

## The protoliths to the sillimanite gneisses from the Larsemann Hills and geological implication in their formation

Ren Liudong(任留东)<sup>1</sup>, Yang Chonghui(杨崇辉)<sup>1</sup>, Wang Yanbin(王彦斌)<sup>1</sup>, Liu Ping(刘平)<sup>1</sup> and Zhao Yue(赵越)<sup>2</sup>

*1 Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China*

*2 Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China*

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**Abstract** The source rock from which the sillimanite gneisses derive mainly was the biotite plagioclase gneiss in the Larsemann Hills. It is the deformation-metamorphism process under special pressure and temperature condition, not the original rock compositions, that controls the presence of sillimanite. To a great degree, the sillimanite gneiss was the mixture of the detaining materials of the migrating felsic melt from the biotite plagioclase gneiss that underwent partial melting and the relics when the melt was removed. In sillimanitization the original rock had been changed substantially in chemical composition. The related metamorphism process severely deviated from the isochemical series, the process was of, therefore, an open system. In addition, the  $Al_2O_3$  contents of the original rock was an important, but not critical factor for the formation of sillimanite, i.e., the sillimanite-bearing rock need not be of aluminum rich in composition, and vice contrarily, the aluminum rock may not produce sillimanite. The authors of the present paper postulate that the source rock from which the aluminum rich rock derives need not be of aluminum rich, but sillimanitization is generally the  $Al_2O_3$  increasing process. The aluminum rich sediments such as clay or shale need not correspond directly to sillimanite-rich gneisses. No argillaceous rock present equals to sillimanite-rich gneiss in chemical composition. The protoliths to the sillimanite gneisses from the Larsemann Hills, east Antarctica, and their adjacent area may be pelite, shale greywacke, sub-greywacke, quartz sandstone and quartz-tourmalinite. If correct, the conclusion will be of significant implication for the determination of the sillimanite gneiss formation process and the reconstruction of the protolith setting.

**Key words** sillimanite gneiss, protolith, aluminum contents, chemical process, Larsemann Hills

### 1 Introduction

It is generally accepted that the protoliths to the sillimanite-bearing, especially those sillimanite-rich schists or gneisses are pelites or aluminous clay and form in the passive continental margin or stable basin settings. In principle, if metamorphism occurs in closed system and equilibrium obtained between minerals, the above metamorphic-protolith correla-

tion is quite reasonable. In fact, during the research of the metamorphic textures and component activity of the high-grade quartzofeldspathic gneisses of the Larsemann Hills, east Antarctica, the authors are aware of that the premise of closed system may not stand, and further the protoliths to the sillimanite gneisses are not necessary pelite or clay. Thus we try to discuss the protoliths of the gneisses and corresponding geochemical changes in metamorphism in the Larsemann Hills region.

## 2 Regional geology

The Larsemann Hills are situated in southern coast of the Prydz Bay, east Antarctica, and the Mirror Peninsula at eastern Larsemann Hill locate three scientific stations, the Zhongshan Station of China, the Progress II of Russia and the austral summer Law Base of Australia (Fig 1). Tectonically, the Larsemann Hills are positioned in the Pan-African belt

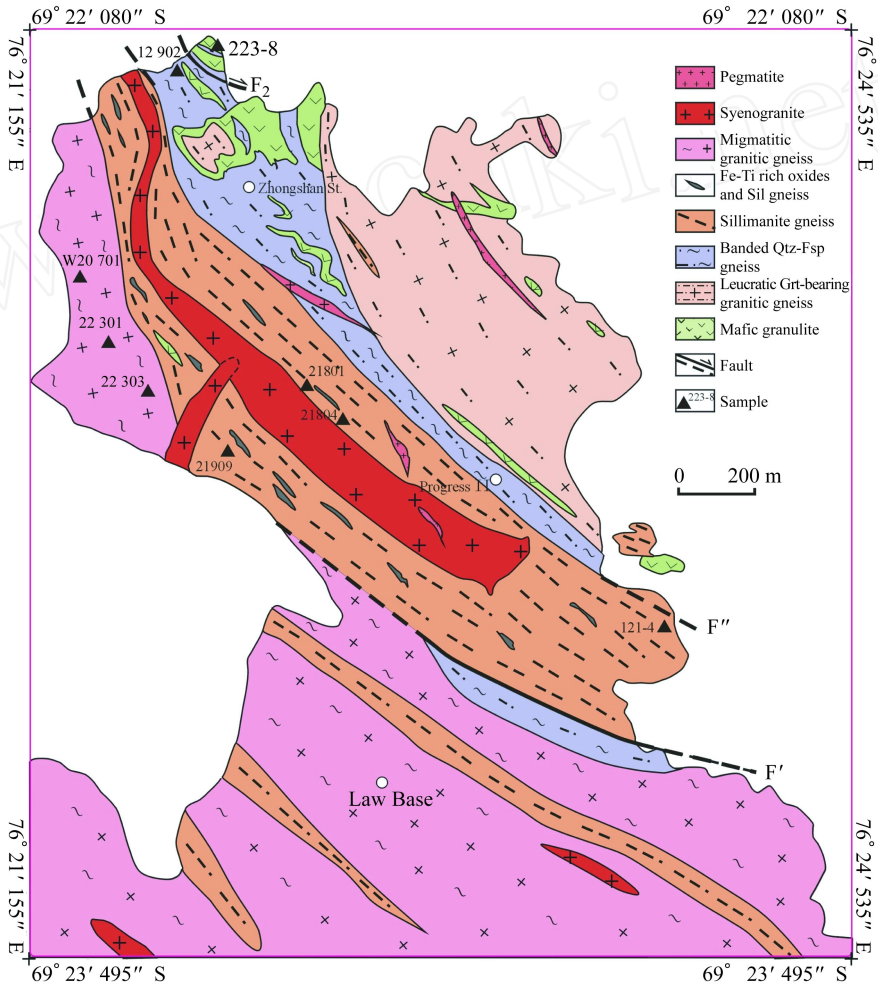


Fig 1 Lithological map of the Mirror Peninsula, Larsemann Hills, East Antarctica (Revised after Ren<sup>[8]</sup> and Tong *et al* 2002<sup>[9]</sup>).

of Gondwanaland and the Pan-African tectonothermal event *c* 550 Ma ago is strongly manifested in the region<sup>[1-6]</sup>. A suite of upper amphibolite to granulite facies metamorphic rocks are exposed<sup>[4,6,7]</sup>. Among them two major lithological associations can be discerned, one is the interleaving mafic granulite and felsic orthogneiss, the other is the metasedimentary sequence, and the latter constitutes the main part of the area

The orthogneisses are generally taken as the basement part of the area<sup>[6]</sup>, where minor mafic granulite (10% -20% in area) occurs. The orthogneisses are in light orange color and consists of medium-grained quartz, feldspar, biotite and/or pyroxene. Trondhjemite can be found, which includes mainly hornblende, orthopyroxene and clinopyroxene, and also biotite, plagioclase in varying amount and minor quartz. While the metasedimentary sequence include the graphite-bearing sillimanite-garnet gneiss, quartzofeldspathic gneiss and minor calc-silicate rocks, it corresponds the conventional khondalites<sup>[8]</sup>. The sillimanite and/or cordierite-bearing gneisses may originate from pelite, pelitic sandstone and sandstone, which constitute the so-called cover sequence of the Larsemann Hills and were deposited over the basement<sup>[6]</sup>. In addition, some granites and pegmatites can be observed.

### 3 Petrology

Pertinent to the paper, here only the sillimanite gneiss is described in the following. Due to the amount of sillimanite and mafic and opaque minerals, the sillimanite can be subdivided into three types

(1) The sillimanite-bearing biotite-plagiogneiss, in which occurs trace amount of sillimanite (1% -2%). The rock shows granoblastic texture and contains quartz, plagioclase, K-feldspar and varying amounts of garnet and biotite and cordierite is generally absent.

(2) Sillimanite schist or gneiss, which is white and mainly consists of sillimanite and quartz, sometimes feldspar is present in certain amount but magnetite is only in trace amount even present.

(3) Spinel-cordierite-sillimanite gneisses, which often has the heterogeneous structure, such as the impenetrative schistosity and varying thickness of individual layers, so do the mineral assemblage and amount. The often minerals present are sillimanite, K-feldspar, plagioclase, quartz, biotite, cordierite, graphite, spinel (hercynite), magnetite, ilmenite, hematite, apatite, monazite and zircon. Occasionally mega-crystal of garnet can be noticed, and locally sulphides-rich quartzite, borosilicate aggregate (grandierite-prismatine-toumaline) are present<sup>[10]</sup>.

### 4 Regional metamorphism feature

As the strong reactivation of deformation and metamorphism in later stages, the earlier metamorphism (M1) assemblage  $Bt + Pl + Kfs + Qtz$  can only be discerned in the weak deformation part of later deformation. Garnet of earlier M1 is seldom present in the biotite plagiogneiss. While the second metamorphism (M2) constitutes the major event in the outcrops. Initially fibrolite with preferred orientation occurred<sup>[11]</sup>, with the assemblages fibrolite +  $Bt + Qtz + Op \pm Ky$ ,  $Bt + Pl + Qtz$ , and the main (or peak) assemblage (M2) prismatic sillimanite, garnet, K-feldspar and occasional orthopyroxene.

In the Larsemann Hills, the S2 foliation related with sillimanite generally has the feature of impenetrative distribution. The biotite plagiogneiss has well-developed foliations and the mineral of the rock shows certain degrees of orientation and differentiation, while the sillimanite schistosity often has the strong foliation and the mineral grains at both sides of the foliation usually don't match each other. This heterogeneity occurs not only on the outcrop scale, but also inside a thin section, and two distinct mineral domains are present. One is the common gneiss assemblage  $Bt + Pl \pm Grt \pm Kfs + Qtz \pm Sil + Op$ , and the other is the well-preferred sillimanite-bearing assemblage,  $Sil + Qtz + Pl \pm Mag (Mt)$ . The later can develop into two contrasting evolving directions, one is the leucocratic sillimanite-rich gneiss, the other is the mafic components-rich, but silica-poor assemblage,  $Sil + Sp1(Hc) + Crd \pm Cm + Mag + Ilm + Ap + Mnz + Zm$ , here quartz and feldspar usually are absent and form the third spinel-cordierite sillimanite gneisses as mentioned above. The two contrasting assemblages may manifest cutting relation: the patchy, lensoid or layers of Mg, Al-rich,

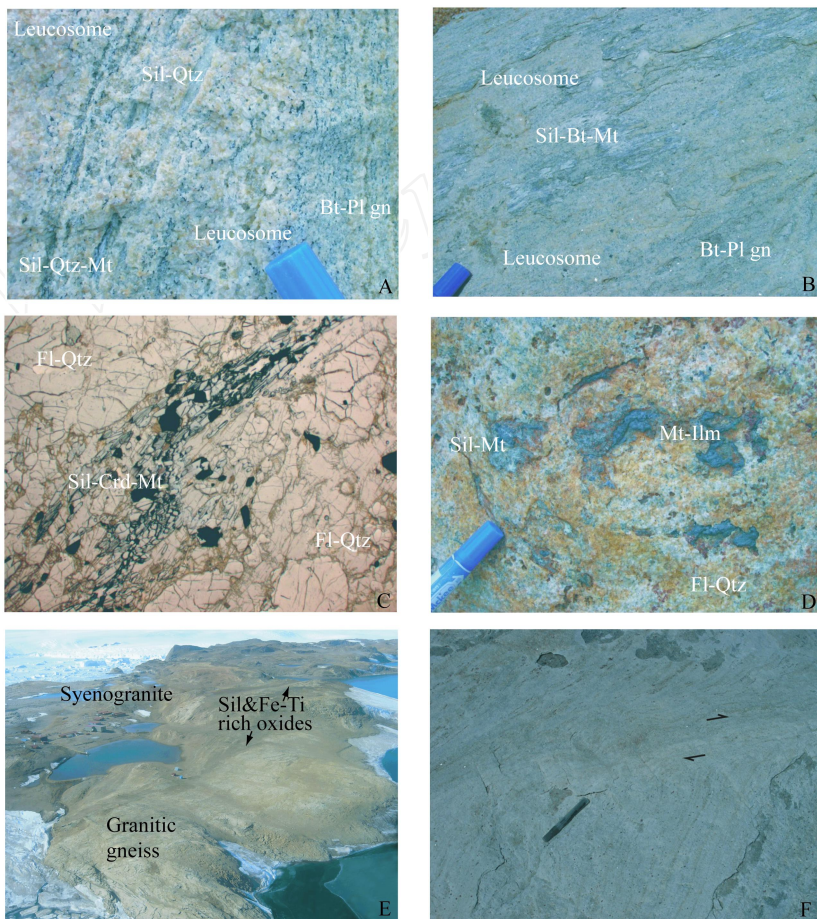


Fig 2 Sillimanite gneisses and related structures A: Sillimanite is followed by leucosome in Bt-Pl gneiss; B: The Sil-Bt-Mt assemblage and leucosome are distributed along certain cleavage; C: Two distinct domains of Sil-Crd-Mt and Fl-Qtz  $\pm Bt$  in Bt-Pl gneiss; D: The residues of Sil-Mt and Mt-Ilm after anatexis E: Outcrop scale sillimanite gneiss, residues and the deriving granite F: late dextral shearing in the grt-bearing granitic gneiss

but Si-poor assemblage transpose or cut the biotite + feldspar gneiss domain. Spatially as the former assemblage decreases the rock may be transitional to the common biotite plagiogneiss. Specially sillimanite gneiss has been observed transitional to tourmaline-quartzite and the complicated borosilicate associations were formed.

## 5 Protoliths to the sillimanite gneisses

Chemical analyses of the sillimanite gneisses have been conducted (Table 1). But the sillimanite-rich tourmaline quartzite was not analyzed. The major components were analyzed with the XRF method in the third Institute of Nuclear Industry Ministry, while the trace elements and REE with ICP-MS in National Analyzing Centre, CAGS. The possible protoliths to the gneisses are listed in table 2 according to the premise of closed system.

Table 1. Representative bulk analyses of the sillimanite gneisses in the Larsemann Hills.

Samples	Sil-rich Pl gn		Sil-bearing Bt-Pl gn				Sp1-Crd-Sil gn				
	223-15	204-3	W20701	21804	121-4	12902	126-1	22301	21801	22303	21909
	sillimanite	Sil-Pl gn	Sil-Grt migmatitic granitic gneiss	Sil-Bt-Gr t Pl gn	Sil-Bt-Gr t Pl gn	Sil-Bt-Gr t Pl gn	Sil-Crd gn	Sil-Gr t-Crd gn	Sp1-Crd-Bt gn	Sil-Crd-Gr t-Bt gn	Sp1-Crd-Sil-Mag aggr
SiO <sub>2</sub>	36.59	76.63	73.22	67.31	55.02	77.70	61.55	33.90	37.78	36.99	28.26
TiO <sub>2</sub>	0.04	0.76	0.18	0.73	1.31	0.55	1.21	2.70	3.15	4.79	1.78
Al <sub>2</sub> O <sub>3</sub>	62.36	16.74	13.66	15.00	22.46	5.47	12.42	36.19	18.59	12.90	26.13
Fe <sub>2</sub> O <sub>3</sub>	0.27	0.33	0	1.53	1.14	0.67	9.64	4.13	5.73	2.39	13.97
FeO	0.40	1.15	1.42	4.06	3.59	6.47	11.49	13.20	14.73	20.47	19.40
MnO	0.04	0.05	0.01	0.12	0.04	0.03	0.11	0.16	0.16	0.08	0.15
MgO	0.34	0.20	0.34	1.29	2.22	5.53	2.02	5.87	10.36	10.80	6.62
CaO	0.03	2.10	1.01	2.63	4.88	0.99	0.83	0.55	0.78	1.04	0.80
Na <sub>2</sub> O	0.65	1.68	2.37	2.70	5.95	0.10	0.75	1.89	1.57	2.36	1.92
K <sub>2</sub> O	0.01	0.58	6.07	4.63	2.46	2.77	0.08	0.60	6.68	7.42	0.14
P <sub>2</sub> O <sub>5</sub>	0.02	0.04	0.08	0.12	0.11	0.18	0.03	0.11	0.03	0.07	0.03
LOI	0.02	0.52	1.33	0.19	0.28	0.10	0.11	0.11	0.90	0.13	0.12
TOT	100.78	100.78	99.69	100.31	99.45	100.00	100.34	99.41	100.46	99.45	99.31
MF/	0.011	0.025	0.020	0.077	0.084	0.132	0.244	0.263	0.343	0.388	0.423
Al/ACNK	0.989	0.793	0.591	0.601	0.628	0.586	0.882	0.923	0.673	0.544	0.901
Ba	17.3	90.8	605.4	913	599	107	11.3	1703	462	543	6906
Co	<1	2.51	8.03	11.0	9.36	9.08	27.1	43.1	66.6	77.3	90.1
Cr	41.4	53.6	14.92	45.3	67.4	83.5	138	398	262	115	232
Cu	6.91	8.45	23.64	25.0	14.9	15.5	<2	46.7	24.2	29.2	9.55
Ga	94.7	21.8	<5.00	9.49	23.9	11.2	123	57.7	78.0	63.0	190
Ni	<4	<4	<4.00	16.0	30.4	36.0	44.8	89.4	123	94.2	96.3
Pb	<12	9.97	49.44	36.0	20.5	<12	30.7	20.3	10.2	44.0	17.4
Sr	3.38	53.8	107	125	539	4.26	2.23	49.2	11.7	15.8	5.43
Th	<3	<3	45	90.8	4.04	58.4	34.9	284	42.8	10.1	6.86
V	32.8	41.5	15.25	63.6	182	149	285	374	507	388	352
Zn	1292	738	30.42	622	34.8	73.0	236	343	656	512	953
Total	1508.5	1027.4	908.1	1957.2	1525.3	558.94	935.03	3408.4	2243.5	1891.6	8858.6
Ba/Sr	5.12	1.69	5.66	7.30	1.11	25.12	5.07	34.62	39.49	34.37	1272
Cr/Ni	10.35	13.4	3.73	2.83	2.22	2.32	0.31	4.45	2.13	1.22	2.41

Samples	Sil-rich Pl gn		Sil-bearing B t-Pl gn				Spl-Crd-Sil gn				
	223-15	204-3	W 20701	21804	121-4	12902	126-1	22301	21801	22303	21909
	sillimanite	Sil-Pl gn	Sil-Grt migmatitic granitic gneiss	Sil-B t-Grt Pl gn	Sil-B t-Grt Pl gn	Sil-B t-Grt Pl gn	Sil-Crd gn	Sil-Grt-Crd gn	Spl-Crd-B t gn	Sil-Crd-Grt-B t gn	Spl-Crd-SilMag aggr
La	0.43	5.45	42.47	104.4	22.66	74.27	33.91	289.6	102.6	15.35	3.71
Ce	1.05	10.78	89.75	218.4	42.82	167.3	71.32	618.5	208.5	36.78	8.85
Pr	0.12	1.52	12.29	25.75	5.47	19.80	8.26	69.00	23.54	5.11	0.93
Nd	0.39	4.93	41.58	100.7	20.42	76.33	33.75	282.3	95.07	21.60	3.22
Sm	0.11	1.24	8.81	16.40	4.06	14.62	6.57	53.44	16.20	5.51	0.61
Eu	0.01	0.60	1.08	2.92	2.44	1.20	0.62	1.68	1.48	0.27	0.04
Gd	0.13	0.36	7.80	9.00	2.75	9.47	4.23	31.14	9.24	6.65	0.53
Tb	0.03	0.30	0.85	1.53	0.49	1.47	0.50	4.62	1.13	1.02	0.08
Dy	0.23	0.45	5.21	7.76	2.32	8.34	2.70	18.45	4.38	6.03	0.39
Ho	0.08	0.10	0.72	1.60	0.38	1.51	0.45	3.27	0.56	1.01	0.11
Er	0.23	0.25	1.07	4.78	1.03	4.13	0.75	8.64	1.43	1.97	0.25
Tm	0.06	0.10	<0.10	0.69	0.14	0.54	0.10	1.20	0.21	0.25	0.05
Yb	0.58	0.35	0.58	4.87	0.80	3.25	0.34	7.03	1.40	1.48	0.52
Lu	0.12	0.10	<0.10	0.65	0.12	0.48	0.10	1.02	0.22	0.20	0.11
L/H	1.43	9.16	11.13	13.78	9.11	11.59	15.71	17.04	13.78	4.47	8.33
Total	5.00	35.69	223.34	513.23	115.01	394.3	179.31	1406.93	479.74	107.7	27.73
Eu/Eu*	0.26	2.120	39.067	2.13	0.29	0.34	0.12	0.67	0.14	0.21	

Note: MF/ =  $(\text{MgO} + \text{FeO} + \text{MnO} + \text{TiO}_2) / \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO} + \text{MgO} + \text{FeO} + \text{MnO} + \text{TiO}_2$ ; Al/AC-NK =  $\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO})$ .

The first type, sillimanite-bearing biotite plagiogneiss, can give the approximately identical result through different geochemical recovering methods, such as samples W 20701, 21804, 121-4 and 12902. The trace and REE features are consistent with the possible protoliths<sup>[12]</sup>. As the weak reactivation and low amount of sillimanite, this type of gneiss can be recovered through isochemistry principle.

As to the second and third types of sillimanite gneisses, the protolith results from different methods vary, and even no sedimentary rocks can be matched for some metamorphics in the diagrams. We can take sample 22301 (sil-grt-crd gneiss) as an example, the possible protoliths to the gneiss may be peridotite – picrite with method of Sang (1992)<sup>[13]</sup>, montmorillonite clay in AF diagram, bauxite in the Si-Fe/(Mg + Ca) diagram, but no rocks can be matched in the  $(\text{Al}_2\text{O}_3 + \text{TiO}_2) - (\text{SiO}_2 + \text{K}_2\text{O})$ -other components diagram. In fact, compared with the possible pelites and clays<sup>[12]</sup>, no sediments can be well matched the sample gneiss in major components. In the Th-Al<sub>2</sub>O<sub>3</sub> diagram, the position was substantially out of the sandstone-shale field, and the same case to the trace elements features. We can say, no magmatic or sedimentary rocks can be correlated to the gneiss in all the components. Actually the gneiss often changes abruptly along the strike, suggesting the strong transposition by deformation. This can be evidenced by the abundant leucosomes and pegmatites in the gneiss, that is, the component migration is obvious and the chemistry of the system is open. So the isochemistry recovering diagrams must lead to erroneous result.

The possible protoliths to the gneiss can be traced through strike searching. The rock should be transitional to some common gneisses, for sample 22301, the sil-gneiss

Table 2 Protoliths of the sillimanite gneisses in the Larsemann Hills

Samples	Rocks	Sang (1992)	AF diagram	( $A_{1/2}O_3 + TiO_2$ ) - ( $SiO_2 + K_2O$ ) -	$SiO_2$ -Fe/ (Ca + Mg)	$SiO_2$ -Al/ (K + Na + Ca + Mg)
21804	Sil-B t-Grt Pl gn	(granite or rhyolite)	greywacke	Argillaceous sandstone	greywacke	greywacke
121-4	Sil-B t-Grt Pl gn	(andesite-andesitic pyroclastics)	greywacke	(strongly differentiated clay)	greywacke	claygreywacke
12902	Sil-B t-Grt Pl gn	arkose	greywacke	Quartz sandstone	subgreywacke	subgreywacke
W20701	Sil-Gr t m ignatitic granitic gneiss	arkose	Acid rock or arkose	arkose	greywacke	greywacke
126-1	Sil-Crd gn	(greywacke, clay)	(hydromica clay)	(composite mineral siltstone)	(greywacke, clay)	(hydromica clay)
22301	Sil-Gr t-Crd gn	(peridotite-Picrite)	(montmorillonite clay)		(bauxite)	
21801	Sp l-Crd-B t gn	(seibergite-nephelinite)	(montmorillonite clay)		(bauxite)	
22303	Sil-Crd-Gr t-B t gn	(seibergite-nephelinite)	(ultrabasic tuffite)	(differentiated clay)	(bauxite)	
21909	Sp l-Crd-Sil-Mag aggr	(seibergite-nephelinite)	(vermiculite clay)		(bauxite)	
223-15	sillimanite	(clay)	(clay)	(strongly differentiated clay)	(bauxite)	(bauxite)
204-3	Sil-Pl gn	(montmorillonite clay)	(arkose-marl)		(subgreywacke)	(subgreywacke)

Note: the rocks in the parentheses are the least possible protoliths

is transitional to the B t-Pl gneiss in both outcrop and microscopic scales, suggesting the sil gneiss being derived the B t-Pl gneiss which gives the possible original rocks like greywacke or shale

Generally speaking, the occurrence of sillimanite suggests the high  $A_{1/2}O_3$  contents of the original sedimentary rock. As to the present study area, sillimanite can be present in the metamorphic rock with low contents of  $A_{1/2}O_3$  to 5.4% (sample 12902). However, many leucocratic gneisses, metasedimentary or orthogneiss rocks, in spite of the  $A_{1/2}O_3$  contents above 5.4%, no sillimanite or kyanite is present. It is specially to point out that the sample 223-8 (biotite-rich plagiogneiss, table 3) has similar composition to that of sample 121-4, and the high  $A_{1/2}O_3$  contents (22.95%), but sillimanite is not present though the metamorphism condition may reach low-pressure granulite facies<sup>[6,7,10]</sup>. Then, what kind of other compositions except  $A_{1/2}O_3$  may influence the formation of sillimanite? We can compare samples 121-4 (sillimanite present) and 223-8 (sillimanite absent), the former rich in K, Na but poor in Ca, it seems that CaO is not sufficient enough to form essential amount of feldspar, and sillimanite occur. While another pair of samples, 21804 (sillimanite present) and 129-2 (sillimanite absent), the former is richer in CaO, K, Na, opposite to the last pair of samples. Detailed investigation to the outcrops we noticed that the sillimanite-bearing

ing gneisses underwent stronger deformation. As the spinel-cordierite-sillimanite gneiss in the area can be derived from almost any rocks except marble or calc-silicate rocks. Thus, the sillimanite-bearing rocks and their protoliths may not be necessarily rich in aluminous composition, furthermore, aluminous rocks may not produce sillimanite, even if PT conditions are appropriate.

In the following we will discuss the possible protoliths and formation setting of the sillimanite gneisses in the area.

The sample 131-14 (orthopyroxene-bearing Bt-Pl gneiss) was collected from the Bolingen Islands, 10 km west of the Larsemann Hills and gives the protolith of greywacke in many recovering diagrams<sup>[8]</sup>. The major components of the sample is similar to that of acid end member (Mk46) of ocean island arc greywacke of the Paleozoic in eastern Australia, while the REE is nearly identical with that of the continent arc greywacke<sup>[14]</sup>.

The protoliths to the high-grade Larsemann Hills region and adjacent areas are mainly bi-modal volcanics<sup>[15]</sup>, alternating greywacke-shale layers (flysch) and minor subgreywacke and quartz sandstone interlayers, overwhelmingly suggesting the turbulent or active setting<sup>[8]</sup>.

Table 3 Bulk analyses of two types of biotite gneisses in the Larsemann Hills

Oxides	SiO <sub>2</sub>	TO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	LOI	TOT
131-14 Px-Bt-Pl gn	67.55	1.02	12.34	2.03	5.57	0.12	3.12	3.52	2.45	1.79	0.12	0.16	99.79
223-8 Bt-rich pl gn	54.3	1.02	22.95	0.22	5.24	0.06	2.22	9.17	3.1	1.27	0.19	0.1	99.84

At the northern end of the Mirror Peninsula (Fig 1) occur the interlayered leucocratic and melanocratic bands (band width 10 ~ 30 cm) of biotite-bearing plagiogneiss and biotite-rich plagiogneiss, respectively. The leucocratic band has SiO<sub>2</sub> = 70wt%, Al<sub>2</sub>O<sub>3</sub> = 13.16%, with the major components richer in TFeO, MgO, P<sub>2</sub>O<sub>5</sub> and poorer in K<sub>2</sub>O than that of the ocean island greywacke of the Paleozoic in east Australia (Bhatia, 1985), suggesting the more active setting of the Larsemann Hills. While the melanocratic band (sillimanite absent) SiO<sub>2</sub> = 54.30% and Al<sub>2</sub>O<sub>3</sub> = 22.95%, the major components, trace and REE elements are similar to that of the Dakota shale (D-2) in Wet Mountains, Colorado<sup>[16]</sup>, and samples in the Larsemann Hills show higher MgO, (FeO), CaO and Co, Cr, Ni, Sc, implying the more mobile depositing setting and lower maturity than that of the Dakota group (marine delta). Thus the protoliths to the banding biotite plagiogneiss are basically greywacke-shale, and formed in continent arc environment<sup>[8]</sup>.

In summary, the protoliths to the sillimanite gneisses of the Larsemann Hills may be pelite, shale, subgreywacke, greywacke, quartzite, even tourmaline quartzite. No direct correlation between the sillimanite gneisses and the aluminous-rich clay or shale. The essential factors in controlling the occurrence of sillimanite are not only the compositions of the original rocks, but also the deformation-metamorphism process in certain temperature and pressure.



### 6 Some geochemical properties of the sillimanite gneisses

Besides the distinct mineral assemblages and textures, the second and third types of sillimanite gneisses also show different geochemical characteristics, the second type is rich in leucocratic and the third is rich in melanocratic components(Fig 3).

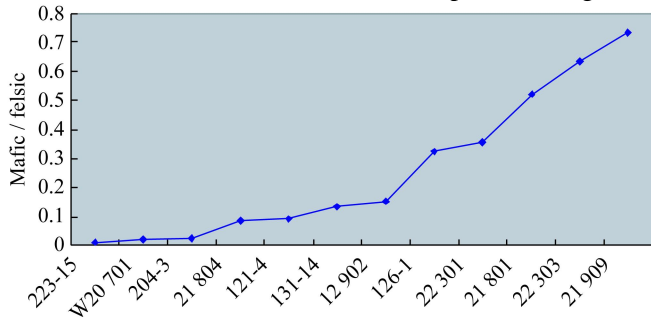


Fig 3 Diagram of the ratio of  $MgO + FeO + MnO + TiO_2$  vs  $SiO_2 + Al_2O_3 + K_2O + Na_2O + CaO$  of the sillimanite gneisses

As mentioned above, much of the protoliths to the sillimanite gneisses are greywacke. To understand the relationships between the sillimanite gneisses and the greywacke, the compositions of them are compared (Fig 4), here the reference sample (131-14) is the quartzofeldspathic gneiss of typical metamorphosed greywacke

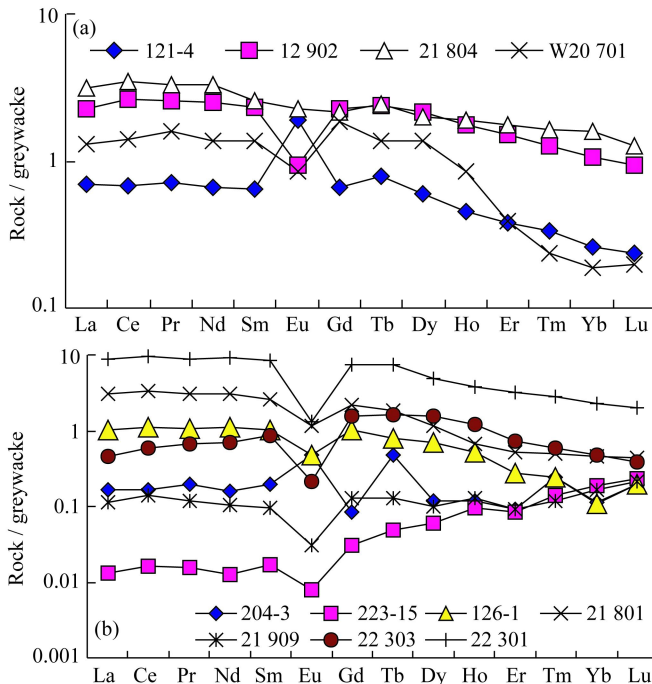


Fig 4 The REE pattern diagrams of sil gneisses vs metagreywacke (A) REE pattern of sil-bearing gneiss vs metagreywacke and (B) REE pattern of sil rich gneisses vs metagreywacke

The second type of sillimanite gneiss is mainly composed of sillimanite and plagioclase, with lower total REE contents (Table 1, Fig 4). While the third type of sillimanite gneiss is melanocratic and rich in cordierite and other accessory mineral, quartz is minor or absent. With high REE contents, the LREE and HREE are strongly fractionated and heavy negative Eu anomaly. We take the garnet-cordierite sillimanite gneiss (sample 22301) as an example. The gneiss has extremely high  $\text{Al}_2\text{O}_3$  (36.19%) and low  $\text{SiO}_2$  (33.90%), abundant in trace elements Ba ( $1703 \times 10^{-6}$ ), Th ( $284 \times 10^{-6}$ ), Cr ( $398 \times 10^{-6}$ ) and V ( $374 \times 10^{-6}$ ) and  $\text{REE} = 1389.89 \times 10^{-6}$ , which is the highest in the area of all the rock types. The LREE and HREE are highly fractionated:  $\text{LREE}/\text{HREE} = 17.04$ , and extremely negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = 0.12$ , the lowest in the area). The sillimanite is transitional to the biotite plagiogneiss and the former is mostly the residue of the later with some components migrated. This is consistent with that of You and Wang (1988)<sup>[17]</sup>, the aluminous rock doesn't necessarily represent the aluminous protolith, but the Al enriching of the residues in the anatexis.

It seems that from quartzofeldspathic gneiss to sillimanite gneiss, the rock tends to be rich in Al but poor in Si, Ca, K, Na (table 1), and if the mafic components depleted, P poorer, but mafic increase, P will be enriched together. Sr is the most distinguished of trace elements in variation: at the initial stage of sillimanitization, Sr depletion is slight, while in the sillimanite-rich gneisses, Sr is heavily depleted, which is keeping pace with the major components of Ca and K.

Compared with the metamorphosed greywacke, the sillimanite-bearing gneisses have the same  $\text{SiO}_2$  contents but higher  $\text{K}_2\text{O}$ , but other major components diverse obviously. So do most trace elements, suggesting the protoliths to this rock type have rather difference from that of the greywacke (Figs 5A, B).

The second and third types of sillimanite gneisses (or sillimanite-rich gneisses) are mostly derived from metagreywacke<sup>[8]</sup>. But the major compositions of the sillimanite-rich gneisses contrast with that of the metagreywacke, even components differentiation occur. In addition, REE contents, fractionization and Eu anomaly all tend to departure from the greywacke, suggesting the formation of sillimanite-rich gneisses is actually not isochemical, that is, the open system.

Due to the non-isochemical feature of sillimanite gneisses formation, some problems like whole-rock isochrons and geochemical properties (compositions of trace and REE elements and parameters like  $\text{Eu}/\text{Eu}^*$ ) for deciphering the protolith environments and the Archean sediments recognition symbols, all must be re-examined<sup>[18,19]</sup>.

Although the  $\text{Al}_2\text{O}_3$  contents is not the only factor in controlling the occurrence of sillimanite, the sillimanitization is generally a process of  $\text{Al}_2\text{O}_3$  increasing (Fig 6), with the parameter  $\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O})$  low in type 1 and high in type 2 and 3 of sillimanite gneisses. Sillimanitization is a process of  $\text{Al}_2\text{O}_3$  enriching. Thus, Paragneisses may predominate in the sillimanite concentrating sequence in the Larsemann Hills. But the possibility of orthogneiss transposed into sillimanite gneisses cannot be ruled out. Actually small patch or lensoid of sillimanite gneiss has been found in the garnet-bearing granitic orthogneiss (Fig 1). Nevertheless, sillimanite gneisses of the area can not be recovered to pelite or clay, bauxite. In many cases, the so-called "metapelite, clay" are actually the

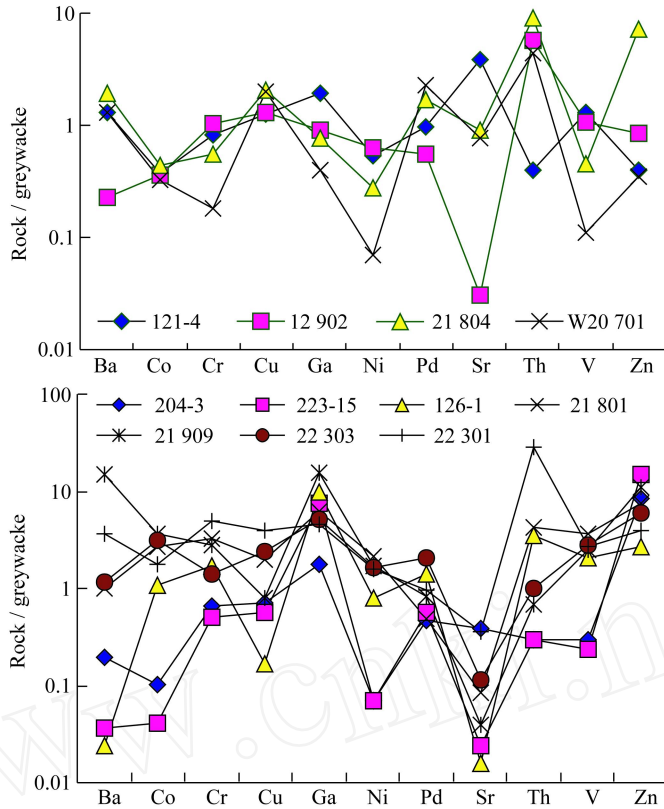


Fig 5 The trace elements pattern diagrams of sil gneisses vs metagreywacke (A) sil-bearing gneiss vs metagreywacke, and (B) sil-rich gneiss vs metagreywacke

artifact result under the false premise of isochemistry of metamorphics having undergone strongly deformation and metamorphism.

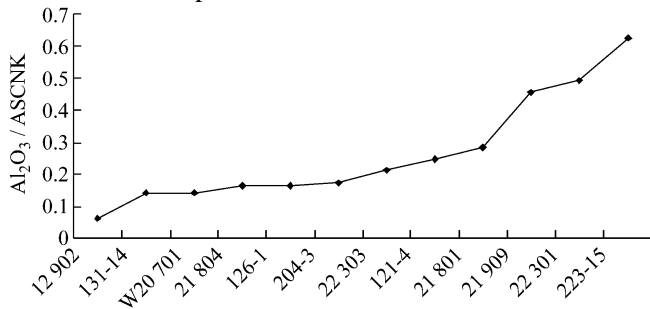


Fig 6 The variation diagram of the ratio of  $Al_2O_3 / (SD_2 + Al_2O_3 + K_2O + Na_2O + CaO)$  of sillimanite gneisses

Sillimanite gneiss is the most typical rock in khondalites. Under the principle of isochemistry in metamorphism, the gneiss can be recovered to aluminous-rich sedimentary formations and should occur in stable basins over cratons or passive continental margins. The result from the present paper shows that original formation is only one of the factors, and the more critical factors lie in the deformation and metamorphism conditions. The protoliths to the sillimanite gneisses of the area are mainly greywacke, which might form in active envi-

ronment The deduction is quite different from that of the conventional one

## 7 Possible origin of sillimanite gneiss

In sillimanitization metamorphic rocks underwent composition changes, especially the leaching of alkaline and alkaline earth metals, even desilicization<sup>[20]</sup>. The formation of sillimanite is related to strain and anatexis<sup>[21]</sup>, or crystallizes directly from the melt<sup>[22]</sup>. On the basis of geochemical comparison between the sillimanite-quartz aggregates and adjacent anatexitic veins in Wanzi group of Hebei Province, China, Wan *et al* (2003) pointed out that the sillimanitization was related with anatexis of K-feldspar leptynite, and both sillimanite and veins (leucosome) were formed from the same process according to the consistent Nd isotope feature<sup>[23]</sup>.

From both the outcrop and the microscopic scales, occurrence of sillimanite in the Larsemann Hills is accompanied by the strong deformation of the felsic gneisses. Sillimanite is often located in the conduits of leucosome migration and the mineral is a symbol of beginning of anatexis. On account of the spatial and texture relations between sillimanite, biotite plagiogneiss and leucosome, sillimanite is perhaps one of the residues after the migration of the felsic materials. The alkaline (earth) metal components, and sometimes silica, can be easily removed, but aluminous and iron components tend to be inert and remain as sillimanite or corundum, being accompanied by the opaque oxides magnetite, ilmenite and hematite, suggesting sillimanitization is meanwhile the composition adjusting process of the related gneisses.

Deformation or strong strain may be critical to formation of sillimanite. In macroscopic scale, the initial arrangement of the metamorphic rocks in the Larsemann Hills may take certain angle to the present major foliation. Because no metamorphic rock can be struck for more than 1-2km and the apparent distribution of the sillimanite gneiss, the leucocratic garnet-bearing granitic gneiss, the migmatitic granitic gneiss (Fig 1) and minor borosilicates seem to oblique to the foliation. The sillimanite gneiss can be concentrated along the shear zone between F and F (Fig 1)<sup>[5]</sup>. As deformation can substantially reactivate and migrate some components<sup>[24]</sup>. The zone may represent the possible change of orthogneiss and paragneiss<sup>[3]</sup>.

## 8 Conclusions

According to the above analyses, the following conclusions can be obtained

(1) The  $Al_2O_3$  contents of the original rock is an important, but not critical factor for the formation of sillimanite, i.e., the sillimanite-bearing rock need not be of aluminous rich in composition, and vice versa, the aluminous rock may not produce sillimanite. The authors postulate that the source rock from which the aluminum rich rock derives need not be of aluminum rich, but sillimanitization is generally the  $Al_2O_3$  increasing process.

(2) It is the deformation-metamorphism process under special pressure and temperature condition, not the original rock compositions, that controls the presence of sillimanite. No argillaceous rock present equals to sillimanite-rich gneiss in chemical composition. The

aluminum rich sediments such as clays or shale need not correspond directly to sillimanite-rich gneisses. The source rock from which the sillimanite gneisses derive mainly is the biotite plagioclase gneiss in the study area. To a great degree, the sillimanite gneiss is the mixture of the detaining materials of the migrating felsic melt from the biotite plagioclase gneiss that undergoing partial melting and the relics when the melt is removed. In sillimanitization the original rock has been changed substantially in chemical composition. The related metamorphism process severely deviate the isochemical series, the process is of, therefore, an open system.

(3) The protoliths to the sillimanite gneisses from the Larsemann Hills, east Antarctica, and their adjacent area may be pelite, shale greywacke, sub-greywacke, quartz sandstone and quartz-tourmalinite. The deduction will be of significant implication for the determination of the formation process of the sillimanite gneiss and the reconstruction of the protolith setting.

(4) The rock-forming condition of the sillimanite gneisses may correspond to strong structure activity (such as shear zone) under certain temperature and pressure conditions. Such conclusion is crucial to understanding the regional structure of the study area.

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