Geologic Field Guide to the Balmat Zinc Mine, St. Lawrence County, New York

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Introduction and Geologic Setting

Orebodies of the Balmat-Edwards-Pierrepont Zinc mining district in the Northwest Adirondacks of New York State rank as world-class deposits with over 45 million tons of past production plus total reserves. Orebodies occur in "clean" Proterozoic siliceous dolomitic marble that was metamorphosed and polydeformed during the Grenvillian Orogeny about 1.1 billion years ago. The NW Adirondack Lowlands are underlain by metasedimentary rocks, predominantly marble, calc-silicate and subordinate paragneiss and metavolcanic rocks. The Adirondack Highlands to the east are predominantly underlain by anorthosite-mangerite-charnockite-granite suite (AMCG) rocks metamorphosed to granulite facies. The two provinces are separated by the Carthage-Colton line or "Highlands-Lowlands" boundary, a narrow northeasterly-trending, northwest-dipping zone of mylonitization separating the upper amphibolite- facies Lowlands from the granulite- facies Highlands to the east. Flat-lying lower Paleozoic rocks surround and unconformably overlie the crystalline rocks of the Adirondack dome.

Regional Stratigraphy

Several lineaments or fault zones divide the NW Adirondack Lowlands into NE-trending fault panels, each of which has a characteristic metasedimentary package and structural style. Differences between adjacent fault panels have led to speculation that individual panels have their own unique structural and stratigraphic histories (Grant and Yang 1992). There are, however, stratigraphic threads across and common to all fault pannels, beginning with the structurally lowermost rock unit, the Hyde School Gneiss. A regional column can be reconstructed by piecing together metasedimentary sections overlying the Hyde School Gneiss in individual fault panels and comparing these with adjacent fault panels. In places thrust faults or tectonic slides can be inferred where significant portions of the stratigraphic column are absent and where there are structural discontinuities across opposite sides of the inferred fault trace. Nevertheless, several key, distinctive marker units spanning the 40-km-wide Lowlands are present within each fault panel, thus permitting reconstruction of the section. There are apparent structural discontinuities between some of the four formations underlying the Lowlands so that in part the column may reflect a lithotectonic stacking sequence.

Leucogranitic gneiss ranging from alaskitic to granitic to trondhijemitic composition lies at the base of the section in the NW Lowlands (Fig. 8) (Editor's note: figures in this paper start with figure 8). Leucogneiss is characterized by relatively high content of disseminated magnetite and presence of thin conformable amphibolite layers. The leucogranitic gnisses is referred to as Hyde School Gneiss and its origin is controversial. Although long regarded as a basal metavolcanic complex, because of conformity of amphibolite layers, unique structural/stratigraphic position underlying the basal member of the Lower Marble formation, lack of sills, apophyses, dykes, or xenoliths of surrounding rocks, the Hyde School Gneiss has recently been interpreted as intrusive in orign. Sillimanite-garnet-corundum-spinel assemblages in surrounding garnet-sillimanite gneiss suggest temperatures of 850°C, much higher than reported regional metamorphic temperatures (McLelland et al . 1992). Hudson (1994) reported 830°-860° for the same garnet gneiss. Accordingly, these assemblages were interpreted as contact metamorphic phenomena associated with intrusion of Hyde School Gneiss. Amphibolite layers were interpreted as highly tectonized dykes resulting in completely transposed "straight" gneiss.

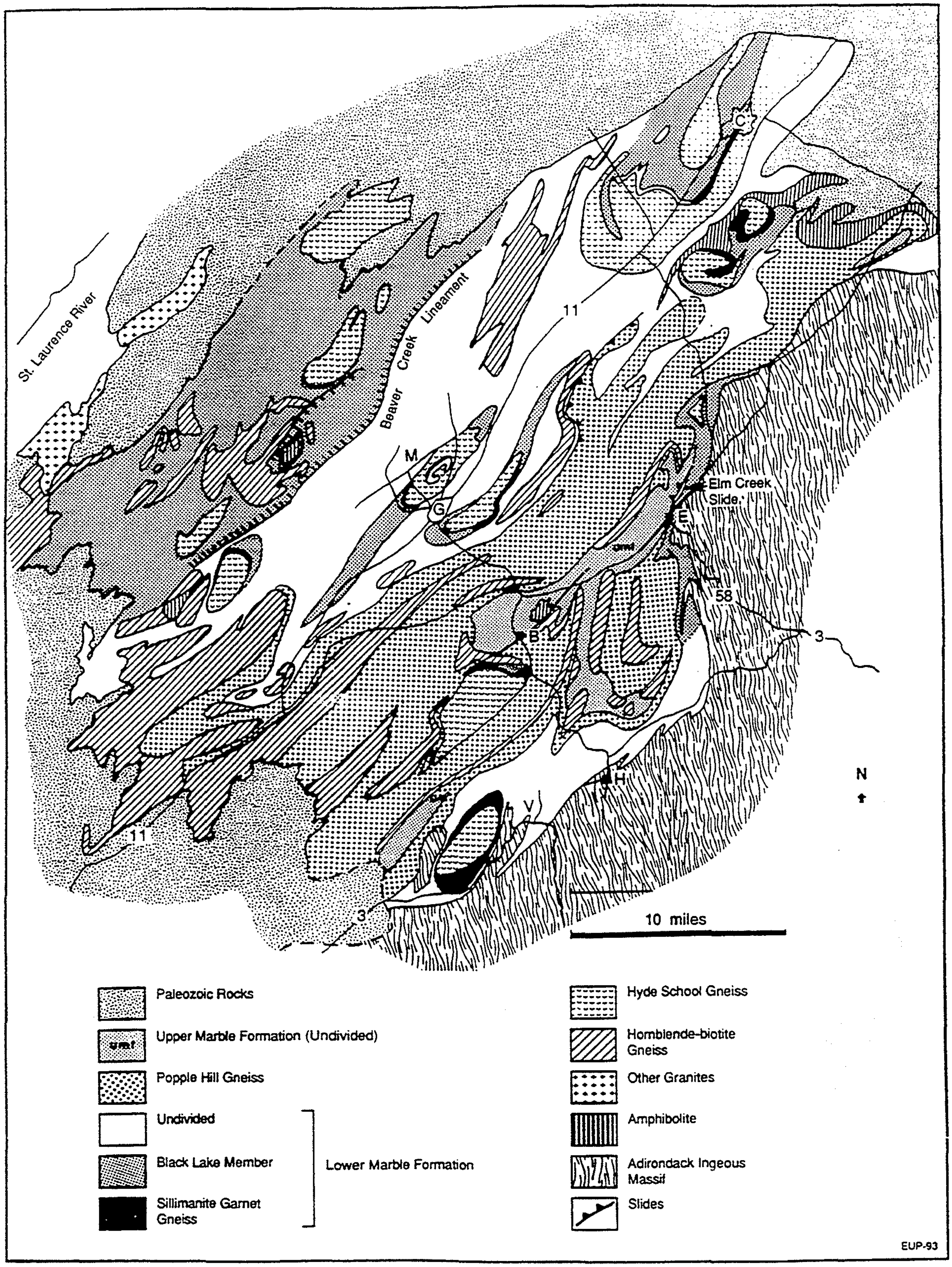

Figure 8. Generalized geologic map of the Northwest Adirondack Lowlands. G = Gouverneur; B = Balmat; E = Edwards. Modified from Isachsen and Fisher (1970).

intrusion of Hyde School Gneiss. Amphibolite layers were interpreted as highly tectonized dykes resulting in completely transposed "straight" gneiss.

Overlying the Hyde School Gneiss is the Lower Marble formation (Fig.8), a diverse assemblage of predominantly calcitic marble with intercalated calc-silicate units, biotite gneiss, quartzite, tourmalinite and pelitic gneiss. Calcitic marble is banded gray and white and characterized by the presence of abundant disseminated granular diopside, graphite, phlogopite, and disseminated brown to black tourmaline. This rock type is common and appears in numerous localities across the Adirondack Highlands and to the northwest in Canada. Migmatitic gneiss of overall dacitic composition referred to as Popple Hill gneiss overlies the Lower Marble formation (Fig 8.) The contact may be tectonic, based on the recognition of structural discontinuities below (Foose 1974), presence of mylonites (Hudson 1994; Hudson and Grant 1989), and excision of several members of Lower Marble formation below (deLorraine, personal mapping observation). Dolomitic and siliceous dolomitic marble of the Upper Marble formation lie at the top of the regional stratigraphic column. Exposures of this unit are limited to narrow fold belts relatively close to the Highlands-Lowlands boundary between Balmat-Edwards and Pierrepont, New York (Fig 8). The Upper and Lower Marble formations are in structural contact at Edwards where the entire section of Popple Hill gneiss has been excised along the Elm Creek slide (Fig. 8). The slide is manifested by the presence of mylonitized slivers of Hyde School and Popple Hill gneiss in addition to the juxtaposition of major stratigraphic units. This major discontinuity was recognized earlier by Gilluly (1934).

Regional Structure and Metamorphism

Metasediments of the northwest Adirondacks have undergone upper amphibolite facies metamorphism and polyphase deformation during the Grenvillian orogeny dated at about 1130-1170 Ma (Grant et al. 1986; McLelland et al.1988; Mezger et al. 1991). The regional structure is complex, the product of at least four phases of deformation. Large-scale recumbent folds, nappe structures, and tectonic slides are believed to have developed during the early phases of deformation (deLorraine 1979; Foose 1980; Wiener et al.1984; Brown 1989; McLelland et al.1993). First-phase deformation at high metamorphic grade produced axial planar foliations which define the regional foliation. Tewksbury (1991), and Tweksbury and Kirby (1992), have shown that what was described as the "main regional foliation" in many places has the characteristics of a ductile shear fabric. Furthermore, these authors propose that the early deformation leading to the main regional foliation occurred in a deep-seated ductile shear regime in a continental collision plate-tectonic setting. In general, grain size in gneiss is fine to medium and at certain levels, such as the base and top of Popple Hill gneiss, mylonite is present. Migmatite also developed during early phase deformation. Recognition of map-scale first-phase folds is uncertain and minor folds are rare as well. Where present, early phase folds are rootless isoclines or intra-folial isoclinal folds with well-developed axial planar foliation. The second-phase of deformation has been subdivided into phases 2A and 2B. Phase 2A minor folds are interpreted to have developed coevally with major second-phase isoclines, and phase 2B folds are interpreted as shear folds associated with southeast overturning of those major isoclines, such as the Sylvia Lake syncline. Phase 2A isoclinal folds refold early isoclines, their axial-planar foliations, and early mylonite. In the Lowlands, axial surfaces of phase 2A folds strike northeast, defining the prominent NE-SW regional grain. Axial surfaces dip moderately to the northwest. Fold axes are curvilinear within second-phase axial surfaces and can be described as "porpoising" within them (Fig.9).The doubly plunging Sylvia Lake syncline between Balmat and Edwards hosts the zinc orebodies of the district and is an example of a major phase 2A isoclinal fold. The North Gouverneur nappe of Brown (1989) is interpreted herein as a second-phase fold, as is the Great Somerville anticline and Sherman Lake syncline of Buddington (1934). Tectonic slides, axial planar shears and thrust faults are common elements of major phase-two isoclines. In contrast to Tewksbury, we do not interpret domes of Hyde School Gneiss as products of progressive regional ductile shear in which irregularities within the shear zone amplified into sheath folds. Rather, domes of Hyde School Gneiss are seen herein as doubly-plunging cores of regional, NE-SW trending accordion-style phase 2A folds superimposed on phase-one shear fabrics and lithotectonic stacking sequences, as the orogen experienced further contraction (deLorraine, internal ZCA documents). Phase 2B isoclinal folds are

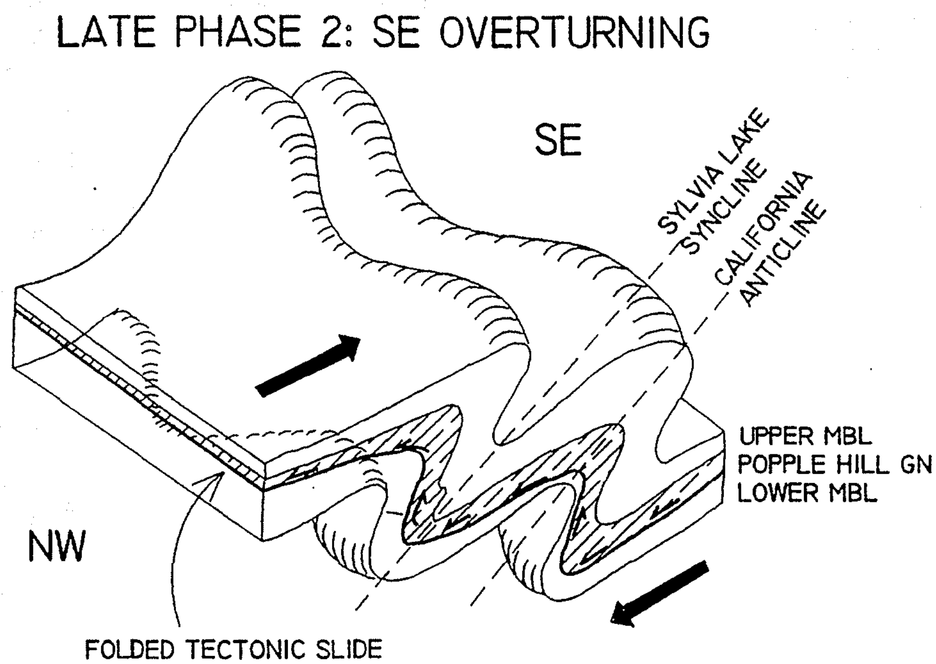

Figure 9. Generalized 3-D, NW-SE section across the Lowlands showing phase 2A isoclines overturned to the southeast during late phase 2 deformation (phase 2B). Note curvilinear hinges of major folds. The basal unit, Hyde School gneiss, is not shown but occupies the cores of doubly-plunging anticlines.

recognized in the mines where they refold straight marble tectonite which developed along phase 2A shear zones and thrust faults. Rotation senses are uniformly clockwise and commonly the short limbs are sheared out in contrast to phase 2A structures which have counter-clockwise asymetrics on the upper limb of the Sylvia Lake syncline and clockwise asymetries on the lower. In the mines, the prinicipal manifestation of phase 2A folds is the re-activation and refolding of phase 2A straight marble fabrics paralleling shear zones and slides. Third-phase folds of "S" asymmetric sense and more or less coaxial with local second-phase folds also trend to the NE. Interplay of phase 2A and third-phase folds locally produced hook and crescent-shaped interference patterns. A fourth weakly developed northwest-trending phase of folding was thought to have produced the apparent modified dome and basin pattern in the northwest Adirondacks by interference with earlier northeast-trending folds (Foose 1974, 1980; deLorraine1979; Wiener et al.1984). The preferred interpretation here, based in part on large-scale reconstructions of the Sylvia Lake syncline at the Balmat No. 4 mine, is that the pattern results from curvilinear or "porpoising," doubly-plunging, phase 2A sheath fold hinges. Thus apparent domical structures cored by Hyde School Gneiss are seen as apical projections of tongue or sheath-like folds protruding through the erosional surface (Fig.9). This view of phase 2A fold geometry derived from mine district observations supports, in part, the interpretations of Tewksbury (1993), who also views domes of Hyde School Gneiss as sheath fold hinges. Many of the "domes" are overturned to the southeast so that interference of southeast- overturned second-phase isoclines with NW-trending folds, if it occurred, should have produced "heart-and-anchor" interference patterns, rather than the observed ovoid patterns.

Metamorphic grade increases gradually from upper amphibolite facies in the Lowlands to granulite facies eastwardly toward the Adirondack Highlands. Reported temperatures of metamorphism were 640°-700° C near Gouverneur increasing to 750° C in the southwestern Highlands; pressure increased from about 7.2 kb to 7.6 kb (Seal 1986). At Balmat, temperatures of at least 625° C are inferred from calcite/dolomite geothermometry and sulphur isotopic fractions between co-existing anhydrite-pyrite pairs (Whelan 1979). Other mineral assemblages including end-member forsterite suggest that temperatures could have been ~725° C at > 0.7 XCO_2 (Petch 1992).

Balmat Lithology And Depositional Environment

The "Balmat" or Upper Marble Formation stratigraphic column is presented in Figure 10. The section is characterized by an alternation of nearly pure dolomitic marble and silicated dolomitic marble units. Distributed throughout this 16 unit sequence are distinct "marker units" and periodic occurrences of anhydrite.

Units 1, 3, 5, 7, 9, and 12 are medium-to coarse-grained, gray to white dolomitic marble with very minor quartz, diopside and serpentine. Serpentine occurs as replacements of both diopside and forsterite. Silicated marble units 4, 6, 8, and 11 consist of interlayered glassy quartzite, gray to white diopside and white to gray dolomitic marble beds with minor buff calcitic marble layers. Much of the quartz-diopside rock is thinly banded to laminated and much of the finely laminated rock may be biogenic in origin. Units 4 and 11 are now recognized as stromatolitic (Isachsen and Landing 1983) thus providing the only unequivocal sense of tops in the Adirondack region to date. Each silicated unit has its own set of distinctive marker sub-strata, textures, and proportions of quartz-diopside relative to dolomite allowing recognition as individual stratigraphic units and not as a single unit repeated by isoclinal folding as had been suggested by Wiener et al. 1984. The same subunits of Unit 6 at Balmat can be recognized in drill cores at the Hyatt Mine some six miles along strike to the northeast. Were it not for the presence of "marker" beds or units intercalated within the Upper Marble section, the structural geology of the Balmat district would be much harder to decipher.

Persistent marker horizons of distinctive mineralogy, texture, or colour include a graphitic pyritic schist, Unit 2, separating dolomitic marble units 1 and 3. The "7 Bed", a medium-grained, dark gray, fetid, dolomitic marble contrasts with other dolomitic units which are white to light gray. The "10 Bed" is a fine-

FORMATION	TYPICAL THICKNESS (FEET)	ORE ZONES	LITHOLOGY
Cp	0-400		Sandstone, Siliceous breccia
		Unconformity	
16	200		Median gneiss: quartz-biotite-felspar
15	30		Calcitic marble: phlogopitic, silicated
14-A	120	Main, Streeter	Dolomitic and dolomitic marble (serpentinized); diopside, siliceous marble
14-B	130		Calcitic marble, quartz augen
14-C	110	Hanging Wall	Quartz-diopside rock, minor dolomite
13	80		Tremolite-talc schist, anhydrite
12	150	Fowler, Sylvia Lake Wight	Dolomitic marble, minor diopside, minor anhydrite
11, 11A	300	Fowler, Sylvia Lake, Number One	Calcitic and dolomitic marble, quartzite, diopside minor anhydrite (11) Same, with over 50% bedded anhydrite (11A)
10	50		Talcose diopside, biotite, anhydrite
9	60	Loomis, Upper Fowler, American	Dolomitic marble
8	130	Loomis, Upper Fowler, American, Mud Pond	Dolomitic marble, quartzite, diopside
7	120		Dolomitic marble, fetid, graphitic
6	550	Gleason, Upper Gleason West Gleason Loomis, C	Dolomitic marble, quartzite, siliceous diopside, anhydrite (locally)
5	170		Dolomitic marble, minor diopside
4	300		Dolomitic marble, quartzite, diopside
3	400		Dolomitic marble
2	100		Pyritic schist: quartz-mica-feldspar-pyrite
1	400		Dolomitic marble
qbg, gg	2500		Quartz-biotite-oligoclase paragneiss; Granitic gneiss

Figure 10. Stratigraphic column for Upper Marble formation at Balmat. The term "quartzite" refers to metamorphosed chert. The relative stratigraphic positions of orebodies are plotted as black bars.

grained, milky pea green, serpentinous calc-silicate rock with anhydrite and a local biotite schist substratum. Unit 13 is perhaps the most useful marker unit consisting of distinctive cream-coloured talc-tremolite-anthophyllite schist, hexagonite schist, and braunite-hexagonite schist.

Lavendar to pink bedded anhydrite occurs in Units 6 and 10 through 14. Anhydrite is most prominent within the upper half of the section, particularly in units 11A and 13. It is believed to be of evaporitic origin on isotopic evidence (Whelan 1974; Whelan et al. 1990), conformity with surrounding units (some of which are stromatolitic), and its internally bedded character. The most significant accumulation of anhydrite is in the 11A unit, particularly notable where it is greatly thickened within the axial region of the Sylvia Lake syncline. (Fig. 11). These Proterozoic anhydrite rocks are thought to represent some of the oldest evaporites in the geologic record of any volumetric significance.

The range of ore-bearing horizons has an estimated stratigraphic thickness of about 1800 feet (550 m). Orebodies are restricted to units 6 through 14 (Fig. 10). Occurrences of anhydrite are limited to the same interval but association with sulphides is indirect in that the two are never in mutual contact except along ductile faults and shears where the contact is structurally imposed.

Protoliths conjectured for some of the Balmat metasedimentary rocks are dolomitic limestone for the pure marble, cherty dolomite for the interlayered quartz-diopside and dolomitic marble units (Hauer 1995), chert for "quartzite" and impure evaporite for the anhydrite-rich units. Protoliths for the pyritic schist (unit 2) might be sulphidic black shale, evaporitic rocks of uncertain composition for unit 10, and siliceous magnesite-bearing and anhydrite-rich evaporite for the tremolite-talc unit 13.

Depositional environment, as conjectured from these assumed protoliths and from stromatolitic evidence, appears to have occurred in a marine, shallow-water continental shelf setting with very minor detrital material derived from the adjacent shield (Whelan et al. 1990; Hauer 1995). Deposition of the Upper Marble formation began after the accumulation of volcaniclastic and pelitic rocks, represented by the Popple Hill gneiss. Deposition was punctuated by periodic episodes of restricted circulation leading to the accumulation of evaporite. Occurrence of stromatolites and some graphite in the marble suggests organic activity, perhaps an abundant supply of algae or cyanobacterial organisms. Chert first appears about a third of the way up the column, also marking the first appearance of stromatolites. Midway in the sequence (unit 6), and thereafter, marine waters became periodically isolated from the ocean, so that under an arid environment evaporite accumulated, locally attaining significant thickness. Evaporite precipitation reached its peak in a long shallow-water period now represented by Unit 11A. Evaporite deposition continued until not long before the sequence was capped by calcareous graywacke or marl (Unit 16), again in somewhat deeper marine water. Unit 13 may record extreme evaporite deposition and perhaps required magnesite and anhydrite as well as silica in the protolith (Petersen et al. 1993).

Balmat Structure

Host rocks of the Balmat mine area have undergone at least four phases of deformation resulting in complex geometry. During first-phase deformation, a prominent axial planar foliation formed in talc-tremolite-anthophyllite schist of Unit 13 and also in Units 2 and 15. Early-phase intrafolial folds deform bedding and compositional layering but not foliation, hence they are the oldest structures recognized in the area. Compositional layering is interpreted as bedding wherein layers of varying thickness, colour, texture, and composition are concordant with each other and with contacts between major lithologic units. Where finely-laminated quartz-diopside rocks persist laterally away from stromatolites, and where the laminations are parallel to compositional layering, this is regarded as relict bedding. Major first-phase folds have not been identified and it is possible that foliation and minor structures formed in a regional ductile shear regime (Tewksbury 1993), with the direction of tectonic transport northwest toward the Grenville Front.

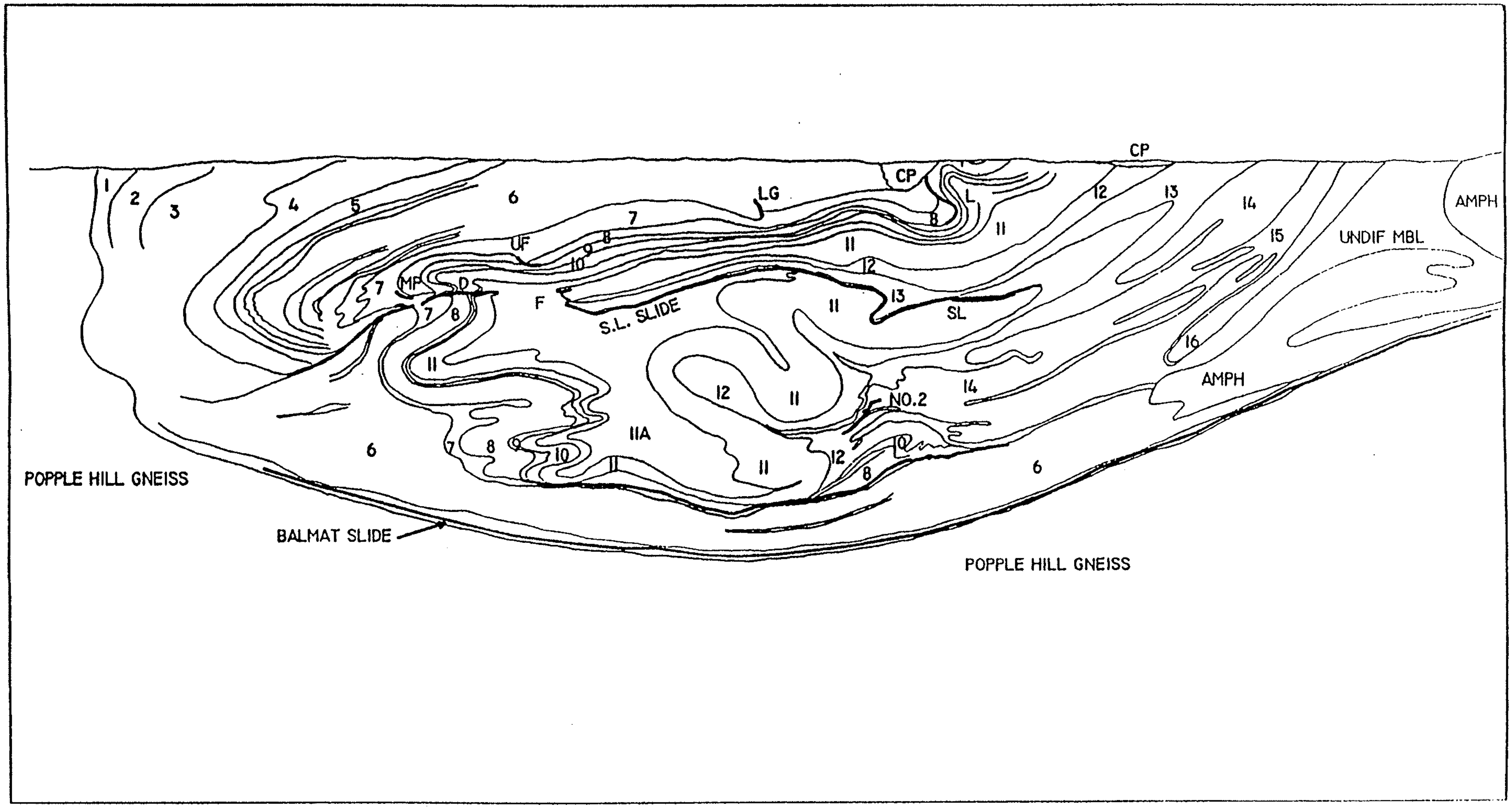

Figure 11. Generalized W–E cross-section through the Sylvia Lake syncline at Balmat. Orebodies represented by black lines as follows: MP = Mud Pond; D = Davis; F = Fowler; UF = Upper Fowler; LG = Lower Gleason; L = Loomis; SL = Sylvia Lake. The Sylvia Lake syncline is a compound fold with its core at "No. 2" and another, the Fowler Lake syncline, lying above, with its upper limb above and its lower limb below the Sylvia Lake slide.

Phase 2A folds isoclinally refold early isoclines and associated axial planar schistositiy. Their axial surface traces strike northeasterly, but vary in strike locally where they are refolded by third-phase folds. The Sylvia Lake syncline is a major, doubly- plunging Phase 2A fold which dominates the structure of the district. It is interpreted as a regional sheath fold, shaped like a "pita pocket" because hinges of the major and associated minor folds are curvilinear, plunging NNW in the southern end of the Balmat district and then swinging to the NE at the northern end. At Edwards the major fold plunges NW back towards Balmat. (Fig. 12).

Similarly, drilling and mining at Pierrepont has shown that structure to be a smaller, doubly-plunging isocline with sheath fold-like geometry (Fig.12). There is no evidence at mine scale or regional scale that later, NW-trending fourth-phase folds interfered with earlier NE-trending folds to produce apparent sheath fold geometry *unless* the movement line of third-phase folds was contained strictly within axial surfaces of the second-phase isoclines. The Sylvia Lake syncline is currently interpreted as a recumbent, compound fold. The Fowler syncline at No. 4 mine shaft, the American anticline, and the syncline at No. 2 mine shaft (Fig. 11), are all Phase 2A minor isoclines located in the core of the fold. The short limb of the Fowler syncline is faulted out, sheared and attenuated along a thrust fault referred to as the Sylvia Lake slide (Fig 11). Apparent net displacement along the slide is on the order of 4000 feet. Outside of the immediate vicinities of the Fowler and the Sylvia Lake orebodies where discordant relationships are obvious, there is scant field evidence to suggest major tectonic discontinuity because in most places compositional layering and major unit contacts are layer-parallel to the slide. The Davis and Mud Pond orebodies occur in stratigraphically lower units farther west along the trace of the Sylvia Lake slide. Mineralization in both is transgressive across Units 7, 8, 9, 10, and 11. Strain within unit 11A anhydrite between the Fowler and Davis orebodies may have been accommodated by ductile flow of anhydrite rather than by shearing along a discrete shear surface. "Straight marble" is common where mineralization transgresses major stratigraphic units, with the foliation defining the layering in the ductile marble parallel to shears cross-cutting less ductile, layered, calc-silicate marble units. Such "straight" marble layering is present in the Fowler, Upper Fowler, Sylvia Lake, Davis and Mud Pond orebodies and where observed is regarded largely as a second-phase ductile shear deformational fabric. Major offset is observed between Fowler/Sylvia Lake orebodies with the Fowler thrust faulted > 4000 feet, N55° W, *relative* to the Sylvia Lake (see Fig.11). Relative offset of the Davis and Mud Pond orebodies, though of similar sense, is of much lesser magnitude, and that of Upper Fowler is of the opposite sense.

Phase 2B folds isoclinally refold straight marble foliation in the Davis, Fowler, Upper Fowler and Sylvia Lake orebodies. Phase 2B folds are isoclinal in style and often take the form of elongate, sheared-out, tabular folds with pointed hinges. Rotation senses are clockwise on both limbs of the Sylvia Lake syncline which suggests a major shear couple was superimposed on the entire fold or alternatively, that the Sylvia Lake syncline was itself of the limb of a much larger regional fold. Clockwise asymmetric sense of phase 2B folds is compatible with southeast overturning of the Sylvia Lake syncline in the later stages of phase 2 folding, hence the term " phase 2B" (Fig. 9). Implications of this are important because on the upper limb of the Sylvia Lake syncline, clockwise phase 2B overprinting of counter-clockwise phase 2A structures had a net subtractive effect. Accordingly, phase 2A rotation or offset along ductile faults was reversed by phase 2B strain of opposite asymmetric sense, partitioned along these reactivated faults. For example, the Loomis, Mud Pond, and Fowler (relative to Sylvia Lake) orebodies show phase 2A counter-clockwise net rotation senses while the Upper Fowler shows clockwise, phase 2B net offset along the Upper Fowler fault. Although all the orebodies on the upper limb experienced phase 2B clockwise rotations, it was only in the Upper Fowler orebody that phase 2B strain was of sufficient magnitude to reverse or negate the effects of Phase 2A. A simpler situation exists on the lower limb of the Sylvia Lake syncline where the effects of phase 2A clockwise, and phase 2B clockwise rotations, were additive. Effects of Phase 2B folding in the Fowler orebody include rotation of Units 12 and 13 from the core of the Fowler syncline into a position axial planar to the Fowler syncline and x-cutting Unit 11 (Figs. 13,14) and clockwise isoclinal refolding of the Davis shear zone and associated straight marble fabrics.

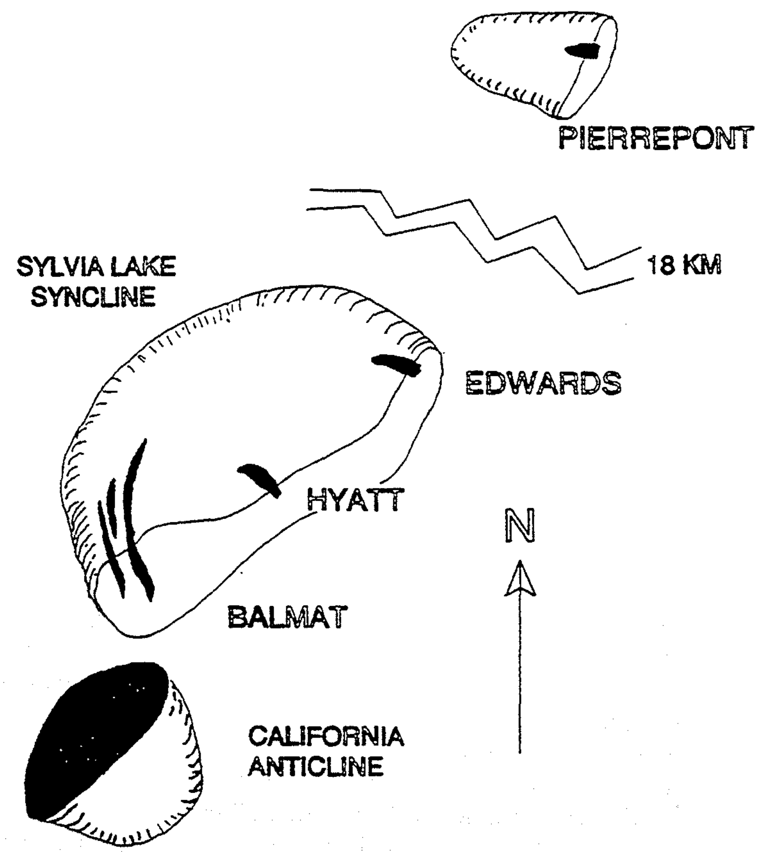

Figure 12. Composite map view and 3D representation of the Sylvia Lake syncline and the Pierrepont fold showing "pita pocket", doubly plunging geometry. The California anticline is sheath fold complementary to the Sylvia Lake syncline.

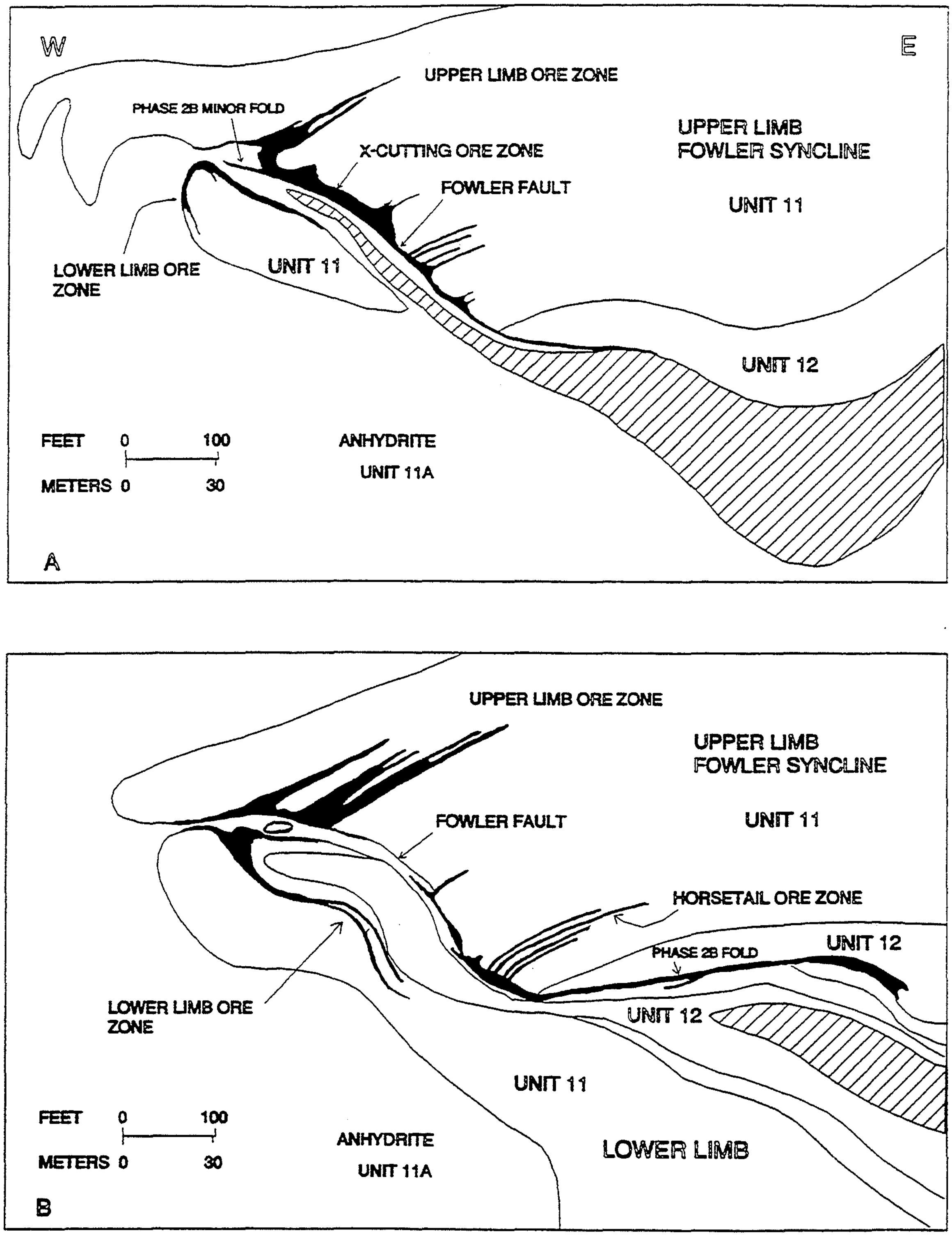

Figure 13. W-E sections through the Fowler orebody showing ore zones and structure. Hatched pattern = unit 13; ore = black; 13A is a section up plunge, 13B several hundred feet farther down plunge to north.

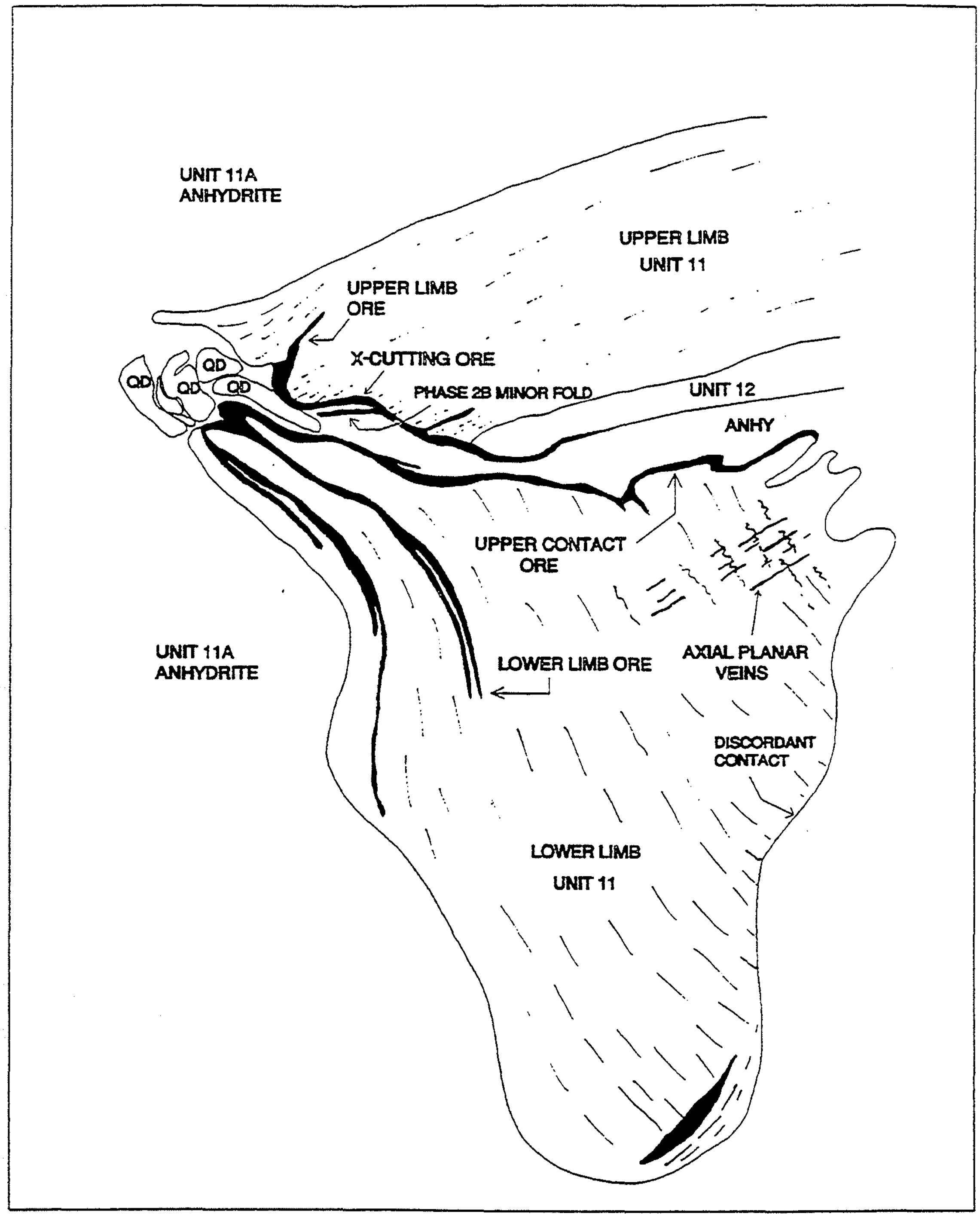

Figure 14. W-E cross section through the Fowler orebody showing large lower limb "tectonic mullion". The wedge-shaped mass is fault-bounded at its eastern contact with unit 11A anhydrite and at its contact with the Upper Contact ore zone. Interpreted as the wedge-shaped core mass of the fold depicted in Figure 18. Axial planar ore veins cross-out bedding in unit 11.

Third-phase minor folds refold Phase 2A and 2B axial surfaces about steeply-dipping, NNE-striking axial surfaces. Plunges of third-phase folds are NNE, roughly co-axial with the local second-phase folds. Manifestations of third-phase folds are observed in Fowler and Upper Fowler orebodies where the latest folding is defined by "top-side-west" or counter-clockwise refolds of Phase 2A straight marble fabrics paralleling ductile faults and Phase 2B sheared-out isoclines.

Fourth-phase folds have NW-striking, steeply dipping axial surfaces and are open in style. They have been observed only locally in the Fowler orebody. Where fourth-phase folds are prominent, as on the 2100 level of the Fowler, they interfere with earlier NE-trending folds to form modified dome-and-basin patterns (deLorraine 1979). Below 2100 level, the plunge of the Fowler orebody steepens to 45°. Fourth-phase folds are not seen in Figure 11 because their axial surfaces parallel the plane of the section.

One might question whether it is really possible to identify stratigraphic successions (which define folds), given the complexity of polyphase deformation and tectonic sliding, especially in view of the high metamorphic grade and extreme strain implied by sheath folding. Might we be looking entirely at shear fabrics or transposition of layering? Part of the answer lies in the mode of preservation of stromatolites now represented by domes of finely-laminated quartz-diopside rock. The senior author believes that bedding, including stromatolites and cryptalgal lamination, was diagenically enhanced or replaced by silica. Reaction of chert and dolomite layers under high-grade metamorphic conditions produced diopside layers which mimic or enhance original bedding — hence the term relict bedding. Quartz-diopside rocks behaved as structural buttresses where as marble units were extremely ductile, having accommodated large strains by plastic flow leaving stromatolites and relict bedding largely intact. Second, overall doubly-plunging aspect of major folds approaches "pita pocket" geometry more so than true sheath fold geometry. Strain was accommodated by plastic flow, tectonic sliding and ductile faulting such that despite attenuation of and breaks between major stratigraphic units, it is still possible to define lithic successions that are predictable from place to place across the northwest Adirondacks. Overall strain was not as extreme as that which would be expected from true sheath fold geometry.

The Orebodies

General

The presently known zinc orebodies of the Balmat mine lie within one mile of the central No. 4 shaft, in an area of approximately two square miles. A majority of the ore shoots are arranged in clusters customarily known as the Balmat No. 2, 3, and 4 mines, after the shafts which service them. In this guide, the ore clusters will be described as belonging to No. 2, 3, and 4 mines, although these are more properly interconnected mining units now centralized around No. 4 shaft, from which Balmat ore is hoisted to the adjacent mill (Fig. 15).

There is much diversity in characteristics of the orebodies, but it is possible to make some generalizations. Sulphides are intimately associated with fold hinges and may be defined as massive stratabound and stratiform. In detail, however, sulphides are locally found along transgressive shear zones and faults associated with major second-phase folds. Ore occurs as tabular, podiform or lenticular bodies of moderate cross-sectional areas (2 to 50 feet thickness by 50 to 800 feet on strike), but characteristically have a large, often extremely large dimension (6000') in the plunge direction of Phase 2 A fold hinges, with which they are initially associated (Figure 15). Thickening of sulphides occurs locally in second-phase fold hinges, with thinning occurring along the attenuated and sheared limbs. Sulphides tend to be localized along boundaries of dissimilar lithologies, such as contacts between dolomite and diopside layers. Contacts of sulphides with bordering rock are generally sharp, with disseminations extending into wall rock being the exception rather than the rule. Wallrock alteration is limited to local envelopes of silicification paralleling shear zones. Cross-cutting veinlets of quartz-sphalerite-pyrite locally mineralize crackle breccia in silicated dolomitic

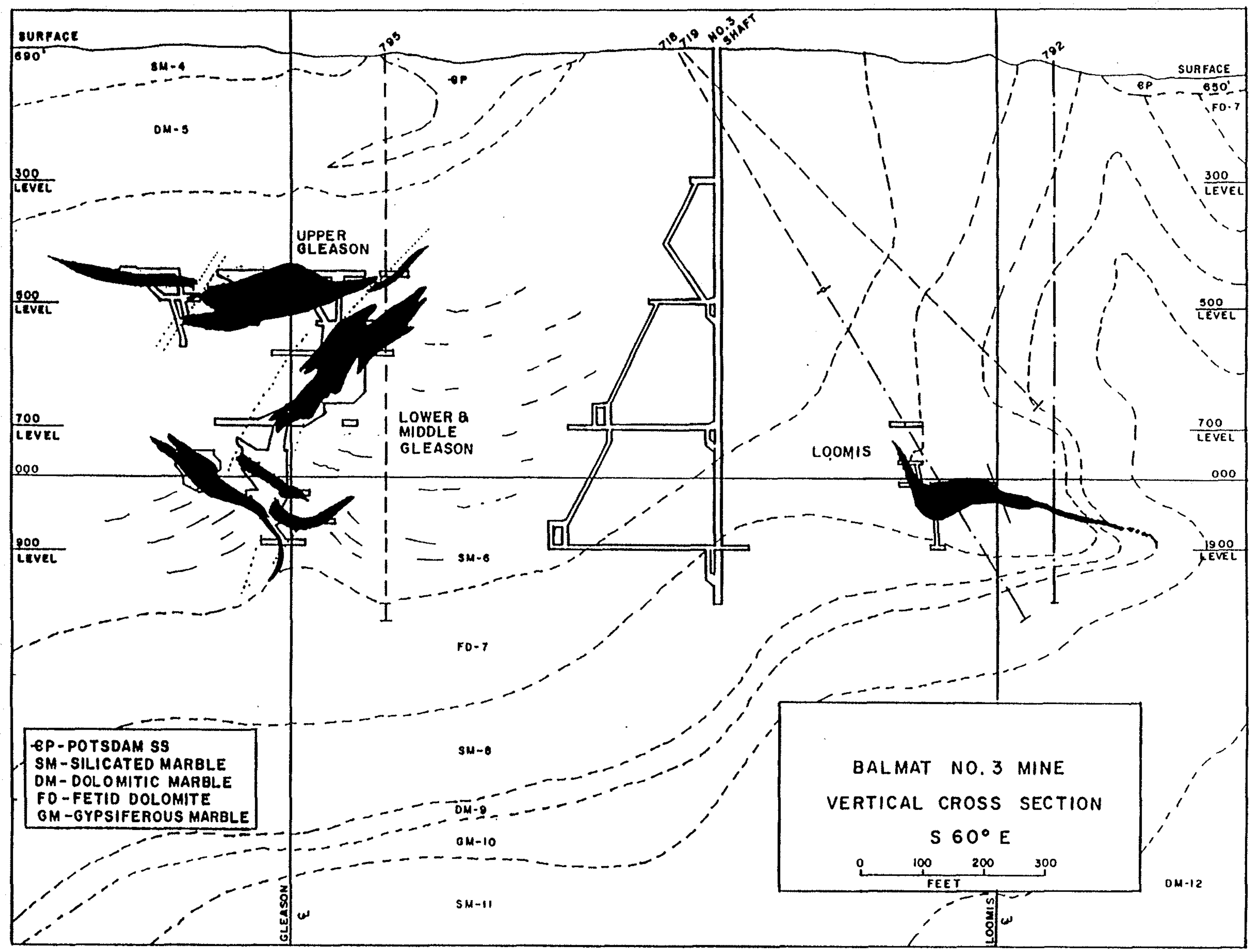

Figure 17. Cross-section through No. 3 mine. Upper Gleason ore is massive high-grade; Middle and Lower Gleason cross-cut stratigraphy and are lower grade.

quartz gangue. "Supergene" hematite derived from oxidation of iron in sphalerite or pyrite occurs locally along fractures.

The **Lower Gleason** orebody occurs in Unit 6 near and at the contact with Unit 7, along a high-angle reverse fault referred to as the Gleason fault (Fig. 17). The Gleason fault is associated with a Phase 2A minor fold plunging sub-horizontally N35° E. Rotation sense of the fold is "S", consistent with its location on the upper limb of the Sylvia Lake syncline. Cross-cutting mineralization dies out rapidly away from the Gleason fault; contacts of the stringers and veinlets with wall rocks are sharp. Much ore is also present as medium-to-fine grained, highly deformed streaks and layers in well-foliated marble tectonite lying parallel to the fault. Later, steeply dipping, WNW-trending faults of dominantly strike-slip character segment the orebody into panels within which hematization of the ore zone and talcose alteration of diopside are locally extensive. Offset between panels is minor. The Lower Gleason orebody attains its greatest grade and tonnage where it passes under and crosses the trend of the Upper Gleason (Fig.17). The reason for this is unclear, but there is a nebulous mineralized zone which crosses stratigraphy and seems to connect the two orebodies at the cross-over point. This raises the possibility that the Upper Gleason orebody may have served as the source reservoir supplying the Lower Gleason orebody.

The **Loomis** orebody occurs in the hinge and along the sheared short limb of a Phase 2A fold referred to as the Loomis "S" Fold, so named for its sense of asymmetry (Fig. 17). The Loomis "S" Fold plunges gently N35°-40° E., but undergoes localized reversals in plunge within the mine area. This may be a consequence of gentle re-folding or natural variations in fold profile and geometry in the down-plunge dimension. Full plunge dimensions are presently uncertain, but mining extended down-plunge over 3500 feet. Ore occurs as coarse-grained masses and veins within Unit 8 at the 7/8 contact, as banded marble-sphalerite tectonite within Unit 9 along a cross-cutting shear zone in the short limb of the "S" fold, and within Unit 10 along the 9/10 contact (Fig. 17). Sphalerite is the dominant ore mineral, while pyrite is very minor in amount and galena present only as traces. Late faults transect and segment the orebody as in the Gleason orebodies; hematite and willemite replacement of sulphides along late faults is locally extensive and in some places complete. Secondary willemite is locally abundant and is restricted to hematitized zones within the orebody. Interestingly, clastic dykes of Potsdam sandstone in places extend downward nearly 750 feet below the present surface.

The undeveloped **West Gleason** mineralized zone lies down-dip a few hundred feet west of the Lower Gleason (Fig. 15). Its structural setting, in Unit 6 near its contact with Unit 7, appears to resemble that of the Lower Gleason but on a smaller scale. The narrow and relatively low-grade ore shoot extends down the plunge for at least 3000 feet. Its remarkably straight course suggests fault control associated with folding in diopside-rich host rocks.

The **Loomis C,** also undeveloped, is a small satellite orebody directly overlying the Loomis. It is confined to a minor structure in Unit 6 near the 6/7 contact and extends for about 1000 feet along the plunge.

Orebodies at No. 4 Mine

In addition to being the main hoisting shaft for most of the orebodies of the Balmat Mine, the No. 4 shaft specifically serves the Fowler, Upper Fowler, Davis and Mud Pond orebodies, which are located 1500 to 3500 feet northwest of the shaft (Fig. 15).

The **Fowler** orebody is localized within the axial region of the Fowler syncline (Fig. 11), which plunges N5-15^0 E at 15-45^0. The mineable portion of the Fowler orebody has a down-plunge longitudinal extent of nearly 5000 feet, from 1200 feet below surface to more than 3000 feet below surface.

The Fowler syncline is interpreted as a Phase 2A recumbent fold whose limbs were dissected by synmetamorphic faults, of which the Fowler fault (Fig. 13) and Upper Contact fault (Fig. 14) are the most prominent. Anhydrite, large slices of Units 12 and 13, and tectonic melange comprised of anhydrite, blocks of Unit 11, and slivers of Units 12 and 13 occur between the Fowler upper and lower limbs (Figs. 13B,14).

The "Lower Limb" (Fig. 14) is a large wedge-shaped body of Unit 11 that is surrounded by 11A anhydrite. Bedding is truncated along the Upper Contact fault and at the footwall of the structure. (Fig. 14) shows that the lower limb is an immense rod-like tectonic block or tectonic mullion. The Lower Limb pinches out down-plunge with a concomitant increase in size of the Upper Limb. Silicified tectonic breccia zones and occurrences of white "bull" quartz are present locally along the Fowler and Upper Contact faults.

Five ore zones have been recognized as subdivisions of the Fowler orebody because they occupy particular structural domains within the axial region of the Fowler syncline. The Upper Limb and Horsetail ore zones each consist of conformable layers which extend updip along bedding into the upper limb where they lense out. (Fig. 13). Sulphide layering is common in both ore zones. The Cross-cutting ore zone is so named because it lies along the Fowler fault. It extends from the beginning of the Upper Limb ore zone down dip to the east across the Horsetail ore zone and thence along the Unit 12/13 fault contact (Fig. 13B). Conformable ore extending away from the Upper Contact fault down dip into the lower limb constitute the Lower Limb ore zone. Lower Limb ore is truncated by the Upper Contact ore zone, which lies along the Upper Contact fault. The Upper Contact and Fowler faults probably represent opposing faces or sides of a single fault separating the Upper and Lower fold limbs, and in any case the Fowler fault is actually a segment of the Sylvia Lake slide, recognized where it transgresses Unit 11 at a high angle.

Ore mineralogy is relatively simple and uniform. Medium to coarse-grained sphalerite, varied proportions of pyrite, gray quartz and local occurrences of galena characterize Upper and Lower Limb ores. Unlike these ore zones, Horsetail ore is essentially monomineralic: massive coarse-grained sphalerite generally with very minor pyrite and quartz. The most interesting concentrations of galena in the Fowler orebody occur at the up-dip ends of some of the Horsetail horizons and in gash fractures between individual Horsetail layers. Sulphides in the Cross-cutting and Upper Contact ore zones are quite varied but normally consist of massive medium- to coarse-grained sphalerite and pyrite with quartz. Segregation layering, defined by alternate sphalerite and pyrite-rich layers, is locally prominent in massive sulphides parallel to the two major faults. In places, inclusions of ribbon-like anhydrite, rounded quartz, diopside, dolomite and tremolite are abundant. There is a tendency toward finer grain size, increasing numbers of inclusions, and greater development of Durchbewegung textures along the Fowler fault in a direction down dip away from the Upper Limb ore zone and thence out along the Unit 12/13 contact. Mineralization in both the Cross-cutting and Upper Contact ore zones truncates bedding at high angles. In places along both faults there are silicified zones consisting of masses and pods of white "bull" quartz+calcite+disseminated pyrite and sphalerite+breccia fragments of diopsidic wallrocks. Silicified zones can be difficult to identify but are inferred where anastomosing veins of diopside form trellis-like patterns in dolomite. Figure 18 shows in diagrammatic form the interpreted "proto" Fowler syncline fold hinge and associated ore zones within it during early stage 2A dismemberment. The Fowler fault is interpreted to have formed as a radial extensional fracture approximately axial planar to the Fowler syncline. Sulphide ore filling it became the cross-cutting ore zone. Another such fracture is located at the base of the Lower Limb. As the Fowler and Sylvia Lake synclines evolved and competed for space, the Upper Limb of the Fowler syncline detached from the Sylvia Lake limb and was transported westerly *relative* to the Sylvia Lake limb along the Sylvia Lake slide. Points of detachment are thought to be in Unit 11 at the Fowler and Sylvia Lake orebodies representing nearly 5000 feet of displacement. Apparent net displacement is 4200' following phase 2B strain of opposite rotation sense. (Fig. 11). The Lower Limb is seen as an immense tectonic mullion that broke out between radial extensional fractures in the hinge of the Fowler syncline. It is now thought that significant differences in mechanical response to folding existed between the Upper Limb of the Sylvia Lake syncline (structurally above Unit 13) and the anhydrite-rich core such that it is possible that much, or most, tectonic transport may have been the Sylvia Lake limb transported to the SE (counter-clockwise rotation).

Evolution of the Fowler Orebody

Just prior to the breakup of the Fowler syncline, conformable ore now represented by the Upper and Lower Limb ore zones is interpreted to have migrated by plastic flow and metamorphic fluid phases into the Crosscutting/Upper contact extensional fracture (Fig. 18). This was accompanied by local silicification as silica was mobilized with sulphides into the extensional (dilatent) zone. There was also considerable migration of calcite and some lead into the extensional zone. With complete segmentation and dismemberment of the Fowler syncline, anhydrite enveloped the Lower Limb rock mass (Fig.14). At this time, anhydrite-sulphide tectonite developed along the Fowler and Upper contact faults and the Fowler and Sylvia Lake orebodies were separated by 5000 feet along the Sylvia Lake slide. Phase 2B deformation of the opposite, or clockwise, rotation sense, subsequently rotated elements of the core of the fold, Units 12 and 13 specifically, into positions cross-cutting Unit 11 and axial planar to the upper limb, (Fig. 13). This was facilitated by phase 2B ductile reactivation of the Sylvia Lake slide.

The **Upper Fowler** orebody structurally overlies the Fowler (Fig. 11) (underlies stratigraphically). It is an elongate, tabular orebody plunging N20°E at 1°-20°; longitudinal dimensions exceed 6000 feet. Width along strike increases down-plunge from 100 feet to over 400 feet. Thicknesses vary from 1 to 10 feet; contacts with footwall and hangingwall are sharp. Upper Fowler ore is localized along a low angle fault referred to as the Upper Fowler fault. As a result, Upper Fowler mineralization is not stratiform, but occurs in contact with Units 7, 8, 9, and 10 (Fig. 19).

Ore consists of fine-to medium-grained, light chocolate brown sphalerite with very minor fine-grained pyrite in a fine-grained calcitic marble matrix. Rounded dolomitic marble or diopside inclusions are abundant yielding Durchbewegung textures. Minor coarser-grained sphalerite occurs in thin layers, extensional fractures, and irregular veins in both the hangingwall and footwall of the fault. Locally, in competent silicated units, ore extends for short distances away from the fault along two sets of fractures, one set paralleling the bedding, the other in a shear orientation parallel to the fault. Upper Fowler ore is unique in that no concordant "source" bed can be identified for any of the host rock units, though the 7/8 contact is suspected.

The **Mud Pond** orebody is the most westerly in the Balmat Mine (Fig.15). It is located in Units 6,7, and 8 in a refolded ductile fault within a minor fold in the hinge of the Sylvia Lake syncline. The orebody extends at least 2000 feet downplunge, trends N25°E and plunges gently at 10°- 15°. A sister orebody, the Davis, occurs along the eastern extension of the same ductile fault that hosts the Mud Pond orebody. It appears at this early point of development of both orebodies that Mud Pond mineralization is transgressive along the base of Unit 8 hangingwall to the ductile fault which crosses it and that Davis ore is transgressive across the top of Unit 8 footwall to the fault some 400-500 feet farther east..

Unassigned Orebodies

The **Sylvia Lake orebody** is located on the northwest limb of the American anticline (Fig. 11). From surface to 900 feet ore may occur as a comformable band in Unit 11 and also along a transverse shear plane extending from the conformable band across Unit 12. Below 1,100 feet the ore is localized along a major ductile fault at the contact of Units 11 and 12. The body is tabular, with thicknesses of 2 to 10 feet and strike lengths of 200 to 300 feet. Characterized by fine to medium grain size and numerous inclusions of wall rock, "Durchbewegung" textures are common. It is now known to represent detached remnants of ore in the Sylvia Lake limb of the Fowler syncline. As such, the Fowler and Sylvia Lake orebodies were initially one contiguous mass before detachment along the Syliva Lake slide.

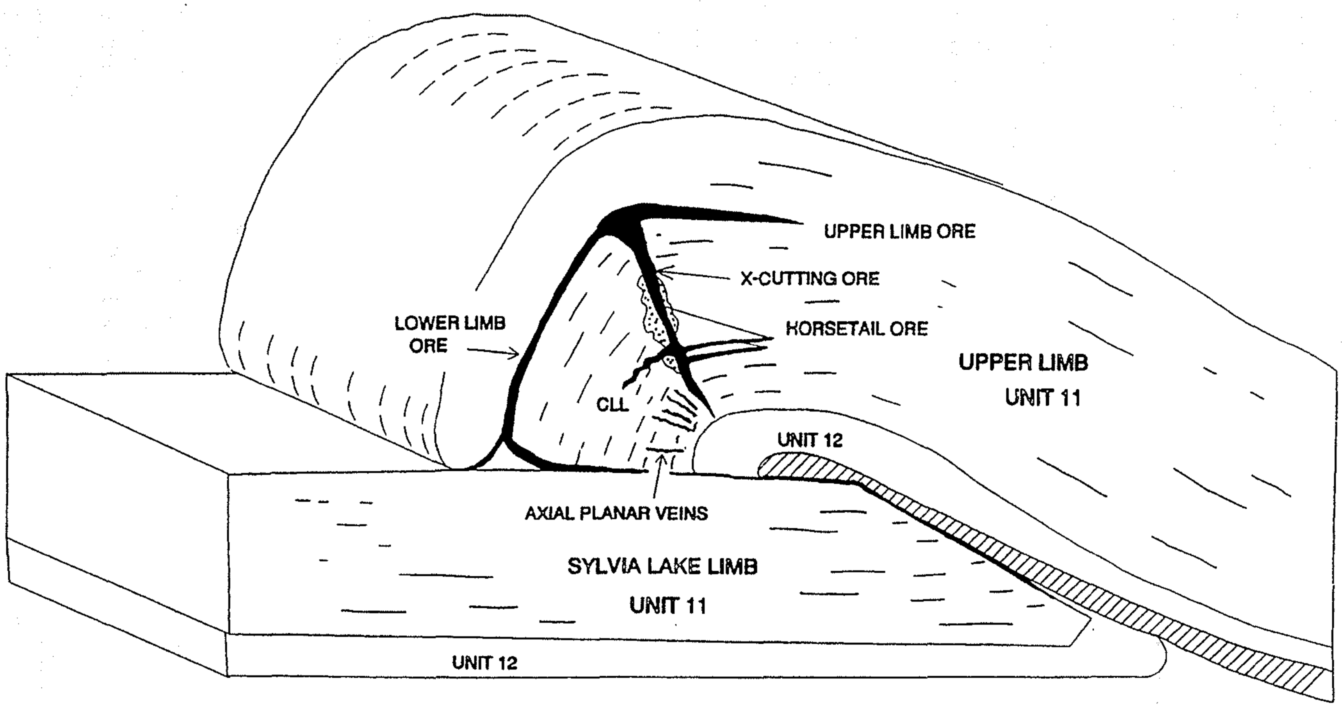

Figure 18. Three-dimensional section through the Fowler/Sylvia Lake orebodies during initial stages of Phase 2A fold dismemberment. Net displacement is N55°W, 4200 feet.

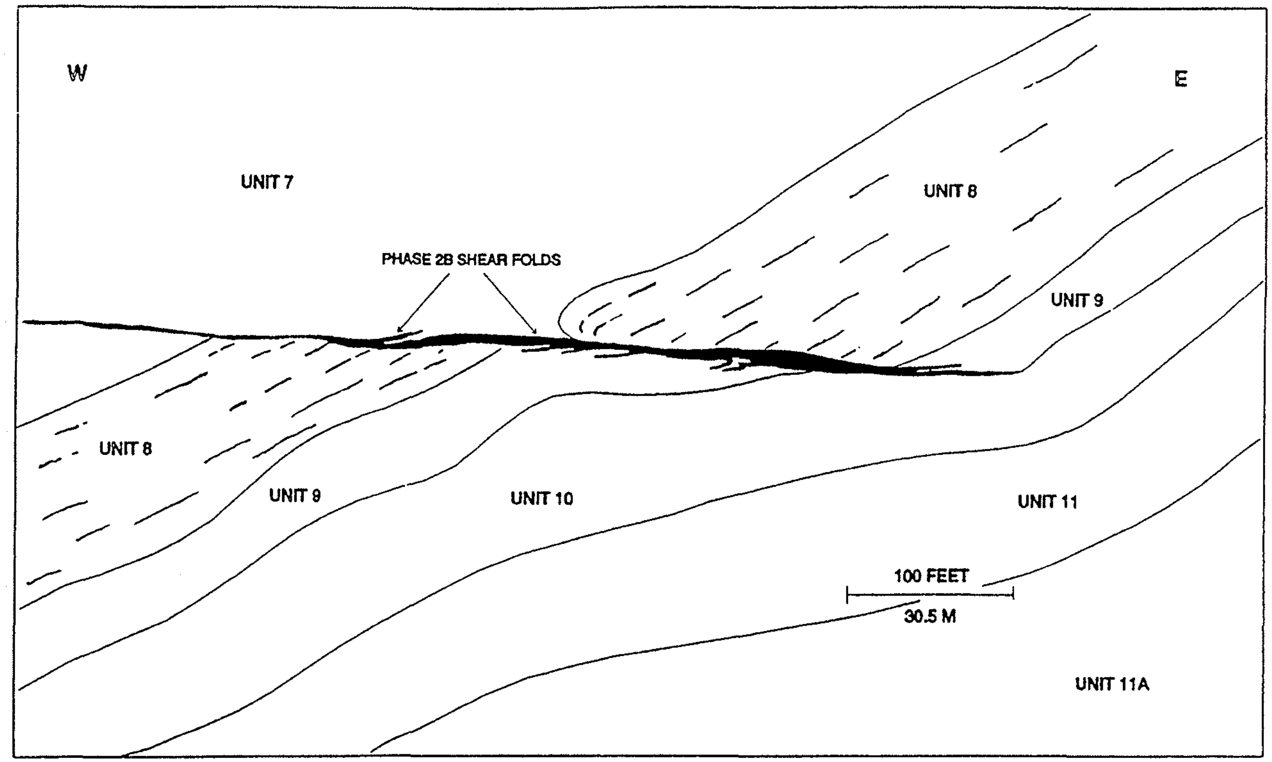

Figure 19. W-E section through the Upper Fowler orebody. Durchbewegung ore cross-cuts units 7–10. Phase 2B shear folds display clockwise rotation senses which oppose those incurred during phase 2A. Hangingwall unit 8 was originally emplaced farther west than footwall unit 8 at the end of phase 2A.

The **Wight** orebody (Fig.15), is a minor occurrence in the immediate hangingwall of the Wight talc mine workings. The ore shoot is lenticular and limited to a thin diopside-quartz member of Unit 12 at the contact with Unit 13. Thickness of the lens is from 2 to 14 feet, strike length a maximum of 600 feet, and down-dip it is restricted to a vertical range of 150 to 400 feet below the surface.

Distribution of Metals in the Ores

Investigation of the distribution of minor and trace metals in the sphalerite, both laterally and stratigraphically, has been done by analysis of flotation concentrates made from drill core composites of orebodies (Swanson 1979). Lateral variations of Fe, Hg, Cu and other minor and trace elements in sphalerite do not appear to fit into well-defined zonal patterns within any of the orebodies. Between orebodies, however, some consistent stratigraphic controls are evident. Most strikingly, the Hg content in sphalerite gradually decreases stratigraphically upward culminating in an abrupt drop to an almost background level in the Main and Streeter orebodies, highest in the column. Content of Fe and FeS in sphalerite consistently increases upward in the column, with the exception of Fe in the stratigraphically intermediate American and Number One sphalerites which is as high as in the uppermost Main and Streeter orebodies. Differences in cobalt and nickel concentrations in orebody pyrite VS. disseminated pyrite in host rock marble led Doe (1962A) to the conclusion that orebody pyrite is not related genetically to that in the surrounding metasedimentary strata, and that the carbonates are not the primary source of the ore metals. Arsenic has been noted in the form of trace to minor occurrences of jordanite, orpiment and realgar, and arsenopyrite in the Main and Fowler orebodies.

Lead Isotopes

Results of early isotopic studies (Doe 1962B) showed that lead isotopic compositions lie close to the normal growth curve for conformable ore deposits (Stanton and Russell 1959). Before that time, sulphide ores were interpreted to be of igneous, hydrothermal replacement origin (Doe 1960). Later, Doe concluded (1962B) that ore lead could have been extracted from nearby granite only if radiogenic lead had been added to the feldspar in the granite after the formation of the ores. While not completely negating this possibility, it was thought that hydrothermal replacement was a less promising candidate for formation of the orebodies. Reynolds and Russell (1968) showed that small but distinct differences exist between orebody lead and rock lead at Balmat. It is apparent from existing analyses that ore lead compositions differ substantially from many Mississippi Valley type deposits (Brown and Kulp 1959; Fletcher et al. 1978) which are characterized by radiogenic, or J-type, lead (Heyl et al. 1974).

Sulphur Isotopes

Isotopic compositions have now been determined for most of the known anhydrite horizons in the Balmat stratigraphic column, demonstrating large changes in composition from isotopically light sulphate sulphur in Unit 6 (average $\delta^{34}S$ = 9‰) to heavy sulphate sulphur in Unit 11A ($\delta^{34}S$ = 30‰ maximum), followed by a decrease to lighter sulphate in Units 13 and 14 ($\delta^{34}S$ = 17 to 20‰; Figure 11; Whelan et al. 1984). Such fluctuations have also been recognized in Phanerozoic evaporite but over longer time spans. Early work by Solomon (1963) led to the suggestion that sulphide sulphur was not magmatic in origin but probably marine.

Close-spaced sampling of two major anhydrite sub-units has shown sulphur isotope variations which further detail cyclical events in the deposition of Balmat evaporite. The lower (Unit 6A) anhydrite and upper (Unit 11A) anhydrite give $\delta^{34}S$ values from 7.6 to 10.2‰ and 24.1 to 30.1‰ respectively, a substantial difference in isotopic composition considering the intervening stratigraphic interval of only about 1000 feet. Further, the values within each anhydrite bed increase systematically from bottom to top stratigraphically.

These variations are believed to be premetamorphic in origin and are attributed to simultaneous evaporitic sulphate deposition and bacterial sulphate reduction within a restricted basin (Whelan et al. 1984; Whelan et al. 1990).

Sulphide $\delta^{34}S$ values also show interesting variations. Two groups were analyzed, one of the same suite of orebody sphalerite composites used in the metal distribution study, the other a collection of various sulphide-sulphate combinations within the Fowler orebody.

Small variations of $\delta^{34}S$ in sphalerite are established in the analysis of orebody composites. Total range of values is 13 to 15‰, considerably less pronounced than the range of 8 to 30‰ for anhydrite (Fig. 20). Sphalerite in Units 6 through 9 has isotopically lighter sulphur, that in Unit 11 the heaviest (up to 15.38‰) and that in Units 12 through 14 again have relatively light sulphur. Curves drawn from $\delta^{34}S$ variability VS. stratigraphic position are dissimilar for both anhydrite and sphalerite (Fig. 20). The two do not vary sympathetically, suggesting that the orebody sulphur was not extracted directly from coeval seawater sulphate (Whelan et al. 1984).

It is evident that large-scale, pre-metamorphic sulphur isotope distributions have been preserved during metamorphism. Preliminary data from the Fowler orebody sulphides, however, indicate that metamorphic changes in sulphur isotope systematics have been superimposed on the original isotope distributions. Specifically, sulphide $\delta^{34}S$ values are lightest in the axial region of the Fowler syncline and increase gradually away from it. Preferential migration of isotopically lighter sulphur to the hinge region of the early fold is consistent with the data. Orebody sulphide $\delta^{34}S$ compositions are distinctively different from those of pyrite from surrounding metasedimentary rocks as reported by Buddington et al. (1969), Brown (1973) and Whelan et al. (1984). Pyrite from meta-sedimentary strata is isotopically light, averaging -10‰ $\delta^{34}S$ (Buddington et al. 1969). Pyrite disseminated in the host marble but removed from massive sulphide is also isotopically light and therefore distinct from orebody sulphide (Whelan et al. 1984).

Ore Genesis

One of the most interesting and greatest challenges of Balmat geology is concerned with the genesis of the ores. It is clear that the ores are pre-metamorphic in origin and have been extensively reworked, remobilized and recrystallized during metamorphism. Genetic clues have been largely erased save for bulk geochemical trends, massive nature of the mineralization, and stratigraphically equivalent disseminated traces of mineralization persistent distal to some orebodies. Accordingly, several genetic models have been proposed. These include: Mississippi Valley type; volcanogenic exhalative; and sedimentary exhalative.

Metamophosed Mississippi Valley Type: Probably because the ores are hosted by carbonate rocks the MVT model is attractive to many. The basic tenet of this model is that upon high-grade metamorphism epigenetic sulphides initially disseminated in the stratigraphic pile were drawn to low pressure sites or dilatant zones in fold hinges where they presumably accumulated as massive sulphides. This would require wholesale evacuation of metal to hinge zones, leaving no traces or depletion haloes behind. Difficulties with this model are that orebody pyrite and host rock pyrite compositions are dissimilar, Pb isotopic compositions between ore and host rocks are different, and there are no geochemical haloes or depleted auras around fold hinges. There are also many unmineralized fold hinges which should host at least minimal mineralization if premetamorphic mineralization was disseminated over broad areas. In the case of Pb isotopic values, the approach to single stage evolution of the lead isotopes requires the metals to have been leached from large volumes of heterogeneous source rocks as suggested by Doe and Stacy (1974). Differences between ore and rock lead, however, preclude the carbonate and granitic rocks in the area as primary sources of the lead.

Volcanogenic Exhalative: This genetic model was proposed by some investigators primarily because of the massive nature of the ores and approach of Pb isotope systematics to single-stage growth compositions

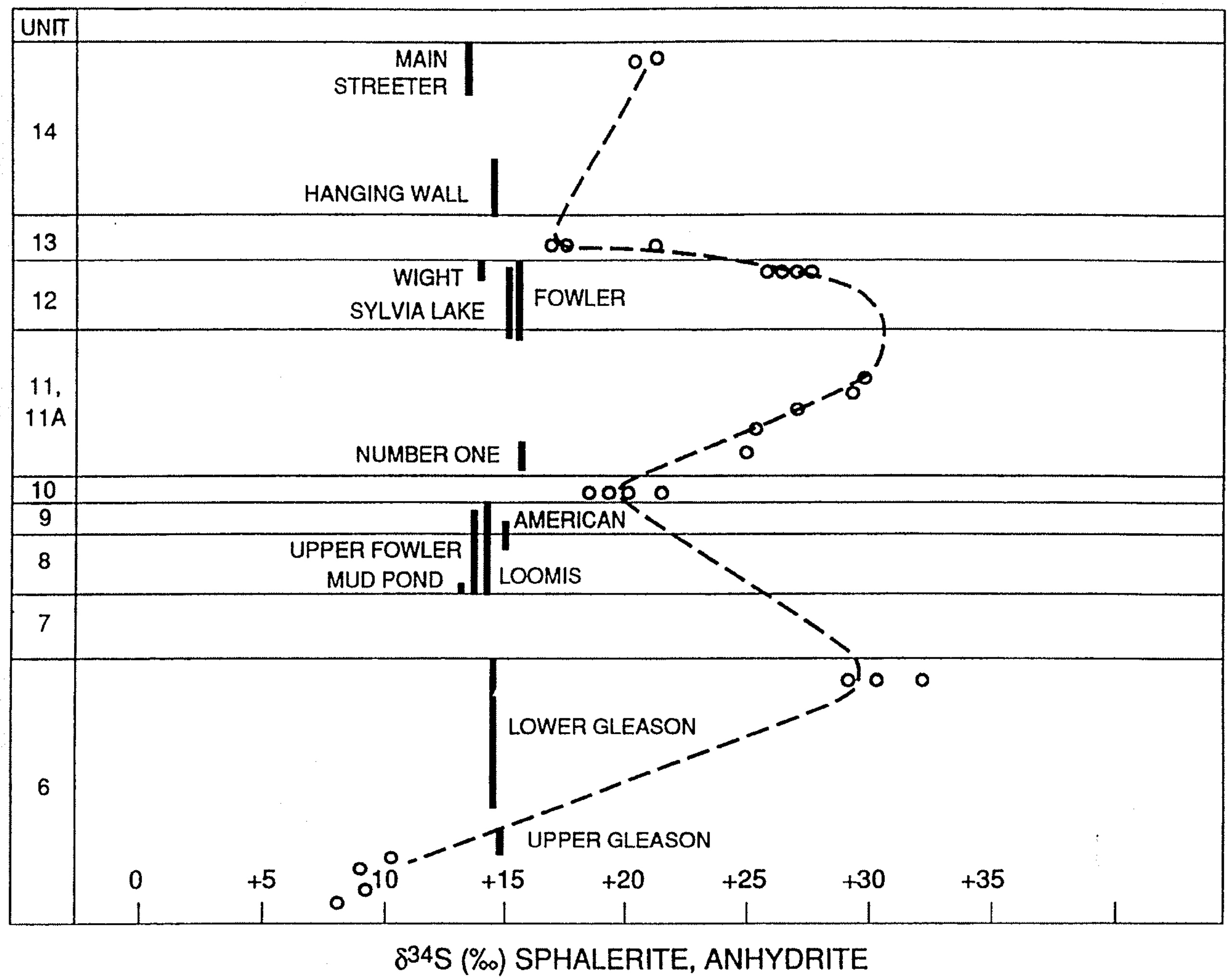

Figure 20. Sulphur isotope variations in orebody sulphur and anhydrite sulphate plotted against stratigraphic position.

similar to many know volcanogenic deposits. A requirement of this model is that vent sites would bear a distal relationship to the site of deposition. Inasmuch as there are essentially no intercalated volcaniclastics rocks in the Balmat stratigraphic section, this genetic model appears inadequate to explain available data. As well, there are no pipe-like "stringer ore" zones developed in altered or silicified volcanics in the stratigraphic footwall of any of the massive sulphide lenses.

Sedimentary Exhalative: Certain aspects of the orebodies lend themselves well to a "SED-EX" model (Swanson 1979; deLorraine and Dill 1982). These are principally the massive nature of the ores, apparent minor element compositional dependence upon stratigraphic position, localization within clean carbonate strata and laterally equivalent . disseminated traces of sulphide. Basic features of this model involve large volumes of chloride-rich fluids leaching metals as they migrated through the sedimentary/volcanic pile. Evolved basin brines, perhaps chemically similar to those having produced Mississippi Valley type deposits (Whelan et al., 1984), would constitute ideal ore fluids. Fluid migration could have been initiated by sudden collapse of the sedimentary pile as it reached a critical thickness, leading to basin dewatering (Cathles and Smith 1983). Migration could also have been the result of seismic pumping, or have been driven by convective circulation driven by plutonism. In any case, metalliferous brines ultimately would be channelled through conduits, such as faults, to discharge sites on the sea floor. The process would have operated repeatedly to produce the observed stratigraphic spread of the mineralization. Deposition would necessarily be rapid, leading to accumulation of massive sulphide sheets and lenses. Metals, ultimately derived from sediments/volcanic rocks and leached from them by large volumes of chloride-rich brines, would be carried in solution in complexed form. Hg would be depleted earliest from source strata correlative with higher values in stratigraphically lower orebodies (Swanson 1979). Sulphur may have been derived from evaporite beds in the sedimentary pile and complexed in the same fluids. Such large-scale fluid movement might be expected to mix and homogenize sulphur isotopes derived from heterogeneous source beds and might have the same effect on lead isotopes as well. Thus, the requirements for essentially uniform sulphur isotopic composition and approach to single-stage Pb isotope systematics of the ores would be satisfied. A "SED-EX" model accounts for the stratiform/stratabound nature of the ores and compositional dependence on stratigraphic position as well. General presence of gray quartz and local conspicuous amounts associated with concordant sulphides may represent silica exhalite. Less obvious is the conduit or discharge vent site(s) for the metalliferous fluids. A purely speculative candidate might be the Balmat Fault. A long, protracted history, perhaps extending back to deposition of host rocks, is suggested by 1) lithic differences in Upper Marble formation on either side of the fault trace, and 2) presence of the Balmat amphibolite body on the fault trace. Foliation in the amphibolite is folded by second-phase isoclines, indicating that it was intruded either pre-or syn-early-phase folding. These two scanty lines of evidence suggest that the Balmat fault is relict of an old structure tapping a deep source for the metagabbro, but are inconclusive as to whether it was an active structure during sedimentation, let alone whether it may have served as conduit to the sea floor. But to speculate further, it might be reasonable to postulate a mild intracratonic rifted environment accompanied by evaporite deposition in foundered crustal blocks. Minor mafic plutonism may have played a role in driving convective cells which leached metals in their paths.

Summary

Orebodies of the Balmat-Edwards-Pierrepont district are believed to have been of the massive stratiform sulphide class of sedimentary exhalative association.

Minor element distribution and sulphur isotope variations suggest that the pre-metamorphic sulphides had a close stratigraphic affinity with the host rocks, whose lithology and sedimentary environment are fairly well understood. Orebody compositions depend on stratigraphic position. Accordingly, the sulphides appear to have been deposited syngenetically on the Grenville continental shelf or shallow intracratonic (rifted?) basin in shallow marine waters of restricted circulation and dimension. Deposition was characterized by cyclical sedimentation of siliceous dolostone and evaporitic anhydrite. Deposition of sulphide ores recurred over a stratigraphic interval of 1800 feet. The Balmat fault may have been active during sedimentation and may be a manifestation of mild intracratonic rifting. Lithic differences across the fault trace suggest the possibility that it exerted some control on sedimentation, perhaps even to the extent that it or others like it caused restricted circulation leading to evaporite deposition.

There is no obvious source of the metals. No evidence exists for sea floor springs nor for association with volcanism. It is tentatively proposed that the sulphides were sedimentary exhalative with perhaps a distal relationship to the vent site. Metals may have been leached from sediments or volcanic rocks lower in the stratigraphic pile and carried as complexes in solution VIA permeable pathways and along faults into restricted basis or lagoons, where they debouched on the sea floor as sulphide sediments. Sulphide sulphur may have also been leached from evaporitic sediments in the pile, homogenized, and complexed into the same ore fluids as the metals. Ore fluids may have been evolved basin brines, chemically similar to MVT-type fluids, or may have been highly-charged chloride brines in convective circulation cells driven by plutonic "heat engines". The exhalative process was repeated numerous times through the stratigraphic sequence.

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