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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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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)	(5)	(9)	(3)	(6)	(5)	(3)	(5)	(3)	(6)	(2)	(10)
	Pl21	Gar21	Bi21	Chl21	St21	Mu21	Pl17	Bi17	Chl17	St17	Mu17	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_2O_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_2O	10.30	---	0.36	---	---	1.49	9.81	0.18	---	---	1.65	---
K_2O	0.04	---	9.15	---	---	9.27	0.05	9.07	---	---	8.94	---
			REACTION (5a)						REACTION (6a)			
	(21)	(8)	(9)	(6)	(6)	(7)	(9)	(3)	(6)	(9)	(6)	(9)
	Gar2	Pl2	Bi2	St1	Mu1	Pl1	Bi3	Ab3	Pl2	Mu2	Ksp3	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_2O_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_2O	---	9.74	0.22	---	1.04	8.36	0.08	11.54	9.74	1.19	0.74	9.04
K_2O	---	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

(1a) 1.74 gar + 5.36 chl + 7.94 mu + 0.21 ilm =
8.07 bi + 2.38 and + 0.29 pl(an12) + 1.00 qtz + (H_2O)

ANDALUSITE + BIOTITE ISOGRAD

(2a) 1.41 chl + 0.48 st + 2.18 mu + 0.04 ilm =
2.15 bi + 2.38 and + 0.29 pl(an15) +0.09 gar +1.00 qtz + (H_2O)

SILLIMANITE + BIOTITE + GARNET ISOGRAD

(4a) 4.98 st + 0.96 mu + 0.46 pl(an_{23}) + 0.47 qtz =
4.08 sil + 1.00 bi + 1.18 gar + pl(an_{15}) + 0.03 ilm + (H_2O)

SILLIMANITE + K-FELDSPAR ISOGRAD

(6a) 1.80 mu + 4.36 pl(an_{15}) + 0.20 qtz =
0.68 sil + 1.00 Ksp(or_{93}) + 1.31 ab + 3.19 pl(an_{19}) + 0.11 bi + (H_2O)

	(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_2O_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_2O	0.24	0.21	-0.36	12.47	0.00	0.00	0.00	0.00
K_2O	0.01	0.00	0.04	4.45	-0.02	0.07	-0.02	0.04
$\sqrt{\Sigma r^2}$	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 H_2O content in minerals; therefore, (H_2O) is qualitatively listed on the side of the equation interpreted to be prograde. Ilmenite, quartz, and aluminum silicate are $FeTiO_3$, SiO_2, and Al_2SiO_5, respectively.

TABLE 4. MINERAL COMPOSITIONS USED TO ESTIMATE TEMPERATURE PRESSURE AND a_{H2O}.

	Garnet			Biotite		Muscovite			Plagioclase	Chlorite
	X_{Alm}	X_{Gro}	X_{Sps}	X_{Ann}	X_{Phl}	X_K	X_{Na}	X^{IV}_{Al}	X_{An}	X_{Cli}
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; X_{Alm} = Fe/(Fe + Mg + Mn + Ca), X_{Gro} = Ca/(Fe + Mg + Mn + Ca), X_{Sps} = Mn/(Fe + Mg + Mn + Ca), X_{Ann} = Fe/3, X_{Phl} = Mg/3, X_K = K, X_{Na} = Na, X^{IV}_{Al} = Al /2, X_{An} = Ca, X_{Cli} = 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)	a_{H2O}	a_{H2O}	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 estimeted 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 activties 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 μH_2O AND X_{Mg} IN THE ASSEMBLAGES BIOTITE + STAUROLITE + ANDALUSITE + MUSCOVITE + QUARTZ AND STAUROLITE + CHLORITE + BIOTITE + MUSCOVITE + QUARTZ

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