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FIBROLITIC SILLIMANITE IN SHEARED ROCKS OF THE AMBELA GRANITIC COMPLEX, NORTHWESTERN PAKISTAN

MOHAMMAD RAFIQ and M. QASIM JAN

NCE and Department of Geology, University of Peshawar

ABSTRACT

Two-mica granites in the northeastern margin of the Ambela granitic complex underwent cataclastic deformation. The resulting shear zones acted as pathways for the migration of a water-rich fluid phase that also contained boron and some fluorine. This resulted in (1) formation cf fibrolitic silimanite and white mica at the expense of feldspars and biotite, especially along micro-shears, (2) bleaching of biotite and release of Fe and Ti oxides, and (3) crystallization of tourmaline and fluorite. Some recrystallization/neo-mineralization of feldspar, quartz and muscovite also occured due to shearing.

INTRODUCTION

The Ambela granitic complex comprises granites, alkali granites, quartz syenites, alkali quartz syenites and syenites (Rafiq, 1987). Along the northeastern contact of the complex, the granitic rocks are marginally cataclasized to granitic gneisses and schists. These display the development of fibrolitic sillimanite along micro-shears. Althongh a few rocks contain andalusite (Rafiq, 1987), non-fibrolitic sillimanite contemporaneous with or pre-dating the micro-shears has not been noted in the samples studied.

The Ambela complex has been affected by a greenschist- to lower amphibolite facies Himalayan regional metamorphism (Rafiq, 1987), here reffered to as R_1. This was overprinted by a variety of mineralogical changes related to subsequent micro-shears (R_2) accompanying cataclasitic deformation. The most conspicuous of these is the development of fibrolitic sillimanite (henceforth called fibrolite). The present studies describe the fibrolite-bearing lithologies and present microprobe analyses for several mineral phases.

PETROGRAPHY

The fibrolitized granites have passed through a polyphase tectonic activity and range from medium- to fine-grained varieties. Some rocks appears to be undeformed, whereas others have been transformed to gneisses and schists. Like their precursors, these consist of potash feldspar, plagioclase (An_{4-22}) and quartz, with biotite as the most important varietal mineral (up to 25%), followed by muscovite. Opaque oxides are ubiquitous accessory phases and trace amounts of sphene, apatite and zicron occur in most rocks. Some rocks contain small quantities of garnet and tourmaline, while andalusite and fluorite are sparingly present.

With the possible exception of fluorite and tourmaline, these mineral phases predate the R_2 event when rocks were cataclasized, with neo-mineralization of white mica, fibrolite, quartz, magnetite, ilmenite, sphene and, in a few rocks, rutile. In rocks more severely affected by R_2, white mica and fibrolite are abundant; in one sample, all the feldspar seems to have been replaced by white mica with subordinate fibrolite. During secondary alteration the feldspars were locally sericitized/saussuritized, iron oxides were hematitized and, in rare cases, biotite was chloritized. In one sample, the K-feldspar component of the mesoperthite is distinctly cloudy but the plagioclase component is fresh.

The R_1-related features in the K-feldspar include some recrystallization and elongation parallel to foliation. During R_2 it was fractured and granulated, especially along micro-shears, thereby imparting a gneissose fabric to the rocks. The K-feldspar grains commonly display wavy extinction and some homogenization, *i.e.* diminished twinning, intergrowths and inclusions, however, perthitic intergrowths are not uncommon. Partial recrystallization to fine-grained aggregates occurred locally. The quartz commonly shows wavy extinction; deformed grains have sutured margins and are elongated along foliation.

The plagioclase (An_{4-22}), apparently, is not affected much by deformation and retains most of its original characteristics such as zoning and twinning. In some cases, however, it is saussuritized internally and recrystallized on the edges to compositions ranging from An_4 to An_{12} (optical determinations). The main effect of deformation in the plagioclase is the development of fractures which are mostly filled with neo- and/or recrystallized quartz. Both the feldspars and quartz may contain fibrolite.

The two micas (Table 1, Anal. 1 & 2) show kinking, bending, and are drawn out at their ends into R_1 foliation. At places the biotite has undergone partial recrystallization or shearing to decussate or aligned flaky aggregates with associated sphene granules. Ilmenite inclusions in the biotite may also be rimmed by sphene. Along the R_2 shears, the two micas lead off into discontinuous folia anastomosing around quartz and feldspar grains. In the more deformed rocks the biotite flakes may form lenticular to stretched aggregates. Replacement of

TABLE 1. SELECTED MICROPROBE ANALYSES OF THE MINERALS ALONG THE MICRO-SHEAR ZONE R_2.

	1 Biotite	2 Muscovite	3 Fibrolitic Sillimanite	4 Ilmenite
SiO_2	33.61	46.43	37.56	0.18
TiO_2	3.20	0 04	0.03	52.23
Al_2O_3	18.40	38.35	60.55	0.19
Fe_2O_3	—	0.53	1.60	—
FeO	27.07	—	—	45.30
MnO	0.04	0.06	0.02	—
MgO	4.83	0.05	0.05	0.07
CaO	0.09	0.05	0.01	0.06
Na_2O	0.16	0.29	0.01	—
K_2O	7.95	9.11	0.18	—
TOTAL	95.35	94.91	100.02	98.03
Oxygens	22	22	20	6
Si	5.290	6.095	4.076	0.009
Ti	0.379	0.004	0.002	2.009
Al	3.414	5.935	7.747	0.011
Fe^{3+}	—	0.052	0.131	—
Fe^{2+}	3.564	—	—	1.938
Mn	0.005	0.006	0.002	—
Mg	1.133	0.009	0.010	0.005
Ca	0.015	0 007	0.001	0.003
Na	0.049	0.074	0.002	—
K	1.596	1.526	0.025	—

Total Fe oxides are FeO in biotite and ilmenite, and Fe_2O_3 in sillimanite and muscovite.

biotite by muscovite, opaque oxide and fibrolite, and intergrowth of the latter with white mica are common features. Pink garnet grains are mostly fresh and may contain abundant inclusions of quartz, Fe-Ti oxides and biotite; there is no replacement of garnet by fibrolite. The tourmaline is greenish and commonly enclosed in quartz. Fluorite grains are in trails and probably grown along fractures.

The R_2-related micro-shears, characterized by the development of local foliation; contain fibrolite, white mica, relict biotite (Table 1), and opaque dust that may be enclosed in pools of sericite. Several mineralogical changes, apparentyl related to R_2, have taken place in the rocks. The extent and intensity of these changes vary from one to another sample but the overall picture is as follows.

1) Local recrystallization of pre-existing mineral phases and neo-mineralization of quartz and white mica.
2) A tendency towards the disappearance of intergrowths, twin boundaries, etc. (homogenization) in feldspar.
3) Boron and fluorine metasomatism leading to the growth of tourmaline and fluorite.
4) Bleaching of biotite and its replacement by muscovite and fibrolite, with concomitant development of Fe-Ti phases such as magnetite, ilmenite (Table 1, Anal. 4), sphene, and rutile.
5) White mica and/or fibrolite growth along/near R_2 microshears at the expense of feldspars and other mineral phases.

MINERAL CHEMISTRY

Microprobe analyses of R_1 biotite and R_2 muscovite, fibrolite and ilmenite are given in Table 1. The ilmenite and fibrolite analyses are close to ideal compositions, however, the fibrolite contains appreciably high quantity of Fe_2O_3, presumably donated by opaque oxides or biotite. It is nearly identical to a sillimanite analysis from Swartrand, S. Africa (Deer *et al.*, 1962a, p. 123, anal. 1). The muscovite composition is simple, with small quantities of Fe and Na, and traces of Ti, Mn, Mg and Ca. Like the biotite, alkalis (especially K_2O) may be underestimated. Monier *et al.* (1984) showed that magmatic, late to post-magmatic, and hydrothermal muscovites from St. Julien, France, occupy different areas when plotted on TiO_2—Fe_2O_3—Mg_2O triangle. The Ambela muscovite plots in the area of late to post-magmatic muscovites.

On Mg–(Al+Ti+Fe^{3+})–(Fe^{2+}+Mn) diagram the biotite plots in the field of biotite granites (Nockolds, 1947; Piispanen, 1983) and monzogranites (Neilson and Haynes, 1973). The Fe/(Fe+Mg) vs Al–K–Na relation, however, suggests a metamorphic origin for it (Marakushev and Tararin, 1965); this may be due to an underestimation of alkalis in the analysis. The Al^{iv} content of the biotite is rather high but whether this is due to temperature control is not clear (compare Deer *et al.*, 1962b, and Kepezhinskas, 1972). Marakushev and Tararin (1965) suggest that the Al content of biotite depends on the alkalinity and activity of K prevailing in the system during crystallization.

PARAGENESIS OF FIBROLITE

Studies related to the development of fibrolite can be grouped into three main categories.

1) There are many occurrences of sillimanite (fibrous or otherwise) which have been attributed to an increase in grade of metamorphism. Wintsch (1975) reported the development of fibrolite at the expense of muscovite by local increase of pressure in deformation zones.

2) Metasomatism or development under the influence of a mobile phase (H_2O, H, ? Al_2O_3), accompanied usually by base-leaching (Pitcher, 1965; Chinner, 1966; Vernon, 1979; Ahmad and Wilson, 1982).

3) Exsolution of Al_2O_3 and SiO_2 from other Al bearing phases such as feldspar and garnet (Sturt, 1970).

In the Ambela rocks, fibrolite occurs as bundles and mats of hair and needles or scattered acicules less than 0.5mm in length. Some bundles are so closely packed that they give the impression of distinctly large grains of brownish hue in plain light. Indeed the fibrolite growth in Ambela has several manifestations summarised in the following and displayed in Fig. 1A to 1D.

1) High concentration of parallel to subparallel fibres along the R_2 shears. In most rocks, abundant fibrolite grows at varying angles to these shears in the neighbouring mineral grains, especially feldspar.

2) In many samples, sillimanite fibres are intergrown with flakes and shreds of white mica ± opaque oxide. The fibres may be randomly or preferentially orientated, but in rare cases they display radial growth. In some rocks, the fibres contained in white mica are tightly microfolded. In wide and intense microshears, lensoid or elongated (? stretched) bundles of fibrolite are enclosed in pools or jackets of white mica.

3) Selective growth of fibers along grain boundaries and their projection into feldspar and quartz at varying (usually high) angles to the boundaries. This micro-texture is suggestive of a late origin for fibrolite (Vernon and Flood, 1977).

4) Dispersed fibres in feldspar, quartz, and mica.

5) Replacement of the bleached parts and margins of biotite by fibrolite and/or muscovite ± opaque oxide.

The petrography of the Ambela rocks suggests that fibrolite did not develop due to isochemical metamorphism. Exsolution of Al_2O_3 and SiO_2 from the feldspar cannot explain much of the fibrolite although this process may have played some role. The concentration of fibrolite along micro-shears, its growth along grain boundaries, and its replacement of the two feldspars, micas and quartz testify the action of mobile components in a fluid phase. Presumably, cataclasis facilitated the migration of water (and hydrogen ?) in the granites. This triggered reactions leading to the liberation of alumina and crystallization of fibrolite.

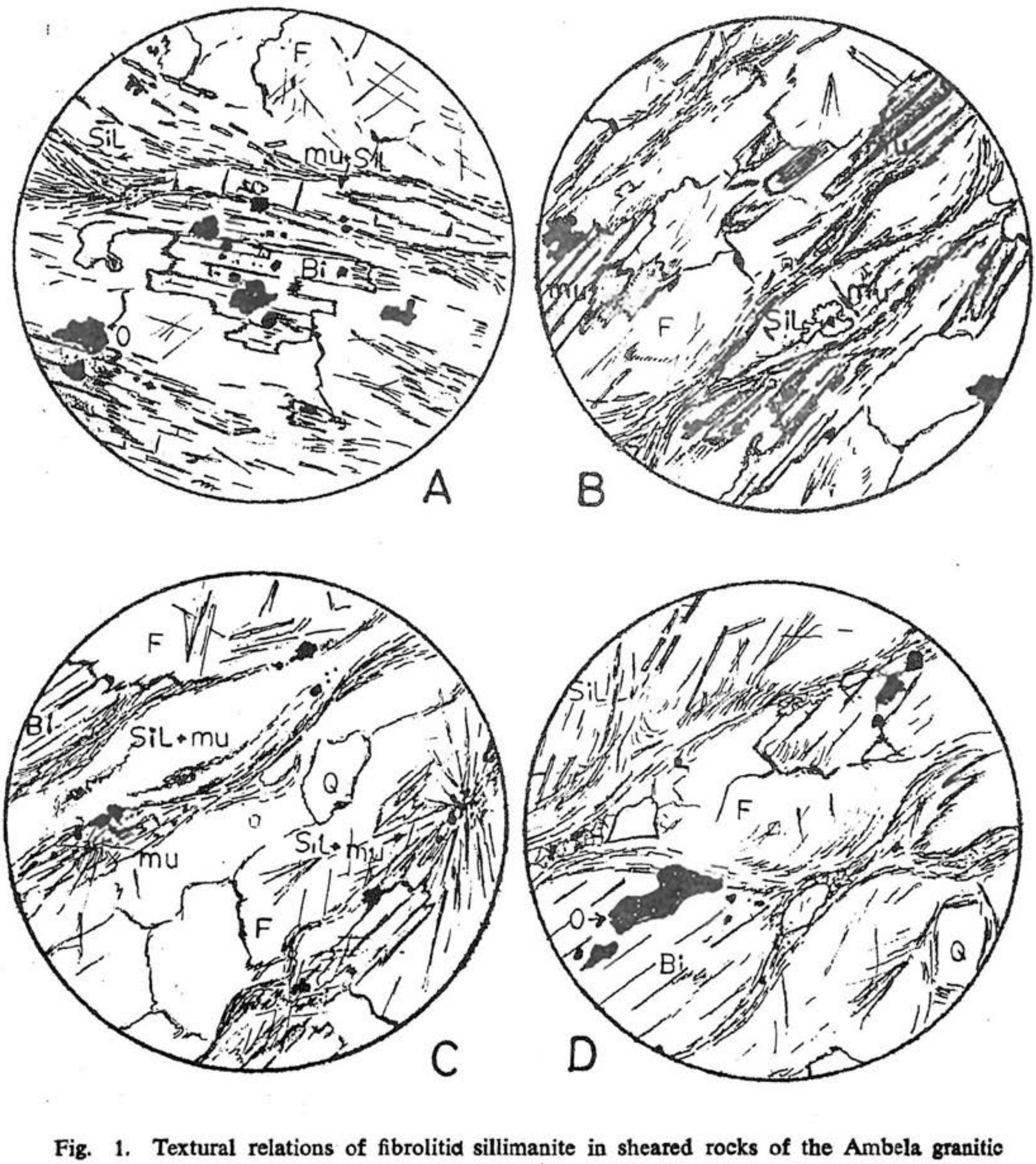

Fig. 1. Textural relations of fibrolitid sillimanite in sheared rocks of the Ambela granitic complex. A) Bleaching of biotite and its replacement by muscovite and fibrolite. The top middle portion of the section (above Bio) contains a mixture of shreds of white mica and fibrolite. B) Intergrowth of white mica + fibrolite along/ near R_2 microshear. C) Intergrowth of sillimanite fibers + white mica and opaque oxide in shear bands. Note also the radial growth of fibrolite subsequent to the shears. D) Growth of sillimanite fibers along grain boundaries, and their projection into feldspars and quartz grains.

Biotite (Bi); fibrolitic sillimanite (Sil); muscovite (mu); feldspar (F); quartz (Q); opaque oxide (O).

Much of the alumina required by fibrolite and white mica may actually have been derived from the feldspars. The formation of tourmaline and fluorite lends further support to the action of mobile components. K.A. Butt (pers. comm.) has noted an extensive growth of tourmaline along shear zones in the Ambela complex.

Such a mechanism, accompanied by base-leaching, has been proposed for the growth of fibrolite in Cooma and Broken Hill, Australia (Vernon, 1979; Ahmad and Wilson, 1982). The microstructural details of fibrolite in these two areas are very similar to those of Ambela. Vernon (1979) has presented several reactions involving hydrogen metasomatism and base-leaching during hydrothermal alteration leading to fibrolite growth. If such a mechanism was actually operative in Ambela, it would require the removal of K, Na, Ca, Mg, Fe, Si and Ti from the sites of fibrolite growth. Some of these components, however, were refixed in newly formed white mica, Fe-Ti oxides, sphene, tourmaline and fluorite.

The mobile ions may be of internal nature and redistributed in the granite mass due to cataclasis, hydration and recrystallization or, more likely, they were introduced from an external source. An igneous origin for the fluids is preferable, but there is no magmatism in the area contemporaneous with, or predating, the microshears of probable Himalayan (Tertiary) age. Since some sillimanite fibers have parallel fabric and are microfolded whereas others are undeformed and have random growth, there is a likelihood that fibrolite growth started during shearing and continued after its cessation.

CONCLUSIONS

The cataclasized two-mica granites of the Ambela Complex display several mineralogical changes along and near micro-shears. The most important of these are the growth of white mica and fibrolite. Combining the experimental data of Chatterjee and Froese (1975) with those of Richardson *et al.* (1969), the assemblage sillimanite+muscovite+quartz would suggest PT conditions in excess of 625°C and 4 kbar. Such conditions appear unrealistic because the R_2 assemblages have not been produced during prograde metamorphism. In fact operating temperatures may have been quite low, as already suggested for fibrolite paragenesses by Vernon (1979). The use of Holdaway's (1971) data instead of Richardson *et al's,* however, allow for lower PT conditions down to about 2–3 kbar and 600–500°C. The fibrolite growth along shear zones and grain boundaries, and the formation of tourmaline and rare fluorite can best be explained if the action of mobile components (such as H, H_2O, B and F) is invoked. Some sort of base leaching should have accompanied the process, as envisaged by Vernon (1979) and Ahmad and Wilson (1982).

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REFERENCES

Ahmad, R. & Wilson, C.J.L. 1982. Microtextural relationships of sillimanite and 'fibrolite' at Broken Hill, Australia. Lithos 15, 49—58.

Chatterjee, N.D. & Froese, E.W. 1975. A thermodynamic study of the pseudobinary join muscovite-paragonite in the system $KAlSi_3O_8$–$NaAlSi_3O_8$–Al_2O_3–SiO_2–H_2O. Am. Mineral. 60, 985—993.

Chinner, G.A. 1966. The significance of aluminium silicates in metamorphism. Earth Sci. Rev. 2, 111—126.

Deer, W.A., Howie, R.A. & Zussman, J. 1962a. Rock Forming Minerals, vol. 1. Longman, London.

———, ——— & ———, 1962b. Rock Forming Minerals, vol. 3. Longman, London.

Holdaway, M.J. 1971. Stability of andalusite and the aluminium silicate phase diagram. Am. J. Sci. 271, 97—131.

Kepezhinskas, K.B. 1972. Composition of biotite in medium-temperature metapelites as a function of pressure. Doklady Acad. Sci. USSR, Earth Sci. Sec. 204. 440—443.

Marakushev, A.A. & Tararin, I.A. 1965. On the mineralogical criteria of alkalinity of the granites. Izv. Akad. Nauk. SSSR, Ser. Geol. 3, 20—37.

Monier, G., Mergoil-Daniel, J. & Labernardiere, H. 1984. Generations successives de muscovites et feldspaths potassiques dans les leucogranite du massif de Millevaches (Massif Central France). Bull. Mineral. 107, 55—68.

Neilson, M.J. & Haynes, S.J. 1973. Biotites in calk-alkaline intrusive rocks. Mineral. Mag. 39. 251—253.

Nockolds, S.R. 1947. The relation between chemical composition and paragenesis in the biotite micas of igneous rocks. Am. J. Sci. 245. 401—420.

Piispanen, R.A. 1983. Major element geochemistry, origin and metallogenetical aspects of biotites of Svecokarelidic granites of northern Finland. Chem. Erde 42, 267—280.

Pitcher. W.A. 1965. The aluminium silicate polymorphs. in Pitcher, W.S. & Flinn, G.W. (Eds.), Controls of Metamorphism. Oliver and Boyd, Edinburgh, 327—341.

Rafiq, M. 1987. Petrology and geochemistry of Ambela granitic complex, N.W.F.P., Pakistan. Unpublished Ph.D. thesis, Univ. of Peshawar.

Richardson, S.W., Gilbert, M.C. & Bell, M.P. 1969. Experimental determination of kyanite-andalusite and andalusite-sillimanite equilibria: the a luminium silicate triple point. Am. J. Sci. 267, 259—272.

Sturt, B.A. 1970. Exsolution during metamorphism with particular reference to feldspar solid solution. Mineral. Mag. 37, 815—832.

Vernon, R.H. 1979. Formation of late sillimanite by hydrogen metasomatism (base-leaching) in some high grade gneisses. Lithos 12, 143—152.

——— & Flood, R.H. 1977. Interpretation of metamorphic assemblages containing fibrolite sillimanite. Contrib. Mineral. Petrol. 59, 227—235.

Watson. J. 1948. Late sillimanite in the migmatites of Kildenan, Sutherland. Geol. Mag. 85, 149—162.

Wintsch R.P. 1975. Solid-fluid equilibria in the system $KAlSi_3O_8$–$NaAlSi_3O_8$–$Al_2SiO_5SiO_2$–H_2O–HCl. J. Petrol. 16, 57—79.