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Sedimentologic, Geochemical, and Mineralogical Features of the Belt Supergroup and their Bearing on the Lacustrine versus Marine Debate

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Abstract

Comparisons of Belt rocks with sediment of the lacustrine Green River Formation have been used to promote the idea that the Belt Supergroup may have accumulated under lacustrine conditions. However, comparison to other sedimentary sequences with similar facies types shows that such an approach yields ambiguous results at best. Because a lacustrine basin is in essence a closed system, the bulk chemistry of its sedimentary fill should compare closely to the average composition of surrounding source rocks. Major-element data show large compositional discrepancies between the likely source rocks of the Belt Supergroup and the average composition of major stratigraphic units of the Belt Supergroup. These discrepancies are most pronounced for highly soluble elements (Na, Mg, Ca) and are best explained through continuous exchange (export/import) with the Proterozoic ocean. The observed chemical imbalances are incompatible with a lacustrine setting for the Belt Supergroup. Sulfur content and sulfur isotope data of Belt rocks also suggest connection to the ocean reservoir. Presence of glauconite in various Belt units further confirms the marine character of the Belt basin.

Introduction

The question whether the Belt Supergroup was deposited in an epeiric sea or an intracratonic lacustrine basin has been of concern to geologists since Walcott (1914) suggested a lacustrine origin nearly a century ago. The idea that Late Proterozoic cratons were assembled in a supercontinent (Rodinia) has led to a variety of paleogeographic reconstructions, relying on various combinations of paleomagnetic data, stratigraphic/lithologic comparisons, and matching of tectonic features (Piper 1982, Sears and Price 1978, Young 1992, Storey 1993). Several of these reconstructions suggest an epicontinental or possibly an episutural setting for the Belt basin (Stewart 1976, Sears and Price 1978, Piper 1982, Hoffman 1988) and have contributed to the revival of a lacustrine interpretation (Winston 1986) in that they allowed for an intracratonic location of the Belt basin. However, with regard to location of Late Proterozoic cratons, paleomagnetic data are limited and allow a whole range of supercontinent reconstructions (Storey 1993, Worsley *et al.* 1993). Published models variably place the Belt basin 1) at the end of a gulf that opens towards the Proterozoic ocean (Piper 1982, Cressman 1989); 2) at a passive continental margin facing the Proterozoic ocean (Bond *et al.* 1984); or 3) along the margins of a rift developing between Antarctica/Australia and North America (SWEAT hypothesis, Moores 1991). The three scenarios are interpretations of essentially the same geologic data base and differ with other constrained paleocontinental reconstructions of Early Cambrian and latest Vendian times (McKerrow *et al.* 1992). For example, in *scenario 1* Siberia is thought to have been connected to the western margin of North America (Sears and Price 1978, Piper 1982), yet this would require substantial and complex movement of Siberia by latest Vendian time (McKerrow *et al.* 1992). *Scenario 2*—although in agreement with an earlier interpretation of the Belt basin as an epicratonic re-entrant of a sea to the west (Harrison 1972)—conflicts with a rift-related interpretation of the Windermere Group (Stewart 1976). The SWEAT hypothesis, *scenario 3,* has problems because there are significant differences between Antarctica and western North America with regard to degree of deformation and geologic history during Late Proterozoic and early Paleozoic times (Storey 1993). The rift suggested by the SWEAT hypothesis (Storey 1993) is wide enough to accommodate an extension of the Proterozoic ocean several times the width of the Red Sea, making it unlikely that a Belt basin bordering such a rift could have remained landlocked. At present, none of these models can be tested because of problems with accurate determinations of the timing of extensional and collisional events. Thus, what is presently known about Late Proterozoic paleogeography is not suited to lend credibility a landlocked interpretation of the Belt basin.

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Sedimentologic Comparisons

Earlier discussions of a marine versus lacustrine origin of the Belt basin have been conducted with a view towards sedimentological comparisons (Winston 1986). One of the major arguments for his lacustrine reinterpretation was a comparison of Missoula Group sediment to the lacustrine Green River Formation (Eocene). In the Green River Formation a lacustrine setting is indicated by a range of features, such as 1) epicratonic location, 2) centripetal facies distribution (Bradley 1964), 3) freshwater biota (Bradley 1931, Buchheim and Surdam 1981), and 4) unusual evaporite minerals, such as trona, shortite, and northrupite (Bradley and Eugster 1969). Considerations of geochemical equilibria and the composition of seawater (Holland 1984) show that these latter minerals could not have precipitated from marine waters but rather from alkaline brines that evolved from the evaporation of terrestrial waters (Bradley and Eugster 1969, Hardie and Eugster 1970, Eugster and Hardie 1975, Surdam and Wolfbauer 1975). The Belt Supergroup lacks features 2, 3, and 4, and the only remaining similarities are a possible epicratonic setting and a general resemblance in sedimentary structures and facies going from basin margin to basin center. However, direct inspection shows that the resemblance is not as close as one might perceive from comparing (already generalized) published descriptions, and one could with equal justification cite the Triassic of central Europe or the western United States, as well as the Late Devonian of the Appalachian basin (Catskill sequence), as containing intervals that are sedimentary analogs of the Missoula Group.

Much of the Belt Supergroup (Ravalli Group, middle Belt carbonate, Missoula Group) shows an analogous development to the tripartite Triassic of central Europe that was deposited in an epicontinental marginal marine basin (Geyer and Gwinner 1986). Sedimentation began with a terrestrially dominated series of red sandstones and mudstones (Buntsandstein) that contains deposits indicative of short marine incursions. The Buntsandstein is followed by a carbonate-dominated marine interval (Muschelkalk). The sequence is capped by varicolored mudstones and sandstones of the Upper Triassic (Keuper) that show a remarkable resemblance to red and green mudstones of the Belt Supergroup. The Keuper contains numerous intervals (dark marls, dolomite horizons, evaporites) deposited during marine incursions. Marine origin of such intervals can usually be verified by considerations of paleogeography and fossil content (Geyer and Gwinner 1986). Possible Beltian analogs of such intervals are light colored, thin intervals of dolomitic argillites that are found within intervals of red and green argillites of the Belt Supergroup.

Similarly, Lower Triassic sediment of the Moenkopi Formation in Utah shows fluvial red beds (Collinson and Hasenmueller 1978, Carr and Paull 1983, McKee 1954) that are comparable to those of the Belt Supergroup (Spokane Formation). Laterally, these redbeds grade into interbedded red and green shales (Thaynes Formation) that are comparable to red-green intervals of the Missoula Group. Interfingering with marine carbonates indicates that red-green intervals of the Thaynes Formation are marginal marine deposits.

Facies development comparable to the Lower Triassic of Utah also is observed in the Upper Devonian of New York and Pennsylvania. For example, the Walcksville, Beaverdam Run, and Irish valley members of the Catskill Formation (Epstein *et al.* 1974, Walker and Harms 1971) show alternating packages of fluvial sandstones and red and green argillites that resemble the facies development observed in various portions of the Missoula Group. These rocks pass laterally into fossiliferous marine mudstones and sandstones, and have been interpreted as the deposits of prograding muddy shorelines (Walker and Harms 1971, Woodrow 1985).

In these three examples, facies and facies associations that are comparable to what is observed in the Belt Supergroup were deposited in an epicontinental marginal marine basin (central European Triassic), and on alluvial aprons and coastal plains bordering a marine foredeep basin (Moenkopi/Thaynes Formation, Catskill Formation). The examples serve to illustrate that examination of sedimentary structures and facies alone does not necessarily supply enough proof of either marine or lacustrine setting. Inland seas and lake basins have comparatively small energy input via wave and/or tidal action (Shaw 1964), and considering that in absence of biological indicators sedimentary structures and facies merely reflect energy level and sediment supply, the great difficulties to distinguish lacustrine from epeiric sea sediment on physical features alone should not be surprising. A similar conclusion was reached by Grotzinger (1986) in a study of sedimentary cycles in the Wallace Formation of the Belt Supergroup.

It has been suggested recently (Awramik *et al.* 1993) that one of the stromatolite types in the Belt Supergroup (*Collenia Undosa*) might be of lacustrine origin. *Collenia Undosa* has been described from the Spokane Formation (Walcott 1914), and occurs within thin intervals or pods (typically less than one meter thick) of limestone and/or dolomitic shale (Birkholz 1967, Phelps 1969). The discontinuous, lenticular, and pod-like nature of *Collenia* beds is consistent with formation in lakes that formed on extensive coastal and flood plains (Winston 1986) of the Spokane Formation. Presence of lacustrine intervals in such a setting is to be expected and also has been described from coastal-plain and flood-plain deposits of the three Phanerozoic sequences mentioned above (Geyer and Gwinner 1986, McKee 1954, Halperin and Bridge 1988). Although *Collenia Undosa* may well indicate lacustrine deposition at various sites within the alluvial/coastal plain bordering the shoreline of the Belt basin, it does not furnish any information about the composition of the water body that occupied the central portion of the basin.

Obviously, the examination and comparison of sedimentary structures, facies, and facies associations do not make the lacustrine versus marine decision any easier. However, this does not mean that the issue at hand cannot be resolved following different lines of inquiry.

Geochemical Mass Balance

An alternative way to test a lacustrine versus marine interpretation is a geochemical mass balance calculation. In essence, the source material of a geochemical process is compared with the final product, and a determination is made as to whether and to what degree a given element has increased or decreased in abundance. The technique has found wide application in the study of element fractionation in various geologic processes, *e.g.*, anatexis (Shaw 1970), magma evolution (Gast 1968), metasomatism (Gresens 1967), and wall rock alteration (Sales and Meyer 1948, Meyer and Hemley 1967). In particular the latter application provides a good analog for a mass balance approach to the Belt basin, with unaltered host rock, altered vein envelopes, and ore fluids being the equivalents of average Belt basin source rock, average Belt basin sediment, and average basin water respectively.

If the Belt basin was a hydrologically closed basin comparable to the Green River basin, particles and solutes produced by weathering in the surrounding drainages should accumulate in the basin and the average chemical composition of the basin fill should closely match the average composition of its source rocks. Conversely, if there was an oceanic connection, a net export or import of soluble species (in particular Na^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}) may show up as a significant compositional imbalance between the average source rock and the average basin sediment.

Over the past 10 years, the author has analyzed a large number of Belt rocks (approximately 400 analyses) with INAA and XRF to compile a comprehensive data base of Belt basin geochemistry. Averages calculated for shale samples of various formations of the Belt Supergroup show the same overall compositional uniformity (table 1) that was noted by Harrison and Grimes (1970), and indicate 1) effective mixing and homogenization of sediment during transport from the source areas, 2) similar average composition of source areas with respect to major elements, and 3) persistence of conditions 1 and 2 throughout Belt basin depositional history.

These data and data published by Ross (1963) were used to calculate average compositions for main lithologies (shale/argillite, sandstone, carbonate) in each formation. For each major subdivision of Belt stratigraphy (lower Belt, Ravalli Group, middle Belt carbonate, Missoula Group) weighted average compositions were calculated (necessary because lithologies do not occur in equal proportions). Weighting took into account proportions of lithologies in stratigraphic sections, thickness and extent of formations, and the state of preservation of the Belt basin. With regard to the latter point, the following should be considered: 1) the Belt Supergroup is strongly dominated by argillites and shales, 2) the Belt basin is a structural basin whose margins have undergone various degrees of erosion, and 3) post-depositional erosion of the basin margins has biased the preserved rock record towards fine-grained clastics. In an attempt to reduce the effect of post-depositional erosion, the sandstone proportion was enhanced so that the assumed sandstone/shale ratio reflected at a minimum the overall ratio of these lithologies in the sedimentary record (Blatt 1992). The fact that the averaged units were deposited over time intervals on the order of 100 million years (Harrison 1972), the domination of sedimentary mass balances by shales (Taylor and McLennan 1985), and the observation that (on a carbonate-free basis) resulting amounts and proportions of immobile elements (Al, Si, Ti, Fe) came close to the upper crustal average (Taylor and McLennan 1985) justifies such an approach.

Besides averages for major stratigraphic subdivisions of Belt stratigraphy (figure 1), average compositions were also calculated for a total of nine lithologic *slices* in the Ravalli and Missoula groups (figures 2, 3), and named after a prominent formation within each *slice*. For lateral equivalency of formations within a *slice*, the correlation charts by Harrison (1972), Harrison *et al.* (1986, 1992, 1993), and Cressman (1989) were consulted.

The mass balance calculation presented in this paper involves numerous assumptions and extrapolations that limit the conclusions that can be drawn from the calculation. For example, determination of weighting factors inevitably involves choices that, to some degree, are arbitrary. Other important factors that influence the calculation are 1) uncertainties about the

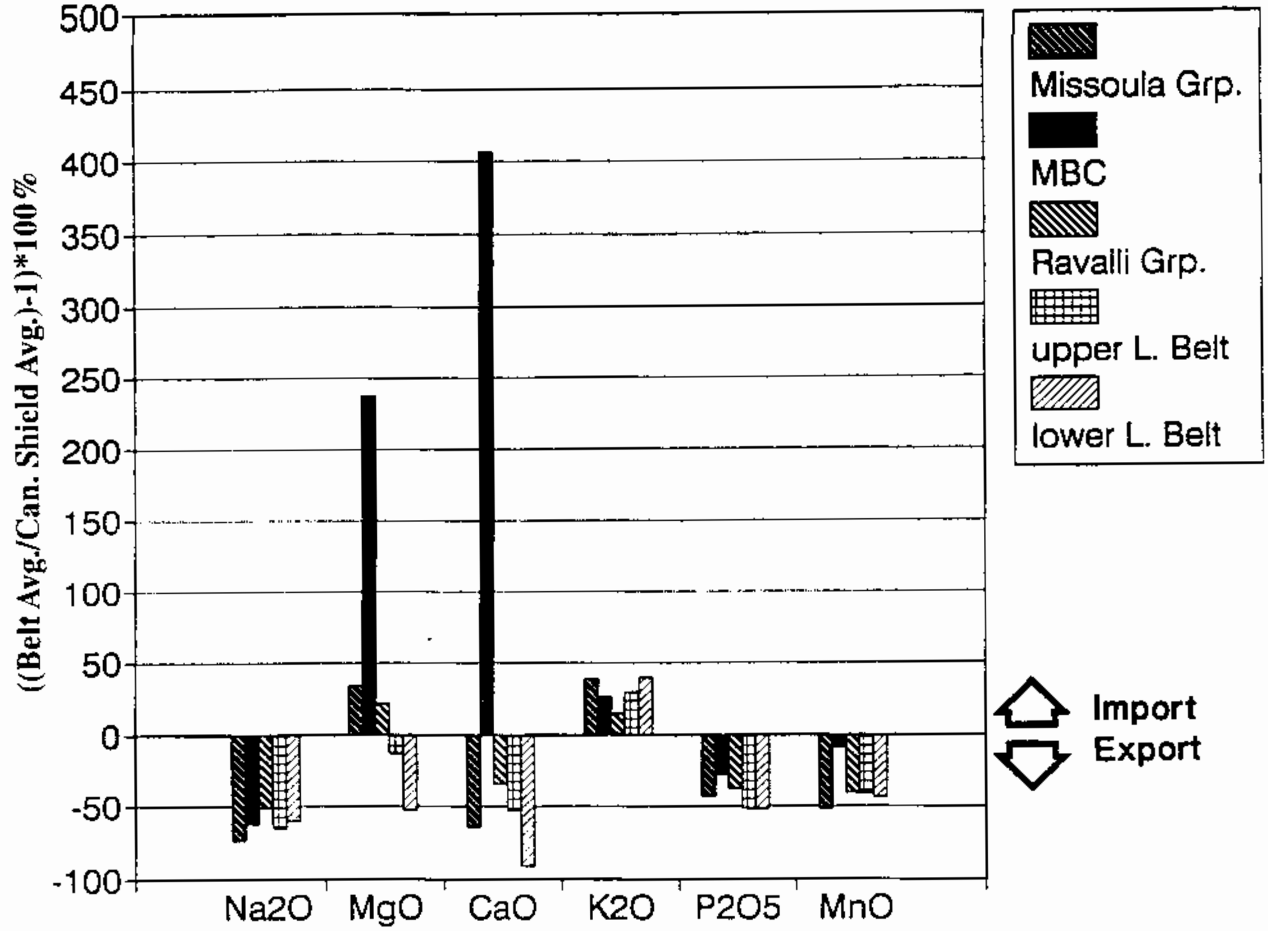

Figure 1. Average compositions of Belt Supergroup subdivisions compared with the Canadian Shield average of Shaw et al. *(1967). The lower Belt (lower) is equivalent of members A–E of Cressman (1989), and the lower Belt (upper) average is calculated for members F and higher and includes data from carbonate rocks of the eastern carbonate shelf of the Belt basin (Newland and Altyn formations). Inclusion of the latter causes the diminished export of Mg and Ca for the upper Lower Belt* slice. *(MBC), middle Belt carbonate. In the legend for figures 1–3, the youngest units are at the top, the oldest at the bottom.*

actual average composition of Belt source rocks, 2) uncertainties about the actual average composition of Belt sediment, and 3) inaccuracies in proportions of lithologies. The impact of these three factors is explored in the following section.

Factor 1: Source Area Composition

Geologic, geochemical and isotopic data strongly suggest that the bulk of the continental crust had formed by the beginning of the Proterozoic, and that from then on the upper crust had an overall granodioritic composition (Taylor and McLennan 1985). Constancy of upper crustal composition is reflected by the absence of secular changes in chemical composition of post-Archean sedimentary rocks, and by the observation that presently exposed upper crust is of fairly uniform composition for widely separated areas (Taylor and McLennan 1985). Table 1 exemplifies this latter point for the major-element composition of the Canadian Shield (Shaw *et al.* 1967) and the Russian Platform (Ronov and Yaroshevski 1969). **G** also shows how closely these regional averages compare to the average upper crustal composition of Taylor and McLennan (1985).

The assumption of an essentially uniform post-Archean, upper crustal composition is well supported by available data (Taylor and McLennan 1985). In principle it can be presumed that comparison of Belt sediments to the average upper crustal composition (Taylor and McLennan 1985, table 1) is sufficient to detect mass conservation versus export or import of soluble species. This conclusion also implies that regardless of which craton the proponents of a landlocked Belt basin wish to place along the west coast of North

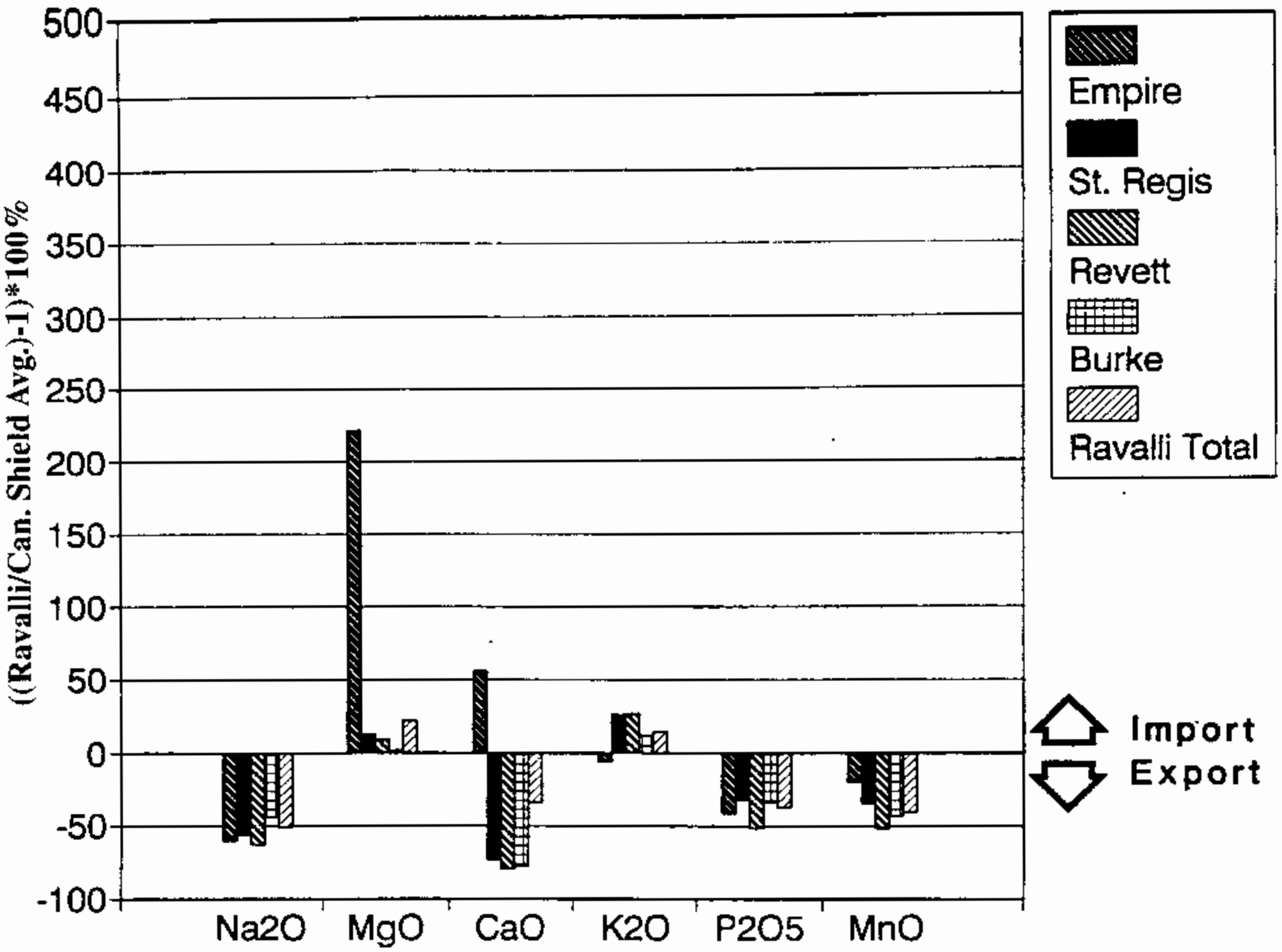

Figure 2. Comparison of lithologic slices of the Ravalli Group to the Canadian Shield average. The Burke slice includes data from the Greyson and Appekunny formations. The Revett and St. Regis slices incorporate data from the Spokane and Grinell formations. The diagram shows the onset of substantial import of Mg and Ca with deposition of the Empire Formation. These conditions continue through deposition of the middle Belt carbonate (figure 1).

America, its average major-element composition will have been very similar to that of the North American craton. Because the Canadian Shield borders the Belt basin, its average composition (Shaw *et al.* 1967) is taken to closely reflect the average source rock of Belt basin sediment.

With regard to the latter assumption, it can be argued that the Canadian Shield only contributed a small portion of the sediment found in the Belt basin, and that its composition should not be used in this calculation (Frost and Winston 1987). Given that there are several upper crustal compositions that can be used (table 1), how do the differences between various average compositions affect the outcome of the observed export/import patterns? To examine this question, the calculation also was performed using the Russian Platform average (table 1) and the average upper crustal composition of Taylor and McLennan (1985) (table 1). However, using these two compositions did not change the already observed export/import patterns (figures 1–3). Most gains and losses showed little change in magnitude (±10%), and with exception of K_2O *(see below)*, changes that were in excess of 10% were all in a direction to further accentuate the already existing imbalances. Thus, no matter what upper crustal average or which shield average is preferred for use as a proxy for the source area of the Belt basin, the outcome of the mass balance calculation will not change substantially.

Finally, if extremes are explored, what impact would an Archean upper crustal source (more mafic composition) have on the mass balance calculation? If an average Archean upper crust composition from Taylor and McLennan (1985) export still dominates Na, and the same export/import patterns as before are observed for Mg and Ca. In any case, crustal residence ages (from

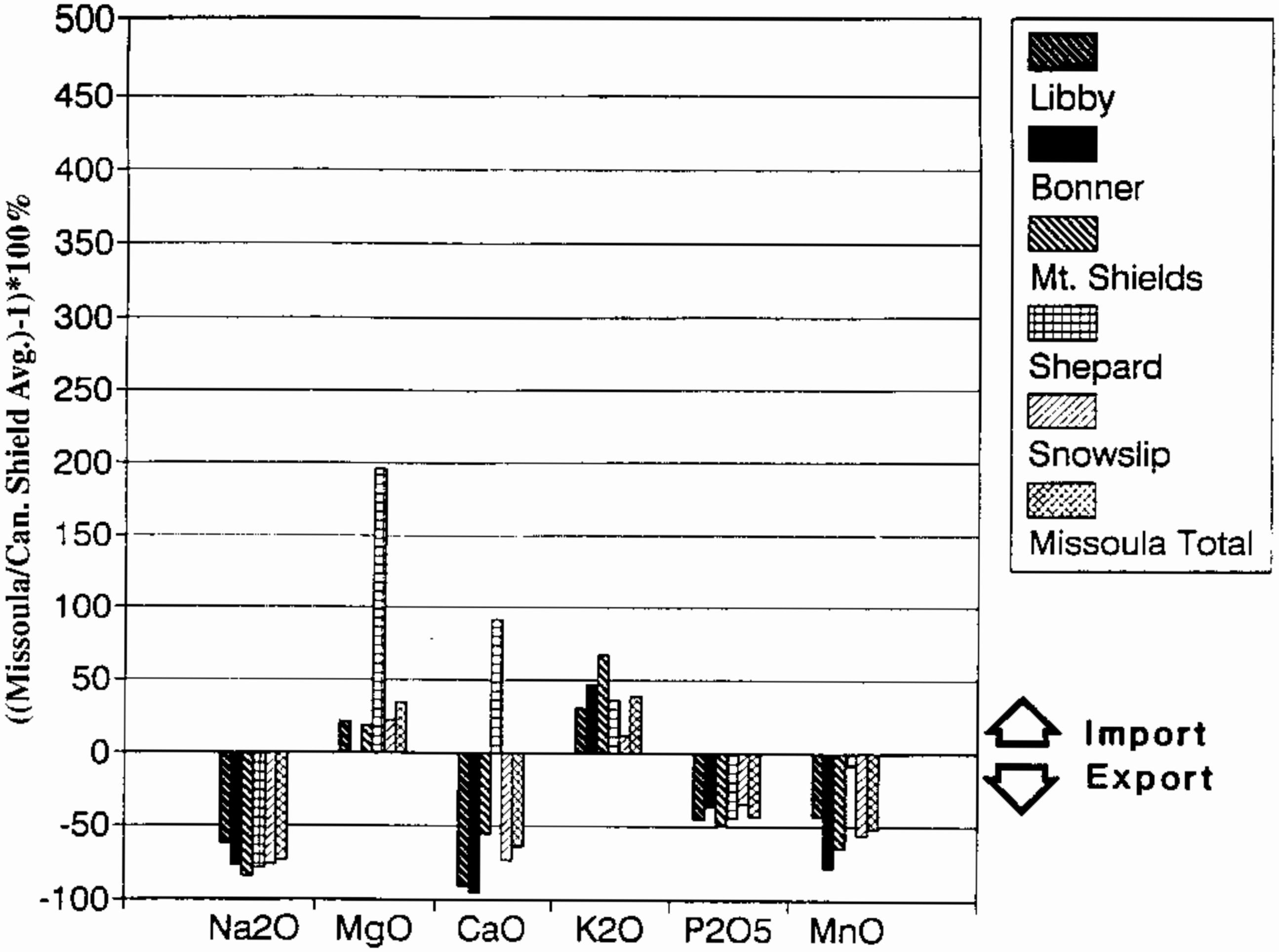

Figure 3. Comparison of lithlogic slices of the Missoula Group to the Canadian Shield average. The diagram shows substantial Mg and Ca import during Shepard deposition, as well as the strong K enrichment in the Mount Shields Formation and the Bonner Quartzite.

Nd isotopes) for Belt sediment average 1.9–2.0 b.y. (Frost and O'Nions 1984) to indicate that there was little contribution of Archean crust to the Belt basin.

Factor 2: Average Composition of Belt Sediment

Determining the average composition of major rock types (shale/argillite, sandstone, carbonate) in a *slice* of Belt sediment is primarily a matter of avoiding sampling biases, and to a lesser degree a matter of analytical procedure. *Slices* were sampled across their stratigraphic thickness, as well as across the extent of the Belt basin. About two thirds of the analyzed samples are shales and argillites, and the remainder are sandstones and carbonates. Also, the observation that the average shale compositions for the various *slices* (table 1) do not differ significantly suggests that sampling biases would only have a minor impact.

Samples were analyzed by XRF and INAA at the University of Oregon, the Radiation Center at Oregon State University, and at the University of Texas at Arlington. Multiple analyses of standards during XRF analyses of Belt rocks show that analytical errors for major elements are below one percent for all elements except Mn (5%). Potassium and iron also were analyzed by INAA and are in good agreement with XRF data. Sodium was only determined by INAA. Multiple analyses of standard rocks indicate that the analytical error for Na is below one percent. Considering this, it is unlikely that analytical errors should have an impact on the calculation.

Factor 3: Proportions of Lithologies

Most of the stratigraphic *slices* considered in this study are a mixture of shales (argillites), sandstones, and carbonates. The proportions of these lithologies

Table 1. Belt basin data recalculated to 100 percent after subtraction of volatiles and expressed in weight percent. Data for Empire, middle Belt carbonate (MBC), and Shepard also corrected for carbonate content. Data for North American Shale Composite (NASC) and post-Archean Australian Shale (PAAS) given for comparison (Gromet and others, 1984; Taylor and McLennan, 1985). (CSA), Canadian Shield Average (Shaw and others. 1967); (RPA), Russian Platform Average (Ronov and Yaroshevski, 1969); (UCA), Upper Crustal Average of Taylor and McLennan (1985). Data for crustal averages are as published, only total iron was recalculated as Fe2O3. These compositions are notaverages *for the respective lithologic slices.*

"Slice"	Prichard	Burke	Revett	St.Regis	Empire	MBC	Snowslip	Shepard	Mt.Shields
Na_2O	1.39	1.61	1.21	1.31	1.60	1.18	1.08	0.88	0.72
MgO	1.31	2.56	3.19	3.10	5.15	2.06	3.65	4.27	2.61
Al_2O_3	19.74	15.43	16.35	16.65	13.14	14.33	14.61	15.90	16.67
SiO_2	66.97	70.05	67.66	67.06	69.53	71.42	69.47	66.75	66.93
P_2O_5	0.09	0.08	0.09	0.12	0.10	0.09	0.10	0.11	0.09
K_2O	5.32	4.41	5.12	5.03	3.37	4.06	4.46	5.93	6.37
CaO	0.44	0.87	0.91	1.12	3.03	2.52	1.57	0.74	0.47
TiO_2	0.58	0.54	0.63	0.59	0.47	0.51	0.54	0.63	0.61
MnO	0.04	0.05	0.04	0.05	0.06	0.06	0.04	0.05	0.02
Fe_2O_3	4.12	4.39	4.80	4.95	3.54	3.77	4.49	4.74	5.51
"Slice"	Bonner	Libby	Ravalli	Missoula	NASC	PAAS	CSA	RPA	UCA
Na_2O	1.09	1.68	1.44	1.20	1.14	1.20	3.46	3.2	3.9
MgO	3.39	3.20	3.12	3.44	2.86	2.20	2.24	2.4	2.2
Al_2O_3	18.39	16.72	15.93	16.34	16.90	18.90	14.63	15.3	15.2
SiO_2	64.34	66.94	68.19	66.73	64.80	62.80	64.93	66.0	66.0
P_2O_5	0.13	0.10	0.09	0.10	0.13	0.16	0.15	0.2	n.d.
K_2O	5.67	5.17	4.76	5.46	3.97	3.70	3.10	3.5	3.4
CaO	0.26	0.49	1.46	0.99	3.63	1.30	4.12	3.7	4.2
TiO_2	1.03	0.61	0.57	0.63	0.70	1.00	0.52	0.6	0.5
MnO	0.02	0.05	0.05	0.04	0.06	0.11	0.068	0.1	0.077
Fe_2O_3	5.68	5.04	4.38	5.07	6.29	7.66	4.41	5.3	5.0

were estimated from published stratigraphic sections and descriptions of the various formations, and average compositions calculated accordingly. As explained above, where necessary sandstone proportions were further enhanced to correct for eroded basin margins.

In principle, the sandstone/shale ratio of a sedimentary sequence will be affected by the intensity of chemical weathering. However, the chemical index of alteration (CIA, Nesbitt and Young 1982) varies little for the successive formations of the Belt Supergroup and indicates moderate chemical weathering (CIA ranges from 65–70). Even changing the assumed proportions of sandstones and shales by ±10% (*e.g.*, from 65% shale to 75% and 55%, respectively) does not significantly change the results of mass balance calculations.

To evaluate whether the calculated chemical imbalances between the source region and Belt sediment are potentially artifacts that can be ascribed to certain combinations of above factors, mass balances were calculated for various combinations of these factors. These combinations were chosen so that they reduced the initially observed chemical imbalances as much as possible. In essence, it appears that 1) it is possibe to explain as much as 10% of the observed compositional imbalance with the composition of the upper crustal average used in the calculation, 2) errors in estimating proportions of lithologies in a *slice* can potentially contribute another 10%, and 3) inadequate sampling of stratigraphic units and analytical errors may contribute several more percent to the observed chemical imbalances. The following conservative view towards imbalances between Belt sediment and Canadian Shield composition has been adopted: first, imbalances in excess of 50% are the most significant ones; second, imbalances between 30 and 50% are significant but may in some instances be an artifact; and last, imbalances below 30% are considered insignificant.

Overall results of the mass balance calculation are shown in figure 1 and illustrate that for most of Belt deposition there was a net export of large quantities of Na, Ca, P, and Mn. All elements shown are either highly soluble (Na, Mg, Ca, K) and/or have considerable mobility during sediment diagenesis (K, P, Mn). With regard to mass balance calculations and the lacustrine versus marine question, three scenarios should be considered (figure 4): 1) an epicontinental basin that receives continental runoff and has an outflow to the ocean, 2) an epicontinental basin that receives continental runoff and exchanges water with the Proterozoic ocean, and 3) an epicontinental basin that receives continental runoff and has no outflow or connection to the ocean. In the latter case, water can only leave via evaporation, and eventually precipitation of dissolved salts will commence.

Approximately half of the total sodium (figure 1) supplied by the source area is still contained in Belt sediment (residing in silicate minerals). The remaining half has been lost from the sequence and, if scenario one were correct, should originally have been stored as halite or trona within the accumulating sediment. Assuming uniform distribution of sedimentary constituents, a density of 2.65 and 2.16 for average sedimentary rock and halite/trona, respectively, and an average Na_2O content of 3.46% (Shaw *et al.* 1967) of the source area, the resulting sedimentary rock should contain 1.95 volume percent halite (representative of half of the total sodium), alternatively, each 10-m-thick layer of sedimentary rock deposited could be thought to contain a 20-cm-thick interval of halite. In lacustrine systems like the Green River Formation, evaporites are found only in the central portion of the basin, whereas sediment deposited towards the basin margin contains no evaporites. However, because the same volume of evaporite minerals still has to be accommodated, the proportion of evaporite minerals increases dramatically in centrally located stratigraphic sections (Surdam and Wolfbauer 1975). In the Green River Formation, the saline mineral facies occupies less than 10% of the basin area (Surdam and Wolfbauer 1975). If these proportions are applied to the Belt basin, central portions of the basin should have contained about 20 volume percent saline minerals (or 2 m for each 10 m of section). Although it cannot be expected that areal proportions from the Green River Formation exactly mirror those of the Belt basin, the comparison illustrates that sizeable portions of a lacustrine Belt basin should once have contained proportions of evaporite minerals too large to have been dissolved without leaving a trace. The only indication of sodic evaporites in the Belt Supergroup are halite cast horizons in various units (for example, the salt cast member in the Mount Shields Formation), but these are neither numerous nor extensive enough to have contained significant quantities of sodium.

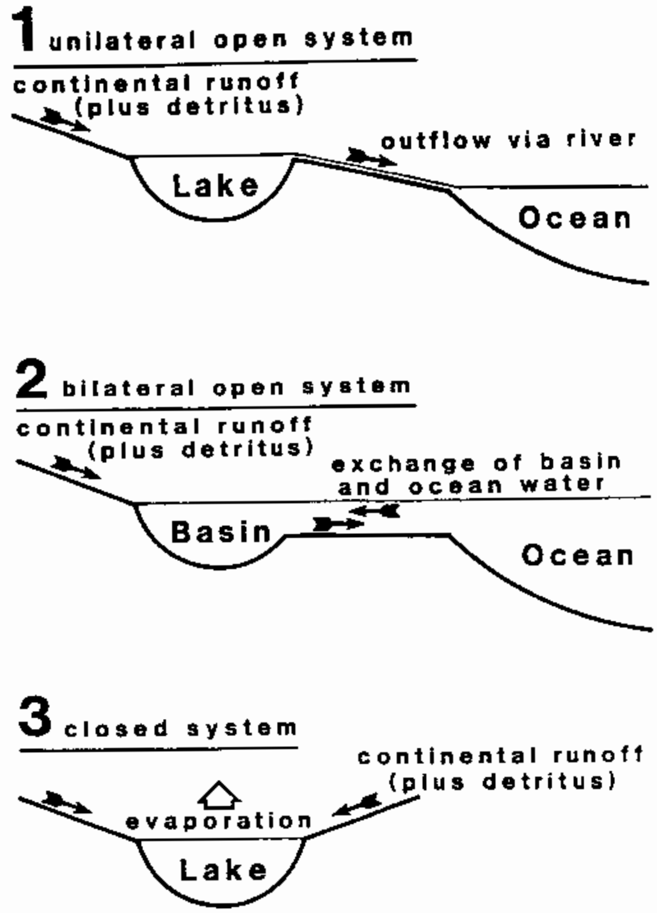

Figure 4. The three hydrographic scenarios that are considered in the mass balance calculations of this paper. A possible fourth scenario might be a hybrid of scenarios one and two.

Although above reasoning still leaves us with scenarios one and two, once Mg and Ca are considered, it is obvious that at least during deposition of the Middle Belt Carbonate a 240–400% excess of Mg and Ca was supplied to the basin. Replenishment of Mg and Ca, via a connection to the Proterozoic ocean, is clearly required (scenario two; figure 4). Though less pronounced, for the Ravalli and Missoula groups, figure 1 indicates influx of Mg but nonetheless an outflow of Ca, reflective of the fact that dolomite is the predominant carbonate phase in these intervals. On a more-detailed level, substantial Mg and Ca influx is seen in the Empire and Shepard *slices* (figures 2, 3). Shales of these two *slices* contain comparatively large amounts of dolomite (disseminated and in thin laminae), which is primarily responsible for the excess Mg and Ca. In the case of the Shepard *slice*, the presence of carbonate-dominated horizons further enhances this effect.

Figure 1 also shows consistent K enrichment in Belt rocks, ranging from 19 to 40%. In the Belt Supergroup illites dominate the K mass balance, and considering that these illites probably were derived from precursor smectites (Eslinger and Sellars 1981, Schieber 1985), it might be suggested that the present K excess simply came from marine formation waters and was bound to Belt sediment during diagenetic illite formation. Thus, one might think that general K enrichment of Belt sediment is merely a further indication of marine influence throughout depositional history. However, textural observations on many sedimentary sequences suggest that typically most of the K in illites comes from K-feldspar dissolution (Hower *et al.* 1976), and thus the bulk composition should not be affected. Also, the amount of seawater required to increase K to the extent observed in the Belt Supergroup, exceeds by at least an order of magnitude that amount of seawater that could reasonably be expected to be incorporated in the accumulating sequence (judging from the K content of modern seawater and the water content of freshly deposited muds). One possible explanation for the excess K could be that 1) the K data used in this study are systematically too large due to analytical error, or 2) that there was actually more K in the surrounding upper crust than was assumed. However, possibility one) is highly unlikely because K was analyzed twice for each sample by different methods (INAA and XRF), and because abundances conform with analyses published by Ross (1963). If the K content of actual basement rocks in the periphery of the Belt basin is examined (Mueller and Wooden 1982), possibility two) seems quite unlikely as well.

Because the Canadian Shield average has the lowest K_2O content of the three upper crustal averages shown in table 1, the apparent K import may simply be a consequence of the upper crustal average chosen for the calculation. By using the two averages shown in table 1, the K excess can be placed below the 30% significance threshold.

However, because the precise average source rock composition of the Belt Supergroup will never be known, the elevated K contents might well be equally real. This allows for speculation the possibility that there was another, as yet unrecognized source of K that was not linked to weathering and erosion of surrounding source areas. One such source might be volcanic tuff beds. Although present in the Belt Supergroup lithologies (Obradovich and Peterman 1968), tuff beds seem to be a rare feature. However, in light of recently described volcaniclastic beds from the Greyson Formation with associated diagenetic K feldspar and gold mineralization and earlier described tuff beds from the Yellowjacket Formation (Hahn and Hughes 1984), tuff layers in the Belt Supergroup are possibly not as rare as once thought. Proterozoic sequences with abundant tuff beds whose K content is raised above upper crustal averages include the McArthur and Mount Isa groups of Australia (Veizer and Garrett 1978) but even at those locations, the presence of tuff beds was only revealed through very detailed studies (Croxford 1964, Lambert 1983). Beds that strongly resemble the Mount Isa tuff beds were shown to me by Garth Grosby of Hecla Mining Co. (1984 personal communication) in samples from the upper portion of the Prichard Formation near Wallace, Idaho. These beds were strongly enriched in K as indicated by their response to a sodium cobaltinitrate stain and may well be metamorphosed tuff beds.

Although identification of metamorphosed tuff beds is difficult, and while recognizing that the observed K excess may be an artifact, the steady trickle of tuff bed identifications in Belt rocks in conjunction with an apparent K excess is tantalizing. It suggests that there might have been a much larger volcanic contribution to the Belt Supergroup than is presently known.

The Mount Shields Formation and Bonner Quartzite of the Missoula Group show the largest K enrichment (figure 3). Their enrichment is still significant when the assumed average source rock composition is changed (table 1). These two units contain the most voluminous sandstone units of the Missoula Group, and petrographic examinations reveal a common presence of diagenetic K eldspar (overgrowth on detrital K feldspar). Thus, although a volcanogenic origin for some of the K in Belt rocks has been speculated upon above, the Mount Shields and Bonner formations need not be interpreted in terms of increased volcanic activity. The extensive sandstones of both units probably served as channel ways for diagenetic fluids that were squeezed out of compacting shale units. Dissolved K carried by these fluids may have led to increased deposition of diagenetic K feldspar in the sandstones.

Figure 1 shows that approximately 40–50% of the potentially available P and Mn were removed throughout Belt deposition. From available geologic evidence

(Schopf 1980, Holland 1984), the oxygen content of the Mid-Proterozoic atmosphere was large enough to oxidize Mn and P on the land surfaces to the 4+ and 5+ state, respectively. Judging from the geochemistry of phosphorous (McConnell 1979) and the operation of the present-day phosphorous cycle (Pierrou 1979), P probably reached the basin in dissolved and particulate form. Reduction of particulate phosphates (*e.g.*, vivianite, strengite) in reducing sediment can lead to a release of phosphate to the basin waters (Schopf 1980) and lower the P content of the accumulating sediment. Mn oxides were probably introduced into the basin together with iron oxide coatings on sediment grains (Carroll 1958, Li 1981). Because of the generally reducing character of the majority of Belt sediment, large quantities of the detrital Mn could have been remobilized during early diagenesis and entered the overlying basin waters. The same process is active in modern marine sediment (Buckley and Cranston 1988), and in the case of sediment that accumulates in the modern Mississippi Delta, approximately 45% of the Mn that initially accumulates is lost to overlying seawater (Trefry and Presley 1982). Considering that there are no known sedimentary accumulations of P and Mn in the Belt Supergroup, it must be concluded that analogous to the modern cycling of these elements, the missing P and Mn were most likely lost (exported) to the Proterozoic ocean.

Other Observations

Early diagenetic sulfides in the Belt Supergroup have by comparison with other Proterozoic basins so strongly negative sulfur isotope values (Strauss and Schieber 1990) as to require open-system conditions with respect to sulfur. This indicates that the Belt sea was connected to the Proterozoic ocean rather than being an isolated inland basin. Supporting data come from studies of the Sullivan ore body and the Ravalli Group (Campbell *et al.* 1978, Rye *et al.* 1984). In a study of sulfides from the Sullivan ore body, Campbell *et al.* (1978) found sulfur isotope values as small as -10.4 per mil. In that study, the strongly negative sulfur isotope values towards the top of the deposit were viewed to indicate an open system with unrestricted influx of marine sulfate. The negative isotope values were thought to have been produced in carbonaceous bottom sediments by anaerobic bacteria. Similarly, diagenetic copper sulfides in the Belt Supergroup are biased towards negative values (Rye *et al.* 1984) and are consistent with bacterial reduction of seawater sulfate.

In contrast, Lyons *et al.* *(this volume)* have found much more positive sulfur isotope ratios in pyrites from the Sheep Creek deposit (Zieg and Leitch *this volume)* and concluded that the Belt basin might have been isolated from the open ocean. However, an alternative interpretation is that the Sheep Creek sulfides accumulated in an isolated sub-basin along the margin of the Belt basin, and that conclusions from its isotope signature can not be applied to the Belt basin as a whole. This is quite likely, as suggested by the strongly negative sulfur isotope data reported by Strauss and Schieber (1990). Samples for the latter study came from distal lateral equivalents of the pyritic shales that contain the Sheep Creek deposit, as well as from younger units of the Newland Formation that can be traced far into the Helena embayment (Schieber 1985). Similarly, negative sulfur isotope values for the Sullivan ore body (Campbell *et al.* 1978), the Ravalli Group (Rye *et al.* 1984), and the Newland Formation (Strauss and Schieber 1990) suggest that these data much more likely reflect the composition of the basin waters than do the data by Lyons *et al.* *(this volume)*. Thus, the overall *open system* sulfur isotope signature of the Belt basin is best interpreted to indicate its connection with the Proterozoic ocean.

From analyses of rocks from the eastern Belt basin and the Prichard Formation, the lower Belt Supergroup contains on average between 0.5 and 1% sulfur in sedimentary pyrite (Schieber 1985 *unpublished data)*. Such sulfur concentrations are on an order of magnitude above the average for the Canadian Shield (0.06%, Shaw *et al.* 1967), requiring influx of sulfur from the ocean reservoir and confirming the conclusion that the Belt basin was connected to the Proterozoic ocean.

Boron

Boron concentrations in illites of the middle Belt carbonate interval (Reynolds 1965) are comparable to those found in Phanerozoic marine sediment. According to various investigators (Schopf 1980, Holland 1984, Grotzinger and Kasting 1993), Proterozoic seawater was probably comparable in composition to Phanerozoic seawater. Considering that Belt illites were not recycled sedimentary material, their boron contents may thus indeed be indicative of marine basin waters.

Evaporites

During evaporation of a salt solution, types of precipitating minerals as well as their sequence of precipitation, are constrained by physicochemical principles and the original water composition (Stewart 1963). As a consequence, evaporite minerals and their paragenesis can give clues to the composition of the solution they precipitated from. This was demonstrated by Holland (1972), who showed that mineralogy and paragenesis of ancient marine evaporites severely limits the compositional variability of seawater.

The chemical evolution of continental brines is predetermined by a combination of source rock composition and weathering conditions (Eugster 1984). In general, whereas seawater is dominated by Cl-, Na^{+}, and SO_4^{2-} (in order of abundance), continental waters are generally dominated by HCO_3-, Ca^{2+}, and SO_4^{2-}. As a result, lacustrine evaporites tend to be characterized by precipitation of alkaline earth carbonates (*e.g.*, trona, gaylussite etc.). Physicochemical constraints suggest that it is impossible that a continental brine could evolve to yield a marine evaporite paragenesis. The only exception to this rule seem to be those lacustrine systems that originated as remnant ocean basins (*e.g.*, Caspian Sea) and basins receiving recycled marine evaporites (*e.g.*, Dead Sea, Zak and Freund 1981).

Work by various investigators (Schopf 1980, Holland 1984, Grotzinger and Kasting 1993) suggests that by the time of Belt deposition, Proterozoic seawater had essentially reached a composition comparable to Phanerozoic sea water. In that case, dolomite, gypsum, and halite should precipitate in that sequence during evaporation. The Belt basin contains various units with evidence of vanished evaporites (*e.g.*, Eby 1977, White 1977, Schieber 1985, Winston 1986). Among the many indications of vanished evaporites described by Eby (1977) were halite casts, haloturbation, cerebroid and broken ooids, pseudomorphs of gypsum/anhydrite, and molar tooth structures (calcite replaced gypsum/anhydrite fills). The presence of large amounts of scapolite in metamorphosed portions of the middle Belt carbonate (Hietanen 1967) suggests that the unit originally contained large quantities of evaporite minerals. From description of sedimentary features, it appears that the general mineral sequence in the middle Belt carbonate was dolomite, calcium sulfate, and halite (Eby 1977). This same sequence is characteristic of mineral precipitation from seawater (Holland 1972) and strongly suggests that the middle Belt carbonate evaporites precipitated from waters of marine origin. The same applies to observations by White (1977) concerning the Altyn Formation, similarly suggesting marine waters for the lower Belt.

Glauconite

Chamosite occurs in several units of the Newland Formation (Schieber 1985) and glauconite has been reported from the Spokane, Empire, Shepard, Mount Shields, Bonner, and McNamara formations (Obradovich and Peterman 1968, Mudge 1972). Both minerals form in shelf areas of modern seas (Porrenga 1967) and are common in Phanerozoic marine deposits (Van Houten and Purucker 1984). Particularly, glauconite is considered a very reliable indicator of marine conditions (Schopf 1980).

Conclusions

Sedimentological criteria are not useful for differentiating between a lacustrine and marine origin of the Belt Supergroup, whereas chemical mass balance considerations, sulfur isotopes, and boron contents serve to document the influx of marine water. Pseudomorphs of evaporite minerals show the same minerals and mineral sequence to be present as typically found in marine evaporites, requiring precipitation from waters of marine origin. Glauconite formation in Belt sediment also necessitates marine conditions. Its presence has been known for over 20 years, and it is still incumbent on those favoring a lacustrine Belt basin to explain its presence. The results of the study are as follows:

- Throughout Belt deposition there was an outflow (export) of Na, P, and Mn.
- Simultaneous export/import and exchange with the Proterozoic ocean can be demonstrated for the lower Belt (S import), the Empire Formation, the middle Belt Carbonate and the Shepard Formation (all three show import of Mg and Ca).
- With glauconite as an additional marine indicator, the only remaining portions of the sequence that do not show clear marine affinities (export/import patterns and/or glauconite) are the lower portions of the Ravalli and Missoula groups (Burke and Snowslip formations, respectively).
- Because the Burke and Snowslip were deposited during the shoaling of the Prichard and middle Belt Carbonate sea, respectively, marine influence can be inferred for those units as well.
- A possible volcanic contribution to the Belt basin is suggested by discrepancies between the likely K content of the hinterland and the actual K content of Belt sediment.

Lacustrine deposits may well have accumulated on the coastal plains bordering the Belt basin, but its central water body was connected with the Proterozoic ocean throughout Belt history. Although the evidence presented here leaves open the question whether the Belt Supergroup accumulated in a rift basin, an episutural basin (Hoffman 1988), an epicratonic reentrant, or an epeiric basin (Shaw 1964), a persuasive argument can be made that it definitely was not lacustrine. Variable salinity of the Belt sea (ranging from brackish through normal to hypersaline) is indicated by the geologic record and was probably caused by changing relationships between continental runoff, basin volume, and water depth.

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