Layered mafic sill complex beneath the eastern Snake River Plain: Evidence from cyclic geochemical variations in basalt

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ABSTRACT

The eastern Snake River Plain in southern Idaho, western United States, is characterized by 1–2 km of Pleistocene to late Pliocene basalt overlying rhyolite caldera complexes. Cyclic variations in the chemical composition of basalts from 1136 m of scientific drill core show that the parent magmas of these lavas evolved by crystal fractionation at shallow to intermediate crustal depths, punctuated by episodic recharge with more primitive compositions and assimilation of adjacent wall rock. We have identified 10 upward fractionation cycles and four reversed cycles; assimilation of sialic crust was limited and mainly affects the oldest basalts, which directly overlie rhyolites. We infer that the crystal fractionation and/or recharge cycles took place in a series of sill-like intrusions at intermediate crustal depths that now form a layered mafic intrusion that underlies the eastern Snake River Plain at depth. This layered sill complex is represented by the ~10-km-thick "basaltic sill" that has been imaged seismically at ~12–22 km depth. The association of this mid-crustal sill complex with geochemical fractionation cycles in basalt supports the concept that exposed layered mafic intrusions may be linked to overlying basalt provinces that have since been removed by erosion.

Keywords: basaltic volcanism, basalt, layered intrusions, crustal structure.

INTRODUCTION

Petrologists have long used layered mafic intrusions to infer magmatic liquid lines of descent and to speculate about processes that control the compositions of volcanic rocks erupted at the surface. The most important processes inferred from layered mafic intrusions include crystal fractionation (by gravitational settling or crystallization fronts at the base and sides of the magma chamber), magma recharge and mixing, and the progressive assimilation of roof or wall rocks (e.g., Wager and Brown, 1967; Irvine, 1970; Jackson, 1970, 1971; McBirney and Noyes, 1979; Pallister and Hopson, 1981). Petrologists invoke these processes to explain chemical variations observed in lavas erupted on the Earth's surface, but it is rarely possible to relate these processes to stratigraphic successions of lava in a way that correlates with the multiple cycles of fractionation, recharge, and mixing observed in layered mafic intrusions.

We document here a 1136-m-thick stratigraphic section of basalt sampled by scientific drilling that preserves geochemical variations consistent with crystal fractionation, magma recharge, and assimilation in a layered magma chamber at mid-crustal depths. Upward fractionation sequences are inferred to represent fractional crystallization cycles identified in layered intrusions; reversed intervals are inferred to document progressive recharge of a previously fractionated magma system. The chemical stratigraphy of these basalts provides a clear link between processes inferred from layered mafic intrusions and the chemical evolution of basaltic magmas.

GEOLOGIC RELATIONS

The Yellowstone–Snake River Plain volcanic system of the western United States represents one of the best examples of hotspot volcanism preserved within continental lithosphere, although the significance and origin of the volcanic rocks are controversial (Fig. 1). Rhyolite caldera complexes and their associated ignimbrites are overlain by a thin veneer of basalt, ~1–2 km thick, erupted from small shield volcanoes and cinder cones. Major and trace element systematics of the basalts are consistent with a sublithospheric mantle plume origin, similar to the source of ocean island basalts, but their isotopic compositions reflect an enriched subcontinental mantle lithosphere source (Leeman, 1982; Geist et al., 2002; Hughes et al., 2002; Shervais et al., 2003, 2005). Core from adjacent scientific drill holes NPRE (0–185 m) and WO-2 (cored from 152 to 1515 m total depth) at the Idaho National Laboratory (INL) preserves a nearly complete record of volcanism at this site, comprising 1136 m of basalt overlying 380 m of rhyolite tuff and breccia. Basalts at the surface are dated as ca. 230 ka (Champion et al., 2002). A sediment horizon at 215–233 m depth has been correlated with the Bruhnes-Matuyama magneto-stratigraphic boundary (780 ka), while the magnetic polarity chronozone C2n (Olduvai, ca. 1.81 Ma) occurs at ~526 m depth (Champion et al., 2002; Morse and McCurry, 2002). The underlying rhyolites are correlated with the Heise volcanic complex, the youngest rocks of which have been dated as ca. 4.45 Ma (Morgan and McIntosh, 2005).

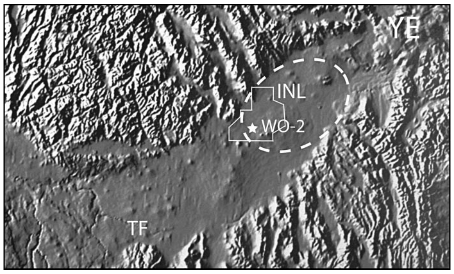

Figure 1. Digital topographic map of central and eastern Snake River Plain (SRP), southern Idaho, showing location of Idaho National Laboratory site (INL; outline), core hole WO-2 (white star), and Heise volcanic complex (dashed outline). Note abrupt termination of Basin and Range structural trends at margins of SRP, which trends NE and culminates at Yellowstone (YE) plateau. TF—Twin Falls.

The eastern Snake River Plain is underlain by a mid-crustal layer ~10 km thick and ~90 km wide that has a seismic velocity (Vp ~ 6.5 km/s) intermediate between the granulitic lower crust and more felsic upper crust (Braile et al., 1982; Peng and Humphreys, 1998). The mid-crustal layer has been interpreted to represent a sill formed by the intrusion of basaltic magma into the middle crust, but it is not possible to distinguish a single 10-km-thick sill from a sill complex consisting of many semi-contiguous sills intruded over a prolonged time. McQuarrie and Rodgers (1998) and Rodgers et al. (2002) proposed that downwarping of the eastern Snake River Plain is driven by sinking of the excess mass in this mid-crustal sill, which is found only under the eastern Snake River Plain and is absent from adjacent crust.

METHODS

We selected 59 whole-rock samples for analysis, representing all 38 major basalt flow groups documented in the core. Major elements were analyzed by fused bead electron microprobe analysis, and trace elements were

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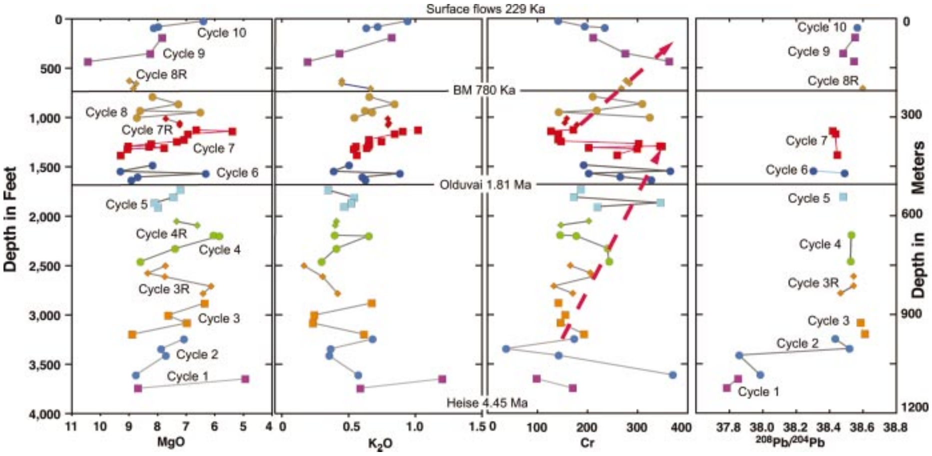

Figure 2. Plots of chemical and isotopic composition as a function of depth below surface (in feet) for MgO wt%, K_2O wt%, Cr ppm, and $^{208}Pb/^{204}Pb$ isotopic composition. Data define 10 upward enrichment cycles (decreasing MgO, Cr; increasing TiO_2 and K_2O), and four crude reversals, which are thought to represent progressive fractionation of basaltic magma in the mid-crustal magma chamber, and replenishment of this system with new magma, respectively. Note upward increase in Cr, which forms at least two megacycles (shown by red arrows) that cannot be attributed to simple fractionation.

analyzed by X-ray fluorescence spectrometry and by inductively coupled plasma mass–spectroscopy; three samples are altered and have been excluded from the data set (for details see Data Repository Table DR1[1]).

RESULTS

Plots of fractionation index versus depth show that at least 10 upward fractionation series can be identified within the 1136 m of basalt core. The upward fractionation cycles are defined by decreases in MgO and Cr upsection, and by increases in FeO*, K_2O, TiO_2, P_2O_5, Zr, La, and La/Lu (e.g., MgO, K_2O, Cr; Fig. 2). The plagiophile elements CaO, Al_2O_3, and Na_2O vary more irregularly, possibly reflecting plagioclase flotation in some cumulates. Transitions between evolved compositions at the top of one cycle and primitive compositions at the base of the superjacent cycle may be abrupt or gradual; the gradual transitions are represented by reversed cycles in which the basalts become progressively more primitive upsection. There are four of these reversed cycles that occur above normal cycles 3, 4, 7, and 8 (cycles 3R, 4R, 7R, and 8R; Fig. 2). Cr concentrations define two or three megacycles above 970 m depth superimposed on the upward fractionation trends (Fig. 2).

Basalts from cycles 1 and 2 (below ~970 m depth) display wide fluctuations in major element, trace element, and isotopic compositions that are difficult to correlate with simple fractionation or recharge. For example, K_2O/P_2O_5 ratios vary from 1.2 to 8.1 below 970 m, but in the cycles above 970 m depth K_2O/P_2O_5 ratios vary from ~0.4–2.5, with a few alteration-induced fluctuations. Below 970 m depth, $^{208}Pb/^{204}Pb = 37.8–38.6$ and $^{87}Sr/^{86}Sr$ ranges from 0.7063 to 0.7083; above 970 m depth, $^{208}Pb/^{204}Pb \geq 38.3$ and $^{87}Sr/^{86}Sr$ ranges from 0.7061 to 0.7075 ($^{208}Pb/^{204}Pb$: Fig. 2; see also Table DR1 [see footnote 1]).

The negative correlation of La/Lu with Mg# implies that assimilation was concurrent with fractional crystallization, but K_2O/P_2O_5 (and K_2O/TiO_2) ratios correlate positively with Mg# from 970 m toward the surface (Fig. 3). Thus, the assimilant must have been enriched in Ti, P, and the light rare earth elements relative to the lithophile elements that dominate normal sialic crust. Further, the relatively constant radiogenic isotope ratios above 970 m depth show that the assimilant must have had an isotopic composition similar to the parent magmas of the intruded basalts (Fig. 3).

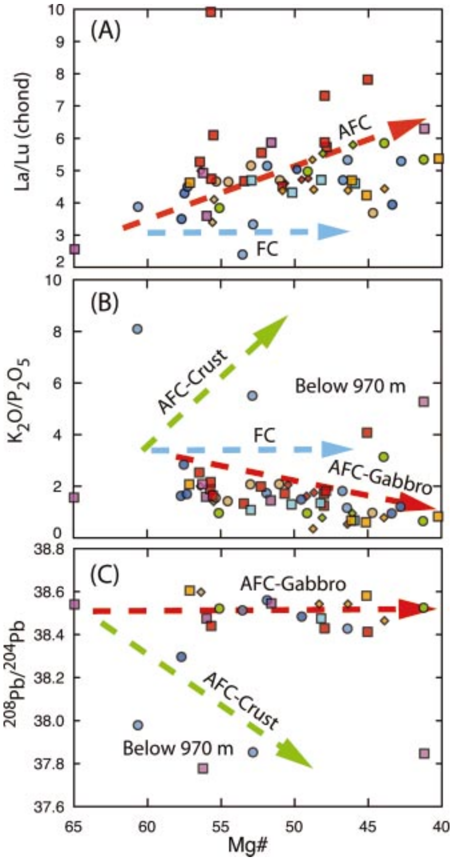

Figure 3. Ratio plots of Mg# (100*Mg/[Mg + Fe]) vs. La/Lu (chondrite normalized), K_2O/P_2O_5, and $^{208}Pb/^{204}Pb$ isotopic ratios. A: Increase in La/Lu with decreasing Mg# suggests assimilation of crustal component during fractionation (arrow). B: Decrease in K_2O/P_2O_5 shows that assimilant was rich in P_2O_5 (and other high field strength elements) relative to K_2O (and other felsic components); arrows show expected paths for fractional crystallization (FC), fractional crystallization with assimilation of felsic crust (AFC-crust), and fractional crystallization with assimilation of previously intruded basalt (AFC-gabbro); altered samples from cycle 3R are not shown. C: Relatively constant $^{208}Pb/^{204}Pb$ ratios imply that assimilant had isotopic composition similar to intruded magma, and could not represent old continental crust.

DISCUSSION

Layered Mafic Intrusion Paradigm

The cyclic repetition of phase assemblages and compositions observed in layered mafic intrusions has long been interpreted as the response of a basaltic magma to fractional crystallization and magma recharge (e.g., Wager and Brown 1967; Jackson, 1970, 1971; Irvine, 1970; McBirney and Noyes, 1979; Pallister and Hopson, 1981). Progressive changes in phase assemblages and/or compositions within each cycle represent the instantaneous crystal extracts from an evolving magma. Changes in phase assemblages represent interception of a new phase volume, while changes in phase compositions (the so-called cryptic layering of cumulate rock assemblages) represent the progressive evolution of the magma toward lower temperatures. In contrast, the repetition of cycles involving the same or broadly similar phase assemblages upsection has been shown to represent an influx of primitive magma that mixes with any residual magma remaining in the system and draws the system back toward its original starting point. This recharge of an evolved magma with new primitive melt is the most important factor in forming the repetitive cycles that are characteristic of layered mafic intrusions (e.g., Irvine, 1970). Careful analysis of these repeated cycles has shown in several cases that assimilation of the adjacent wall rock must be operating to pull these mixed

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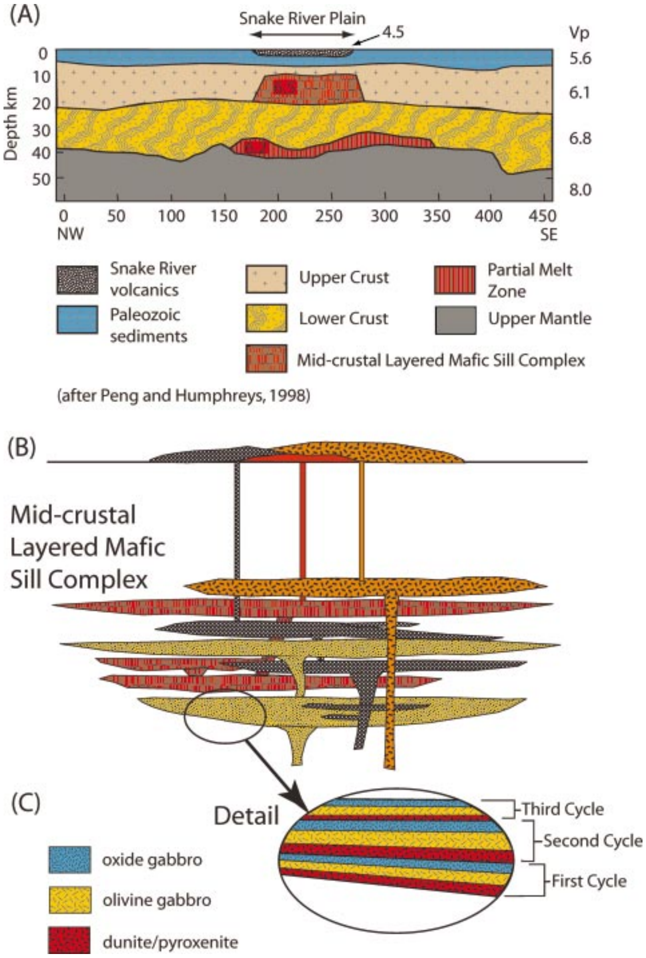
[1] GSA Data Repository item 2006072, Table DR1, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



(after Peng and Humphreys, 1998)

Figure 4. Model cross sections of crust with sill complex. A: Seismic velocity model of Peng and Humphreys (1998), showing location and thickness of inferred mafic sill complex. B: Detailed schematic with our interpretation of mafic sill complex as interpreted from compositional trends in lavas; separate magma batches may pond at more than one level in crust and may interact with partial melts or residual melts in partly congealed Fe-Ti basalt cumulates prior to replenishment. C: Inset showing detail of layered sill with multiple fractionation cycles forming layered intrusion; repeated cycles form in response to magma replenishment.

magmas off simple mixing trends (e.g., Jackson, 1970, 1971).

Origin of Depth-Related Variations in the Basalts

The depth-correlated variations in basalt chemistry described here imply the superposition of several different enrichment and/or fractionation mechanisms that operated with different periodicities and at different rates throughout the section. Based on our examination of these data, we can surmise that these processes included fractional crystallization, assimilation, and recharge by primitive magmas. These are the same processes inferred from phase relations observed in layered mafic intrusions (e.g., Irvine, 1970).

The upward fractionation cycles are consistent with fractional crystallization of the more primitive (high Mg#, low incompatible elements) lavas in each cycle, as confirmed by forward modeling using MELTs (Ghiorso and Sack, 1995) and Comagmat (Ariskin et al., 1993). There are distinct variations between some cycles, showing that the same parent magma cannot be used for all cycles. In particular, basalts in the upper 130 m of core require a distinct parent magma, with higher Mg#, CaO, and Al_2O_3, and lower FeO*, TiO_2, and K_2O at a given MgO content, that is unrelated to basalts lower in the core. Cr concentrations define two or three megacycles, each of which may represent a distinct magma stem (Fig. 2).

Transitions between some upward fractionation cycles are not abrupt, but occur gradationally over 30–60 m of section (cycles 3R, 4R, 7R, 8R). We infer that these gradual reversals are due to magma recharge; the gradational transitions imply that the influx of new magma batches occurred over a period of time, and did not completely overwhelm residual magma from the previous fractionation cycle. In contrast, abrupt transitions from evolved to primitive compositions imply a complete turnover in the magma supply, consistent with observations in many layered intrusions for a return to phase assemblages and compositions that are as primitive as the basal cumulates in the underlying cycle (e.g., Irvine, 1970). Alternatively, abrupt reversals may represent tapping of a new magma storage chamber, or nonuniform distribution of the erupted lava.

Assimilation of Consanguineous Basalt Intrusions: The Sill Complex as a Reactive Filter

The changes displayed by incompatible element ratios in response to decreasing Mg# require that assimilation occurred in concert with fractional crystallization, but the constant isotopic compositions above 970 m depth require that the assimilant had an isotopic composition similar to the intruded magma (Fig. 3). This assimilant could not have been older continental crust, which is characterized by high K_2O, high $^{87}Sr/^{86}Sr$ isotopic ratios, and low $^{208}Pb/^{204}Pb$ ratios. We propose that above 970 m depth, the assimilant was a partially crystallized ferrogabbro derived from a parent magma that was the same or similar to the recharge magmas. Melts derived from this ferrogabbro, or residual melts in the interstices of partially crystallized cumulates, will have isotopic compositions similar to the primitive recharge magma, but will be enriched in FeO, TiO_2, P_2O_5, and La/Lu (Fig. 3). The observed increase in K_2O/P_2O_5 upsection in the core thus represents a progressive decrease in assimilation through time, probably in response to earlier melt extraction and/or assimilation events that depleted the crust in low melting components (e.g., Geist et al., 2002).

It is unlikely that each new batch of primitive magma feeding the layered complex was identical in composition to previous batches of magma, even if they are broadly similar; each magma batch was likely to reflect small variations in source composition and percent melting, as proposed by Hughes et al. (2002). The occurrence of the reversed fractionation cycles, however, implies that these individual magma batches did not erupt directly at the surface, but were processed through a crustal storage system.

Layered Mafic Sill Complex in the Middle Crust

Where layered mafic intrusions are sufficiently well exposed, it can be shown that their form factor is sill-like, either as a funnel-shaped lopolith or as true sills that have significant horizontal extent. Less commonly described are sill complexes that represent the progressive migration of melts upward through the crust, pausing to fractionate and assimilate at crustal depths where the magma is neutrally buoyant (e.g., Marsh, 2004).

Based on the chemical stratigraphy of the NPRE and WO-2 cores, we propose that the 10-km-thick ‘‘sill’’ imaged seismically below the eastern Snake River Plain represents a complex of layered mafic sills that are partially interconnected, each feeding one or more major volcanic centers on the surface (Fig. 4). The presence of reversed cycles between some normal cyclic units implies magma recharge within a layered intrusion. The lack of reversed cycles between other normal cycles may indicate eruptions from a distinct unrelated sill, or a complete recharge of the sill that flushes out any residual melt. Alternatively, it could result from the fact that drill core is an imperfect record of basaltic volcanism: shield volcanoes may remain emergent for hundreds of thousands of years on one flank while being inundated by an adjacent volcano on another flank, and a drill core penetrating what was the emergent flank will record a hiatus in deposition even though volcanism was continuous.

Upward enrichment megacycles in the compatible element Cr, along with abrupt changes in incompatible elements, suggest that at least three large magma systems were present under the eastern Snake River Plain at this location; we speculate that these represent three layered sill complexes. Other layered sills are probably present along strike in the plain, to the NE and SW.

CONCLUSIONS

The preservation of chemical cycles in erupted lavas that are consistent with formation in layered mafic intrusions represents a unique confirmation of petrologic theory. The importance of layered mafic sill complexes in controlling magma evolution was highlighted by Marsh (2004), and the fact that a 10-km-thick ''sill'' has been imaged seismically below the lavas studied here confirms the validity of this model.

Because magmas will tend to pond near their depth of neutral buoyancy and thus interact with previously ponded melts and their solidified extracts, assimilation of this consanguineous material is virtually assured. The sill complex thus becomes a reactive filter that affects any magmas that attempt to traverse it on their way to the surface, forcing assimilation of previously intruded magmas (now largely crystallized to ferrogabbros) and crystallization of the equilibrium phase assemblage. This model is fundamentally the same as that proposed by Bédard (1993) for oceanic crust.

Our data show that it is possible for basaltic melts to traverse thick sections of continental crust without substantially interacting with the granitic to dioritic gneisses that dominate this crust. The data imply that once a robust conduit system has been established through the felsic crust, the ascending melts are protected from interacting with this crust by armoring of the conduit walls.

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REFERENCES CITED

Ariskin, A.A., Frenkel, M.Y., Barmina, G.S., and Nielsen, R.L., 1993, Comagmat: A Fortran program to model magma differentiation processes: Computers & Geosciences, v. 19, p. 1155–1170, doi: 10.1016/0098-3004(93)90020-6.

Bédard, J.H., 1993, Oceanic crust as a reactive filter; synkinematic intrusion, hybridization, and assimilation in an ophiolitic magma chamber, western Newfoundland: Geology, v. 21, p. 77–80, doi: 10.1130/0091-7613(1993)021<0077:OCAARF>2.3.CO;2.

Braile, L.W., Smith, R.B., Ansorge, J., Baker, M.R., Sparlin, M.A., Prodehl, C., Schilly, M.M., Healy, J.H., Mueller, S., and Olsen, K.H., 1982, The Yellowstone–Snake River plain seismic profiling experiment; crustal structure of the eastern Snake River plain: Journal of Geophysical Research, v. 87, no. B4, p. 2597–2609.

Champion, D.E., Lanphere, M.A., Anderson, S.R., and Kuntz, M.A., 2002, Accumulation and subsidence of the Pleistocene basaltic lava flows of the eastern Snake River Plain, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation; Idaho National Engineering and Environmental Laboratory, eastern Snake River Plain, Idaho: Geological Society of America Special Paper 353, p. 175–192.

Geist, D.J., Sims, E.N., Hughes, S.S., and McCurry, M., 2002, Open-system evolution of a single episode of Snake River Plain magmatism, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation; Idaho National Engineering and Environmental Laboratory, eastern Snake River Plain, Idaho: Geological Society of America Special Paper 353, p. 193–204.

Ghiorso, M.S., and Sack, R.O., 1995, Chemical mass transfer in magmatic processes. IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures: Contributions to Mineralogy and Petrology, v. 119, p. 197–212.

Hughes, S.S., McCurry, M., and Geist, D.J., 2002, Geochemical correlations and implications for the magmatic evolution of basalt flow groups at the Idaho National Engineering and Environmental Laboratory, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation; Idaho National Engineering and Environmental Laboratory, eastern Snake River Plain, Idaho: Geological Society of America Special Paper 353, p. 151–173.

Irvine, T.N., 1970, Crystallization sequences in the Muskox intrusion and other layered intrusions, *in* Symposium on the Bushveld Igneous complex and other layered intrusions: Geological Society of South Africa Special Publication 1, p. 441–476.

Jackson, E.D., 1970, The cyclic unit in layered intrusions—A comparison of repetitive stratigraphy in the ultramafic parts of the Stillwater, Muskox, Great Dyke, and Bushveld complexes, *in* Symposium on the Bushveld Igneous complex and other layered intrusions: Geological Society of South Africa Special Publication 1, p. 391–424.

Jackson, E.D., 1971, The origin of ultramafic rocks by cumulus processes: Fortschritte Der Mineralogie, v. 48, p. 128–174.

Leeman, W.P., 1982, Development of the Snake River Plain–Yellowstone Plateau province, Idaho and Wyoming: An overview and petrologic model, *in* Bonnichsen, B., and Breckenridge, R.M., eds., Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26, p. 155–177.

Marsh, B., 2004, A magmatic mush column Rosetta Stone: The McMurdo Dry Valleys of Antarctica: Eos (Transactions, American Geophysical Union), v. 85, p. 497–508.

McBirney, A.R., and Noyes, R.M., 1979, Crystallization and layering of the Skaergaard Intrusion: Journal of Petrology, v. 20, p. 487–554.

McQuarrie, N., and Rodgers, D.W., 1998, Subsidence of a volcanic basin by flexure and lower crustal flow, the eastern Snake River plain, Idaho: Tectonics, v. 17, p. 203–220, doi: 10.1029/97TC03762.

Morgan, L.A., and McIntosh, W.C., 2005, Timing and development of the Heise volcanic field, Snake River plain, Idaho, western USA: Geological Society of America Bulletin, v. 117, p. 288–306, doi: 10.1130/B25519.1.

Morse, L.H., and McCurry, M., 2002, Genesis of alteration of Quaternary basalts within a portion of the eastern Snake River Plain Aquifer, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation; Idaho National Engineering and Environmental Laboratory, eastern Snake River Plain, Idaho: Geological Society of America Special Paper 353, p. 213–224.

Pallister, J.S., and Hopson, C.A., 1981, Samail ophiolite plutonic suite; field relations, phase variation, cryptic variation and layering, and a model of a spreading ridge magma chamber, *in* Coleman, R.G., and Hopson, C.A., eds., Oman ophiolite: Journal of Geophysical Research, p. 2593–2644.

Peng, X., and Humphreys, E.D., 1998, Crustal velocity structure across the eastern Snake River plain and the Yellowstone Swell: Journal of Geophysical Research, B, Solid Earth and Planets, v. 103, no. 4, p. 7171–7186, doi: 10.1029/97JB03615.

Rodgers, D.W., Ore, H.T., Bobo, R.T., McQuarrie, N., and Zentner, N., 2002, Extension and subsidence of the eastern Snake River plain, Idaho, *in* Bonnichsen, B., et al., eds., Tectonic and magmatic evolution of the Snake River Plain volcanic province: Idaho Geological Survey Bulletin 30, p. 121–156.

Shervais, J.W., Hanan, B.B, and Vetter, S.K., 2003, Chemical stratigraphy of basalts from the 5000′ borehole NPR-E/WO-2, eastern Snake River Plain, Idaho: Evidence for mixed asthenosphere-lithosphere sources. Eos (Transactions, American Geophysical Union), v. 84, fall meeting supplement, abs. V32H–03.

Shervais, J.W., Kauffman, J.D., Gillerman, V.S., Othberg, K.L., Vetter, S.K., Hobson, V.R., Meghan Zarnetske, M., Cooke, M.F., Matthews, S.H., and Hanan, B.B., 2005, Basaltic volcanism of the central and western Snake River Plain: A guide to field relations between Twin Falls and Mountain Home, Idaho, *in* Pederson, J., and Dehler, C.M., eds., Guide to field trips in the western United States: Geological Society of America Field Guide, v. 6, p. 27–52.

Wager, L.R., and Brown, G.M., 1967, Layered igneous rocks: San Francisco, California, W.H. Freeman and Company, 588 p.

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