31. The lateral secretion origin of Fe and Zn ores, resulting from metasomatism and/or recrystallization of amphibolites and biotite-rich gneisses in New Jersey and New York, USA

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Introduction

During K- and Si-metasomatism of deformed, relatively-mafic parent rocks to form more felsic, granitic rocks containing myrmekite, Ca, Mg, and Fe must leave the system as the modified rock is enriched in K, Na, and/or Si. When this kind of metasomatism occurs, the subtraction of Ca, Mg, and Fe would also be accompanied by losses of other metals present in the ferromagnesian silicates that were replaced by quartz. Such metallic elements could be deposited in adjacent rocks in ore concentrations by a process of lateral secretion. Such a process may explain the origin of Zn concentrations in New York.

Lateral secretion of Ca, Fe, Mg, and Zn in the Balmat-Edwards terrane, New York

Origin of the sphalerite ore in the Upper Marble unit in the Balmat-Edwards terrane has been problematic. Studies of the nearby Hermon-type, megacrystal, Fowler and Fullerville granites in the Grenville Lowlands of northwestern New York (Fig. 1) show that they were formed by K- and Si-metasomatism of the Popple Hill gneiss; see http://www.csun.edu/~vcgeo005/Nr30Grenville.pdf. Because of this metasomatism, displaced Ca, Fe, Mg, and Zn could have moved laterally in fluids, and the Zn and some of the Fe could have precipitated in the sphalerite concentrations.
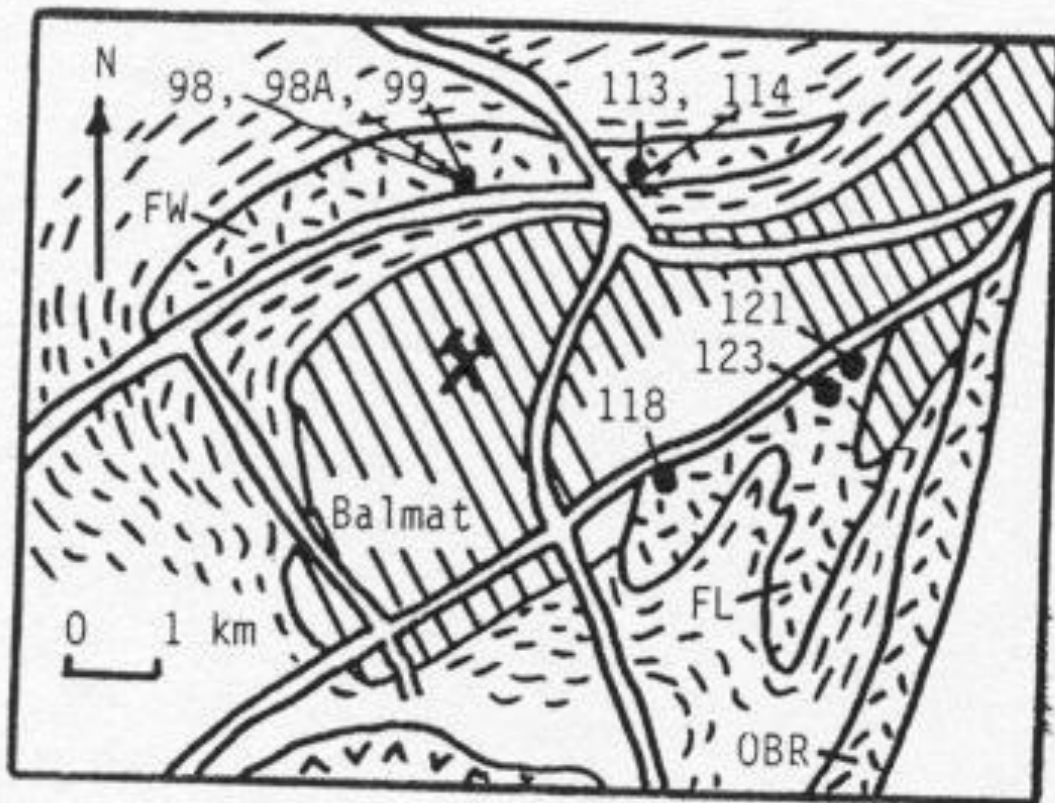
Fig. 1. Geologic map of the Balmat area in the Grenville Lowlands of New York, showing locations of the Hermon-type Fowler (FW), Fullerville (FL), and Ore Bed Road (OBR) granites (patterned symbols). The lenticular granites are in the Popple Hill gneiss (dashes) in the limbs of an isoclinal fold, the core of which consists of the Upper Marble unit (lined pattern). A portion of the California granite (v-pattern) occurs at the bottom of the map. Modified after deLorraine *et al.* (1982) and omitting some other associated rock types. Location of analyzed samples on Table 1 are shown on map by number.

Earlier hypotheses for the origin of the Balmat-Edwards Zn ores

Several hypotheses have been proposed for the origin of the Zn ores in the marble near Balmat and Edwards (deLorraine *et al.*, 1982). On the basis of trace element analyses and determinations of S and Pb isotopes in ore and associated rocks, constraints were placed on each of these hypotheses. A syngenetic bacterial origin of the Zn ores by reduction of seawater sulfates was discounted on the basis of the homogeneity of the ore S in contrast to the variability of the sulfate S. Although a syngenetic origin by deposition in some unknown way associated with

evaporite sedimentation could not be completely eliminated by the isotope data, it is an unlikely explanation. Fletcher (1979) proposed a volcanic source, but the lack of volcanic rocks in the host marbles casts doubt on that possibility. Deriving the Zn from the marble is *unlikely* because ore Pb (in galena) coexisting with the Zn has different isotope composition from that in marble Pb (Doe, 1962b). Nevertheless, isotope Pb compositions *in granites* outside the marble are compatible for the granites being the source of the ore Pb provided that, *if the ore lead had been extracted from the granites, radiogenic lead must have been added to the granites subsequent to the formation of the ores* (Doe, 1962b). Reynolds and Russell (1968) found systematic differences in ore Pb and rock Pb and proposed a large-scale convective mixing model of upper mantle and crust to explain the origin of the ores. DeLorraine *et al.*, (1982) favored an exhalative source because of the massive conformable nature of the Zn ores although mineralogic zonation that is common in many massive exhalative sedimentary or volcanogenic deposits is not present. However, these investigators suggested that an epigenetic "*lateral secretion origin is compatible with sulfur isotope data and cannot be eliminated on the basis of lead isotope data but requires the assumption that large volumes of rock were leached in such a way that overall lead compositions approaching single stage conditions were attained.*" Geologic and geochemical studies of the Popple Hill and Hermon-type granites (http://www.csun.edu/~vcgeo005/Nr30Grenville.pdf) support an epigenetic lateral-secretion model. These data are consistent with the granite being the source of the Zn in the Balmat-Edwards ores and also allow radiogenic Pb to be added to the granite following deposition of the Zn ore, as stipulated by Doe (1962b).

Geologic relationships and chemical analyses

DeLorraine and Carl (1997) report that the Zn contents in nine different Hermon-type granites in the Grenville Lowlands (Fig. 2), which includes the Fowler and Fullerville granites, range from a low of 25 ppm to a high of 156 ppm. Because all these granites show similar broad ranges in Zn content (Fig. 2), these investigators saw no evidence from the scatter of data that any of the altered granites could have been a source of Zn for ore concentrations. However, in an evaluation of a lateral secretion model, if chemical data from the associated, relatively-mafic wall rocks are also included (Table 1), and entirely different picture is seen. From these data, trends for the different rock types are apparent in plots of Fe_2O_3 (total Fe), MgO, and CaO wt. % versus SiO_2 wt. % (Fig. 2, Fig. 4, and Fig. 5), and of Zn ppm versus SiO_2 wt. % (Fig.6).
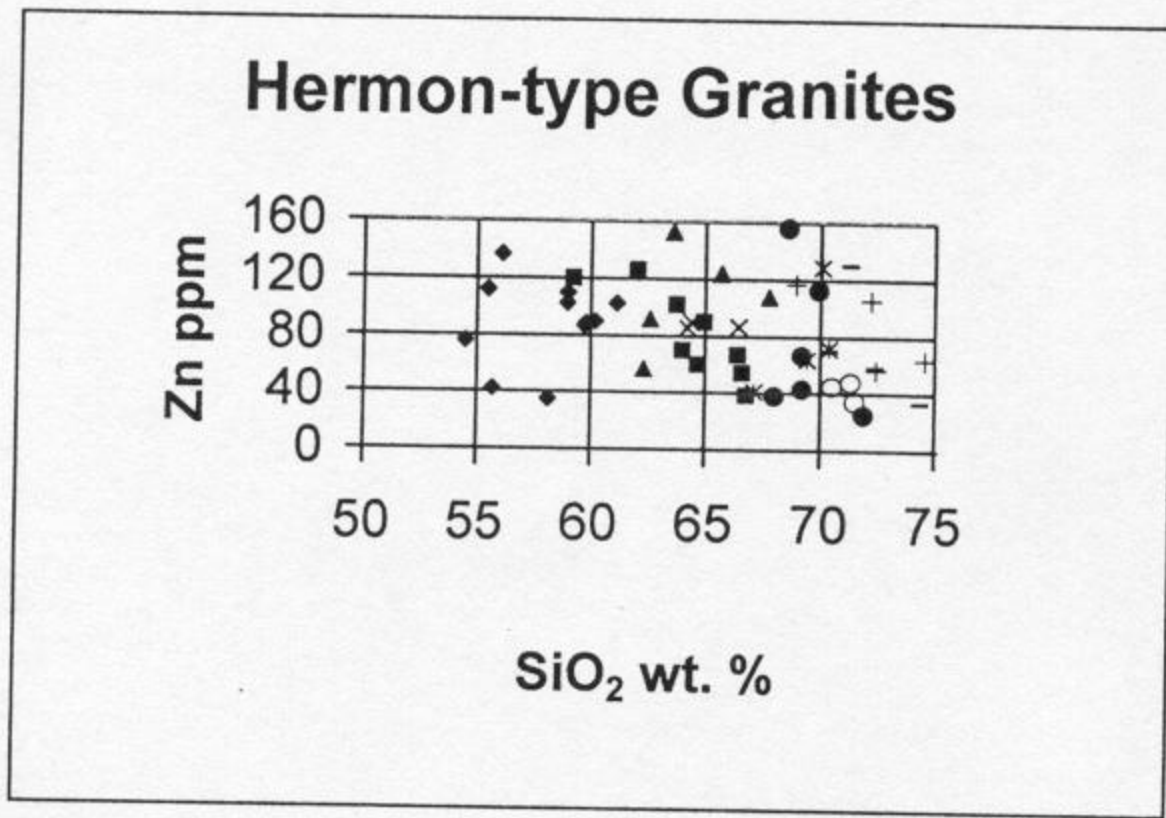
Fig. 2. Zn in ppm versus SiO₂ wt. % in Herman-type granites. Solid diamond = Gray's School; solid square = Hermon Village; solid triangle = Trout Lake; X = Shermon Lake; star = Ore Bed Road; open circle = Shiner Pond; plus = Mott Creek; solid circle = Fullerville; dash = Fowler. Data are from Carl and deLorraine (1997) and Table 1.
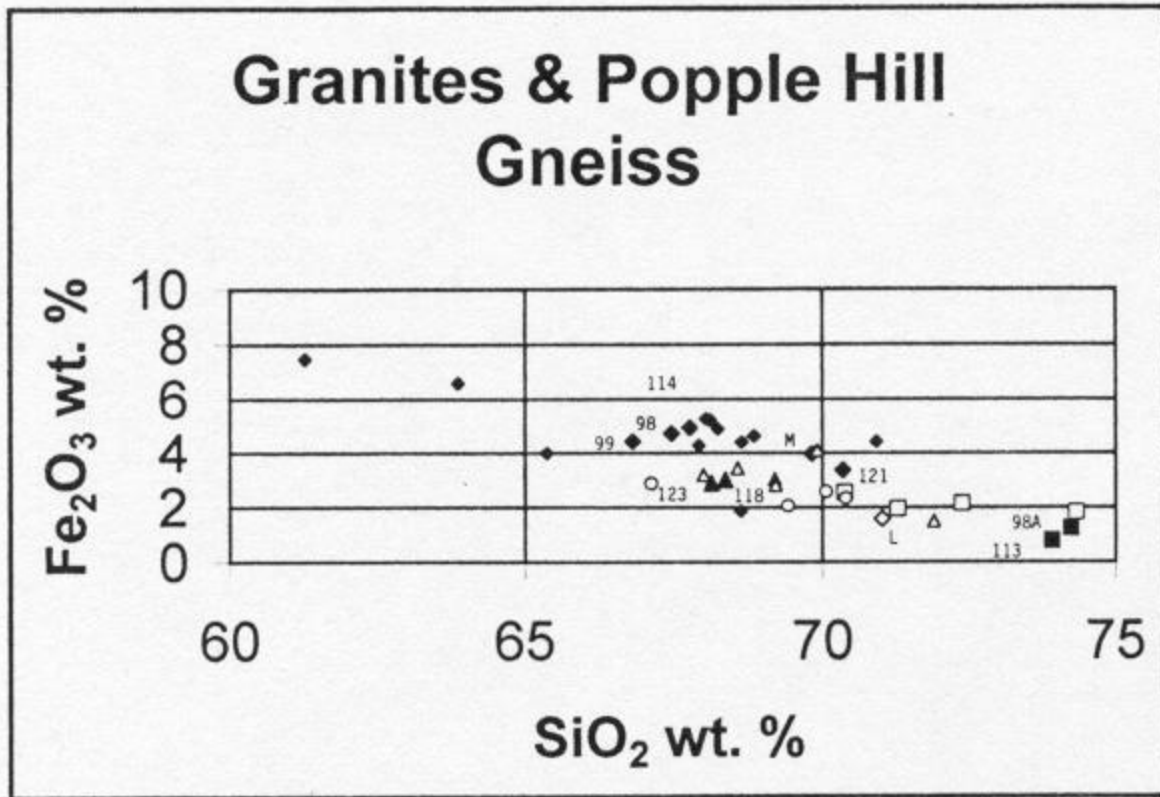
Fig. 3. Plot of Fe$_2$O$_3$ wt. % versus SiO$_2$ wt. for the Fowler, Fullerville, and Ore Bed Road granites and associated Popple Hill gneisses. Fullerville granite (open triangle); Ore Bed Road granite (open circle); and Fowler granite (open square); data from Carl and deLorraine (1997). Fowler paired biotite gneiss (114; solid diamond) and leucogranite (113; solid square) and coexisting biotite-rich gneiss (98 and 99; solid diamond) and leucogranite (98A; solid square); Fullerville fine-grained granite (118) and megacrystal granite (123; solid triangles), in association with Popple Hill gneiss (121; solid diamond). Least altered Popple Hill gneiss (solid diamond; Table 7 of Engel and Engel, 1958); average of seven Popple Hill gneiss samples (M; solid diamond) and average of four Popple Hill leucosome gneiss samples (L; open diamond; data from Carl, 1988). Numbered data points are from Table 1.
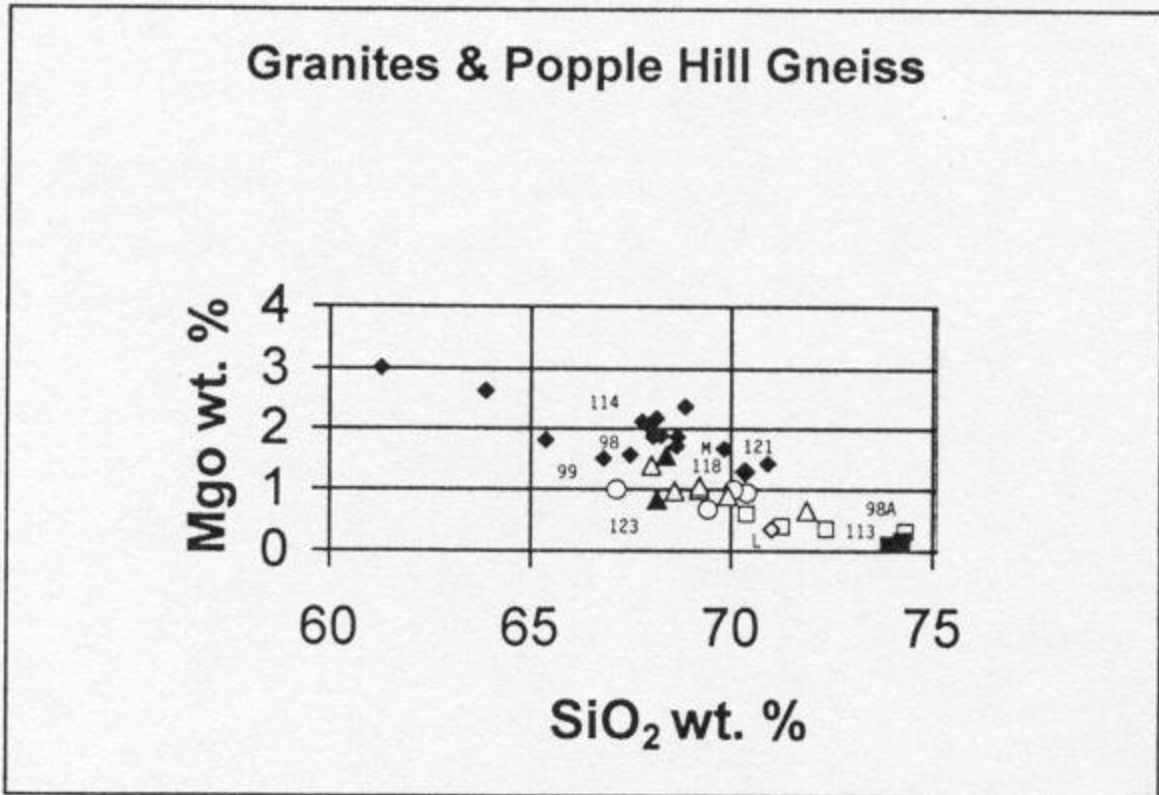
Fig. 4. Plot of MgO wt. % versus SiO_2 wt. % for the Fowler, Fullerville, and Ore Bed Road granites and associated Popple Hill gneisses. The same symbols are used as in Fig. 4. Numbered data points are from Table 1.
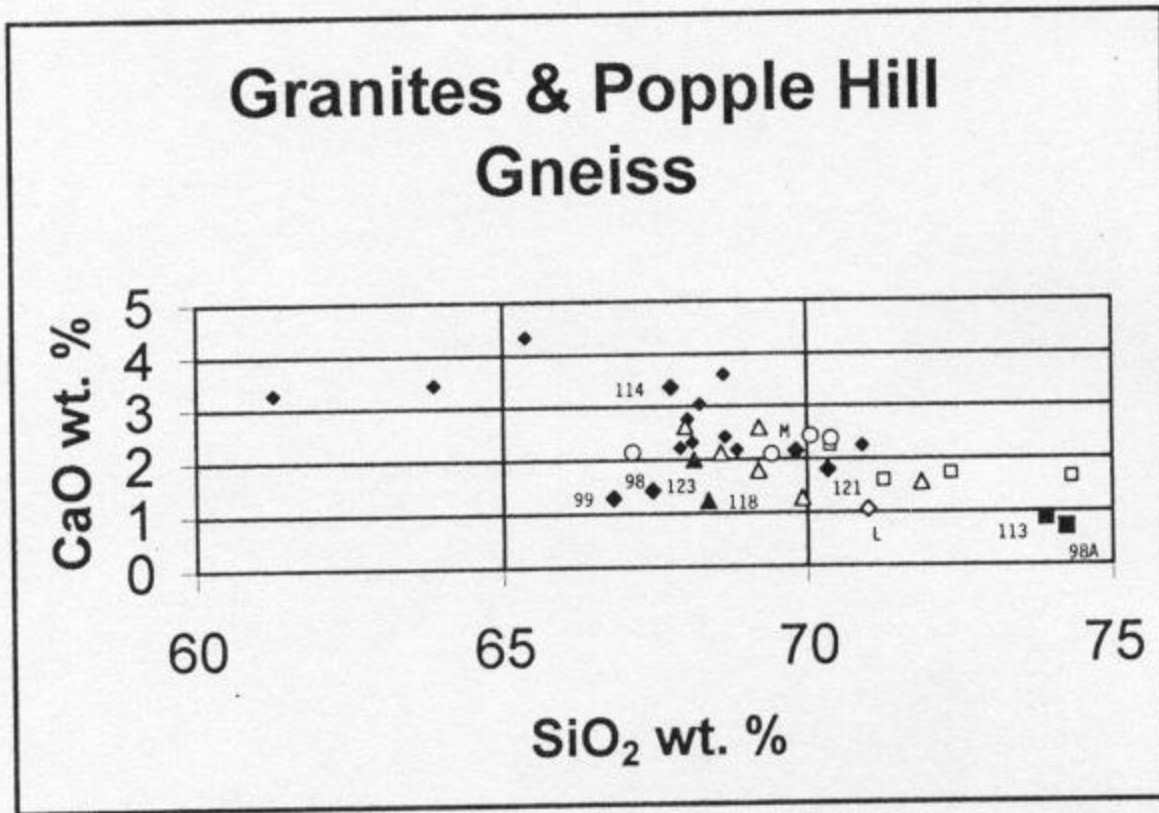
Fig. 5. Plot of CaO wt. % versus SiO_2 wt. % for the Fowler, Fullerville, and Ore Bed Road granites and associated Popple Hill gneisses. The same symbols are used as in Fig. 3. Numbered data points are from Table 1.

Fig. 6. Zn in ppm versus SiO$_2$ wt. % for the Fowler, Fullerville, and Ore Bed Road granites and associated Popple Hill gneisses. The same symbols are used as in Fig. 3. Numbered data points are from Table 1.
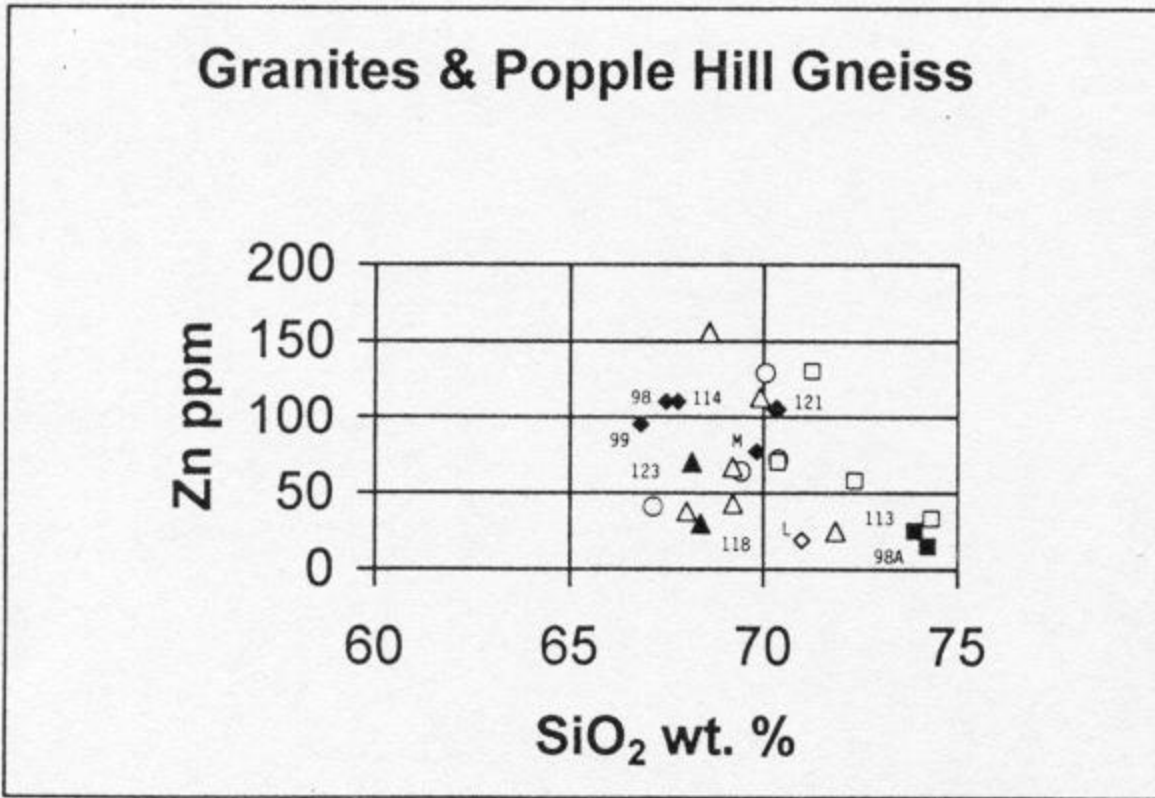
Rock	SiO$_2$	TiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	MgO	MnO	CaO	Na$_2$O	K$_2$O	P$_2$O$_5$	LOI	Total
77B	66.92	0.47	16.22	1.55	0.89	0.04	3.21	3.78	4.86	0.16	0.93	99.03
84	71.91	0.29	14.33	1.58	0.81	0.02	2.17	3.53	3.51	0.08	0.52	98.75
98A	74.24	0.05	15.29	1.23	0.18	0.12	0.71	2.41	5.08	0.04	0.52	99.87
113	73.91	0.09	14.02	0.78	0.11	0.03	0.87	3.86	4.77	0.01	0.44	98.89
118	68.37	0.46	15.02	3.01	1.55	0.04	1.23	3.97	4.10	0.14	1.19	99.08
123	68.14	0.44	15.83	2.89	0.83	0.05	2.00	3.88	4.30	0.15	0.54	99.05
64	52.32	1.12	17.69	7.87	4.79	0.08	4.41	4.51	3.25	0.72	2.50	99.25
77A	50.19	0.99	15.51	9.52	6.32	0.16	8.14	3.72	1.86	0.50	1.63	98.54
89	50.60	1.80	16.68	9.23	4.37	0.09	5.27	4.00	4.19	1.18	1.25	98.66
82	62.04	1.06	15.04	6.69	2.43	0.05	1.35	1.99	7.26	0.11	0.64	98.66
85	60.51	1.09	16.20	4.05	3.85	0.03	0.87	2.21	6.84	0.11	3.28	99.04
97	52.57	1.25	17.16	7.46	4.17	0.11	5.45	4.67	3.21	0.79	1.69	98.53
98	67.46	0.66	14.49	4.73	1.56	0.07	1.43	3.17	4.27	0.07	0.79	98.70
99	66.81	0.53	14.58	4.43	1.50	0.06	1.29	2.67	5.67	0.08	0.84	98.46
114	67.77	0.65	14.29	4.94	2.12	0.07	3.37	2.62	2.04	0.14	0.75	98.76
121	70.34	0.58	13.50	3.38	1.29	0.07	1.80	3.25	3.12	0.10	0.61	98.54

ppm	Ba	Sr	Rb	Pb	Co	Ni	Cu	Zn	V	U	Th	Y	Zr	Nb
77B	1085	607	66.8	5	4.0	5	5	15	25	6.0	19	59.0	359	21
84	396	220	86.0	10	2.5	5	5	20	30	3.0	24	10.0	206	13
98A	773	129	188.0	20	<0.5	5	25	15	<5	6.5	1	22.5	56	7
113	115	88	160.0	35	0.5	5	<5	25	<5	3.0	4	29.0	60	11
118	745	345	81.4	5	5.0	5	<5	30	40	2.0	11	14.0	214	10
123	915	468	110.0	15	5.0	5	<5	70	30	3.0	15	23.5	231	10
64	939	921	90.2	135	22.0	88.5	120	115	160	3.0	15	39.0	332	14
77A	202	577	30.2	<5	29.0	35	15	100	215	3.5	9	34.0	164	10
89	1260	1130	109.5	5	22.5	5	10	105	180	2.0	20	44.5	90	18
82	772	147	230	25	14.0	30	20	35	105	1.0	11	10.0	210	13
85	870	181	157.5	<5	14.0	40	<5	30	95	5.0	15	33.0	193	16
97	541	661	75.6	<5	16.5	30	<5	105	130	3.0	7	77.5	301	24
98	326	102	212.0	5	10.0	20	<5	110	70	6.5	28	45.0	374	25
99	554	119	240.0	10	7.0	15	<5	95	70	5.0	14	39.5	272	19
114	252	198	112.0	<5	11.0	30	<5	110	90	2.0	9	26.5	218	7
121	613	286	109.0	5	6.5	15	<5	105	50	1.5	8	18.0	237	9

Table 1. Whole-rock and trace-element chemical analyses of selected samples
from the Popple Hill gneiss, Fowler, Fullerville, and Gray's School granites, and
amphibolite in the Grenville Lowlands. Locations of samples are shown on Fig. 6
and Fig. 12 of http://www.csun.edu/~vcgeo005/Nr30Grenville.pdf. Analyst:
Chemex Labs Inc.

Data shown in Figs. 3-6 come from samples of biotite-rich Popple Hill
gneiss (98 and 99) that are interlayered with the Fowler granite (98A) in outcrops
along the Farm-to-Market Road (former Fowler Road) and from a Fowler
leucogranite (113) that is adjacent to a biotite-rich Popple Hill gneiss (114) on the
Emeryville Road near Fowler. Data for samples in and near the Fullerville granite
are from the Popple Hill gneiss (121) adjacent to Fullerville megacrystal granite

(123), northeast of the Four Corners in Balmat (southeast of the Earl Murphy property) and from the fine-grained Fullerville granite (118) in a strongly deformed area on the limb of a drag fold. Additional data points obtained from analyses by Car and deLorraine (1997) for the Fowler, Fullerville, and Ore Bed Road granites are shown for comparison (Fig. 1). These additional data have similar ranges of CaO, Fe_2O_3, MgO, SiO_2, and Zn to that of the numbered samples on Figs. 3-6 except that two data points for Fullerville granite have higher Zn values (113 and 156 ppm Zn). Unfortunately, Engel and Engel (1958) did not do Zn analyses for the Popple Hill gneiss samples from distant terranes which are plotted on Figs. 3-5, so comparisons of Zn content in the lower SiO_2 range are not possible on Fig. 6.

In the relatively biotite-rich Popple Hill gneisses (98, 99, and 114), the Zn content (95 to 110 ppm Zn), as might be expected, has higher values than in the associated granites (98A and 113; 15 to 25 ppm Zn). In the Fullerville granite (123), the microcline megacrysts are relatively small (1.0 to 1.5 cm) and, therefore, the amount of replacements of plagioclase by microcline are minimal relative to the adjacent Popple Hill gneiss (121). This may explain the lesser drop in Zn content from 105 ppm in the gneiss (121) to 70 ppm in the megacrystal granite (123) in comparison to the greater drop to 30 ppm in the fine-grained granite (118), which is closer to the marble and has been more strongly deformed and replaced; see discussion of these granite samples in http://www.csun.edu/~vcgeo005/Nr30Grenville.pdf.

The loss of Zn from Popple Hill gneiss that is replaced by granite is also supported by chemical analyses of both mesosomes and leucosomes in terranes several km from the Balmat-Edwards Zn ore concentrations (Carl, 1988). The average Zn content in seven mesosome samples is 77 ppm (+/- 20 ppm), whereas the average Zn content in four leucosome samples is 19 ppm (+/- 15 ppm). Myrmekite and other replacement textures in the leucosome veins support a replacement origin for the leucosomes rather than their resulting from anatexis; see http://www.csun.edu/~vcgeo005/Nr28Popple.pdf for additional evidence supporting the metasomatic origin of the leucosomes.

Discussion of an epigenetic lateral-secretion model

When the large volumes of Popple Hill gneiss that were replaced to become the Fowler and Fullerville granite (each body being 10 km long, 0.5 km wide, and an assumed 5 km deep), large volumes of Ca, Mg, and Fe must have been displaced in that process. Fig. 3, Fig. 4, and Fig. 5 show that less CaO, MgO, and Fe_2O_3, are in the granites relative to the adjacent Popple Hill gneiss from which the

granites were derived. The displaced Ca and Mg ions, being quite soluble and less inclined to be precipitated, likely moved in fluids out of the system. Potentially, some of the Fe could have been precipitated in the Fe-rich sphalerite or pyrite in the nearby Zn ores. Although the amount of Zn in the Popple Hill gneiss is relatively small (about 100 ppm), the theoretical 80 ppm Zn (100 minus 20) that is displaced from such volumes that are now granite (containing about 20 ppm Zn) is large and much more than is needed to account for the volumes of sphalerite in the ore concentrations. Sulfides (pyrite) and other S sources in the Popple Hill gneiss could have supplied the S to the Zn sulfides rather than this S coming from anhydrite associated with the marble. This model is consistent with the fact that S isotopic ratios in the anhydrite layers in the marble *do not match S isotopic ratios in the ore zone* (deLorraine and Carl, 1997). The loss of Co and Ni from the gneisses containing 6.6 to 16.5 ppm Co and 15 to 30 ppm Ni is indicated by the lesser amounts in the replacement granites, which contain 0.5 to 5.0 ppm Co and 5 ppm Ni. The movement and concentration of this Co and Ni with the Zn in the ore zones could explain the 200 ppm each of Ni and Co in pyrite in the ore (Doe, 1962a). Moreover, the process of the K-replacement of gneiss by the granite would have allowed movements of radiogenic Pb to occur and to concentrate this Pb in the K-feldspar because of the similarity of size of the Pb ion to that of the K ion. The Pb content increases from 5 ppm or less in the Popple Hill gneiss to as much as 35 ppm in the replacement granites. Because replacement and deformation are ongoing processes associated with the creation of the granite bodies, the released radiogenic Pb could have been added to the K-feldspar crystals as the K-feldspar megacrysts replaced the plagioclase in the gneisses, and such additions could be at the same time as well as later than movements of the Pb and Zn to the ore concentrations in the marble. These relationships are what Doe (1962b) stipulated as being necessary for the nearby granite to be the source of the Pb and Zn. The conditions of replacement to form the granite bodies also fit the requirement of deLorraine *et al.*, (1982) for an origin of the Zn by lateral secretion in which "*large volumes of rock were leached in such a way that overall lead compositions approaching single stage conditions were attained.*." The mixing of the Pb in the through-going fluids would produce the apparent single stage conditions.

Although Carl and deLorraine (1988) determined that the Zn contents of the Fowler and Fullerville granites had values from 25 to 156 ppm Zn (Fig. 2), the granite samples obtained and analyzed by Carl and deLorraine were not specifically related to possible adjacent, relatively-mafic and Zn-rich Popple Hill gneiss. The existence of such biotite-rich gneisses is difficult to demonstrate because if biotite is abundant, its planar cleavage causes a rock to be structurally weak and easily eroded by Pleistocene glaciers. Therefore, likely most remnant

biotite-rich rocks are buried under soil and glacial drift. The rocks that are exposed are generally the resistant knobs of granite rather than the weaker remnant biotite gneisses from which the granite was derived. The outcrops of the biotite-rich gneisses that were sampled for this study were exposed only in road cuts where a resistant (capping) granite protected the gneiss from erosion and where dynamiting and removal of rock allowed the biotite-rich gneiss to be seen.

Biotite commonly concentrates Zn, and, therefore, potentially large amounts of Zn could have been present in former biotite-rich Popple Hill gneisses, now replaced by the granite. Unfortunately, the metasomatism that produced the granites destroys most of the evidence for the presence of the former Zn-bearing biotite-rich gneisses, and the glaciers buried much, if not most, of the remnants of these gneisses.

Where paired samples of granite and parent biotite-rich gneiss are shown on Fig. 4, a loss of Zn of about four-fifths the amount in the parent gneiss is shown (105 to 110 ppm Zn in the gneiss decreasing to 15 to 25 ppm Zn in the granite). Carl and deLorraine (1988) reported values of Zn as high as 156 ppm, but these values are in places where the content of the Zn in coexisting parent gneiss is unknown. Perhaps the parent gneiss had values as high as 750 ppm, and the value of 156 ppm represents a decrease in Zn content by four-fifths, as shown in other places. On the other hand, perhaps instead of the parent gneiss losing Zn, the displaced Zn could have remained in the granite in some places to enrich its Zn content to 156 ppm relative to lower values that could have been in the Popple Hill gneiss, in the same way that the Pb has been enriched in the granites. Nevertheless, the aforesaid chemical analyses of paired or coexisting samples of granite and parent gneiss indicate losses of Zn, and these losses support the hypothesis that lateral secretion was the means by which the Zn ore concentrations were formed in the marble.

The same arguments for a lateral secretion origin of Zn in the Balmat ore zone can also be applied to the origin of Zn in the Edwards ore zone (Fig. 1). Like the Fowler and Fullerville granites, the megacrystal Trout Lake granite replaces Popple Hill gneiss in the nose and limbs of a tight isoclinal fold surrounding the Upper Marble Unit; see http://www.csun.edu/~vcgeo005/Nr30Grenville.pdf . In a sense, the Trout Lake granite is equivalent to the Fowler granite; it occurs farther northeast but in the same relative position with respect to the Upper Marble unit. In the same way that Zn is displaced to the Balmat ore zone by lateral secretion, movement of Zn, displaced from gneiss that is replaced by the Trout Lake granite to the Edwards ore zone, could also occur.

Conclusions

It is difficult to demonstrate a correlation between granite produced in zones of strong deformation by K-metasomatism and movements of extracted metals displaced during this metasomatism to distant concentrations in metallic ores. However, it is an idea worth further investigation. Forming metal concentrations by subtracting metal ions from deformed, altered, relatively-mafic rocks being converted to myrmekite-bearing granites is a process that should be look for in terranes in other parts of the world (Collins, 1988). Possible examples include: (1) tungsten (scheelite) ores in skarns in the Sierra Nevada of California, (2) zinc, lead, and silver deposits in the Broken Hill district of Australia, (3) copper deposits near Butte and Helena, Montana, and (4) gold deposits in the Cargo Muchacho Mountains in southeastern California.

Acknowledgements

ADDENDUM

Early in December, 1998, the following message was circulated in the granite-research net for comment.

"Wall rocks of many granite bodies contain metal concentrations in ore deposits (Cu, Pb, Zn, W, Ag, Au), yet the adjacent granites are notably devoid of these metals. On that basis, hypotheses are generally proposed that circulating hydrothermal fluids in the wall rocks, supposedly mobilized by the heat of the granitic intrusions, have subtracted these metals from the wall rocks.

Zinc sulfide deposits in marble in the core of tight isoclinal folds near Balmat and Edwards, New York, USA, are examples of metallic ores which have a puzzling origin. I suggest the possibility that the zinc was derived by lateral secretion during K-metasomatism that converted biotite-rich gneisses to myrmekite-bearing, Hermon-type, megacrystal granites.

An epigenetic lateral-secretion model is an idea that may have application to other granite terranes in which K-metasomatism occurs. Are there metallic ore

deposits adjacent to megacrystal granites or augen gneisses in other terranes where this idea might be tested?"

Response from Eric Essene

On 12/11/98, Eric Essene from the University of Michigan offered the following response, which has been included here with his permission.

"*The metamorphosed ore deposits at Balmat do not look like contact skarns in high level granites, such as in the Sierra Nevada. The Balmat ore is of concordant massive sulfide, dominantly sphalerite or sphalerite-pyrite ores with occasional pyrrhotite; small chalcopyrite blebs are common in the sphalerite. Galena and coarse chalcopyrite are rare -- I'm not sure that the mine is even credited for the very minor Pb, Cd, and Ag that is in the ore. No tin minerals are known. Gangue minerals include anhydrite and calcite. Rare Mn-silicates, such as rhodonite, donpeacorite, kanoite, and even braunite and various Mn^{3+} oxides are associated in places. The high oxidation state of some of the Mn suggests that it was a surficial origin. The ore is interbedded with talc-tremolite schist, dolomite, and massive anhydrite rock, all metasedimentary units. Both the anhydrite and the sulfide units may have been differentially transported tectonically during deformation. The ore body does not show a close contact association with granite. I do not understand how such a concentration of sulfides could be obtained by metasomatism during regional metamorphism. There are striking gradients in fO_2 and fS_2 across the lithological units that one would have thought should have been erased or reduced if large fluid/rock ratios were involved transporting elements laterally. I think that the exhalative origin makes sense.*"

Response from Lorence Collins

Eric's arguments regarding an exhalative origin for the metamorphosed zinc ore deposits at Balmat, New Jersey, make a lot of good sense. I am pleased that he took the time to lay out many facts that support an exhalative model. He could be completely right. Nevertheless, his response gives me an opportunity to point out other factors that I think should be considered.

His comparison of the Balmat ores with contact skarns in high-level granites in the Sierra Nevada is not a good one. I agree that the Balmat ores do not have a close contact association with the granite, and, therefore, this argument is a "straw-man" that is easily knocked down as support for lateral secretion. I did not argue

that the Balmat ores formed by contact metasomatism. But that is not the main point of Eric's response anyway, so this comparison is really not at issue.

From my point of view, better comparisons can be made by using the magnetite concentrations near Dover, New Jersey, and the franklinite-zincite-willemite zinc ores at Ogdensburg, New Jersey. Both are in Precambrian terranes, as is the Balmat ore, although neither of the New Jersey ores is a sulfide ore.

At Dover, magnetite concentrations are in deformed amphibolites in limbs of tight isoclinal folds (Collins, 1969). In noses of the folds the ferromagnesian silicates in the amphibolites (essentially devoid of sulfur) are rich in Fe and Zn. Clinopyroxene contains 8.4% Fe and 80 ppm Zn; hornblende, 14.6% Fe and 35-190 ppm Zn; and orthopyroxene, 21% Fe and 190-280 ppm Zn. Plagioclase is calcic andesine, An_{45}. Towards the magnetite concentrations in the limbs of the folds, however, and with increasing degrees of deformation, the Ca-content of the plagioclase decreases progressively, and hornblende, clinopyroxene, and orthopyroxene are reduced in volume, recrystallize, and lose Fe. Near the ore zones the plagioclase composition decreases to albite An_5, losing almost all of its calcium, and the original abundant orthopyroxene (14 vol. %) is totally destroyed. Only hornblende and clinopyroxene remain in coarse masses adjacent to the iron ores, and plagioclase is mostly gone. Some Fe, released from destroyed orthopyroxene is recrystallized in clinopyroxene (8.6-10.3% Fe), but most clinopyroxene has only 20 ppm Zn. Hornblende near the ore zones has less Fe (8.1-9.2 % Fe) and less than 60 ppm Zn, and magnetite in the ore concentrations has less than the detection limit for Zn. More than four times as much Fe was subtracted from the deformed amphibolites than can be accounted for in the recrystallized ferromagnesian silicates. Lateral secretion of the Fe to the magnetite concentrations is apparent, but the lost Ca and Zn cannot be accounted for. These elements must have moved somewhere else.

Because magnetite in the Dover area has an analogous structure to franklinite (a Zn-Fe-Mn oxide), perhaps the Zn lost from similar deformed amphibolites in another locality may move into a similar oxide deposit. On that basis, the Zn in the Ogdensburg franklinite-zincite-willemite ore (associated with marble as at Balmat) may explain where such displaced Zn has moved if nearby amphibolites are Zn-bearing. Perhaps the presence of marble may help in the precipitation of the displaced Zn.

Relatively undeformed amphibolites in the Ogdensburg ore zone contain as much as 260 ppm Zn and lack S and Pb as does the zinc ore (Collins, 1971). If

these amphibolites were deformed and replaced to form myrmekite-bearing, biotite garnet gneisses, then Mn, Zn, and Fe could have been displaced and moved by lateral secretion to the marble. These biotite-garnet gneisses contain less than the detection limit of Zn. Unfortunately, the gneiss and amphibolite do not crop-out at the surface, so that transitions showing progressive replacements can be established between the two rocks. Moreover, drill cores are of no help because they are at right angles to the structure. One can say only that lateral secretion of Zn, Fe, and Mn from replaced amphibolite is a possibility as a means of supplying the Zn, but the movements have not been demonstrated. Myrmekite provides evidence for replacements, but perhaps only to me. Nevertheless, in the Dover terrane, it is clear that zinc has moved from deformed relatively-mafic rocks by lateral secretion, and, therefore, the possibility should also exist in the Balmat terrane.

The Ogdensburg ores have many Mn silicates, and some Mn has a high oxidation state. Therefore, the points made by Eric regarding the Mn-silicates and the high oxidation state of Mn may not be necessarily evidence for the exhalative origin of the Balmat ores. The history of the Ogdensburg ores is quite complex, and other kinds of processes have operated to change its mineralogy. Such complexity could also occur at Balmat. The Ogdensburg ore could have had a prior history of metasomatism and lateral secretion prior to later modifications, and so could the Balmat ores. Likely, there are striking gradients in fO_2 across the ore zone at Ogdensburg as a result of these additional processes. I would expect the same to occur in the Balmat ores where striking fS_2 gradients might result, particularly if introduced exhalative fluids are interacting with associated anhydrite. Why should introduced exhalative fluids be any different from introduced Zn-bearing fluids derived by lateral secretion? Because no volcanic rocks are found in the Balmat terrane, should not some other source be more plausible?

One final observation is that tin is barely detected in the Popple Hill gneiss, and, therefore, the absence of tin in the Balmat ores is not unexpected. Silver, cadmium, and lead in minor amounts would not be unusual in either a lateral secretion or exhalative model.

Thus, I am not in disagreement with Eric's well thought-out arguments, but as in most geologic investigations, there are other ways of looking at the problem. A multiple-working hypothesis always has to be utilized, and then, perhaps, one final solution will be the best explanation..."

Further comments

I then added a further comment as follows to which Eric gave his arguments.

"There is a subtlety or nuance to Eric's comment about the Balmat ore body that I realized that I did not respond to. Among his remarks is the statement: '*I do not understand how such a concentration of sulfides could be obtained by metasomatism during regional metamorphism.*'

A common perception of regional metamorphism is that it is simply a high-P-high-T process (dynamo-thermal metamorphism) in which little movement of elemental material occurs accept for loss of fluids. In that case, nearly isochemical recrystallization occurs in most places to produce new minerals that are stable at higher grades of metamorphism."

Eric's response: "*Fluid (or a melt at high grades) is continuously removed in many metamorphosed rocks. Some initially dry meta-igneous rocks can undergo addition of fluid (metabasalts, metagabbros, meta-anorthosites, metagranites). Sometimes these lithologies may simply recrystallize (or NOT!) without much fluid migration. The only other common rock types to simply recrystallize during metamorphism are pure quartzites and pure marbles.*

"In all three places, however, that I used as examples (the Ogdensburg, Dover, and Balmat areas), isoclinal folds are involved in which rock units in the limbs of the fold have undergone strong deformation and sliding in order for the tight folding to occur. In these places the system is open, because of fracturing of crystal grains, to large movements of fluids that allow the metasomatism."

Eric's response: "*At Balmat the sulfide units and all the other rocks are deformed and recrystallized, but they did not fracture much during high grade metamorphism. Large sphalerite crystals (up to 0.1 to 0.2 m across) that must have grown during the metamorphism show spectacular deformation features. Many smaller sulfide grains have fully recovered textures. Balmat sphalerite was used by Clark and Kelly (1973) in deformation studies. Fracturing at Balmat is mostly a late feature. In thin section the Balmat rocks show interlocking grains with nice equilibrium textures. Late features include chalcopyrite "disease" in the sphalerite and exsolution of K-feldspar in nearby felsic units. Mesoscopic boudinage occurs between units of different ductility. Some late marble mylonites are found well west of Gouverneur and probably mark high strain at relatively low temperature late in the history of the terrane. The adjacent "major paragneiss" is heavily cut by pre- to syn-deformational aplites and pegmatites*

that involved hydrofracting during their intrusion. The major paragneiss is a semipelitic unit described by Engel and Engel (1958) some 50 years ago in terms of metasomatic processes. It is strongly migmatitic. Most observers would now conclude that it was partially melted during upper amphibolite to granulite facies metamorphism.

The striking chemical variations mapped in detail underground at Balmat as nearly concordant lithologies, talc-tremolite schist, anhydrite rock, dolomite and calcite marbles, sulfide ore, and paragneiss, suggest that these are all pre-metamorphic metasedimentary units, subjected to high grade metamorphism (Whelan et al., 1984; deLorraine et al., 1982; deLorraine et al., 1993)."

"So, I agree with Eric's comments if only regional metamorphism were simply involved in the sense I have indicated above. But I disagree in the sense of the situation where tight isoclinal folding occurs."

Closing comments

Eric has undoubtedly presented the majority opinions regarding (1) a possible exhalative origin of the zinc ore and (2) the magmatic origin for the associated, nearby granites, aplites, pegmatites, and migmatites. If science is solely done by popular vote, however, then obviously the ideas outlined in this web site are incorrect. Heisenberg has suggested that the theory decides what one will see. So we both see different things when examining the same or nearly the same data. Perhaps neither my model nor that proposed by Eric is correct, but both should be carefully examined by anyone else doing research on this problem. Before reaching conclusions, readers should also look at http://www.csun.edu/~vcgeo005/Nr28Popple.pdf, which discusses the Popple Hill gneiss and its possible metasomatic alterations, and at http://www.csun.edu/~vcgeo005/Nr30Grenville.pdf, which describes the possible metasomatic origin for the Hermon-type granites.

On 7/16/00 Marcus Tomkinson, Epigenesis Consulting Pty Limited, Perth, Western Australia, mjt@mypostbox.com, offered the following comments which also oppose my ideas for the possible epigenetic origin for the Balmat-Edwards mineralization.

"I have never been to Balmat, but the deposit has the classical signs of sediment hosted Zn system similar to say McArthur River or Century in Australia. However, great care must be taken before ascribing an exhalative mode of formation to these ore systems, and, in fact, the term SEDEX is much too

genetically specific and in many cases downright misleading. It is now clear that a whole range of Zn ore types can form in sediments. The associations at Balmat (carbonates, sulfidic carbonaceous rocks, and most telling of all, anhydrite) all suggest that the deposit may have originally formed as a peridiapiric sulfide accumulation associated with halokinesis. Typically, only the early Fe-rich sulfides are in any sense syngenetic in these systems. Where not affected by later events, they will characteristically show the high degrees of fractionation in S isotopic compositions typical of bacteriogenic processes. The base metals, however, are usually later and can range from diagenetic to late-stage epigenetic but are related to the large scale mobilization of Zn by flushing of Fe-Cl rich basinal brines from, and focused by, dissolving evaporite sources.

Obviously, given the degrees of deformation and metamorphism involved, it is difficult now to get back to the original state of these ore bodies. I would agree with the comments of some others to your article that the deposits are not typical "skarns." However, it might be wise to remember how important sulfate-bearing evaporites can be in providing reduced S (through thermochemical sulfate reduction) into a mineralizing system at any point (provided a hydrocarbon source is also available).

The whole terrane in which the Balmat ore body occurs is very reminiscent of other mid-Proterozoic terranes elsewhere in the world which host significant, and in some cases unmetamorphosed and undeformed, large Zn deposits (e.g., Mt. Isa Inlier in Australia, the Zinkgruvan area of Sweden, the Aravalli Terrane in India, and the Bushmanland Sequence in South Africa). This type of large stratiform Zn system is very definitely a feature of the middle Proterozoic."

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