Petrotectonics of Tholeiitic and Alkaline Basalts
Iceland: The Mid-Atlantic Ocean Ridge and Wells Gray Volcanic Field, BC Canada

Reykjanes Peninsula, Iceland

Konal Lake volcano cone, Wells Gray Park, BC Canada

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Abstract

The purpose of this study is to compare the geochemical and petrologic signatures of subalkaline, tholeiitic basalts typical of Mid-Atlantic Ocean Ridge basalts (MORB) in Iceland, to the alkaline olivine basalts produced in the Wells Gray-Clearwater volcanic field in east-central BC, which are the result of tectonic differences. Accretion of multiple terranes moved into and welded onto the western coast of British Columbia, Canada, intermittently with periods of quiescence, erosion and subduction of sinking oceanic plates (i.e. Pacific Plate) under the continental crust. Forming ~15 Ma ago in the north Atlantic, Iceland is one of the most active volcanic areas on the Earth today, straddling the divergent North American and Eurasian plates and elevating above sea level as an island on the Mid-Atlantic ocean ridge. The study was conducted by perusing articles, journals and books that discuss geochemical, textural analysis and equilibrium conditions, such as depletion/enrichment in $^{87}$Rb, $^{147}$Sm, silica, lherzolite, K, Ti and LIL elements of the Chilcotin plateau, Anahim volcanic belt, and Iceland’s three magma series with a focus on tholeiitic basalts in the Reykjanes peninsula. Significant progress in major and trace mineral analysis has occurred in geological studies due to technological advances, however, few studies have been completed on the external factors affecting crustal rebound and increased volcanism during rapid deglaciation during the Pleistocene.
Introduction

Petrogenesis, or the origin of igneous rocks, and petrology, the discipline of geology that studies rocks, has made significant and exciting progress in order to understand processes occurring in the geologic past and present, at various depths in the Earth. The following study will first summarize the characteristics of two different basalts, tholeiitic and alkaline, by their geochemical, textural and isotopic signatures.

Volcanic activity on Earth’s surface is a result of complex processes at varying depths in the mantle and crust, thus petrologic studies have associated the composition of basalts to factors such as tectonics, magma mixing and pressure-temperature relationships. The second part of this study discusses two tectonically different locations and the basalts thereby produced, in Iceland, and the west coast of British Columbia, Canada, in the Wells Gray-Clearwater volcanic field.

Tholeiitic Basalts

The most voluminous basalts are tholeiites, forming from high-degree (>10-20%) melting of mantle rocks that contain amounts of silica where quartz can exist under equilibrium conditions (Foulger, G.E. 2010). Tholeiitic basalts are found within the Mid-Atlantic Ocean Ridge (MORB) at plate divergent zones, and are depleted due to ancient melting at its source (asthenospheric mantle) during the formation of continental crust. Lherzolite, a fertile mantle peridotite, is a source of partial melting leading to tholeiite. Enriched tholeiites compose oceanic plateaus and continental flood basalts. Radiogenic isotope ratios reflect long-term depletion in $^{87}\text{Rb}$ and $^{147}\text{Sm}$ enrichment (Foulger, G.E. 2010).
Subalkaline, tholeiitic rocks are enriched in Fe relative to Mg, compared to calc-alkaline rocks, while silica remains relatively the same (Best, M.G. 2003). Mafic oceanic or thin continental crust is host to low-K rocks equivalent to tholeiitic suites typical in island arcs (Best, M.G. 2003). This is in contrast to either medium to high-K rocks, namely calc-alkaline or silica-undersaturated, felsic rocks equivalent to alkaline suites typical for oceanic islands and some continental settings (Best, M.G. 2003). Silica saturation further identifies the type of basalt from greatest to least saturation: quartz tholeiite, olivine tholeiite and alkaline basalt, respectively (Best, M.G. 2003).

Mid oceanic ridges are characteristic of tholeiitic, rather than andesitic basalts and are commonly termed ridge tholeiite. The shallow depths of magma production along the constructive Mid Oceanic Ridge and earthquake zone, form alkali-poor tholeiitic magma (Jokat et al, 1992). Subduction zones, however, draw moisture down into the upper mantle to form andesitic magma in contrast to moisture dissipating along expanding fissures in the Mid-Ocean Ridges (Zou, C. 2013).

Characteristics of ridge tholeiite:

1. Olivine phenocrysts and/or plagioclase, with matrix minerals of olivine, plagioclase, klinaugite and iron, commonly with crystallite, a vitreous and crystallographic mineral.

2. Low in potassium (K2O < 0.4%) and P2O5 (<0.25%); high titanium (TiO2 0.7-2.3%); and FeO+Fe2O3/MgO of 0.7-2.2%.

3. Distinguished from continental and island arc tholeiite by high Al2O3 and Cr; high LIL elements (Rb, Cs, Sr, Ba, Zr, U, Th); and a deficit of light REE’s.
Enriched in gabbro and peridotite, the ridge tholeiite of the MOR is formed by 20-30% partial melting of peridotites in the depleted mantle within depths of 30km. Fractional crystallization of the original melt is related to gabbro and peridotite content.

**Alkaline Basalts**

Alkali basalts are non-tholeiitic basalts produced from small-degree (<5%) melting of mantle rocks, resulting in readily melted source rock having a higher concentration in alkali basalt than tholeiite (Foulger, G.E. 2010). Although alkali basalts are less voluminous than tholeiites, it is the composition of most oceanic islands, seamounts and smaller-volume continental volcanism. The parent rocks of alkali basalts are melt products from ancient melting events.

**Wells Gray Volcanic Field, British Columbia, Canada**

British Columbia is the result of over one hundred terranes that collided with the coastline, then accreted and welded to the continent, followed by long geologic periods of uplift, erosion and subduction of sinking oceanic plates under the continent (Cannings, S. et al 2011). This complex geological history over ~ 200 Ma hosted significant active periods of orogeny and volcanism (Cannings, S. et al 2011). The Pemberton volcanic belt, Anaheim volcanic belt, Intermontane belt, Chilcotin group basalts underlying the Interior Plateau, and the Quesnel Highlands are to name a few.
During the late Cenozoic (~3.5 Ma), predominantly during the past 0.5 Ma, through the Holocene and up until as recent as 1550 CD, volcanoes in Wells Gray-Clearwater (52.33°N 120.57°W) of east-central BC produced alkali olivine basalt flows. The volcanic field, in Figure 1, lies within the Quesnel-Shuswap Highlands east of the Chilcotin Group plateau and Anahim volcanic belt (Hickson, C.J. 1984). Further north, the northern Cordilleran volcanic province (NCVP) produced mafic alkaline volcanic rocks from the Miocene to Holocene (Edwards, B. 2000). The Wells Gray volcanic field overlies the Shuswap Metamorphic Complex, with an estimated uppermost mantle depth of 30-36 km (Canil, D. 1988), and is made up of primarily cinder cones in a central volcanic complex (Charland, A. 1992). A debated hot spot
hypothesis for the Anahim volcanic belt exists, supported by evidence such as the absence of lherzolite nodules by age and mantle origin (Hickson, C.J. 1984).

Chilcotin basalts, illustrated in Figure 2, cover approximately 25,000 km² of central and southern BC at intervals from 24 Ma, with characteristics of olivine tholeiites and mildly silica-undersaturated alkali basalts (Dostal, J. 1996). There is a resemblance to oceanic island basalts from a garnet peridotite source, and spinel peridotite xenoliths are common. It is thought that a subcontinental lithospheric mantle enriched by earlier subduction processes is the source of Chilcotin basalts, which was triggered to melt by upwelling of the underlying asthenospheric mantle (Dostal, J. 1996).
The basalts in Wells Gray are similar to Chilcotin basalts yet less petrochemically altered (Hickson, C.J. 1984). It has been proposed that a thinning crust, in addition to displacement and subducted extension of the Nootka fault contributed to magma generation from asthenospheric upwelling and alkaline composition of basalts in Wells Gray (Madsen, J.K. 2006). The underlying Kootenay terrane may have contributed to contamination of a radiogenic crustal component, due to Sr and Pb isotope data (Madsen, J.K. 2006).

Following the separation of the Juan de Fuca slab and Explorer plate (Figure 1), the slab steepened, developing dip angles that differed and a subsequent vertical gap between the two plates, establishing the Wells Gray volcanic field, illustrated in Figure 3 (Madsen, J.K. 2006).

Petrographic thin sections show consistent alkali olivine basalt with 1-4 mm olivine phenocrysts. In fact, while crystallizing in upward magma transport, the only mineral phase apparent is the olivine phenocryst
(Hickson, C.J. 1986). When unstrained, there are iron-rich rims with uniform cores of ~ Fo$_{80}$ and sized less than 5 mm. Orthopyroxene is not present in thin section, while clinopyroxene phenocrysts appear in a few Holocene flows (Hickson, C.J. 1986). Groundmass minerals of plagioclase, titanaugite, olivine, Fe-Ti oxides and interstitial glass have a variance of intersertal to granular hypidiomorphic textures (Metcalfe, P. 1987). Minor phases of apatite, ilmenite, and magnetite occupy matrix space between plagioclase laths (Hickson, C.J. 1986). In subaerial flows, clear and unaltered glass have dendritic and skeletal Ilmenite crystals, a sign of varied growth phases. Some pyroxenes are euhedral with pale green pleochroism, whereas if colours exist they are acmitic, suggesting a soda-rich residual liquid during fractionation. In quenched samples, there are microlites that suggest a short crystallization period before eruption (Hickson, C.J. 1986).

Fluvial sands, gravels and subaqueous features such as pillow lavas, breccias and tuff breccia give evidence of at least two glacial advances coinciding with volcanic activity (Hickson, C.J. and Souther, J.G. 1984). Resulting hyaloclastite deposits of quenched basalts with pillow lavas have diktytaxitic textures and interstitial titaniferous augite enclosing plagioclase. Euhedral olivine phenocrysts are abundant, and over 75% of the pyroxene and feldspar are palagonitized with small radiating skeletal crystals. Fine-grained hyaloclastites are almost wholly olivine crystals indicating olivine was the only mineral on the liquidus during eruption.

Phlogopite can be found with olivine and pyroxene and most commonly occurs within course-grained peridotite xenoliths that have been carried up to the Earth’s surface by kimberlite, a likely result of
metasomatism (Canil, D. 1988). Two cinder cones in Wells Gray, aged less than 7500 BP and within the Kostal Lake eruptive centre (Figure 3), produced ultramafic xenoliths and phlogopite-bearing xenoliths, known by samples collected from ejecta surrounding the rim and a lava tube of the southernmost cinder cone (Canil, D. 1988).

Hydrothermal activity has weathered or altered the xenoliths. Type I xenoliths were subrounded, 2 to 8 cm in size, of granular texture, and composed primarily of olivine with orthopyroxene, spinel, apple green clinopyroxene, lherzolites, dunites and olivine websterites and clinopyroxenites (Canil, D. 1988). Type II xenoliths, illustrated in Figure 4, were also subrounded, but of cumulate texture, 2 to 10 cm in size with large grains (2-4 mm) of olivine or olivine aggregate enclosed in poikilitic clinopyroxene characterized by a dark green-black colour (Canil, D. 1988).

Spinels from phlogopite-bearing xenoliths in the Kostal Lake eruptive centre are more Fe-rich and anomalously rich in Cr$_2$O$_3$ and TiO$_3$ compared to lherzolite xenoliths in other areas of BC (Canil, D. 1988). Zoning is apparent with grain rims hosting higher Mg, likely due to heating in the mantle before
entrainment in the host magma (Canil, D. 1988). Intercumulous clinopyroxene has produced peraluminous glasses that are heterogeneous in alkalis and silica (Canil, D. 1988). It is likely that the upper mantle was infiltrated with a fluid phase containing Na, K, Cl, P, S and H_2O beneath Kostal Lake, in order to precipitate the fluid inclusions with phlogopite-bearing xenoliths. Anhydrous xenoliths collected from Kostal Lake and other locations in the Canadian Cordillera have spinels with higher Fe^{3+}, from phlogopite-bearing xenoliths (Canil, D. 1988). Thus, fluid and melt metasomatism is thought to have occurred during a period between initial volcanism in Wells Gray (3-5 Ma) and the lavas containing xenoliths during post-glacial volcanic activity (400 BP) at Kostal Lake (Canil, D 1988).

**The Petrogenesis and Petrology of Icelandic Basalts**

During the closure of the Lapetus Ocean ~440 Ma years ago, present-day Greenland and Scandinavia collided, creating the Caledonian suture subduction zone and subsequent formation of Iceland and the North Atlantic Volcanic Province (Gunn, B.M. 2006). Iceland’s petrotectonic complexity today is due to divergence of the Eurasian and North American plate and its orientation to the ~ 54 Ma year old constructive Mid-Atlantic Ridge at its centre.

Iceland’s rocks are typical of oceanic ridges, and are considered Oceanic Ridge Basalts rather than Oceanic Island Basalts, due to its larger fractionated members. The east and west coast are Tertiary aged basalts (~15 Ma), whereas the inner active spreading axis is less than 0.7 Ma with abundant Holocene basalt flows and currently active volcanism (Gunn, B.M. 2006). Three principal mantle components are
thought to reside beneath Iceland: recycled oceanic crust, an enriched mantle plume and a depleted upper mantle source (Sigmarsson, O. 2007).

Other than the Galapagos Rise and the East Pacific Rise (EPR), the range of basalt and eruptive compositions in Iceland, illustrated in Figure 5, are unique for an oceanic environment (Gunn, 2006).

Compositions range from depleted high-degree melt olivine basalts and picrites to ferrobasalts, high Nb-Ta ‘rholites’ with albitic feldspar and quartz, rhyodacite, and silicic rocks including the low-Al andesine-bearing andesite, and icelandite (Gunn, 2006). Rhyolitic edifices from volcano-ice interactions have occurred in over fifteen volcanic systems during the past 0.8 Ma in Iceland, and are unique to any other volcanic province (McGarvie, D. 2009).

Iceland’s Holocene basalts vary depending on their location relative to the central rift zone, illustrated in Figure 6, and produce three magma series. First, tholeiitic alkaline basalts in the sub-alkaline series are
produced in the central active rift zone of the diverging tectonic plates. Second, basalts in the alkaline series are located only in the two off-rift volcanic zones of the Snaefellsnes Peninsula and South-Central Iceland, including the Vestmannaeyjar volcanic system (Sigmarsson, O. 2007). Third, transitional alkaline basalts in the sub-alkaline series geographically link the other two basalts and are recognized by having high iron, titanium and alkali metals for silica-saturated basalts. A summary follows, of three magma series comprising Iceland’s Holocene basalts:

<table>
<thead>
<tr>
<th>Basalt Series/Type</th>
<th>Characteristics</th>
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<tbody>
<tr>
<td>Sub-alkaline (Tholeiitic alkaline)</td>
<td>Highest primordial (less radiogenic) and enriched composition, with He-isotope signature near assumed mantle plume; Basalts with higher MgO reflect partial melting of mantle (refractory) that’s already been depleted in melts initially water-rich; increased temperatures in the mantle at Iceland’s centre cause increased magma production/diluted signatures of garnet pyroxenites; Evolved tholeiites show derivation of the crust. Locations: Veiðivötn and Grimsvötn volcanic systems within the rift zone.</td>
</tr>
<tr>
<td>Sub-alkaline (Transitional alkaline)</td>
<td>Enriched in trace elements that are incompatible; higher radiogenic Pb, Sr, and He-isotope compositions; lithologically heterogeneous mantle has partial melting with larger proportions of melt derived from oceanic crust that’s been recycled, and in the form of garnet pyroxenites. Locations: Katla and Hekla volcanoes in non-rifting volcanic zone.</td>
</tr>
<tr>
<td>Alkaline</td>
<td>Enriched in trace elements that are incompatible; higher radiogenic Pb, Sr, and He-isotope compositions. Locations: Iceland’s outer regions including Snaefellsnes Peninsula and South-Central Iceland including Vestmannaeyjar.</td>
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Table 1. Three magma series of Iceland’s Holocene basalts (Sigmarsson, O. 2007)

Olivine-tholeiites and picrites, with plagioclase phenocrysts, are the signature lavas of the Reykjanes peninsula (Gee M.A.M., 1998). The spinel/garnet transition depth in a lherzolite mantle has been thought to be where melting commences, or that variable depths and degrees of melting form mixed instantaneous
melts (Sigmarsson, O, 2007). Petrogenesis of Icelandic basalts suggest crustal contamination due to low-$^{18}$O, or subducted oceanic crust producing enriched basalts and lithological heterogeneity (Sigmarsson, O 2007).

![Figure 6 Icelandic basalts. Yellow=0.7Ma to 15Ma. Blue=younger then 0.7Ma. Fissure swarms on Reykjanes peninsula in Axial rift zone (Chauvel and Hemmond, 2000).](image)

Geochemically, Icelandic basalts are anomalous and both spatially and temporally heterogeneous, leading to contrasting explanations for Iceland and the North Atlantic Volcanic Province (Meyer, P.S. 1984). For example, provided Iceland’s geologic history, signatures should exist such as the high pressure form of basalt, eclogite, formed when oceanic crust moves down a subduction zone (Foulger, G.A. 2003).

The plume hypothesis is unsupported by numerous geochemical, thermal and isotopic anomalies, such as the absence of picrite glass and lack of radial pattern found near plume centres (Foulger, G.A. 2003).

Higher marine temperatures and mantle temperatures of at least 250 – 600 degrees C are associated with
mantle plumes, but geothermometers indicate similar (~ 100 K higher temperature) than beneath the MOR (Stein, C. 2003). Eruptive temperatures of ~ 1240 C in primitive lavas located in Central Iceland are similar to Mg-rich Northern MORB (Foulger, G.A. 2003).

Magma mixing of an enriched plume and depleted MORB does not explain geochemical evidence found in Iceland (Foulger, G.A. 2010). For example, Pb-isotope ratios are not higher near the proposed SE-central Iceland plume and high $^{87}\text{Sr}/^{86}\text{Sr}$ (known to trace plumes), decrease towards the proposed plume location. Elevated He-ratios are a geochemical indicator of a lower mantle and plume, found anomalous with lower $^3\text{He}/^4\text{He}$ ratios in the Northern Volcanic Zone (NVZ) than on the SW Reykjanes peninsula (Foulger, G.A. 2003).

Near plume centres, La/Sm ratios usually increase. From Kolbeinsey ridge in the North Volcanic Zone, La/Sm ratios decrease in a southerly direction toward Iceland’s centre, although La/Sm ratios increase along the southern Reykjanes ridge northward to the centre (Chavel, C. 2000). Plumes are assumed to be HIMU (high-time integrated $^{238}\text{U}/^{204}\text{Pb}$ or high $u$), such as enriched in $^{238}\text{U}/^{204}\text{Pb}$, but only Iceland’s smaller volume of alkaline basalts are HIMU, with low $^{206}\text{Pb}/^{204}\text{Pb}$ tholeiites making up the majority of volume of Iceland’s basalts (Chavel, C. 2000).
Picrites, matrix glasses and melt inclusions are low alkali, typical for Icelandic tholeiitic rocks and glasses rich in Mg (Gurenko, A.A. 1995). Illustrated in Figure 7, spinels from Reykjanes and Hengill are enclosed in olivine phenocrysts or glasses, and have low TiO\textsubscript{2} levels similar to MORB spinel phenocrysts (Gurenko, A.A. 1995). Decreasing La/Sm and \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios over 15 Ma, towards Iceland's central rift zone indicates a decrease in mantle plume activity and shifting of the spreading axis (Meyer, P.S. 1984).

Depletion of lavas has been recognized to follow glacial unloading, thus related to shorter crustal resident times from glacial unloading (Gee et al, 1998). External factors, such as rapid deglaciation during the Pleistocene (Sigmarsson, O, 2007) or at the end of the Weichselian glaciations 12-13 kyr BP (Gee, M.A.M. 1998), may likely increase melt-production rates and therefore crustal processes either depleting or enriching lavas. Pleistocene basalts are defined by hyaloclastites (volcanic glass that has been weathered and palagonitized) during glacial periods, layered with lava flows from interglacial periods.

Few studies have covered the petrologic or geochemical nature of Pleistocene basalts (Sigmarsson, O, 2007).
Conclusion

The purpose of this study was to compare and summarize the characteristic differences between tholeiitic and alkaline basalts, by focusing on two tectonically different locations, Iceland and Wells Gray, BC, which have produced and exemplify signatures of these basalts. Chemical and isotopic characteristics, such as La/Sm ratios, Pb-isotopes, $^{87}\text{Sr}/^{86}\text{Sr}$, $^3\text{He}/^4\text{He}$ ratios and levels of oxides, i.e. TiO$_2$, of lavas provide guidance on the petrogenesis and evolution of basalts.

Subalkaline, tholeiitic basalts are typical of Mid-Atlantic Ocean Ridge basalts (MORB) while alkaline olivine basalts are associated with oceanic islands, seamounts and smaller-volume continental volcanism.

In Iceland, from ~15 Ma to present, three magma series are produced, from tholeiitic, transitional to alkaline. Geochemical data suggests Pb-isotopes and ratios of $^{87}\text{Sr}/^{86}\text{Sr}$, $^3\text{He}/^4\text{He}$ and La/Sm are not higher (atypical for magma plumes) towards the proposed East-Central plume, yet other interpretations suggest decreased mantle activity and shifting of the rift zone. Icelandic tholeiites have typical signatures of MORB’s, such as low levels of $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and TiO$_2$, and low alkali picrites, matrix glasses and melt inclusions.

Volcanic activity from ~3.5 Ma until 1550 CD in the Wells Gray volcanic field, have produced alkali basalts rich in sodium and poor in silica, primarily composed of olivine phenocrysts with groundmass minerals of plagioclase, titanaugite, Fe-Ti oxides, interstitial glass and minor phases of apatite, ilmenite and magnetite. Microlites suggest a short crystallization period before eruption.
It is interesting that the topic of a plume or hot spot is not entirely accepted for Iceland or the Anahim belt in central BC. Rapid deglaciation and subsequent crustal rebound may interestingly be associated with enhanced volcanism across the Northern Hemisphere between 8 to 15 kyr BP at the end of the Weichselian, thus the production of hyaloclastites and palagonitized volcanic glass. Further petrologic studies and advanced analytical instruments will provide geochemical, textural and isotopic data that help understand petrotectonic relationships.
References


