h) A vertical roll at the hanging wall contact between pegmatite (right) and schist (left) shows the coarse-grained recrystallization of the host rocks for several decimeters away from the contact. (i) Niobium–tantalum oxide, provisionally identified as columbite, in albite plus quartz of the upper wall zone at the pegmatite contact. (j) A surprisingly common and typical hand-specimen consisting of scaly purple lepidolite, white beryl, and blue-green to brick-colored apatite from the wall zone along the hanging-wall contact.

Lumpkin 1990), and it was the source of much of the beryl produced from the pegmatite. Albite having the cleavelandite habit predominates in the wall zone assemblage at its lower contact with a layer (~1 m thick) of pure, massive gray quartz. Beneath the quartz layer, a zone of white spodumene laths radiate or point downward, and their parallel alignment and flaring habit signify that they grew down from their contact with the massive quartz layer (Figs. 7–10b, d). The central unit of the pegmatite is texturally the most complex. It is marked by a predominance of microcline, with lesser spodumene + quartz. The microcline has been extensively replaced by fine-grained lavender lepidolite (Fig. 7–10e). In places, spodumene also appears to have been replaced (Fig. 7–10f), and roundish relics of white spodumene and microcline in lavender lepidolite give this rock the name "spotted rock" zone (Chakoumakos & Lumpkin 1990). This central intermediate zone contains a second generation of spodumene that is fresh and finer-grained than the giant laths of the upper spodumene zone. A second generation of recrystallized microcline is also evident as bright white and glassy masses that in some cases have the blue-green tinge of amazonite. Quartz, albite with the cleavelandite habit, lepidolite, pinkish white beryl, blue apatite, and yellow-brown or black microlite are interstitial to the spodumene laths; the proportions and assemblages of the interstitial minerals are exceedingly variable on the scale of centimeters (Figs. 4–9c, 4-18i).

The mineralogy of the Harding pegmatite and the immediately adjacent, metasomatically altered host-rocks is presented in Table 7–3. Three samples of potassium feldspar from the Harding mine are Rb-rich, and one is high in Cs (Shmakin et *al.* 2000), even if compared to a database from other rare-element pegmatites. The few samples studied also

TABLE 7–3.

MINERALS REPORTED FROM THE HARDING PEGMATITE, NEW MEXICO

Abundant	Common	Minor	Rare			
quartz	apatite	columbite	allanite	cassiterite	magnetite	topaz
microcline	beryl	eucryptite	amblygonite	chalcocite	malachite	wavellite
albite	microlite	kaolinite	amphibole	chalcopyrite	monazite	zircon
muscovite	biotite[WR]	illite	andalusite	chloritoid	pyrite	
lepidolite	tourmaline[WR]	montmorillonite	azurite	cordierite	pyrolusite	
spodumene	bityite[WR]	epidote[WR]	bertrandite	gahnite	pyrophyllite	
	spessartine[WR]	holmquistite[WR]	beyerite	ilmenite	rutile	
	calcite[WR]		bismite	limonite	tenorite	
			bismuthinite	lithiophilite	thorite	
				löllingite	titanite	

[WR] Minerals prevalent in the adjacent, altered host rocks.
Rare: minerals reported by Jahns and Ewing (1976) but rarely found today.

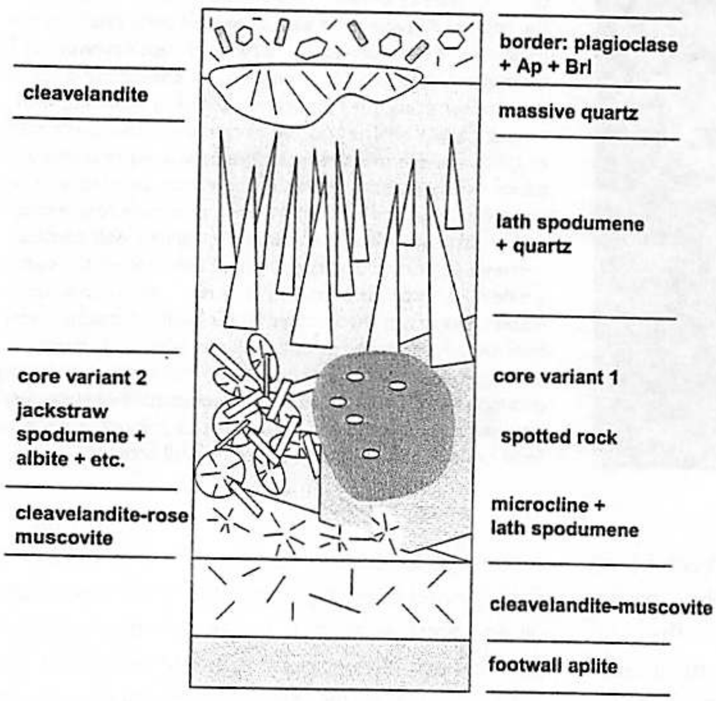

FIG. 7–11.

Schematic cross-section through the Harding pegmatite, modified from Jahns & Ewing (1977).

show a high degree of obliquity, or Al–Si order (*Al concentrated at the T1 site of the feldspar*). The highly ordered (*maximum microcline*) structures follow from an extended history of subsolidus, hydrothermal recrystallization that is evident in the pegmatite. Lead contents are high, as might be surmised by the presence of pale amazonitic material. Micas are rich in Li and Rb, but also in Zn, Tl, and B, compared to the entire dataset from other rare-element pegmatites in the southwestern United States (Shmakin *et al.* 2000). Beryl is high in Fe (1.41 wt% FeO) and Mg (1.03 wt% MgO) near the contacts, suggesting some influx of wallrock-derived components (Northrup *et al.* 1989). Among the elements studied by Northrup *et al.* (1989), cesium showed the widest variation, from a low value of 0.06 wt% Cs_2O in beryl from the basal aplite to 3.13 wt% Cs_2O in beryl from the spodumene – quartz zone. The manganese content of apatite crystals decreases from core to rim, and Mn contents in the apatite cores also decrease from values of 3.57 and 3.90 wt% MnO in the basal aplite and border zone, respectively, to 2.04 wt% MnO in apatite from the central spodumene zone (Northrup *et al.* 1989). Apatite of apparently secondary origin is lowest in Mn (*cf.* London & Burt 1982c), and also low in F compared to the typical, coarse-grained blue-gray-orange crystals found in most units (Northrup *et al.* 1989).

Areas of wallrock alteration are exposed on the eastern and southwestern contacts of the pegmatite. To the east, where the pegmatite is in contact with amphibolite, metasomatic modification converted hornblende and plagioclase to holmquistite, tourmaline, and epidote. The holmquistite-altered rock has a deep blue tinge in bright light, and an abundance of associated epidote (Figs. 7–12a, c). To the southwest, at contacts with the mica schist, the schist consists mostly of coarsely recrystallized muscovite at the contact, grading to coarsely recrystallized biotite 5–11 cm outward, isolated large crystals of orange spessartine garnet, and crystals of the bityite–margarite series of brittle Li–Be–Ca micas (London 1986c, Evensen *et al.* 2002). The bityite is colorless, platy, with very high luster, and resembles gypsum (Fig. 7–12b). Tourmaline is common in the altered amphibolite (Fig. 7–12c), and the mica schist is locally altered completely to tourmaline with or without quartz (Fig. 7–12d). A large mass of clear calcite has been prospected at the "Iceberg Pit" (Jahns & Ewing 1977) along the ridge south of the exposed pegmatite; it is not known if this calcite vein is related directly to the pegmatite-forming events.

The Department of Earth and Planetary Sciences at that University of New Mexico provides a descriptive walking tour for visitors to the Harding pegmatite. In addition to the walking tour, visitors to the pegmatite

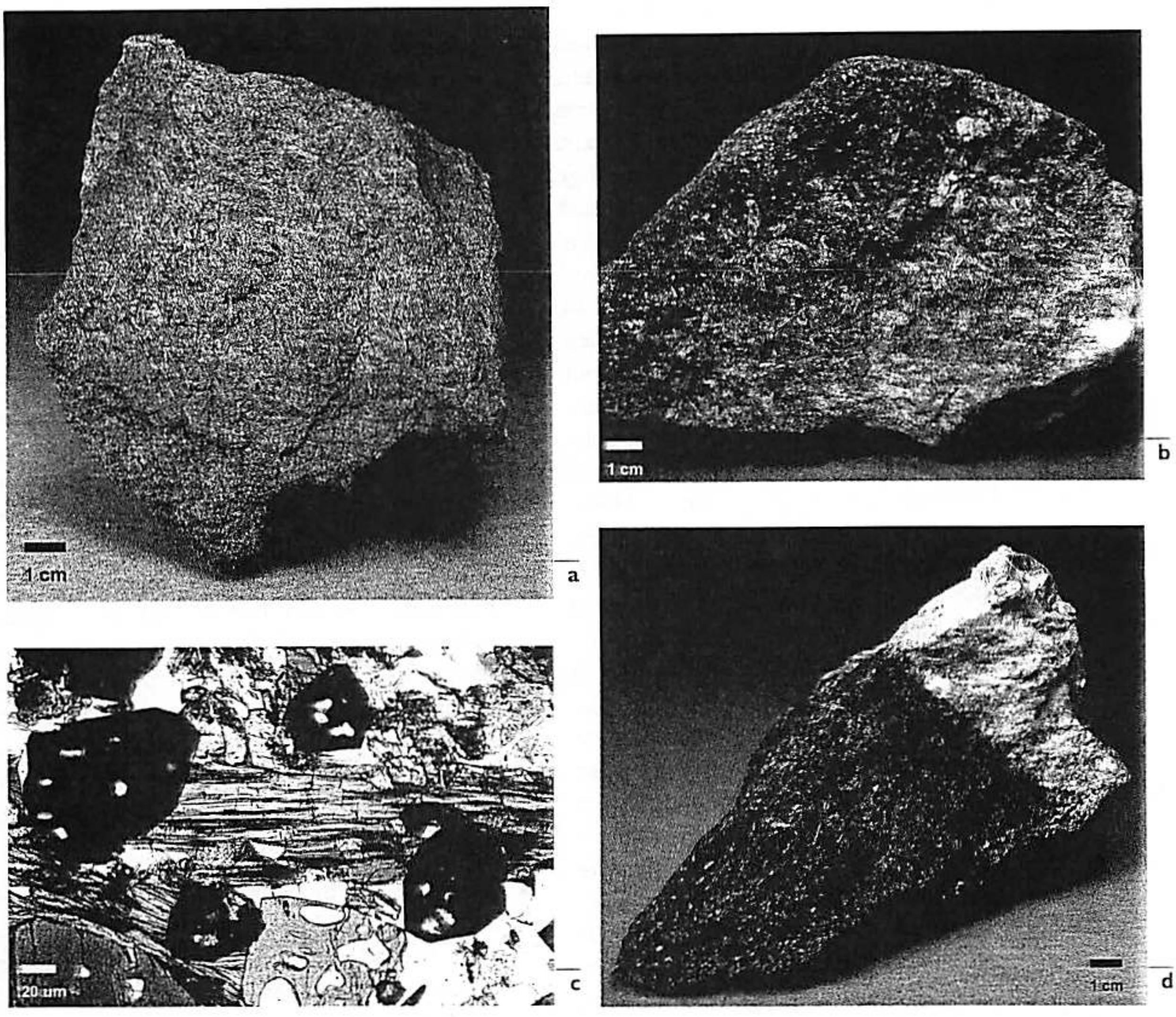

Fig. 7–12.

Altered host-rocks at the Harding mine. (a) Amphibolite replaced by deep blue radial holmquistite. (b) Altered schist sample at the contact, rich in rectangular white crystals of bityite–margarite. (c) Photomicrograph in plane-polarized light of tourmaline associated with holmquistite and epidote in altered amphibolite. (d) A border zone containing albite, muscovite, beryl, and minor albite abuts schist that has been almost completely replaced by massive black tourmaline.

may gain additional insights into the problems and idiosyncrasies of pegmatite geology by paying special attention to the following features.

- The "spotted rock zone" (Figs. 7–10f) represents an uncommonly good example of replacement of pre-existing pegmatite material. Relict spodumene and microcline megacrysts appear to be floating in masses of fine-grained lavender lepidolite. Crystallographic continuity can be seen in some adjoining relics of spodumene, and the spodumene is partially altered to pinkish micas and clays. In the "rose muscovite" zone, scaly lavender micas appear to form pseudomorphs after small laths of spodumene, all in a matrix of massive albite. Visitors will note, however, that the case for replacement is less obvious in the most evolved portions of the innermost unit, which contains smaller (centimeter-scale) crystals of spodumene laths with an interstitial matrix of quartz, albite, beryl, apatite, micas, and microlite (Fig. 7–10g). Though the mineralogy of the matrix is variable on the centimeter scale, the spodumene laths are fresh and sharply defined, and the microcline also is fresh and vitreous (and tending toward an amazonitic aspect). Tabular albite crystals radiate perpendicular to their spodumene substrates, but do not appear to have replaced spodumene. Late-stage assemblages rich in albite, lepidolite, polychrome tourmaline, and a host of phosphates and oxides of the high-field-strength elements (HFSE) are very typical of Li-rich pegmatites around the world. At the Harding mine, Jahns & Ewing (1977) regarded this assemblage as a "core variant", and it contains the highest grades of microlite ore. Textural evidence for replacement, however, is notably absent, unless one can make a sound argument that the interstitial feldspar – mica – beryl – apatite – microlite assemblage has replaced massive, interstitial quartz but left the spodumene unscathed. Otherwise, the spodumene – albite – microcline – lepidolite – beryl – apatite – microlite assemblage should be construed as primary, *i.e.*, deposited directly from a silicate melt or aqueous vapor phase in fluid-filled space. With very rare exceptions, this core assemblage is entirely solid and lacks miarolitic cavities. Lacking textural evidence for replacement or for vapor-filled cavities, the most objective hypothesis might be that this unit formed by crystallization from a silicate melt. But what kind of melt, so far from the granite minimum composition and so enriched in lithium, beryllium, phosphorus, and tantalum, could this be? Here is the crux of the problem for pegmatite geology: how far can melts fractionate and *still* be called silicate melts? How much of the exotic mineralogy of pegmatites can be attributed to the subsequent actions of an aqueous fluid, as was so often called upon in the past to explain evolved mineral assemblages? I will offer my opinions later, but visitors should not fail to see and consider the difficulty of distinguishing primary from secondary mineral assemblages here.

- Bodies of massive quartz constitute the core of many common pegmatites, but visitors should note that the massive quartz layer at the Harding mine, which is exposed in the quarry faces, is quite evidently an exception to this generalization. The massive quartz layer acted as a substrate for the lath spodumene zone, and hence had crystallized before spodumene + quartz, and the evolved central core units described above began to grow. The zoning sequence down from the hanging wall at the Harding mine, therefore, appears to have begun with the mineralogically complex assemblage of the border zone (albite – quartz – muscovite – beryl – apatite – columbite–tantalite), shifted suddenly to the deposition of only quartz, then quartz with the addition of lath spodumene, and finally the assemblages of the core unit noted above. Except for the presence of spodumene and a slightly more evolved composition of the individual mineral species (*e.g.*, microlite rather than columbite–tantalite, lepidolite rather than muscovite), the core unit is similar in mineralogy to the border zone. Suffice it to say here that this sequence of crystallization, in which the deposition of complex mineral assemblages is interrupted by an interval of crystallization with a single phase only, does not readily fit the concepts of crystallization from melt or vapor as far as these are known and understood.

- Finally, it is worth the effort for visitors to seek out exposures of the host schists and amphibolites that have recorded the influx of pegmatite-derived fluids. These examples can be found in a few outcrops, but samples are more prevalent in the dump material (Figs. 7–10h, 7–12a, b). Outcrops show the alteration of mica schists by fluids derived from the upper border zone, the replacement of amphibolite by holmquistite + tourmaline + epidote, and along the northwest entrance to the pegmatite, wholesale replacement of the schist by tourmaline + quartz with preservation of the finely laminated mica–quartz protolith (original rock). In the first case, the composition of the border-zone assemblage is imposed upon the schists near the contact. Beryllium, lithium and calcium, which produced abundant beryl, lithian muscovite and apatite in the border zone, formed the exotic bityite–margarite mica in the host schists. In the second case, the formation of holmquistite is associated with crystallization of the spodumene-rich zone, an intermediate zone at the Harding mine, as at Tanco and other similar Li-rich pegmatites (von Knorring & Hornung 1961b, Heinrich 1965, London 1986c). In the third case, tourmaline is common or abundant in the altered wallrocks, but entirely absent in the Harding pegmatite itself. These relationships explain in part why London (1986a, Morgan & London 1987) suspected that much of the boron contained by pegmatites was not conserved as tourmaline within, but rather was lost to surrounding rocks, where it formed tourmaline upon reaction of B-rich pegmatite fluids with ordinary host metamorphic rocks.

Petrogenesis

Based on a summary of fluid-inclusion microthermometry by C.W. Cook (Brookins *et al.* 1979), Chakoumakos & Lumpkin (1990) constructed a cooling history for the pegmatite using extrapolations of fluid-inclusion isochors. The cooling history they present (their Fig. 5) shows isobaric cooling from ~650°C down to 300°C at 250–300 MPa. In another figure (their Fig. 6), Chakoumakos & Lumpkin placed the cooling curve at higher pressure, to be consistent with crystallization mostly, if not entirely, in the stability field of spodumene + quartz, with isobaric cooling to 350°C at 325 MPa, followed by cooling along a geotherm to surface conditions. Cooling curves for the Tanco and Harding pegmatites, therefore, are qualitatively similar in that both bodies appear to have cooled more or less isobarically to 300°C (Harding) and 420°C (Tanco, see Fig. 7–7), which was followed by cooling along an isotherm from that point. If the inflection in the cooling curves is real, then this inflection point corresponds to the temperature of the host rocks at the time of pegmatite emplacement.

Chakoumakos & Lumpkin (1990) added one more important aspect to their assessment of the cooling history of the Harding pegmatite. They used a conductive cooling model (from Jaeger 1964; also, see Jaeger 1968) to estimate the temperature profile through the pegmatite at different times after emplacement. As boundary conditions, they set the initial temperature of the magma at 650°C, the initial wall-rock temperature at 350°C, and the thermal conductivity of magma and host rock as equivalent. Their cooling history shows the center of the pegmatite body, 10 meters from the contact, cooling to 550°C, the inferred solidus temperature for the magma, in about two years. The dike margins would have cooled instantaneously to the average temperature of the magma and host rock at the time of emplacement, 500°C in this case. Though studies of dike cooling were not new, this was the first such application of conductive heat-flow models to a pegmatite, and it placed pegmatite cooling on the time frame of months to years, orders of magnitude faster than had been previously supposed. What was also interesting was the reticence of the authors to accept this result. In the end, they concluded, on the basis of this model, that the consolidation of the Harding pegmatite may have occurred over only "thousands" of years.