

(Me_{75-83}), aluminous diopside, green amphibole, colourless spinel, large poikilitic blue tourmaline, and a little calcite. Tourmaline includes several minerals, especially clinopyroxene, spinel, and a few small crystals of serendibite. Scattered grains of the latter in one crystal of tourmaline are in optical continuity, suggesting that tourmaline is a breakdown product after serendibite. The serendibite is colourless to very light green. The mineral is much less coloured than the prussian blue crystals in a calcsilicate rock associated with clintonite clinopyroxenites from Ianapera, in SW Madagascar (Nicollet, 1988, 1990). The Ihoisy serendibite has low birefringence and fine polysynthetic twinning. It may be mistaken for sapphirine, but it is distinguishable from the latter by a larger extinction angle and by its occurrence in calcic rocks. The ferromagnesian minerals in the rock are magnesium rich. Tourmaline (Table 1) is a magnesian uvite and the X_{Mg} ratio of the spinel is greater than 0.9. Hornblende and clinopyroxene are close to their Mg end-members ($X_{Mg} \approx 0.97$). The Fe–Mg partitioning between tourmaline and serendibite (K_d) is ≈ 0.4 as in the more iron rich pair from Ianapera; it is lower than the K_d of coexisting tourmaline and serendibite from Melville Peninsula, Canada ($K_d = 0.61$; Hutcheon *et al.*, 1977).

The P – T conditions of the crystallization of this rock are similar to those estimated for the neighbouring seven-phase anatectic gneisses (Nicollet, 1988).

KEYWORDS: grandidierite, serendibite, tourmaline, Ihoisy, Madagascar, metamorphism.

Département de Géologie, UA 10,
5 Rue Kessler, Clermont Fd, 63038, France

CHRISTIAN NICOLLET

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Serendibite from the northwest Adirondack Lowlands, in Russell, New York, USA

SERENDIBITE, to a first approximation, $Ca_2(Mg, Fe^{2+})_3(Al, Fe^{3+})_{4.5}B_{1.5}Si_3O_{20}$, has been reported from about eight localities worldwide (Deer *et al.*, 1978; Nicollet, 1988), including Johnsbury, New York, in the southern Adirondack Highlands (Larsen and Schaller, 1932; Grew *et al.*, in press). It is a mineral of high-temperature calc-silicate skarns, mostly in the granulite-facies. In this

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paper we report a new occurrence from the northwest Adirondacks Lowlands. This occurrence has many mineralogical and chemical features in common with the serendibite–diopside rocks in the Johnsbury deposit, although located 130 km distant.

Serendibite occurs in core from hole 1872 drilled by St. Joe Resources Company (presently

Zinc Corporation of America) near Cassidy Road, 350m south of Town Line Road, town of Russell, NY (44°31'N, 75°09'E). The drill hole penetrated calc-silicate rocks and marbles typical of the northwest Adirondack Lowlands (e.g. Bohlen *et al.*, 1985). A summary of the core log to 40m is as follows (compositional layering intersected at high angle by the vertical core).

0–6m: Overburden.

6–8.5m: Biotite–diopside calc-silicate granulites (e.g. at 7m, plagioclase–biotite–titanite–hornblende–diopside)

8.5–30m: Diopside granulite with disseminated cm-sized books of phlogopite, alternating with amphibole–phlogopite rock at 16.8m, serendibite–diopside rock at 17.7m, and finely layered quartz-rich diopside–K-feldspar–titanite granulite at 22–25m.

30–37.5m: Dolomite–calcite marble with serpentine (after forsterite?), minor spinel and phlogopite.

37.5–40m: Diopside-rich granulite.

The serendibite–diopside rock occurs over an interval of 13–20cm (largest core fragment is 5cm long). Recovery of the core was not complete and we are not able to fully characterise the layering in this section of the core. The closest rocks to the serendibite–diopside rock are diopside granulite with phlogopite books at 0.6m below and amphibole–phlogopite rock at 0.9m above. The latter is a relatively coarse intergrowth of phlogopite and calcic clin amphibole in which diopside occurs sporadically, mostly included in the amphibole.

Important constituents of the serendibite–diopside rock are apatite, calcite, pargasite, and secondary phyllosilicates resembling sericite and chlorite, while scapolite, tourmaline, grandidierite, phlogopite, sulfide, sinhalite (?), and spinel are rare. Serendibite is deep blue in hand specimen, while in thin section it forms pale-blue polysynthetically twinned grains up to 1cm across with highly irregular outlines. Preferred orientation of the grains is implied by parallelism of the twin lamellae from grain to grain. Serendibite is partly replaced by a birefringent material in which traces of the twinning lamellae are preserved. A similar material replaces serendibite at Johnsbury (Grew *et al.*, in press). Diopside occurs as inclusions in serendibite and as a granular matrix (grains mostly ≤ 0.5 cm) to it. Patches and overgrowths of pargasite are locally developed in and around diopside, most commonly along contacts with serendibite. Apatite is relatively coarse-grained (≤ 0.5 cm). Larger calcite grains (1–4mm) are mantled and penetrated by a phyllosilicate; these intergrowths may have resulted from alteration

of scapolite. Fresh scapolite in grains ≤ 1 mm across occurs sparingly in and between diopside or calcite and serendibite. Grandidierite, spinel, and phlogopite occur in trace amounts within serendibite and appear to have formed from serendibite breakdown. Tourmaline forms irregular, poikilitic patches around serendibite and in places, margins around apatite enclosed in serendibite. A mineral tentatively identified as sinhalite occurs with spinel in serendibite.

Textures suggest a 3-stage history for the serendibite–diopside rock: (1) primary serendibite–diopside \pm scapolite–apatite assemblages; (2) secondary assemblages with grandidierite, tourmaline, pargasite, spinel and/or phlogopite which could have formed by reactions such as serendibite + diopside + Na₂O + K₂O + H₂O + CO₂ = grandidierite + pargasite + calcite + B₂O₃ (see Grew *et al.*, in press); and (3) alteration to fine-grained phyllosilicates. The stage 2 minerals, notably grandidierite, are also characteristic of the Johnsbury serendibite–diopside rocks and thus we infer that a second high-temperature event affected the Russell locality. Conditions of formation of the primary serendibite–diopside assemblage could be 660–750°C and 6.7–7.4 kbar, values estimated at nearby localities (maps of Bohlen *et al.*, 1985; Edwards and Essene's, 1988, 700°C isotherm passes close to the locality), and consistent with conditions inferred for serendibite at other localities (Grew *et al.*, in press). The core was drilled about 1 km northwest of Buddington's (1963) isograd marking the northern limit for orthopyroxene in amphibolite, implying near granulite-facies conditions for serendibite at Russell, that is, somewhat lower temperatures than the clearly granulite-facies Johnsbury deposit.

Serendibite and associated minerals (1–2 grains each) were analysed with a wavelength-dispersive MAC 400s electron microprobe at the University of Maine (procedure of Yates and Howd, 1988) (Table 1). Assuming that the boron content is similar to the values measured in the Johnsbury serendibite (Grew *et al.*, in press), analytical totals for serendibite are reasonable and the formulae approach Ca₂(Mg, Fe)₃Al_{4.5}B_{1.5}Si₃O₂₀. Compositions of the two analysed grains can be related by the Tschermarks substitution (Mg,Fe) + Si = 2 Al. Compared to serendibite from most other localities (Deer *et al.*, 1978); Nicollet, 1988), the Russell serendibites are magnesian and sodian, but less so than the Johnsbury serendibites. Incorporation of Na in the Russell and Johnsbury serendibites appears to be through the substitution Na + Si = Ca + Al, which is characteristic of the related minerals aenigmatite and rhönite (Deer *et al.*, 1978). Diopside compositions are also

Table 1. Compositions of minerals in the serendibite-diopside rock from Russell, N.Y.

Mineral Grain	Serendibite		Diopside		Pargasite	Scapolite	Grandidierite
	1	2	1	2			
	Weight Percent						
SiO ₂	24.05	25.35	52.09	53.63	43.10	46.73	20.81
TiO ₂	0.02	0.04	0.06	0.07	0.30	nd.	.03
Al ₂ O ₃	35.76	34.04	4.58	3.35	16.69	26.41	52.03
FeO	1.94	2.10	1.07	1.09	2.09	0.17	1.14
MnO	0.05	0.09	0.16	0.12	0.01	nd.	0.06
MgO	15.34	15.49	16.84	17.51	18.94	nd.	13.08
CaO	14.22	14.39	23.93	23.65	12.75	16.31	0.07
Na ₂ O	0.50	0.63	0.40	0.54	2.74	4.10	0.01
K ₂ O	0.00	0.00	0.02	0.04	1.40	0.16	0.05
Cl	nd.	nd.	nd.	nd.	nd.	0.50	nd.
SO ₃	nd.	nd.	nd.	nd.	nd.	1.08	nd.
B ₂ O ₃	7.43*	7.44*	nd.	nd.	nd.	nd.	11.92*
CO ₂	nd.	nd.	nd.	nd.	nd.	3.54*	nd.
H ₂ O	nd.	nd.	nd.	nd.	2.13*	nd.	nd.
Total	99.31	99.57	99.15	100.00	100.15	98.89†	99.20
	Cations						
Oxygens	20	20	6	6	24	(Si+Al)=12	9
Si	2.811	2.962	1.899	1.935	6.068	7.203	1.012
Al	1.689	1.538	0.101	0.065	1.932	4.797	nd.
B	1.500*	1.500*	nd.	nd.	nd.	nd.	1.000*,#
Total	6.000	6.000	2.000	2.000	8.000	12.000	2.012
Ti	0.002	0.004	0.002	0.002	0.032	nd.	0.001
Al	3.238	3.150	0.096	0.077	0.837	0.000	2.981
Fe	0.190	0.205	0.033	0.033	0.246	0.022	0.046
Mn	0.005	0.009	0.005	0.004	0.001	nd.	0.002
Mg	2.673	2.699	0.915	0.942	3.975	nd.	0.948
Total	6.108	6.067	1.051	1.058	5.091	0.022	3.978
Ca	1.809	1.802	0.935	0.914	1.923	2.693	0.004
Na	0.113	0.143	0.028	0.038	0.748	1.225	0.001
K	0.000	0.000	0.001	0.002	0.251	0.031	0.003
Total	1.922	1.945	0.964	0.954	2.922	3.949	0.008
Total Cations	14.030	14.012	4.015	4.012	16.013	15.971	5.998
	Anions						
OH	nd.	nd.	nd.	nd.	2.000*	nd.	nd.
CO ₃	nd.	nd.	nd.	nd.	nd.	0.744*	nd.
SO ₄	nd.	nd.	nd.	nd.	nd.	0.125	nd.
Cl	nd.	nd.	nd.	nd.	nd.	0.131	nd.
Total Anions					2.000	1.000	

* Calculated Value; # Trigonally Coordinated; † Total corrected for Cl=O; nd. - not determined or calculated.

related by the Tschermarks substitution. It was not possible to obtain satisfactory analyses of either tourmaline or spinel. Rough values for tourmaline are 34–35 wt. % SiO₂, 0% TiO₂, 31–32% Al₂O₃, 1% FeO, 12% MgO, 3.4% CaO, 1.3% Na₂O. One spinel is Mg_{0.9}Fe_{0.1}Al₂O₄. In terms of Mg/Fe ratio, the minerals increase as follows: spinel < serendibite < pargasite < grandidierite < diopside, and Na/Ca ratio: diopside < serendibite ≪ pargasite < scapolite.

We suggest that the serendibite–diopside rock results from the metamorphism of boron-bearing sediments of evaporitic affinities. The marble–calc–silicate unit that was penetrated by hole 1872 locally hosts anhydrite-rich rocks of probable evaporitic origin. Similar rocks are exposed in the Balmat and Edwards Mines 20 to 30 km away. Moreover, Swihart and Moore (1989) reported that boron isotope compositions of tourmaline in calc–silicate rocks from other localities in the

northwest Adirondack Lowlands lie between isotope compositions of boron from normal marine sediments and present-day seawater. Consequently we have reason to infer a marine sedimentary origin, rather than an igneous origin, for the boron in the Russell serendibite. It is possible that the serendibite–diopside rock developed by isochemical metamorphism of a boron-rich calcareous sediment. However, certain features suggest that limited metasomatism may have also played a role in its formation. In particular, the Russell serendibite–diopside rock closely resembles the serendibite–diopside zone in the metasomatic sequence developed between K-feldspar rock and marble at the Johnsbury locality. Such metasomatic rocks are characterized by a simple mineralogy although the number of constituents (components) in the rock is fairly large. Only 3 or 4 phases in the Russell rock formed during the first metamorphic stage, but 7 non-

volatile components are needed to describe the phases (serendibite, diopside, apatite, and scapolite): CaO, Na₂O, MgO, Al₂O₃, SiO₂, B₂O₃, and P₂O₅ (phase rule would allow 7 phases to be stable). By analogy with Johnsburg, we suspect that the constituents in the Russell rocks were mobilized, though possibly over distances of 1m or less. Nonetheless, even such limited mobilization may have been sufficient to concentrate dispersed boron into a thin boron-rich serendibite–diopside rock.

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*Department of Geological Sciences,
University of Maine,
Orono, ME 04469, USA*

EDWARD S. GREW
MARTIN G. YATES

*Geology Department, Zinc Corporation of America,
Mining Division, Balmat, NY 13609, USA*

WILLIAM DELORRAINE