

Synorogenic Crustal Fluid Infiltration in the Idaho-Montana Thrust Belt

Gray E. Bebout, David J. Anastasio, and James E. Holl¹

Department of Earth and Environmental Sciences, 31 Williams Drive, Lehigh University, Bethlehem, Pennsylvania 18015-3188, USA

Abstract. Mississippian carbonates in the Sevier thrust belt in Idaho-Montana show shifts in $\delta^{18}\text{O}_{\text{V-SMOW}}$, from marine carbonate values to as low as +11‰, which are best explained by exchange with externally-derived, low- $\delta^{18}\text{O}$ fluids. Late-stage, synkinematic calcite veins are depleted in ^{18}O relative to the host-rocks and earlier-formed veins, many having $\delta^{18}\text{O}$ of +5 to +10‰. These veins could have equilibrated with H_2O with $\delta^{18}\text{O}$ of -7.5 to +2.5‰, perhaps reflecting infiltration of the Sevier thrust wedge by nearshore meteoric waters to depths of ~10 km. Calcite veins in the hangingwall and footwall of the Pioneer Metamorphic Core Complex, produced during later Paleogene extension, have $\delta^{18}\text{O}$ of -8.7 to +1.4‰ consistent with equilibration with meteoric waters with $\delta^{18}\text{O}$ as low as -14‰. Transition from a Cretaceous crustal fluid regime influenced by the nearby Western Interior Seaway to one influenced by lower- $\delta^{18}\text{O}$, more inland meteoric waters is consistent with seaway retreat during thrust wedge emergence and Paleogene uplift and subaerial volcanism.

1. Introduction

Hydrologic regimes in orogenic belts are thought to undergo a complex evolution in response to transitions in structural style (affecting permeability), topographic relief, and contributions from surficial and deeper-sourced fluid reservoirs over extended periods of geologic time. Popular fluid flow models have included the tectonic "squeegee" model of Oliver [1986], in which fluids mechanically expelled at depth in actively deforming thrust wedges are transported updip along thrust structures, and models incorporating topography- and buoyancy-driven recharge and mixing (see Evans and Battles [1999]; Koons *et al.* [1998]). However, many questions remain concerning the evolution and pathways of fluids during orogenesis, particularly at regional scale. Field-based structural, petrologic, and geochemical studies of orogenic fluid flow suggest differing styles and sources of deep crustal fluid infiltration during compressional and extensional stages in orogenic belts (Nesbitt and Muehlenbachs [1995]). Numerical models suggest relationships, between orogen geometry and directions and magnitudes of large-scale fluid flux (Garven and Freeze [1984]; Deming and Nunn [1991]), which are largely untested against field studies.

In this paper, we present oxygen and carbon isotope data for veins and variably deformed carbonate rocks in the Sevier thrust belt of the northern U.S. Rocky Mountains (Montana

recess, central Idaho-SW Montana) and for metasomatized rocks in the hangingwall and footwall of the Eocene Pioneer Metamorphic Core Complex (central Idaho). We emphasize implications of the O isotope data for the Late-Cretaceous to Eocene hydrogeology of the evolving orogen.

2. Geological Setting

The Pioneer Mountains, Lost River, Lemhi, and Beaverhead Ranges form a series of NW-SE trending mountains east of the Idaho batholith, west of the Sevier thrust front, and north of the Snake River Plain (Fig. 1). These ranges, separated by extensional half-graben basins active in the Tertiary to Recent [Janecke, 1992; Anders *et al.*, 1993], are dominated by imbricate thrust sheets containing variably sized, often disharmonic, fault-related folds (e.g., Skipp [1988]; Janecke and Wilson [1992]). For westernmost field areas, regional stratigraphic reconstructions, balanced and restored cross sections of the Idaho-Wyoming-Montana thrust belt south of the Snake River Plain, geobarometry around the Idaho batholith, and geothermometry and deformation mechanism partitioning for the Lost River Range, all suggest that compressional deformation of the outer-shelf Late Paleozoic miogeocline occurred ~10 km beneath the synorogenic surface (Allmendinger [1990]; review by Anastasio *et al.* [1997]; Fig. 2). Removal of the post-early Pennsylvanian-to-middle Eocene section in the hinterland complicates depth assessments. Emergent thrusting and fan delta development along the SW Montana thrust front provide constraints on the geometry and position of the synorogenic surface near the orogen's toe [Schmitt *et al.*,

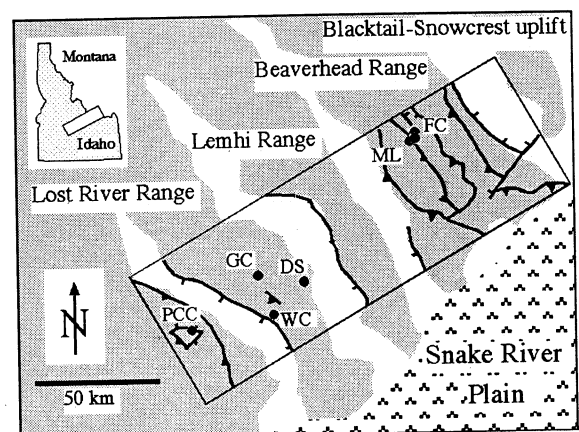


Figure 1. Reference map of major mountain ranges and study localities (D = Doublesprings duplex, GC = Grouse Creek anticline, WC = Willow Creek anticline, PCC = Wildhorse detachment of the Pioneer core complex, ML = Medicine Lodge thrust sheet, FC = Four Eyes Canyon thrust sheet).

¹Current Address: Exxon Production Research Company, Houston, TX, USA

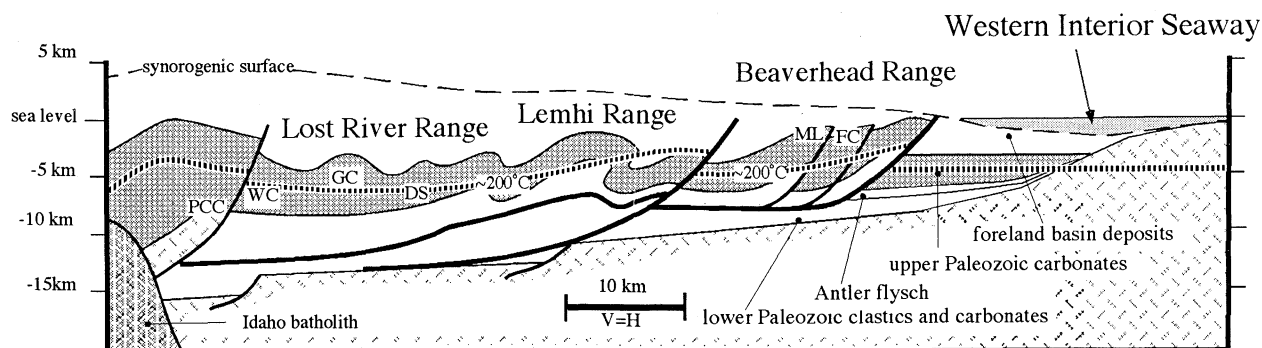


Figure 2. Schematic reconstruction of Sevier foreland thrust wedge during emplacement in Late Cretaceous showing relative spatial distribution of localities with respect to major structures, 200°C paleo-isotherm (dashed line), and the interior seaway.

1995]. The Blacktail-Snowcrest uplift, a foreland (Laramide) feature buttressed the easternmost thrust sheets of the Sevier belt in SW Montana, resulting in out-of-sequence thrusting throughout the Montana recess [Kulik and Perry, 1988]. After the Sevier orogeny, the Northern Rockies experienced extension, vertical axis rotation, and tilt as a result of Middle Eocene-Recent extension on steep and gently-dipping listric extensional faults (e.g., Janecke [1992]; Anders *et al.* [1993]). During extension, much of the region was blanketed by the Challis Volcanic Group ~55-45 Ma [Janecke and Sneek, 1993].

3. Sampling Strategy and Results

The sketch in Fig. 3 demonstrates typical multiple vein generations and the sampling strategy employed in this study. In general, mildly deformed massive layers are interbedded with more intensely deformed zones at scales ranging from mm's to m's. The deformed zones are characterized by penetrative cleavage ranging in intensity from moderate to very strong, and later-stage brittle shear zone and cleavage-parallel extensional veins. These deformation zones, which formed during fault-related folding [Fisher and Anastasio, 1994; Hedlund *et al.*, 1994; Anastasio *et al.*, 1997], are often bounded by bedding-parallel faults (Fig. 3). Bedding-parallel veins contain shear fibers kinematically related to fault-related folding; these veins are occasionally cleaved, suggesting that the formation of some of these veins was initiated early in the folding history. Some late-stage veins cross-cut some layers (veins labelled "3" on Fig. 3) and can be temporally related to folding by offsets along bedding plane faults.

Vein samples at the three Lost River Range localities show a large range in $\delta^{18}\text{O}_{\text{V-SMOW}}$, from carbonate protolith-like values near +25‰ (particularly fibrous veins developed on chert nodules; Fig. 4b) to minimum values near +5‰ (particularly relatively late-stage veins; Figs. 4a,b). In several cases, complex bedding-parallel vein complexes show $\delta^{18}\text{O}$ ranges of greater than 10‰ (see Figs. 4a,b). Variably cleaved whole-rocks and microsampled cleavage selvages (drilled at ~1 mm scale) are generally lower in $\delta^{18}\text{O}$ than uncleaved whole-rocks and microsampled microlithons (less deformed zones between cleavage selvages), the latter two of which have O- and C-isotope compositions typical of marine carbonate rocks (Figs. 4b,c). Using the minimum-range calcite $\delta^{18}\text{O}$ values (range of +5 to +10‰), employing calcite- H_2O fractionation factors (from O'Neil *et al.*, 1969) for estimated temperatures of formation of the cleavage (~220°C for the Doublesprings locality, using illite crystallinity; Hedlund *et al.* [1994]), and allowing for precipitation of veins over the temperature range of 150-250°C (appropriate for the three exposures in the Lost River Range), calculated $\delta^{18}\text{O}$ values for H_2O are in the range of -7.5

to +2.5‰. Vein and microsampled host-rock samples from Sevier-aged structures in Beaverhead thrust sheets show $\delta^{18}\text{O}$ ranges similar to those of the Lost River Range localities (Fig. 5), but assessment of fluid $\delta^{18}\text{O}$ in the Beaverhead Range awaits better constraints on paleotemperature.

Also shown in Fig. 5 are calcite $\delta^{18}\text{O}$ values of calcite + epidote + chlorite + actinolite veins in brecciated mylonites and footwall intrusive rocks and brecciated and intensely veined hangingwall Mississippian limestones in the Wildhorse detachment fault system of the Pioneer core complex. $\delta^{18}\text{O}$ values for veins in the intrusive rocks and mylonite range from -8.7 to -5‰, and hangingwall limestone has $\delta^{18}\text{O}$ of +4 to +9‰ (calcite veins in limestones range from -2.5 to +1.4‰). Calculated H_2O $\delta^{18}\text{O}$, using the vein calcite data and a rough maximum T estimate of 300°C based on mineral assemblages in the lowerplate veins, fall in the range of -14.3 to -4.2‰, and lower temperatures produce only lower H_2O $\delta^{18}\text{O}$.

4. Paleohydrogeology in the Northern Rockies

We interpret the leveling-off in $\delta^{18}\text{O}$ and the range of $\delta^{18}\text{O}$ values of the late-stage veins in the Sevier-aged structures to reflect penetration of the crust by surficial fluids such as near-shore meteoric water of the nearby Western Interior Seaway with $\delta^{18}\text{O}$ near to slightly lower than 0‰ (for discussions of paleogeography, see Jewell [1996]). We consider it unneces-

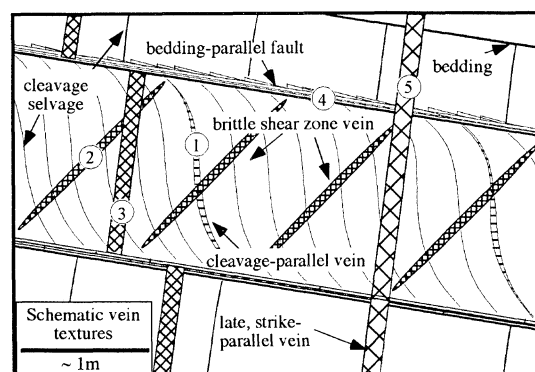


Figure 3. Sketch of cleavage geometry in Lost River Range deformation zones and commonly observed relative timing (1 earliest, 5 latest) of vein sets sampled for isotope analyses in the Lost River and Beaverhead Ranges. Data for veins that postdate Sevier folding (e.g., vein type 5) are not included.

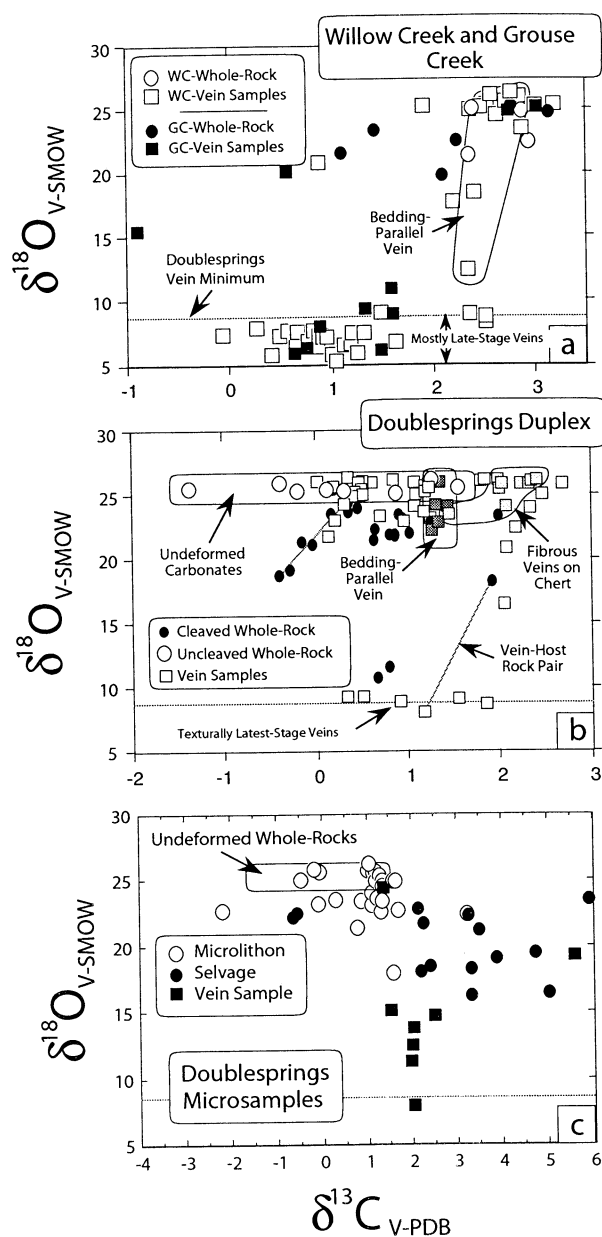


Figure 4. Oxygen and C isotope data for carbonate samples from the Willow Creek and Grouse Creek localities (a), and the Doublesprings locality (b). On these plots, trajectories of isotopic shift in carbonates during exchange with infiltrating C-poor, low- $\delta^{18}\text{O}$, H_2O -rich fluids at the estimated temperatures would be nearly vertical at first, downward toward lower $\delta^{18}\text{O}$. (c) Oxygen and C isotope compositions of microsampled veins, cleavage selvages, and microlithons for Doublesprings duplex (data in this figure are for five hand samples).

sary to invoke regional buffering, by crustal fluid-rock interactions, of meteoric H_2O initially with $\delta^{18}\text{O}$ considerably lower than -7.5‰ to produce the values nearer 0‰ (-7.5 to $+2.5\text{‰}$) calculated for the later-stage veins studied here (cf. Nesbitt and Muehlenbachs [1995]) because the nearby interior seaway could have resulted in nearshore meteoric waters with the calculated values (see studies of analogous modern settings by Kendall et al. [1995]). The $\delta^{18}\text{O}$ values calculated for the waters that infiltrated the thrust belt (as low as -7.5 to $+2.5\text{‰}$) are lower than those expected for aqueous fluids ex-

solving from magmatic rocks ($\sim+5.5$ to $+10\text{‰}$; Sheppard [1996]). Likewise, aqueous fluids equilibrated at higher temperatures with rocks similar to those presently exposed, but at greater depths in the thrust belt, are likely to have had $\delta^{18}\text{O}$ values higher than those calculated for the late-stage veins examined in this study. Oxygen-isotope equilibration of aqueous fluids at $>300^\circ\text{C}$ with carbonate-rich sections with $\delta^{18}\text{O} >+20\text{‰}$ would have resulted in fluid $\delta^{18}\text{O}$ of $>+14\text{‰}$. The $\delta^{18}\text{O}$ of Late Cretaceous rainfall from more isotopically evolved air masses originating in elevated regions to the west is likely to have been lower than the range calculated here.

The results presented here, and our studies of processes leading to cleavage formation and the kinematics of fault-related folding in the Lost River Range [Hedlund et al., 1994; Anastasio et al., 1997; Davidson et al., 1998; Anastasio et al., in prep.], suggest that (1) the systems evolved from closed to open as a result of deformation, (2) fluid flow evolved from porosity-based to discontinuity-based (along cleavage, faults, and fracture networks) as deformation progressed, (3) mass transfer was accommodated by diffusion early and advection late in the deformation history, and (4) zones of focused fluid flow were kinematically related to larger-scale structures (faults, fault-related folds). We interpret the high $\delta^{18}\text{O}$ of fibrous veins and overgrowths at the Doublesprings locality (Fig. 4b) to reflect rock-buffered fluid isotopic evolution during early, dominantly diffusional stages of mass transfer. The large $\delta^{18}\text{O}$ range ($+10$ to $+24\text{‰}$) for variably infiltrated whole-rocks and many veins probably reflects a range in fluid $\delta^{18}\text{O}$ values produced by varying degrees of upstream fluid-rock exchange and, for the whole-rocks, varying amounts of fluid-rock exchange. Alteration of initial fluid $\delta^{18}\text{O}$ by upstream fluid-rock interactions was perhaps less likely during later-stage deformation because of an increased flux of fluid along discrete fractures (cf. Rye and Bradbury [1988]). This could explain the larger number of late-stage veins with lower $\delta^{18}\text{O}$ ($+5$ to $+10\text{‰}$) for which calculated H_2O $\delta^{18}\text{O}$ values appear to most directly reflect surficial fluid sources.

The fold-and-thrust belt and extensional tectonic features in our study area are continuous with time-correlative parts of the Canadian Rockies orogenic belt in which other studies of fluid regimes have been conducted (Nesbitt and Muehlenbachs [1995]), and to the south, with the Absaroka thrust

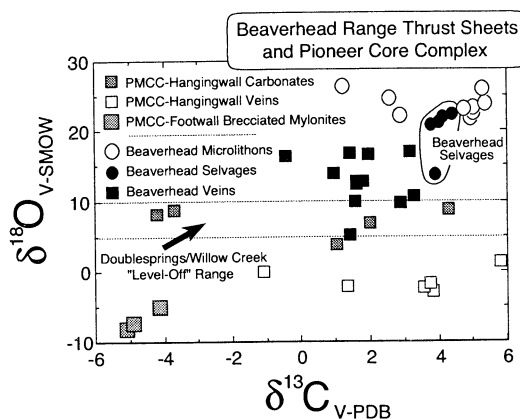


Figure 5. Oxygen and C isotope data for hangingwall and footwall lithologies of the Pioneer core complex and for microsampled veins, selvages, and microlithons from the Beaverhead Range thrust sheets ("ML" and "FC" on Figs. 1, 2). Some of the negative $\delta^{18}\text{O}$ shift in the upper-plate limestones could reflect previous, Sevier-aged fluid flow.

sheet in Wyoming (*Budai and Wiltschko* [1989]). We suggest that regional variation in the $\delta^{18}\text{O}$ of meteoric waters infiltrating deep parts of the orogen (e.g., as low as -20‰ estimated by *Nesbitt and Muehlenbachs* [1995], for parts of Canadian Cordillera) could have resulted from varying proximity of the thrust belt and its highlands to the Western Interior Seaway, and variations in temperature and topographic relief. Stratigraphic and structural positions of the rocks in the evolving thrust belt also likely governed local extents and styles of fluid infiltration (*Bradbury and Woodwell* [1987]).

$^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology for the Pioneer core complex [*Silverberg*, 1990] attaches an Eocene-Oligocene age to the inferred hydrogeology based on O-isotope analyses of the hangingwall and footwall rocks and veins. The calculated water $\delta^{18}\text{O}$ near -14‰ is extremely similar to values of ~-16‰ estimated by *Criss and Taylor* [1983] for waters which hydrothermally altered rocks in aureoles of nearby, shallowly-emplaced Eocene intrusives of the Idaho Batholith. The inferred regional hydrogeologic transition, from a shallow crustal fluid regime possibly influenced by the presence of the Western Interior Seaway to one influenced by more inland meteoric waters with lower $\delta^{18}\text{O}$, is consistent with the Late Cretaceous to Paleocene paleogeography involving retreat of the Western Interior Seaway and emergence and aerial exposure of the Sevier thrust wedge (see *Erickson and Slingerland* [1990]; *Elder et al.* [1994]). Our results provide a demonstration of the interplay between surface hydrology (reflecting topographic relief, latitude, and proximity to ocean masses) and deformation magnitudes and styles which contributes to the hydrogeology deep in orogenic belts.

Acknowledgments This research was supported by National Science Foundation grant EAR-9405626 to DJA and GEB, and grants from Lehigh University. We thank C. A. Hedlund, S. Davidson, G. Kendall, and L. Chizmadia for their involvement in parts of this project.

References

- Allmendinger, R. W., Fold and thrust tectonics of the western United States, exclusive of the accreted terranes, in *Cordilleran Orogen: U.S.* (ed. by Burchfiel, B.C., Lipman, P.W., and Zoback, M.L.) *Geol. Soc. Am. DNAG G-3*, 1990.
- Anastasio, D. J., D. M. Fisher, T. A. Messina, and J. E. Holl, Kinematics of Décollement folding in the Lost River Range, Idaho, *J. Struct. Geol.* **19**, 355-368, 1997.
- Anders, M. H., Rodgers, D. W., and J. T. Hagstrum, The growth of fault-bounded tilt blocks, *Tectonics* **12**, 1451-1459, 1993.
- Bradbury, H. J., and G. R. Woodwell, Ancient fluid flow within foreland terrains, *Geological Society Special Publication* **34**, 87-102, 1987.
- Budai, J. M., and D. V. Wiltschko, Isotopic exchange during tectonic veining: example from Absaroka Sheet in Wyoming overthrust belt, *Amer. Assoc. Petrol. Geol. Bull.* **73**, 338, 1989.
- Criss, R. E., and H. P. Taylor, Jr., An $^{18}\text{O}/^{16}\text{O}$ and D/H study of Tertiary hydrothermal systems in the southern half of the Idaho batholith, *Geol. Soc. Amer. Bull.* **94**, 640-663, 1983.
- Davidson, S., D. J. Anastasio, G. E. Bebout, J. E. Holl, and C. A. Hedlund, Volume loss and metasomatism during cleavage formation in carbonate rocks, *J. Struct. Geol.* **20**, 707-726, 1998.
- Deming, D., and J. A. Nunn, Numerical simulations of brine migration by topography-driven recharge, *J. Geophys. Res.* **96**, 2485-2499, 1991.
- Elder, W. P., E. R. Gustason, and B. B. Sageman, Correlation of basinal carbonate cycles to nearshore parasequences in the Late Cretaceous Greenhorn seaway, Western Interior U.S.A., *Geol. Soc. Amer. Bull.* **106**, 892-902, 1994.
- Erickson, M. C., and R. L. Slingerland, Numerical simulations of tidal and wind-driven circulation in the Cretaceous interior seaway of North America, *Geol. Soc. Amer. Bull.* **102**, 1499-1516, 1990.
- Evans, M. A., and D. A. Battles, Fluid inclusion and stable isotope analyses of veins from the central Appalachian Valley and Ridge province: implications for regional synorogenic hydrologic structure and fluid migration, *Geol. Soc. Amer. Bull.* **111**, 1841-1860, 1999.
- Fisher, D. M., and D. J. Anastasio, Kinematic analysis of a large-scale leading edge fold, Lost River Range, Idaho, U.S.A., *J. Struct. Geol.* **16**, 571-584, 1994.
- Garven, G., and R. A. Freeze, Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits. 2. quantitative results, *Amer. J. Sci.* **284**, 1085-1174, 1984.
- Hedlund, C. A., D. J. Anastasio, and D. M. Fisher, Kinematics of Fault-Related Folding in a Duplex, Lost River Range, Idaho, U.S.A., *J. Struct. Geol.* **16**, 571-584, 1994.
- Janecke, S. J., Kinematics and timing of three superimposed extensional systems, east central Idaho: evidence for an Eocene tectonic transition, *Tectonics* **11**, 1121-1138, 1992.
- Janecke, S. J. and L. W. Snee, Timing and episodicity of middle Eocene volcanism and onset of conglomerate deposition, Idaho, *Jour. Geol.* **101**, 603-621, 1993.
- Janecke, S. J., and E. Wilson, Geologic map of Borah Peak, Burnt Creek, Elkhorn Creek, and Leatherman Pass 7.5 minute quadrangles, Custer and Lemhi Counties, Idaho, *Idaho Geol. Surv., Tech. Rep.* **92-5**, Moscow, ID, 1992.
- Jewell, P. W., Circulation, salinity, and dissolved oxygen in the Cretaceous North American Seaway, *Amer. J. Sci.* **296**, 1093-1125, 1996.
- Kendall, C., M. M. G. Sklash, and T. D. Bullen, Isotope tracers of water and solute sources in catchments, in *Trudgill, S. T., ed., Solute Modelling in Catchment Systems*, John Wiley & Sons, Ltd., 261-303, 1995.
- Koons, P. O., D. Craw, S. C. Cox, P. Upton, A. S. Templeton, and C. P. Chamberlain, Fluid flow during active oblique convergence: a Southern Alps model from mechanical and geochemical observations, *Geology* **26**, 159-162, 1998.
- Kulik, D. M. and W. J. Perry, Jr. The Blacktail-Snowcrest foreland uplift and its influence on structure of the Cordilleran thrust belt-geological and geophysical evidence for the overlap province in southwestern Montana, *Geol. Soc. Am. Mem.* **171**, 291-306, 1988.
- Nesbitt, B. E., and K. Muehlenbachs, K., Geochemical studies of the origins and effects of synorogenic crustal fluids in the southern Omineca Belt of British Columbia, Canada, *Geol. Soc. Amer. Bull.* **107**, 1033-1050, 1995.
- Oliver, J., Fluids expelled tectonically from orogenic belts: their role in hydrocarbon migration and other geologic phenomena, *Geology* **14**, 99-102, 1986.
- O'Neil, J. R., R. N. Clayton, and T. K. Mayeda, Oxygen isotope fractionation in divalent metal carbonates, *J. Chem. Phys.* **51**, 5547-5558, 1969.
- Rye, D. M., and H. J. Bradbury, Fluid flow in the crust: an example from a Pyrenean thrust ramp, *Amer. J. Sci.* **288**, 197-235, 1988.
- Schmitt, J. G., H. Haley, J. C., Lageson, D. R., Horton, B. K., and P. A. Azevedo, Sedimentology and tectonics of the bannack-McKnight Canyon-Red Butte area, southwest Montana: new perspectives on the Beaverhead Group and Sevier orogenic belt, *Northwest Geology* **24**, 245-313, 1995.
- Sheppard, S. M. F., Characterization and isotopic variations in natural waters, *Mineral. Soc. Amer. Rev. Mineral.* **16**, 165-184, 1986.
- Silverberg, D. S., *The Tectonic Evolution of the Pioneer Metamorphic Core Complex, South-Central Idaho* [Ph.D. dissert.], Massachusetts Institute of Technology, 280 p, 1990.
- Skipp, B. Cordilleran thrust belt and faulted foreland in the Beaverhead Mountains, Idaho and Montana, *Geol. Soc. Am. Mem.* **171**, 237-266, 1988.

G. Bebout, D. Anastasio, and J. Holl, Department of Earth and Environmental Sciences, 31 Williams Drive, Lehigh University, Bethlehem, PA 18015 (geb0@lehigh.edu).

(Received July 2, 2001; accepted August 20, 2001.)