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An occurrence of staurolite in the Llano uplift, central Texas

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Abstract

Staurolite, not previously reported from the Precambrian metamorphic rocks of the Llano uplift of central Texas, occurs as inclusions in a spessartine-rich garnet from a biotite gneiss in the Rough Ridge Formation of the Packsaddle Group. The initial crystallization of staurolite and its subsequent elimination from the quartzose micaceous matrix surrounding the garnet may require a more complex metamorphic history than has so far been documented for these rocks.

Introduction

Staurolite has formerly been reported as *absent* from pelitic schists of the Proterozoic Packsaddle Group of the Llano uplift in central Texas (Barnes et al., 1972, p. 15; McGehee, 1979, p. 29; Garrison et al., 1979, p. 361). In pelitic rocks of this group, kyanite has not been reported, and typical parageneses include andalusite ± sillimanite, abundant cordierite, and scarce spessartine-almandine garnet (cf. McGehee, 1979). In the context of these assemblages, the absence of staurolite has been regarded as evidence for an exclusively low-pressure metamorphic history for the Precambrian metamorphic rocks of the southeastern Llano uplift. Those low-pressure assemblages make the Llano rocks an unusual part of the Grenville-age metamorphic belt, which exposes medium-pressure facies series in the Grenville province of Canada and New York, the central and southern Appalachians, the Van Horn region of central Texas, and the area near and north of Oaxaca in central Mexico.

This article describes the discovery of staurolite (exclusively as inclusions within a spessartine-rich garnet) in a multiply deformed biotite gneiss from the type section of the Rough Ridge Formation (Packsaddle Group) and discusses the implications that this occurrence and related observations hold for the evolution of metamorphic conditions in the Llano region.

Occurrence

During an analysis of the structural and metamorphic history of exposures of Rough Ridge Formation along Sandy Creek in southeastern Llano County, Texas, Nelis (1984) mapped a biotite gneiss in which distinct layers up to 5 m thick contain either cordierite or Mn-rich garnet, but never both. One garnetiferous layer, exposed on the south bank of Sandy Creek approximately 500 m downstream from the low-water crossing of the Click Road, bears abundant 1–5-mm euhedral garnet porphyroblasts, set in a matrix of quartz, biotite, calcic oligoclase, and microcline; accessory magnetite, ilmenite, apatite, and zircon; and rare patches of altered biotite producing secondary chlorite that is stained along fractures and cleavages by orange iron oxides. The paragenesis is unusual insofar as it lacks both muscovite and aluminum silicate. Approximately 50 garnets from this rock were examined in thin section. Of these, one garnet crystal 4 mm in diameter was found to contain six euhedral inclusions of staurolite, the largest of which measures 0.2 by 0.5 mm. The staurolite crystals appear to be in textural equilibrium with the garnet; their euhedral outlines are sharply preserved and show no evidence of incipient reaction. Additional inclusions in the garnet are principally plagioclase, with sparse ilmenite, apatite, and tourmaline.

Optical and chemical characterization

The staurolite inclusions are optically unexceptional. They were determined to be compositionally unzoned; consequently the chemical analysis shown in Table 1 is an average of electron-microprobe analyses obtained at 25 randomly chosen points on three distinct grains. The staurolite is chemically ordinary, except perhaps for its Mn content, which is higher than the maximum encountered by Griffen and Ribbe (1973) in their study of staurolite crystal chemistry, but still lower than some of the values reported by Ganguly (1972) and by Holdaway (1978). [No attempt was made to analyze for Li or F; cf. Dutrow and Holdaway (1983).] The garnet with staurolite inclusions (like other garnets in the rocks) preserves small gradients in chemical composition, ranging from approximately $Alm_{58}Pyp_{12}Sps_{25}Grs_5$ at its core to approximately $Alm_{60}Pyp_{12}Sps_{23}Grs_5$ at its rim. Figure 1 presents data on elemental partitioning of Mg, Fe, and Mn between the staurolite and the garnet immediately surrounding it, providing a comparison between the Llano occurrence and the Barrovian-series garnet-staurolite pairs analyzed by several other investigators. The agreement of the distribution coefficients indicates that the staurolite inclusions were in chemical equilibrium with the garnet at the time of their incorporation.

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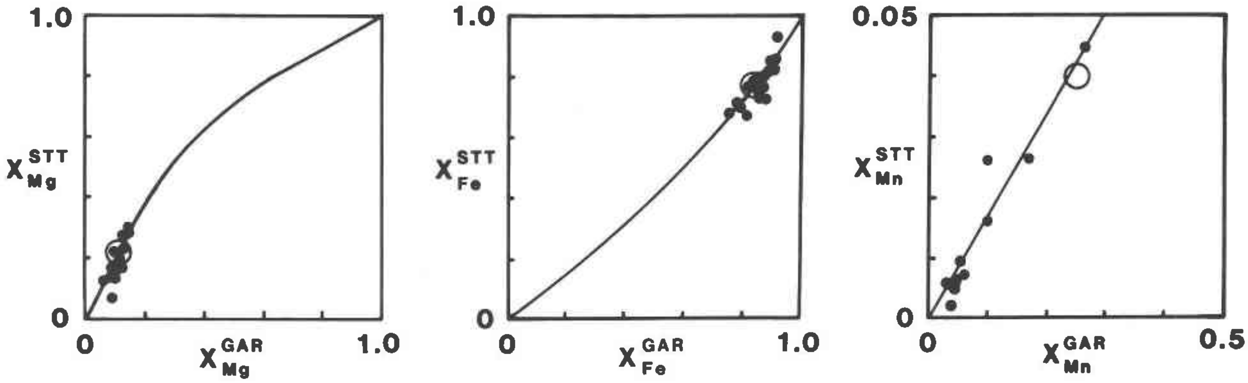

Fig. 1. Partitioning of Mg, Fe, and Mn between staurolite and garnet. Indicated mole fractions are X_{Mg} = Mg/(Mg + Fe + Mn + Ca); X_{Fe} = Fe/(Mg + Fe), after Ganguly (1972, p. 353); X_{Mn} = Mn/(Mg + Fe + Mn + Ca). Solid dots are data presented by Hounslow and Moore (1967, fig. 16), Ganguly (1972, fig. 7), Green (1963, table 1), and Holdaway (1978, tables 8 and 9); large open circles portray partitioning between minerals in biotite gneiss of the Rough Ridge Formation. Curves are contours of constant K_D from Hounslow and Moore (1967) for Mg and Mn and from Ganguly (1972) for Fe.

Discussion

The initial growth of the staurolite and its subsequent elimination from the matrix record successive stages in the evolution of metamorphic conditions of the Rough Ridge Formation, but attempts to provide a convincing interpretation of these features are frustrated by the lack of textural evidence to identify the specific reactions involved. The stability of staurolite in natural occurrences is a complex function of pressure, temperature, fugacities of O_2 and H_2O, bulk composition as expressed in the compositions of mineral solid solutions, and the presence or absence of quartz, biotite, and muscovite in the mineral assemblage, as documented by the experimental data of Hoschek (1967, 1969), Richardson (1968), Ganguly (1968, 1972), Rao and Johannes (1979), Dutrow and Holdaway (1983), and Holdaway et al. (1983). Few of these parameters are well constrained in this occurrence.

The mineral assemblage present at the time the staurolite inclusions were incorporated into the garnet evidently included biotite and quartz, as both minerals are found as inclusions within the poikiloblastic staurolite, and together they comprise 60–80% of the matrix mode. It is therefore likely, although not unequivocally demonstrable, that the reaction(s) that account for the disappearance of staurolite in the matrix are those that limit the stability of the assemblage staurolite + biotite + quartz. Unfortunately, few reliable estimates of the limits of stability of this assemblage are available. Rao and Johannes (1979, fig. 3) present three unreversed "preliminary" experiments in the Fe-Si-Al-O-H system and estimate a maximum pressure for the stability of this assemblage (relative to almandine + muscovite + H_2O) ranging from 8 kbar at 550°C to 4.5 kbar at 650°C. Taking into account the range of mineral solid solution reported from natural occurrences, Ganguly (1972, p. 360) suggested that the equilibrium staurolite + biotite + quartz = cordierite + magnetite + H_2O cannot extend below 2.3 kbar at 550°C and 4.6 kbar at 650°C. Winkler (1979, p. 229) cited a personal communication from Hoffer indicating that the reaction of staurolite + biotite + quartz to cordierite + garnet + muscovite + H_2O "may take place at a temperature somewhat higher" than 575°C at 2 kbar and 675°C at 5.5 kbar. Although these studies do not impose rigid quantitative constraints on the metamorphic conditions affecting the rocks of the Rough Ridge Formation, they do necessitate that those rocks, at some point late in their history, must have re-equilibrated to conditions on the high-temperature, low-pressure side of a "staurolite-out" reaction boundary that evidently passes with shallow positive dP/dT slope through the vicinity of 3.5 kbar at 600°C.

Quantitative estimates of temperatures of final equilibration for rocks of the Rough Ridge Formation are limited by the available assemblages to inferences based upon the partitioning of Fe and Mg between garnet and biotite,

Table 1. Electron microprobe analysis of staurolite in the Rough Ridge Formation, Llano uplift

	Weight Percent (std err of mean)		Cations per 44 oxygens and 4 hydroxyls
SiO_2	26.51	(0.06)	7.41
TiO_2	0.47	(0.01)	0.01
Al_2O_3	54.01	(0.30)	17.82
FeO	13.14	(0.08)	3.07
MnO	0.74	(0.01)	0.18
MgO	2.05	(0.04)	0.85
ZnO	0.74	(0.01)	0.15
Total	97.66		29.58

Data obtained using wavelength-dispersive techniques on an ARL-EMX instrument (15kV, 15 nA on brass, 200 sec analyses), using natural and synthetic silicate standards, and employing the correction scheme of Albee and Ray (1970).

and these depend critically upon the solution models used for determining activities of endmembers. Application of the uncorrected calibration of Ferry and Spear (1978), using the composition of the garnet rim near its contact with matrix biotite, yields a temperature of 605°C. If the activities of Mn and Ca components in the garnet are taken into account according to the solution model of Ganguly and Saxena (1984), the estimated temperature ranges from 645°C to 655°C, for pressures in the range 2–4 kbar. Indares and Martignole (1985) developed models that account not only for the nonideality of garnet solution as above, but also for the influence of Ti and Al in biotite; their "Model B" formulation yields temperatures in the range of 540°C to 560°C for pressures of 2–4 kbar, but it should be noted that these authors urge caution in the application of their models to rocks of the amphibolite facies.

Pressure estimates involve still greater uncertainties. Regionally, pressures of final equilibration are most likely in the range of 2–4 kbar (e.g., McGehee, 1979), based upon the Buchan-series mineral assemblages that predominate in the Llano uplift. Less commonly encountered are rocks (mostly garnetiferous amphibolites and garnet-pyroxene lithologies from the northern and northeastern portions of the uplift) that contain textural evidence of changing pressure conditions. In such rocks, garnet is nearly always partially or totally resorbed by postkinematic reaction to assemblages of larger total molar volume (Lidiak et al., 1961, p. 273; Jordan, 1970, p. 32; Moseley, 1977, p. 15), indicating partial re-equilibration to lower pressures (cf. Chesworth, 1972, p. 73; Bohlen et al., 1983).

Attempts to evaluate these estimates of pressures and temperatures in the Rough Ridge Formation must also take into account the mounting evidence for two kinematically distinct thermal events, consisting of an early metamorphism accompanied by regional deformation, and a later static reheating and rehydration event coincident in time with the widespread emplacement of voluminous granitic intrusives. The overprinting of sequentially developed schistosity surfaces by later recrystallization to fine-grained granoblastic polygonal textures is observed throughout the uplift and is well documented in rocks of the Rough Ridge Formation by Nelis (1984). For a variety of rock types in the Llano uplift, Garrison et al. (1979) reported Rb-Sr whole-rock ages on metamorphic units clustering near 1180 m.y., in contrast to K-Ar ages on hornblende and biotite in related units that are near 1050–1000 m.y. and that match Rb-Sr whole-rock ages for the plutonic intrusive units; these authors interpreted their results in terms of a widespread reheating of the uplift at the time of granite intrusion to temperatures sufficient to reset the K-Ar systems in the previously metamorphosed units. Bebout and Carlson (1986) have presented stable-isotope data that link the development of postkinematic assemblages in calc-silicates to aqueous fluids genetically related to the granitic intrusives. Given these observations, it is possible that staurolite may have formed during the dynamothermal event but was destroyed (except where preserved as inclusions) in a distinct postkinematic event over 100 m.y. later.

Considered together, these indicators of pressure and temperature histories suggest that the conditions of final equilibration of rocks of the Rough Ridge Formation were very near the high-temperature and low-pressure limits of stability of staurolite + biotite + quartz. Thus one can envision several possible explanations for the disappearance of staurolite outside the garnet, and, by extension, its absence from pelitic units throughout the uplift. Among the most likely of these possibilities are (1) a prograde temperature increase at relatively low pressure during the dynamic recrystallization episode, (2) retrograde decompression at temperatures in the vicinity of 600°C at the conclusion of the episode of dynamic recrystallization, and (3) re-equilibration during the postkinematic recrystallization. (The additional possibility that late-stage oxidation was responsible for the elimination of staurolite seems unlikely in view of the fact that the Fe and Ti oxides surviving as inclusions within the garnets are identical in composition to those present in the matrix external to the garnet.)

Thus, although this discovery of staurolite does not yield unequivocal constraints on the metamorphic evolution of the Packsaddle Group, it does demonstrate that the unit's history is more complex than previously supposed. Perhaps the discovery will also serve to stimulate a search for additional clues to the nature of early metamorphic events in the Precambrian of central Texas.

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