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Title of article Petrogenesis of Early Proterozoic pelitic schists of the southern Black Hills, South Dakota: Constraints on regional low-pressure...

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see Bulletin v. 103, p. 1324 - 1334

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TABLE 1. MINERAL ASSEMBLAGES OCCURRING AT SAMPLE LOCATIONS IN FIGURE 1

SAMPLE	ilm	gar	st	sil	ky	and	chl	cor	ksp	hem	mag
1	◆	◆	◆								
2	◆	◆	○	◆							
3		◆		◆						◆	
4				◆					◆		
5	◆	◆		◆							
6	◆	◆	○	◆							
7	◆	◆	◆			◆	◆				
8		◆				◆	◆	◆		◆	
9	◆	◆	◆	◆		◆	◆			◆	◆
10	◆	◆					◆				
11	◆	◆					◆				
12	◆	◆					◆				
13	◆	◆					◆				
14	◆	◆				◆					
15	◆	◆				◆					
16	◆	◆	◆				◆				
17	◆	◆	◆			◆	◆				
18	◆	◆				◆					
19	◆	◆					◆				
20	◆	◆	◆					◆			
21	◆	◆	◆					◆			
22a	◆	◆					◆				
22b	◆	◆	◆								
23	◆	◆	◆					◆			
24	◆	◆	◆					◆			
25a	◆	◆					◆				
25b	◆	◆		◆							
25c	◆	◆		◆			◆				
25d	◆	◆	◆	◆							
27	◆	◆							◆		
28	◆	◆		◆							
29	◆	◆			◆						

Note: ◆ Mineral present; ○ Mineral present as inclusion only. Mineral abbreviations: ilm, ilmenite; gar, garnet; sil, sillimanite; st, staurolite; and, andalusite; cor, cordierite; ksp, K-feldspar; hem, hematite; mag, magnetite; chl, chlorite.

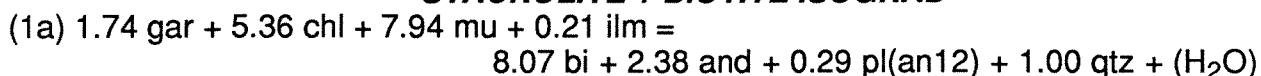
TABLE 2. MINERAL COMPOSITIONS USED IN MASS-BALANCE
CALCULATIONS

	REACTION (1a)						REACTION (2a)					
	(4) Pl21	(5) Gar21	(9) Bi21	(3) Chl21	(6) St21	(5) Mu21	(3) Pl17	(5) Bi17	(3) Chl17	(6) St17	(2) Mu17	(10) Gar17
SiO ₂	65.87	36.31	34.64	24.04	27.33	46.86	63.85	35.05	23.33	27.17	46.44	36.67
Al ₂ O ₃	21.67	21.36	20.75	21.75	53.58	36.05	22.74	19.26	22.78	54.03	36.86	20.78
TiO ₂	--	--	1.37	0.04	0.48	0.28	--	1.48	0.11	0.21	0.27	0.02
FeO	--	38.58	20.64	28.09	14.66	1.16	0.01	22.13	28.48	13.76	0.83	34.05
MnO	--	1.53	8.45	12.56	1.33	0.57	--	8.42	11.80	1.12	0.38	1.66
MgO	--	1.50	0.09	0.13	0.43	--	--	0.09	0.21	0.33	--	6.45
CaO	2.67	0.66	--	0.08	--	--	3.56	--	0.00	--	--	0.93
Na ₂ O	10.30	--	0.36	--	--	1.49	9.81	0.18	--	--	1.65	--
K ₂ O	0.04	--	9.15	--	--	9.27	0.05	9.07	--	--	8.94	--
	REACTION (5a)						REACTION (6a)					
	(21) Gar2	(8) Pl2	(9) Bi2	(6) St1	(6) Mu1	(7) Pl1	(9) Bi3	(3) Ab3	(6) Pl2	(9) Mu2	(6) Ksp3	(9) Pl3
SiO ₂	36.46	64.31	33.99	27.62	46.49	61.84	35.18	68.44	64.31	45.78	64.50	62.92
Al ₂ O ₃	21.01	22.41	19.54	53.32	35.44	24.26	18.98	19.89	22.41	36.40	18.41	23.41
TiO ₂	0.02	--	1.91	0.62	0.41	--	2.70	--	--	0.48	--	--
FeO	39.30	0.11	24.85	14.40	1.03	0.12	19.73	0.09	0.11	1.12	0.05	0.10
MnO	1.06	--	0.03	0.16	--	--	0.20	--	--	--	--	--
MgO	1.76	0.06	6.26	1.53	0.69	--	8.50	--	0.06	0.35	--	--
CaO	0.89	3.32	--	--	--	5.70	--	0.31	3.32	--	0.01	4.42
Na ₂ O	--	9.74	0.22	--	1.04	8.36	0.08	11.54	9.74	1.19	0.74	9.04
K ₂ O	--	0.05	8.97	--	9.37	0.05	9.82	0.10	0.05	9.60	15.84	0.17

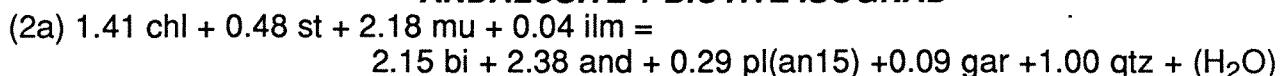
Note: The number in parenthesis above each mineral composition is the number of analyses used in the average. Garnet compositions are from rim analyses.

TABLE 3. LEAST-SQUARES MASS-BALANCE EQUATIONS AND RESIDUALS

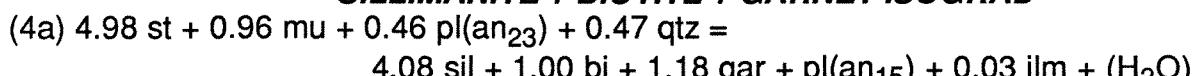
STAUROLITE + BIOTITE ISOGRAD



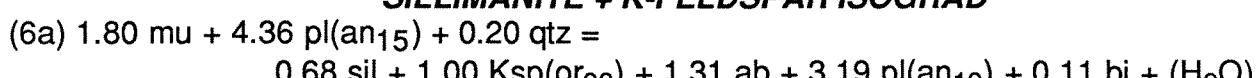
ANDALUSITE + BIOTITE ISOGRAD



SILLIMANITE + BIOTITE + GARNET ISOGRAD



SILLIMANITE + K-FELDSPAR ISOGRAD



	(1a)		(2a)		(5a)		(6a)	
	r	r/v	r	r/v	r	r/v	r	r/v
SiO ₂	-0.01	0.01	-0.02	0.06	0.00	0.00	0.00	0.00
Al ₂ O ₃	0.00	0.00	0.03	0.02	0.00	0.00	0.00	0.00
TiO ₂	0.00	0.11	0.09	0.41	0.57	5.58	0.57	5.52
FeO	-0.01	0.00	-0.10	0.23	0.02	1.48	-0.06	0.25
MgO	0.03	0.02	0.21	0.36	0.02	1.10	-0.02	0.40
MnO	0.70	2.73	0.30	0.51	-0.20	3.43	0.05	0.76
CaO	-0.68	11.98	1.11	3.35	0.00	0.15	0.00	0.00
Na ₂ O	0.24	0.21	-0.36	12.47	0.00	0.00	0.00	0.00
K ₂ O	0.01	0.00	0.04	4.45	-0.02	0.07	-0.02	0.04
$\sqrt{\sum r^2}$	1.01		1.23		0.61		0.58	

Note: Mineral compositions used in the mass-balance equations are listed in TABLE 2. Mineral abbreviation: ab, albite; and, andalusite; an, anorthite; bi, biotite; chl, chlorite; gar, garnet; ilm, ilmenite; ksp, K-feldspar; mu, muscovite; pl, plagioclase; sil, sillimanite; st, staurolite; r is the residual (weight %) on each oxide. r/v is the residual on an oxide divided by the measured variation (1 standard deviation about the average) on that oxide. The variation v is weighted by the stoichiometric coefficients of the mass-balance equation. No attempt was made to estimate H₂O content in minerals; therefore, (H₂O) is qualitatively listed on the side of the equation interpreted to be prograde. Ilmenite, quartz, and aluminum silicate are FeTiO₃, SiO₂, and Al₂SiO₅, respectively.

TABLE 4. MINERAL COMPOSITIONS USED TO ESTIMATE TEMPERATURE
PRESSURE AND a_{H_2O} .

	Garnet			Biotite		Muscovite			Plagioclase	Chlorite
	XAlm	XGro	XSp	XAnn	XPhl	XK	XNa	XIVAl	XAn	XCli
1	0.788	0.072	0.045	0.429	0.375	0.796	0.134	0.940	0.273	—
2	0.895	0.018	0.023	0.539	0.240	0.815	0.154	0.949	0.158	—
3	0.750	0.020	0.140	0.421	0.324	0.931	0.053	0.927	0.202	—
4	—	—	—	0.432	0.301	0.924	0.049	0.936	0.198	—
5	0.748	0.024	0.150	0.446	0.321	0.849	0.130	0.946	0.196	—
6	0.864	0.052	0.034	0.537	0.215	0.831	0.052	0.940	0.230	—
8	0.534	0.048	0.303	0.312	0.497	0.755	0.234	0.916	0.220	0.585
9	0.540	0.044	0.293	0.291	0.538	0.760	0.201	0.881	0.242	0.617
10	0.726	0.028	0.171	0.436	0.375	0.854	0.103	0.942	0.021	0.440
11	0.639	0.043	0.231	0.381	0.441	0.818	0.145	0.902	0.207	0.500
12	0.638	0.056	0.266	0.474	0.327	0.852	0.077	0.880	0.225	0.384
13	0.876	0.047	0.020	0.508	0.294	0.823	0.151	0.934	—	—
14	0.798	0.019	0.111	0.454	0.336	0.779	0.190	0.942	0.156	—
15A	0.763	0.038	0.115	0.443	0.337	0.788	0.186	0.954	0.196	—
15B	0.805	0.028	0.100	0.464	0.313	0.780	0.179	0.948	0.169	—
16	0.790	0.025	0.106	0.458	0.334	0.809	0.191	0.934	0.176	—
17	0.770	0.027	0.131	0.453	0.339	0.755	0.216	0.964	0.154	0.377
18	0.834	0.020	0.063	0.432	0.359	0.779	0.201	0.942	0.125	—
19	0.828	0.019	0.095	0.485	0.305	0.785	0.138	0.955	0.020	—
20	0.796	0.031	0.087	0.420	0.389	0.777	0.204	0.939	0.181	0.448
21	0.872	0.019	0.033	0.466	0.329	0.781	0.198	0.955	0.156	0.407
22	0.769	0.043	0.112	0.452	0.338	0.772	0.176	0.947	0.215	—
23	0.696	0.031	0.172	0.392	0.428	0.760	0.223	0.924	0.183	0.502
24	0.781	0.032	0.100	0.426	0.376	0.729	0.257	0.933	0.160	0.455
25A	0.786	0.028	0.122	0.449	0.316	0.781	0.185	0.957	0.128	—
25B	0.768	0.024	0.138	0.469	0.318	0.773	0.158	0.955	0.154	—
25C	0.799	0.021	0.109	0.460	0.323	0.807	0.174	0.944	0.163	—
25D	0.785	0.024	0.120	0.469	0.321	0.766	0.179	0.958	0.147	—
27	0.495	0.060	0.411	0.468	0.322	0.962	0.032	0.888	0.230	—
28	0.790	0.055	0.092	0.468	0.316	0.815	0.185	0.954	0.155	—
29	0.745	0.047	0.086	0.362	0.392	0.802	0.121	0.899	0.254	—

Note: Averaged mineral compositions and average garnets rim compositions; XAlm = Fe/(Fe + Mg + Mn + Ca), XGro = Ca/(Fe + Mg + Mn + Ca), XSp = Mn/(Fe + Mg + Mn + Ca), XAnn = Fe/3, XPhl = Mg/3, XK = K, XNa = Na, XIVAl = Al/2, XAn = Ca, XCli = Mg/5; Fe is assumed to be all Fe^{2+} .

TABLE 5. REPRESENTATIVE AND COMPARATIVE RESULTS OF GEOLOGIC THERMOMETRY AND BAROMETRY

Sample	GB		AMPH		GBSH		GASP			AS	GBMP
	FS T (°C)	GS T (°C)	T(max) (°C)	aH ₂ O	aH ₂ O	IS P (kbar)	GS P (kbar)	NH P (kbar)	P (kbar)	P (kbar)	
Sillimanite Zones											
2	537	582	≤564	1.14	—	3.46	1.05	4.10	>2.59	3.35	
28	454	528	≤566	0.70	—	3.53	1.99	4.10	>3.43	5.45	
25B	483	549	≤551	0.99	—	3.40	1.68	4.04	~3.09	3.30	
6	504	551	≤560	0.92	—	3.43	2.29	3.91	>3.08	4.15	
5	511	543	≤548	0.96	—	2.48	1.32	3.11	>3.18	2.70	
3	520	563	≤662	0.43	—	2.02	0.49	2.72	>2.89	3.54	
27	487	527	—	—	—	—	—	—	—	3.83	
Andalusite + biotite zone											
9	463	505	≤529	0.78	0.79	3.09	3.69	4.17	<3.68	3.66	
15A	503	545	≤540	1.10	—	2.17	0.88	2.45	<3.64	3.98	
8	483	534	≤537	0.98	—	3.31	3.77	4.52	<3.50	4.22	
19	431	480	≤558	0.45	—	—	—	—	—	—	
14	455	501	≤511	0.90	—	2.02	0.71	2.78	<3.77	2.55	
22	451	531	≤511	1.24	—	2.19	1.50	2.95	~3.35	3.89	
17	461	513	≤517	0.98	1.07	2.28	1.35	2.98	<3.60	2.96	
Kyanite zone											
29	523	530	≤533	0.98	—	4.48	3.61	4.07	>4.20	4.22	
Staurolite + chlorite + biotite zone											
24	468	501	—	—	0.92	—	—	—	—	3.63	
23	481	518	—	—	0.89	—	—	—	—	3.50	
20	443	474	—	—	0.81	—	—	—	—	2.63	
21	458	488	—	—	0.76	—	—	—	—	2.56	
Garnet -zone											
12	390	469	—	—	0.97	—	—	—	—	3.50	
10	515	492	—	—	0.84	—	—	—	—	—	
11	448	500	—	—	0.79	—	—	—	—	3.65	

Note: Abbreviations; GB - garnet-biotite geothermometer, FS- Ferry and Spear (1978) calibration of the garnet-biotite geothermometer, GS- Ganguly and Saxena (1984) corrected version of the garnet-biotite geothermometer; AMPH - aluminum silicate + muscovite + plagioclase + quartz + H₂O equilibria, the activity of paragonite component was estimated from Chatterjee and Froese (1975); GBCH - garnet + chlorite + biotite + muscovite + quartz + H₂O equilibria (reaction 13 estimated from Holland and Powell, 1985); GASP - garnet + aluminum silicate + plagioclase + quartz geobarometer based on reaction (8), IS - GASP geobarometer, the activity of anorthite estimated from Saxena and Ribbe (1972) and the activity of grossular is estimated as ideal, GS - GASP geobarometer, the activity of anorthite is estimated from Saxena and Ribbe (1972) and the activity of grossular is estimated from Ganguly and Saxena (1984), NH - GASP geobarometer where the activities of grossular and anorthite are estimated with the models in Newton and Haselton (1981); AS - aluminum silicate equilibria from Holdaway (1971); GBPM - garnet + biotite + plagioclase + muscovite equilibria (Ghent and Stout, 1981).

TABLE 6. SYSTEM OF HOMOGENEOUS DIFFERENTIAL EQUATIONS NECESSARY TO DESCRIBE
THE RELATIONSHIP BETWEEN μ_{H_2O} AND X_{Mg} IN THE ASSEMBLAGES BIOTITE +
STAUROLITE + ANDALUSITE + MUSCOVITE + QUARTZ AND STAUROLITE + CHLORITE +
BIOTITE + MUSCOVITE + QUARTZ

$$\begin{bmatrix}
 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & X_{Fe}^{Chl} & X_{Mg}^{Chl} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 1 & 0 & 0 & 0 & 0 & 0 & X_{Fe}^{Bi} & X_{Mg}^{Bi} & 0 & 0 & 0 & 0 \\
 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X_{Fe}^{St} & X_{Mg}^{St} & 0 & 0 \\
 -20 & 69 & 0 & 0 & 62 & 0 & -69 & 0 & -36 & -212 & 0 & 0 \\
 18 & 8 & -62 & 0 & 0 & 0 & -8 & 0 & 12 & -12 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 2 & -2 & -3 & 3 & 0 & 0 & 0 \\
 0 & 0 & 0 & 2 & -2 & -3 & 3 & 0 & 0 & 0 & 0 & 0 \\
 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & \left(\frac{\partial^2 g_{Bi}}{\partial X_{Fe}^{Bi}^2} \right) T, P, X_i & 0
 \end{bmatrix} \bullet \begin{bmatrix}
 d\mu_{Qtz} \\
 d\mu_{Mu} \\
 d\mu_{And} \\
 d\mu_{Fe-Chl} \\
 d\mu_{Mg-Chl} \\
 d\mu_{Fe-Bi} \\
 d\mu_{Mg-Bi} \\
 d\mu_{Fe-St} \\
 d\mu_{Mg-St} \\
 d\mu_{H_2O} \\
 dX_{Fe}^{Bi}
 \end{bmatrix} = 0$$