Lava Extrusion and the Age of Iceland

Peter Klevberg*

Abstract

The Mid-Atlantic Ridge is both a salient feature in the earth's crust and a centerpiece for plate tectonics. It emerges from the sea in Iceland, a land famous for its active volcanism. Field and published data are integrated to better quantify lava extrusion rates and apply these results to natural history scenarios, including the uniformitarian and diluvial geologic paradigms. Also relevant are tectonic models, particularly the standard plate-tectonics model and its diluvial counterpart, catastrophic plate tectonics. Iceland provides a unique opportunity to compare diluvial predictions with those of common uniformitarian origin theories. Both field and published data are better explained by the diluvial geologic paradigm than by traditional theories. Both plate-tectonics models can be applied to the Mid-Atlantic Ridge in general and to Iceland in particular; however, a number of problems remain, and plate tectonics cannot change the chronological implications of the structure of the Icelandic lava pile.

Iceland as a Guide to Global Geology

There is probably no country in the world that has a higher percentage of geologists among its tourists than Iceland, and this in spite of its relative isolation in the North Atlantic Ocean touching the Arctic Circle. There are good reasons for this. Iceland is the only place where the Mid-Atlantic Ridge emerges from the sea, and it is one of the most volcanically active places on the planet. This high degree of activity is widely attributed to the Mid-Atlantic Ridge, generally believed to be the divergent margin between the North American and Eurasian tectonic plates, and a mantle hot spot (Saunders et al., 1997). Tuyas—volcanic table mountains attributed to subglacial volcanism—are unique to Iceland (Sigurjónsson and Tulinius, 2001). Vatnajökull, the world's third largest ice cap, and a score of prominent glaciers provide a means of studying glacial erosion. Catastrophic releases of meltwater from subglacial eruptions provide invaluable insight into sedimentation processes. But Iceland's main claim to geologic fame results from the virtually universal acceptance of the plate-tectonics paradigm and the special role that Iceland has in plate-tectonic theory (Figure 1).

Iceland is unique not only for the sheer magnitude of volcanic activity, but also for a strong tradition of accurate and detailed history that has characterized the Icelandic people since the time of settlement (*Landnám*) in A.D. 874. In 1783–1784, the priest Jón Steingrímsson recorded in detail his experience of the eruption that occurred along the Laki fissure (Lakagígar), the largest outpouring of lava for which reliable extrusion rate estimates are available (Fell, 1999; Self et al., 1997). The Eldgjá eruption in A.D. 940 (Figure 2) was comparable to Lakagígar, though apparently even larger (Bardintzeff and McBirney, 2000).

Much of Iceland consists of flood basalts, vast strata of conformable lava flows. Although immense in area and

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Accepted for publication: December 2, 2006

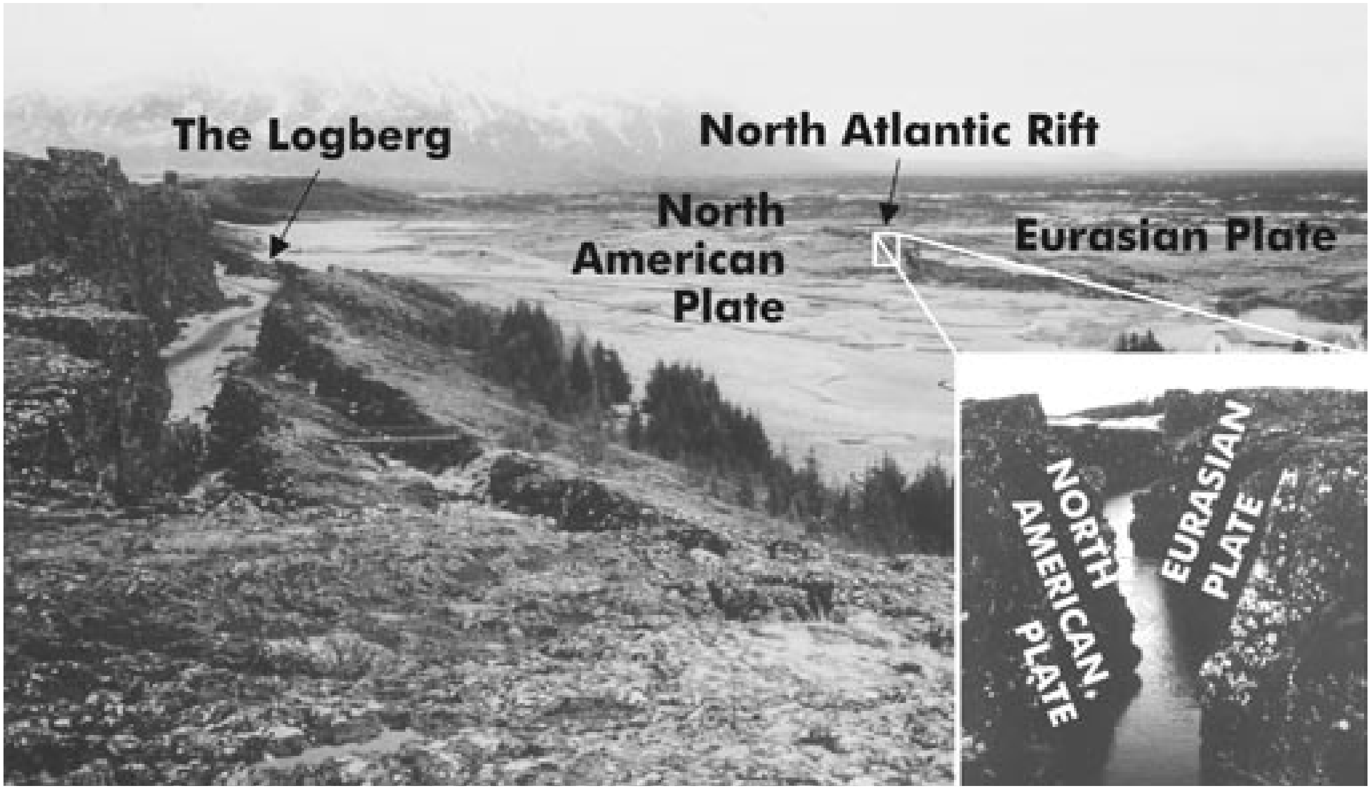


Figure 1. "The rift" at Þingvellir with the North American and Eurasian plates claimed to show plate tectonics in action. In reality, the situation is more complex. Þingvellir forms the north end of an en echelon fault zone at the west end of the southern offset in the North Atlantic Ridge (see Figures 3, 4, 5, and 6).

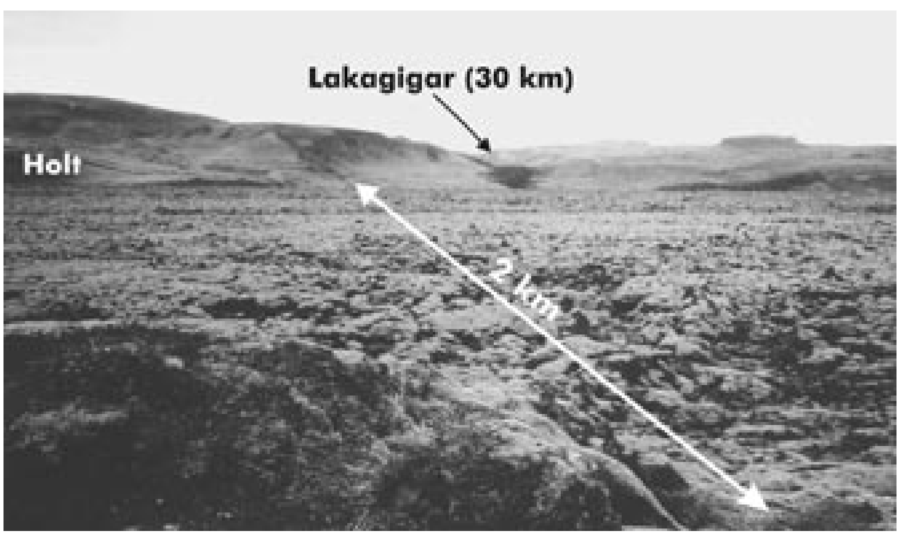


Figure 2. Eldhraun, a huge lava flow that issued from Eldgjá in 934 A.D. It was comparable to the famous Lakagígar eruption that occurred nearby in 1783. In the 1,068 years between Eldgjá and the time of the photograph (2002), lichens and mosses colonized Eldhraun, and soil formation is underway. Photograph taken north toward farm of Holt; at this location, Eldhraun is 16 km wide. Total volume of Eldhraun is estimated at 15 km^3 (closer to 20 km^3 according to some); Lakigígar was 12 km^3.

volume, continental flood basalts are uncommon. They are characteristic of large igneous provinces (Table I) and have not been observed in recorded history. Many geologists speculate that flood basalts originate when a rift opens or a "hot spot" begins to burn through a drifting tectonic plate (White and McKenzie, 1989; Hooper, 2000). After the initial release of pressure, extrusion rates fall. The origin of Iceland is thought to be connected to the creation of the North Atlantic Igneous Province (or North Atlantic Volcanic Province) approximately 62 million years ago (Ma) (Hooper, 2000), at the opening of the Atlantic Ocean upon the breakup of Pangea. The North Atlantic Igneous Province (NAIP) stretches from Greenland to Scotland and includes the island group of Færöyane (Faeroe Islands) and a large swath of sea floor; much of the province consists of flood basalts (Figure 3).

Table I. Dimensions of Several Large Igneous Provinces.

Large Igneous Province	Estimated Initial Area (km^2)	Approximate Present Volume (km^3)	Estimated Initial Volume (km^3)
Ontong Java Plateau[1,2]	$1.5 \cdot 10^6$	$1.5 \cdot 10^6$	$>5.7 \cdot 10^7$
Kerguelen Plateau[1]	?	?	10^7
North Atlantic Igneous Province[1,2]	$1.3\text{-}2 \cdot 10^6$	$6.6 \cdot 10^6$	$6.6 \cdot 10^6$
Keweenawan[1]	?	$1.5 \cdot 10^6$	$>2.0 \cdot 10^6$
Ethiopia-Afar-Yemen[1]	$6 \cdot 10^5$	$3.5 \cdot 10^5$	?
Siberian Traps[1,2]	$2.5\text{-}3.4 \cdot 10^5$	$3.4 \cdot 10^5$	$>2 \cdot 10^6$
Deccan Traps[1,2]	$5 \cdot 10^5$	$5.2 \cdot 10^5$	$1\text{-}2 \cdot 10^6$
Karoo[1,2]	$2\text{-}3 \cdot 10^6$	?	$1\text{-}2 \cdot 10^6$
Parana[1,2]	$1.2\text{-}2 \cdot 10^6$	$8 \cdot 10^5$	$1.5 \cdot 10^6$
Columbia River Basalt Group[1,2]	$1.6 \cdot 10^5$	$1.8 \cdot 10^5$	$1.8 \cdot 10^5$

Data from [1]Hooper, 2000, p. 349; [2]Bardintzeff and McBirney, 2000, p. 67.

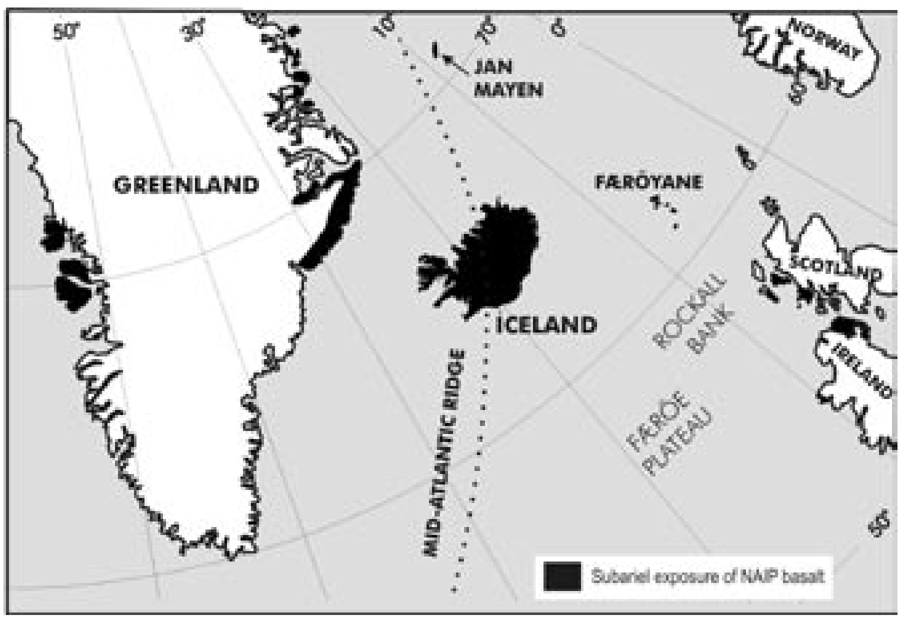


Figure 3. Map of the North Atlantic Igneous Province. Modified from Comité National Français de Géologie (1980) and Mahoney and Coffin (1997).

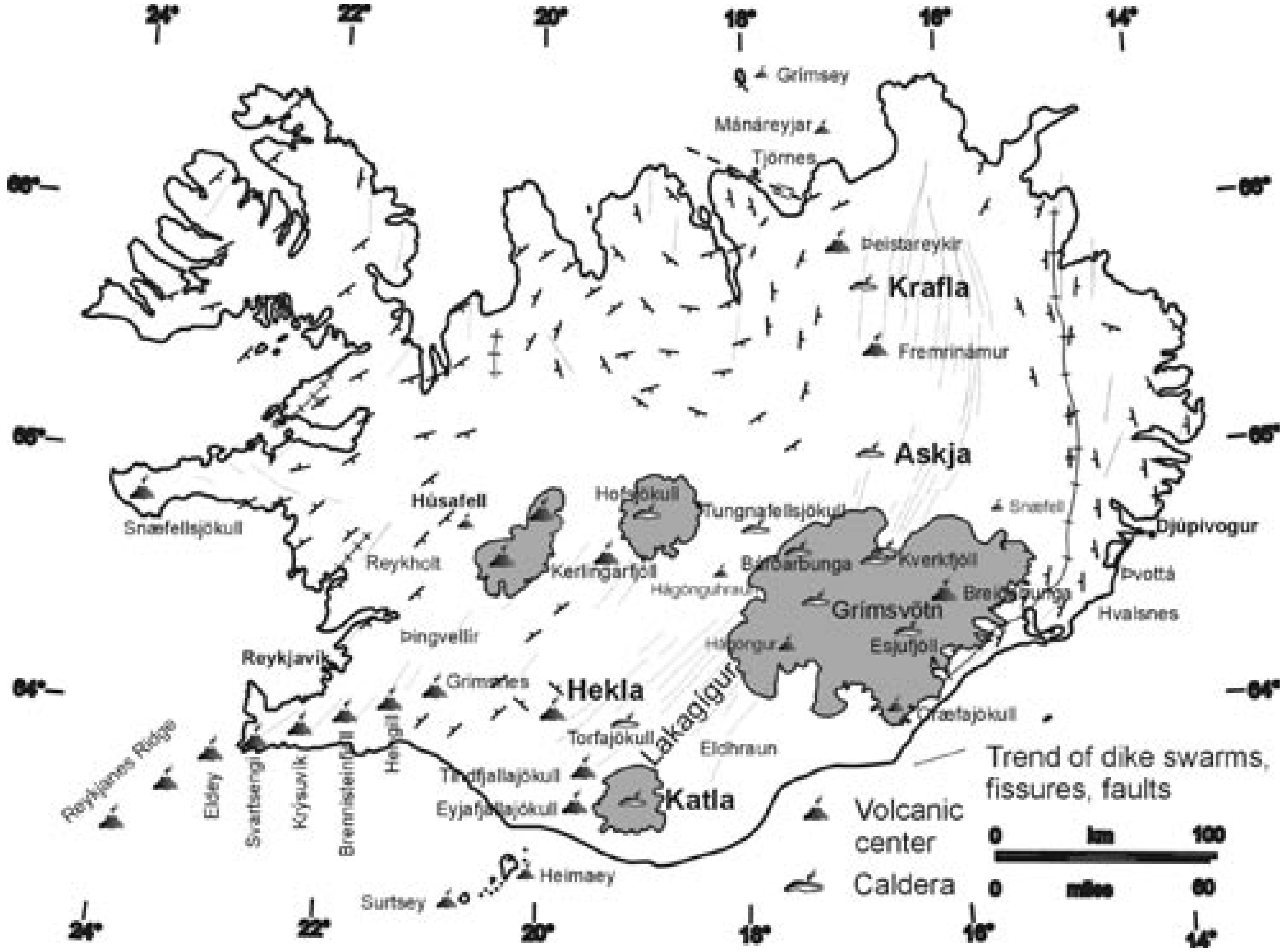
This paper integrates limited fieldwork with published data relative to lava extrusion rates at the Mid-Atlantic Ridge and Iceland. In an effort to gauge the reliability of published information and to accurately assess the geologic situation in Iceland, I spent one week conducting a field reconnaissance of southern Iceland in April of 2002 and collected rock samples for subsequent study. Nongeologists may benefit from Appendix A —a "volcanology primer"—and the glossary of fundamental geologic terms included in the text.

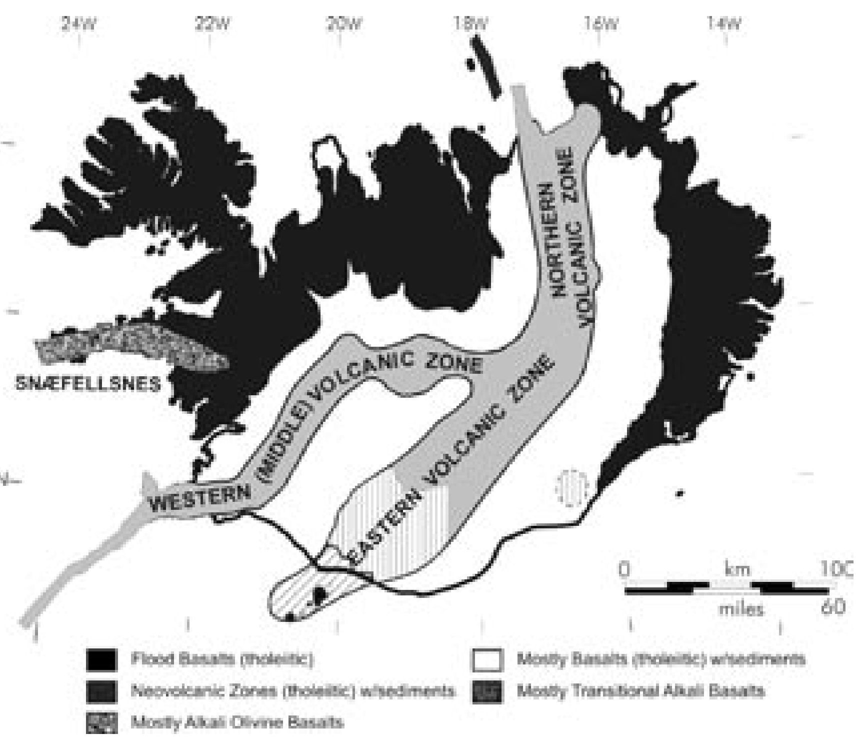
Field Observations in Iceland

My reconnaissance followed the southern coastal highway from Reykjavik to Djupavógur as well as north of Reykjavik to Reykholt (Figure 4). Sites investigated included Þingvellir, Hekla, Eldhraun, Hvalsnes, Þvottá, and Tunga near Húsafell. (Lakagígar, Askja, and Krafla, though immensely important historically, were not accessible due to typical April weather.) Fieldwork followed a day at the University of Iceland viewing geologic maps and gathering other information (Guðmundsson et al., 1992; Jóhannesson and Sæmundsson, 1998; McClelland et al., 1989; Sæmundsson and Noll, 1974; Uppdráttur Íslands, 1989). Figures 4 and 5 are based on this limited fieldwork and considerable published information.

In general, Iceland consists of vast plateaus and ridges of flood basalts in the eastern and western portions of the country, with a split and curved zone of modern volcanism divided into the West, East, Middle, and North Volcanic Zones (Foulger et al., 2001). The Mid-Atlantic Ridge emerges from the ocean in the form of the Reykjanes Peninsula (Figure 6) and, after following the circuitous path of the volcanic zones, is offset from its continuation north of Iceland, the Kolbeinsey Ridge, by the Tjörnes Fracture Zone. Historic flows are most concentrated along these volcanic zones. Flows and plutons interpreted as intermediate in age by geologists are largely found flanking the volcanic zones.

Flood basalts are commonly highly regular, conformable, tabular flows. In the west, they dip slightly (< 10°) to the southeast (Figures 4 and 7). In the east,





above: Figure 4. Simplified tectonic map of Iceland modified from Comité National Français de Géologie (1980); Einarsson and Björnsson (1980), Fridleifsson (1980), Jakobsson (1980), Jóhannesson and Sæmundsson (1998), Kristjansson (1980), Þorarinsson (1980), Þorarinsson and Sæmundsson (1980).

left: Figure 5. Simplified geologic map of Iceland modified from Comité National Français de Géologie (1980) and Jóhannesson and Sæmundsson (1998).)

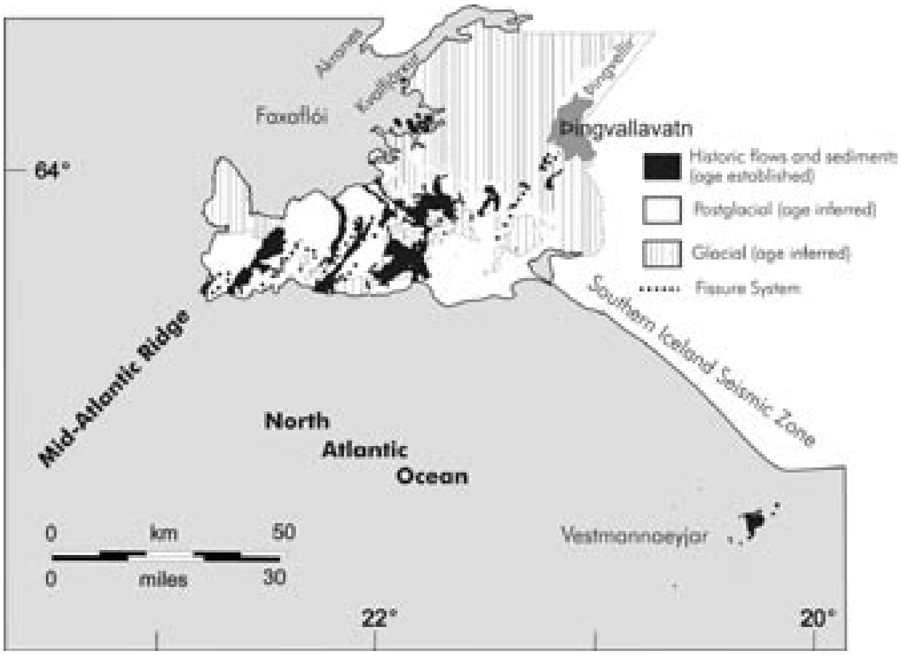


Figure 6. Map of Reykjanes Peninsula showing inferred ages of rock units. Modified from Jóhannesson and Sæmundsson (1998).

Figure 7. View south toward Skarðsheiði, showing continuity and attitude of conformable flood basalt flows in western Iceland.

they dip slightly (< 15°) to the northwest (Figures 4 and 8). Columnar jointing is common but not pervasive. Historic flows and rocks of the "intermediate" areas include both pahoehoe (Figure 9) and block flows (Figure 10); a'a is associated with some block flows (Figure 11). Contacts are sometimes planar but more often nonplanar, especially the smaller flows. In general, contacts throughout the southern part of the country are remarkably conformable (Figure 12), though volcanisedimentary and ignimbrite interbeds do occur, increasingly with proximity to neovolcanic zones. Weathering profiles at contacts between flows or evidence of paleosols were not observed. Only minor buried expressions of topography were seen, and only in the volcanic zones (Figures 13 and 14).

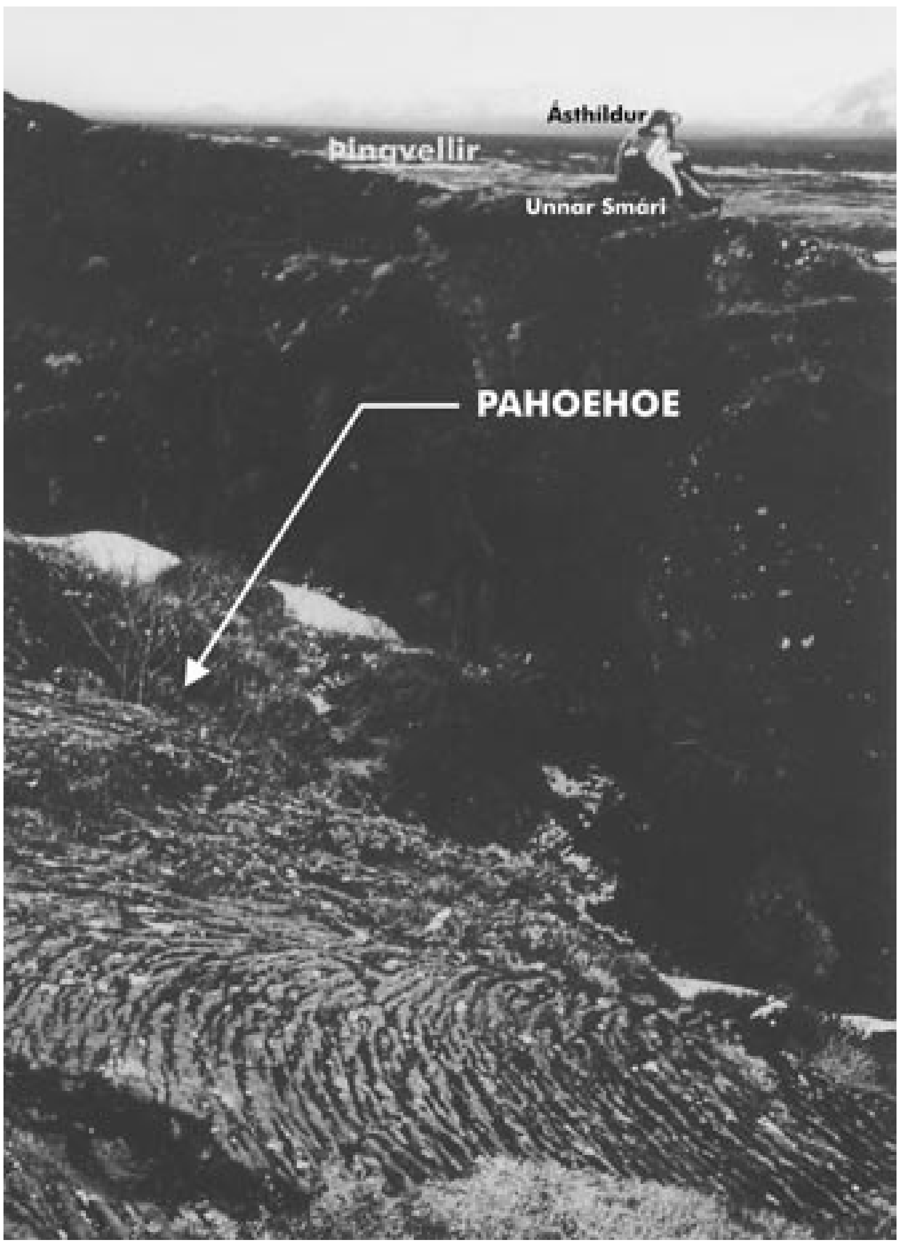
Soil erosion, especially due to wind, is extensive (Figure 15), yet soil formation appears to commence quickly as a result of rapid colonization of new basalt by mosses and lichens and entrapment of aeolian sediment (Figure 16).

By far the most common lithology I encountered in Iceland was basalt (tholeiitic), but intermediate and acid rocks were also observed near Hvalsnes, Þvottá, and Tunga (near Húsafell, Figure 4). Calc-alkaline rocks reportedly dominate Hekla, especially at the beginning of each eruption (Jakobsson, 1980; Stesky, 1997), but were not observed. Rhyolite is reportedly present northeast of Hekla (Sigurjónsson and Tilinius, 2001) and near Húsafell (Sæmundsson and Noll, 1974), but most of these areas were not accessible. Acid and intermediate rocks tend to occur in relatively small bodies closely associated with basalt in the rift zones and not the flood basalts (Saunders et al., 1997). Fine laminations and inclusions of glass were observed in dacite and associated rocks at Tunga (Figure 17).

Significance of Lithologic Data to Origin of Iceland

The most common lithology of Iceland is tholeiite, resembling mid-ocean ridge basalt (MORB), though lithologic variations are not uncommon (Figure 5), especially in the transitional and neovolcanic regions (Jakobsson, 1980). Basalt forms 90% of the lava pile (Sæmundson, 1980), resulting from Iceland's position

left: **Figure 8. View west-southwest toward Búlandstindur from north side of Berufjörður near Berunes on the east coast of Iceland. Flood basalt flows dip 10 to 15° toward the west.**



below left: **Figure 9. Pahoehoe flow at Þingvellir. Scale provided by 14-year-old Ásthildur and 8-year-old Unnar Smári.**

astride the Mid-Atlantic Ridge. The less common lithologies are less readily explained; they are not characteristic of the Mid-Atlantic Ridge. Subducted continental crust, the previously favored explanation (McBirney, 1993), cannot explain intermediate and acid rocks observed at Hekla and elsewhere. While appeals to recycling of crust are regularly invoked to explain strontium ratios, neodymium ratios, and other geochemical data (McBirney, 1993; Oskarsson et al., 1985), data are amenable to explanation by differentiation in magma chambers (Bardintzeff and McBirney, 2000; McBirney, 1993), interaction with water (Oskarsson et al., 1985), and mantle heterogeneity (Jakobsson, 1980; McBirney, 1993).

While efforts to find evidence of a fragment of continental crust beneath Iceland have been largely abandoned, neither diverse lithologies nor trace element studies have supported a simple MORB differentiation model: "Reconciling the chemical and isotopic evidence that indicates a lithospheric source with the large melt fractions that require a hot mantle plume source remains a fundamental problem in modeling the origin of flood basalt provinces" (Hooper, 2000, p. 351). Re-

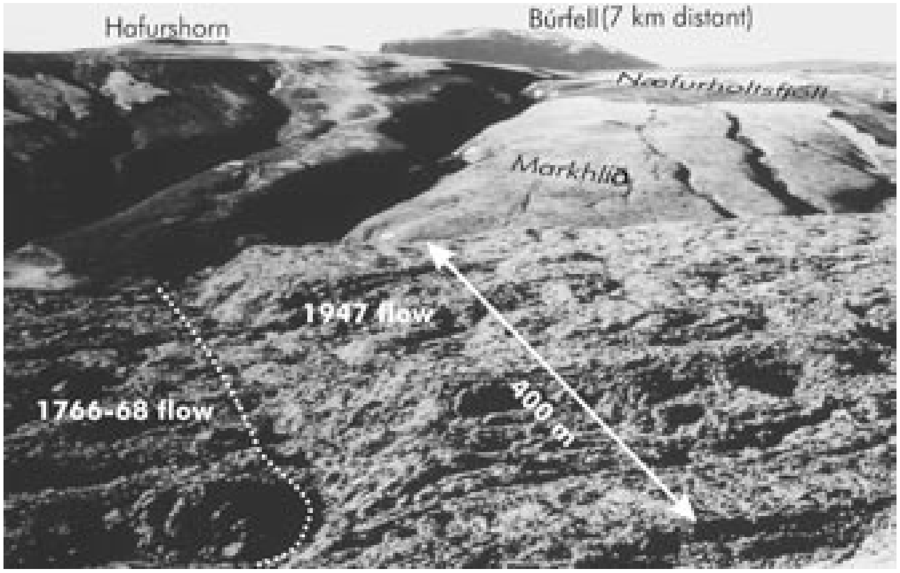


Figure 10. View northwest from Melfell over 1947 block flow from Hekla.

Figure 11. Lava blocks resembling a'a basalt on 1970 flow on west slope of Hekla. Most of exposed surface of lava blocks has already begun to be colonized by lichens.

Figure 12. Vast conformable lava flows such as these exposed in the face of 767 m high Lomagnúpur are typical of Iceland. (Lomagnúpur is on the southern coast between the Eastern Volcanic Zone and Vatnajökull.)

cycling of oceanic crust and new ideas about mantle composition and structure are gaining favor among researchers (Anderson, 2001; 2002; Federova et al., 2005; Foulger and Anderson, 2005; Oskarsson et al., 1985). These studies are very significant to understanding possible origins of flood basalts and are thus pertinent to any model of global tectonics.

Magma chamber "plumbing" and behavior are complex beneath Krafla, Hekla, and other volcanic centers (Einarsson and Björnsson, 1980; Feigl et al., 2000; Sturkell and Sigmundsson, 2000). Hekla, with its regularity of eruption and progression from highly developed (calc-alkaline and intermediate) to less developed (basic) lavas during eruptions, lends credence to the concept of relatively rapid differentiation in magma chambers (Guðmundsson et al., 1992). Nonetheless, this alone cannot explain the observed lithologies when the assumed parent magma is a MORB-like tholeiitic basalt (Jakobsson, 1980) without invoking crustal recycling (Oskarsson et al., 1985) or complex mixing of sources. The assumption of mantle homogeneity is more than a long-standing simplifying assumption; it is based on belief in the nebular hypothesis (Snelling, 2000). Data increasingly indicate this assumption is wrong (Anderson, 2001; 2002; Batiza and White, 2001; Lassiter and DePaolo, 1997; Oskarsson

Figure 13. Topographic development in the modern environment, such as this at Drangshlíð, is very evident on the present surface but seldom seen in the rock record.

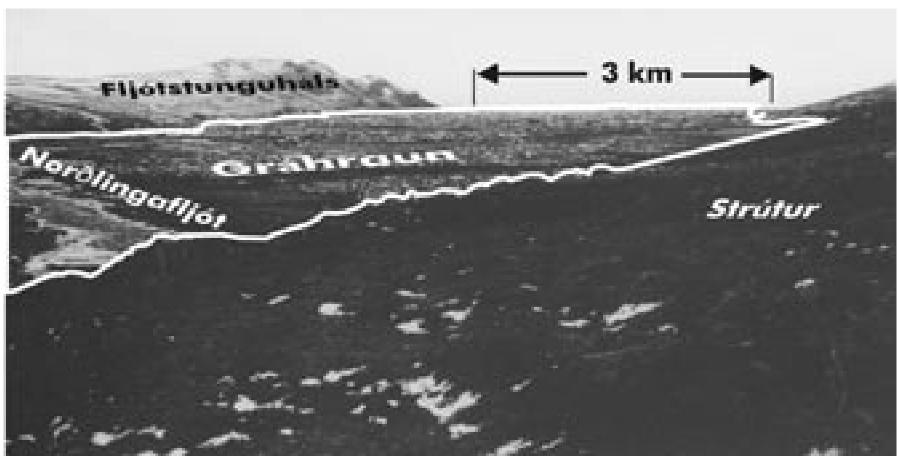


Figure 14. Gráhraun, a pahoehoe flow from ca. A.D. 880. View toward northeast with flow outlined in white. Note that flow fills valley bottom and has diverted the river (Norðlingafljót).

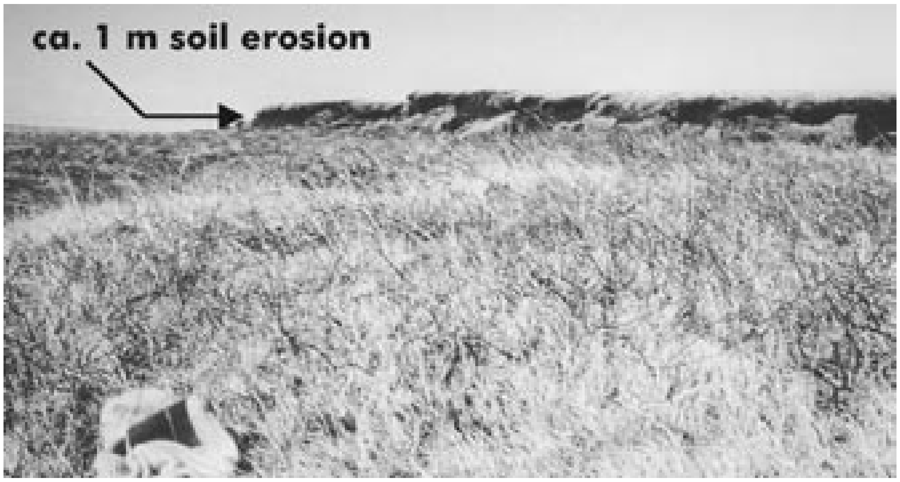
et al., 1985; Saunders et al., 1997; Snelling, 2000). Since the crust has always been heterogeneous (Genesis 2:11, 12; 4:22), the mantle may also be heterogeneous. In general, Iceland's lithology is amenable to explanation as derivatives of MORB or possibly plume-derived magmas from a heterogeneous mantle.

Much of the lava pile is described as "subaerial" (Fridleifsson, 1980; Jóhannesson and Sæmundsson, 1998; Sæmundsson, 1980), though there is good reason to question this (Froede, 2000). Where pillow lavas, hyaloclastites, and palagonite are encountered, these are invariably interpreted as subglacial (Jakobsson, 1980). Marine fossils indicative of warm (nonglacial) environments are present in sediments at Tjörnes, and igneous fossils of plants have been reported from several locations (Símonarson, 1980). Unconformities between the flood basalts and subsequent strata are reported from Snæfellsnes (Figure 4) and Skagi, but are rare in Iceland (Sæmundsson, 1980). In general, there is no evident hiatus between the flood basalts and lavas up section (Figure 5), which follow the volcanic zones in the center of the country (Jakobsson, 1980). Diluvialists are more inclined to accept the possibility of subaqueous emplacement and fossilization of organisms not native to the modern environment, while adherents of the establishment geological paradigm (EGP) can be expected to favor subaerial interpretations and climatic fluctuations over vast ages.

As shown in Figure 3, Iceland sits astride the Mid-Atlantic Ridge at the center of the NAIP. According to the EGP, rocks in western Greenland and the British Isles are that province's oldest, approximately 50 to 60 Ma. Lithologically, these rocks and those elsewhere in the NAIP reportedly exhibit variations similar to those observed in Iceland (Saunders et al., 1997), consistent with my limited observations (Figure 18). Presumably, these rocks are related to a common source. Evolutionists and creationists disagree about the time required for emplacement. Old ages are based on natural history assumptions and radiometric "ages," concepts neither scientifically valid nor compatible with the diluvial geological paradigm (DGP) (Malcolm, 1997; Middelmann and Wilder-Smith, 1980; Reed, 1996; 1998; 2000a; 2001; 2003; Vardiman et al., 2000; 2005; Woodmorappe, 1999a; 1999b).

Inferring Time Required for Emplacement

The time required for Iceland to form requires: (1) a long-term average extrusion



above: **Figure 15. Approximately one meter of soil has been eroded by anthropogenic and aeolian factors on Hafurshorn west of Hekla.**

above right: **Figure 16. Pedogenesis pioneered by lichens and mosses is evident on the 1766-1768 lava flow on the southwest flank of Hekla.**

below: **Figure 17. Columnar dacite with glass inclusions, Tunga, Reykholtsdalur in western Iceland.**

rate and (2) the total extruded volume. The first is impossible to determine; the second is slightly more tractable. Science is useful to this speculation by setting upper and lower bounds on the time of formation by using suitable assumptions and historical data from flows (Þorarinson and Sæmundsson, 1980).

Many eruptions in Iceland and other places around the world have been studied and either direct measurements or fairly reliable estimates obtained for extrusion rates and other properties. Eruptions observed in Iceland have been from both fissures and volcanic

Table II. Summary of Lava Extrusion Rate Observations

Flow	Date	Composition	Vent Type	Extrusion Rates (m³/sec) *		Unit Rate (m³/sec per meter length)	
				Min.	Max.	Min.	Max.
Hekla [1,2,3,4]	1104	mostly calc-alkaline basalts, but also basaltic andesite, andesite, dacite, and rhyolite (larger eruptions more basaltic); forms block flows					
	1206						
	1222						
	1766-68						
	1845						
	1878						
	1913						
	1947		<7 km fissure				
	1970		½ - 25 km fissure	2.5	7,500	*0.01*	0.30
	1980		7 km fissure	1,160	2,300	*0.16*	0.33
	1981		fissure	*50*	100		
	1991		fissure	*2,000*	1	*0.02*	*8.00*
Laki [2,4] (estimated initial)	1783 to 1784	fluid basalt, yet block flows resulted	≤27 km fissure	*5,000*	*9,000*	*0.19*	*0.60*
Laki [4,5] (8-month avg.)				570	840	*0.02*	*0.03*
Krafla [1]	1724–29	"very fluid basaltic lava" forming smooth or pahoehoe flows	fissure				
	1976–78 subterranean		magma chamber	*4*	*5*	subterranean activity only	
	3/1980		4.5 km multiple fissures	120	360	*0.03*	*0.16*
	7/1980		4 km multiple fissures	*75*	*150*	*0.02*	*0.08*
	10/1980		0.2–0.3 km fissure	50	*200*	*0.17*	*1.00*
	11/1981		½–8 km en echelon fissures	30	*100*	*0.00*	*0.20*
	1980–1984 average of five flows		½–8.5 km multiple fissures	90	100	*0.01*	*0.18*
Eldfell, Heimaey [5] (Vestmannaeyjar)	1973		4 km fissure	40	50	*0.01*	*0.10*
Eldgja [2]	940		fissure	*500*	*15,000?*	*0.05*	*0.50*
Iceland Historical Average [4,5]	874 to 2002	basalt	all (mostly fissure)	0.90	*?*	*1.33*	*2.50*
Kilauea, Hawaii, U.S.A. [4]	1983 to present	basalt, both a'a and pahoehoe flows	crater: 250 m by 400 m	0.01	*24.0*	0.00	*0.01*
Kilauea, 19-year average [4]				3.8	3.8	0.01	0.01

Table II (continued). Summary of Lava Extrusion Rate Observations

Flow	Date	Composition	Vent Type	Extrusion Rates (m^3/sec) *		Unit Rate (m^3/sec per meter length)	
				Min.	Max.	Min.	Max.
Etna, Sicily, Italy Estimated long-term average [4,6]	probably most of post-diluvian time (to present)	tholeiitic basalt to trachyte	mostly radial fissures	*0.30*	*0.30*	*?*	*?*
Etna, Sicily, Italy Observed modern rates [4,7]	1971		fissure	*7?*	13	*?*	*?*
	1991 to 1993		1 km? fissure	5	6	*0.00*	*0.00*
	1999 S.E. Crater		crater: <250 m diameter	5	5	*0.02*	*0.02*
Columbia River Basalt Group [2,8]	diluvial?	basalt, smooth (flood) flows	multiple fissure	*4,000*	*1,200,000*	*0.04*	*12.00*
Arenal, Costa Rica [2,9]	1968 to 2000	andesite, some a'a-block, but mostly block flows	crater: <500 m diameter	0.24	*0.50*	*0.00*	*0.01*
Mount Saint Helens, Washington, U.S.A. [4]	1980 to 1986	dacite plug dome	crater: 365 m diameter	0.70	23.7	*0.00*	*0.06*

Sources: [1] McClelland et al., 1989; [2] Bardintzeff & McBirney, 2000; [3] Guðmundsson et al. 1992; [4] Pyle, 2000; [5] Zeilinga de Boer and Sanders, 2002; and Saunders et al., 1997; [6] Walker, 2000; [7] Behncke, 2001; [8] Shaw and Swenson, 1970 (high value); [9] http://www.arenal.net/arenal-volcano-overview.htm.

craters and include tholeiitic basalt and transitional alkali basalt lavas. Data from these eruptions are relevant to long-term volcanic behavior in Iceland. Data from other places are useful for comparison, particularly to assess the role of vent geometry and lithologic composition on extrusion rates.

Some flows, particularly flood basalts of large igneous provinces (Table I), have no historic example of an eruption. Their behavior can only be inferred by extrapolating from historic data and applying the tools of physics and geology, especially the principles of fluid mechanics. Diluvialists have done preliminary work on both the Columbia River Basalt Group (Nevins, 1974; Woodmorappe and Oard, 2002) and the North American Midcontinent Rift System (Reed, 2000b), though work remains to be done on these and other large igneous provinces. Extrusion rate estimates of these unobserved flows often exhibit uniformitarian bias and are less useful than historic data. All Icelandic flood basalts predate the *Landnám*.

Table II provides a summary of lava extrusion rate data from several sources. Data are expressed both in terms of total extrusion rate and unit extrusion rate (rate per unit length of vent). They are presented to show the relationships between vent type and size, rock type, and extrusion rate. Not surprisingly, fissure eruptions tend to release larger volumes of lava in a given time than crater eruptions. Craters may be associated with sialic, intermediate, or mafic lithologies, but fissure eruptions are typically associated with mafic lavas. The largest extrusion rates are from basalt fissure eruptions, which differ enormously in total extrusion rate, but much less in unit extrusion rate. Tabulated values of minimum and maximum rates of extrusion per meter of fissure length from eruptions of Krafla range from 0.01 to 1.00 m^3/s. Other historic flows in Iceland, including Lakagígar, fall within this range.

Table II supplies part of what is needed to approximate an average extrusion rate. Other needed variables are: (1) the fraction of total time during which eruptions occurred, and (2) the length of active vent. My assumptions and

Figure 18. Flood basalts are evident in the east coast of Stremöy, Færöyane. Photograph taken from approximately one km at sea in typical Færoese weather.

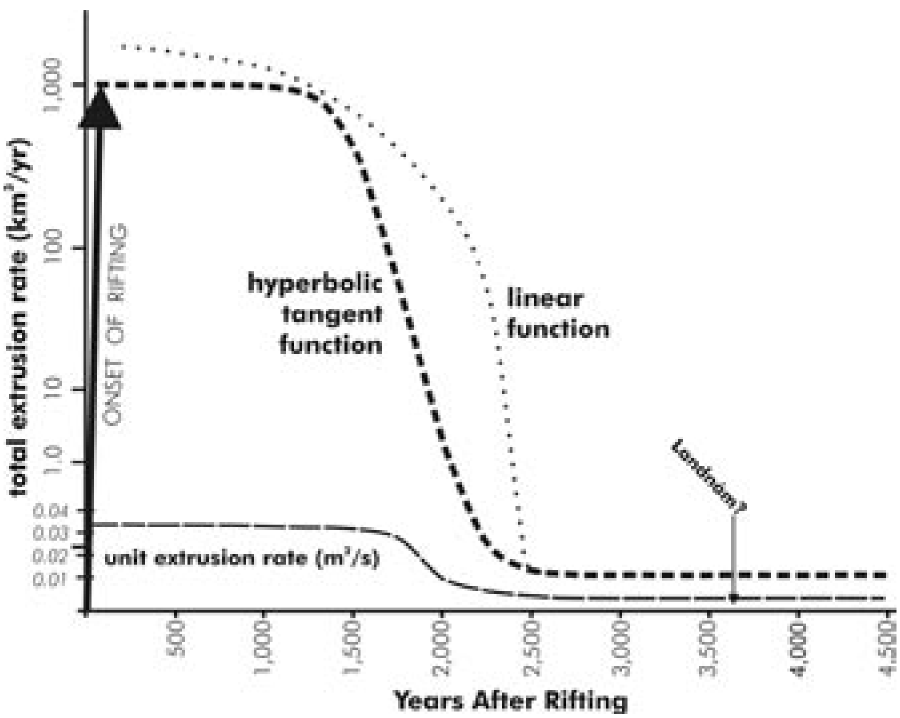


Figure 19. Hypothesized lava extrusion rate functions for emplacement of Iceland.

methods are summarized in Appendix B. The primary limit is that the total amount of time for Iceland's formation cannot be less than the amount of time required to extrude that volume of lava, though it may be more. Additional time can only be inferred from the character of contacts: the longer the time of quiescence, the greater will be the extent of erosion and sedimentation, topographic development, weathering, and soil formation.

Table III summarizes my analysis of lava extrusion parameters. The first two figures are unrealistic extremes. Based on the historic average rate of lava production (Þorarinson and Sæmundsson, 1980), approximately 56.4 Ma would be required to form Iceland. Yet its age is generally believed by evolutionists to be less, about 21 Ma (Sigurjónsson and Tulinius, 2001). Any calculation must address the fact that historic flows differ greatly from earlier ones. Modern flows are mostly block flows; pre-*Landnám* flows are mostly flood basalts, which form rapidly; four years for formation is the minimum published estimate for the Columbia River Basalt Group (Shaw and Swanson, 1970). This is unrealistically short, since not all of the rocks of Iceland are flood basalts. However, since such a large volume of Iceland does consist of flood basalts, shorter time estimates appear more plausible than evolutionists' guesses.

More realistic estimates can be obtained by estimating the percentages of various types of flows, respective fissure lengths, and appropriate unit discharge values. The second pair of time estimates used minimum unit extrusion rates and minimum estimated fissure length to obtain the maximum time, and maximum discharge and fissure length to obtain the minimum time. These estimates are both tighter and more realistic, ranging from under 2,000 to 15,000 years.

In general, lava eruptions tend to exhibit two important trends: (1) initial near maximum discharge gradually declines, and (2) fissures tend to concentrate into localized vents (Þorarinson and Sæmundsson, 1980). Thus, for fissure eruptions, unit discharge may actually increase while the total extrusion rate falls. To reflect this tendency, a third

Table III. Estimated Time for Emplacement of Iceland

Scenario	Years to Form
Total time to form lava pile based on historic average extrusion rate	56,400,000
Total time based on maximum published estimate for CRBG[1]	4
Time based on minimum fissure length and minimum extrusion rate	15,000
Time based on maximum fissure length and maximum extrusion rate	1,819
Time based on minimum fissure length and maximum extrusion rate	3,706
Time based on maximum fissure length and minimum extrusion rate	6,415
Age of Iceland based on evolutionist (EGP) scenario[2]	21,000,000
Age of Iceland based on biblical history (DGP)	4,500

[1]See Table II.
[2]Sigurjónsson and Tulinius, 1994, p. 133.

pair of total time estimates was generated by pairing minimum discharge with maximum effective fissure length, and maximum extrusion rate with minimum fissure length. The resulting total time estimates are approximately 3,700 to 6,400 years.

Table III's final pair of numbers compare the predictions of the EGP and DGP for the age of Iceland. The time required for lava extrusion must be less than or equal to any presumed age for Iceland. Although the most realistic estimates in Table III are compatible with the 4,500-year strict biblical chronology, this does not "prove" that Iceland formed in 4,500 years. But if it took 21 Ma, volcanism was quiescent for approximately 99.98 percent of that time. Science is only useful in testing historical scenarios, not in generating or "proving" them (Klevberg, 1999; 2000a; 2000b; Reed, 1998; 2000a; 2003; Reed et al., 2004). However, the analysis showed that Iceland could have formed within the time constraints of either the DGP or the EGP. Thus, the extent of quiescent time must be tested to differentiate between the two models. This can be done by evaluating evidence of significant hiatuses in the form of contacts marked by features requiring substantial time to form—the DGP predicts their absence; the EGP the opposite.

Plausibility of DGP Scenario for Age of Iceland

Table III provides conservative estimates corresponding to the DGP's anticipated age for Iceland, based on data and methods from Table II and Appendix B. I devised the models displayed in Figure 19 to better constrain the parameters and reflect general eruption trends, especially the tendency for initially prolonged outpouring of flood basalts (Hooper, 2000). These models are speculative; they therefore implicitly incorporate the estimated total extruded volume, the historic average lava discharge rate, and the expected 4,500-year history of the DGP.

Probably the greatest break these models make with the EGP is the initial extrusion rate. The linear function included in Table IV and Figure 19 is simple, but does not appear to resemble the actual history of Iceland since it does not mimic the kind of decline in discharge with time typical of eruptions, and because its arbitrary threshold is the modern value. The more complex hyperbolic tangent function, also included in Table IV and Figure 19, appears more realistic. Its first inflection point marks the end of flood basalt emplacement; the second represents a transition to current conditions (end of glaciation isostatic adjustment?). A higher initial extrusion rate followed by more rapid, exponential decrease might be more realistic (Sigurdsson, 2000b), and glaciation and deglaciation would likely produce subsequent episodes of increased volcanic activity, but without historical control, such "fine tuning" is unwarranted. Thus, while other models could be devised; most should resemble the hyperbolic tangent function.

But are these models plausible? Are their initial rates realistic? The estimated initial lava extrusion rate for these models is enormous (Table IV). It is easily

Table IV. Postdiluvial Emplacement Scenario for Iceland

Parameter	Value	
	Hyperbolic Tangent Function	Linear Function With Threshold
Assumed date of initial eruption	2498 B.C.	2498 B.C.
Maximum initial extrusion rate (total) in m^3/s	33,778	30,290
Maximum initial extrusion rate (unit) in m^3/s per m	0.03	0.03
Historic average extrusion rate (total) in m^3/s	0.90	0.90
Time for emplacement of half of total volume, years	750	981
Approximate date predicted to reach sea level	1575 B.C.	1230 B.C.

four times higher than the initial extrusion rate for the Lakagígar eruption, and the discharge for the hyperbolic tangent (nonlinear) model would decline only gradually at first. However, the picture changes dramatically when one begins with the assumption that Iceland was simply an arbitrary 1,000 km stretch of the Mid-Atlantic Ridge. Thus, the *unit* discharge would have been a mere 0.03 m^3/s, equal to the eight-month average rate for Laki and well within modern values (Table II). This value may actually be too *low* based on estimates for flood basalts from other large igneous provinces.

Figure 19 and Table IV predict that half the volume of lava constituting Iceland would have been extruded in the first 750 to 1,000 years. Today's sea level would have been reached in 900 to 1,300 years, meaning the age of Iceland as an island (or group of islands) would be approximately 3,300 to 3,600 years. Total annual lava discharge would decrease with time. If one assumes the average flow thickness is 4 m (flood basalts average 5 m to 15 m according to Sæmundsson, 1980), decades could pass between flows after Iceland emerged from the sea, and even centuries could pass approaching *Landnám*. Based on modern erosion and sedimentation processes in Iceland and rates of soil formation observed elsewhere (Klevberg and Bandy, 2003a; 2003b; Klevberg et al., 2003; Sæmundsson, 1980), one could expect to see evidence of topographic relief, sedimentary deposits, and soils preserved beneath at least some of these flows. However, as stated above, such evidence is not often apparent, especially in the eastern and western parts of the country. Hornitos are present in some parts of the country; paleosols are no doubt present beneath some of these lava flows.

Soil formation would have been minimized by the presence of ice. If most of Iceland were glaciated for much of its history, the period of time available for pedogenesis would have been greatly reduced. However, if parts of Iceland were nonglaciated for centuries or millennia, deep weathering horizons and soils should be present locally. The number of paleosols would be much reduced by glaciation, but a long history would inevitably produce many recognizable paleosols (unless Iceland was mantled by glaciers for most of its history).

Paleosols and weathered horizons would also be minimized by soil erosion. Iceland has experienced severe soil loss due to wind erosion (Sigurjónsson and Tulinius, 2001), but much of this has resulted from overgrazing and use of four-wheel-drive automobiles in recent times. Prior to *Landnám*, the country was well vegetated with good soil cover (Sæmundsson, 1980). Soil erosion has been largely anthropogenic, though exacerbated by climate change (Dugmore and Buckland, 1991; Gerrard, 1991). Loss of soil would tend to accelerate erosion-sedimentation processes and topographic development. Wind erosion might also transport some of the fine particles into the sea, skewing the sediments trapped between lava flows toward the coarse particles. Evidence of hiatuses would therefore simply differ in character—unconformities instead of paleosols.

Despite these difficulties, peat and loessal soils have been observed to form rapidly, "which means that the soil cover thickens so quickly that tephra layers of small difference in age are separated in the soil sections" (Þorarinsson, 1980, p. 164). This makes tephrochronology possible, though EGP presuppositions may result in unrealistically low estimates for pedogenesis rates. Investigations at

Vatnagarður near Hekla are considered typical, with soil formation rates of 0.1 to 5 mm per year excluding tephra (Þorarinsson, 1980). Documentation of these observations began in 1638 (Þorarinsson, 1980, p. 162). While pedogenesis in the initial century or two may be very slow (Caseldine, 1987), this rate accelerates significantly thereafter (D'Orico, 2000; Klevberg and Bandy, 2003a; 2003b; Klevberg et al., 2003).

The lack of widespread evidence for hiatuses between eruptions remains problematic for the EGP. This disparity could have resulted from significant past climate change (e.g. an ice age), the highly permeable character of many lava flows, or some other variable, but it may also indicate that the models shown on Figure 19 predict too little volcanic activity approaching *Landnám*. Alternatively, the age of Iceland may be even less than predicted by these DGP models. The volume of lava believed to have been extruded since deglaciation (Jakobsson, 1980) would correspond to extrusion since 260 B.C. (approximately 2,235 years after rifting) in this model, and variations in extrusion rate could be expected from isostatic readjustment during glaciation and deglaciation (Zielinski et al., 1997). An ice age of significant extent could be expected from climatic and geographic conditions resulting from the Deluge (Oard, 1990).

Plausibility of EGP Scenario for Age of Iceland

The EGP predicts an age for Iceland of roughly 21 Ma for the islands and 62 Ma for the beginning of the NAIP (Saunders et al., 1997). Even with the generous estimate of 15,000 years for emplacement of the lava pile (Table III), approximately 99.97 percent of the 21 Ma would have been volcanically quiescent. If the average depth for each lava flow was 4 m, the average amount of time that the surface of a given flow would have been exposed is approximately 54,000 years. Recognizing the more rapid discharges at the rift's opening and formation of flood basalts, the time of each flow's exposure after Iceland emerged from the sea would have been even greater. During this time, sedimentation and erosion would have occurred, topography would have developed, and at least several meters of soils would have formed. These factors would act in decades or centuries, not millennia! It is difficult enough to explain the apparent paucity of paleosols and buried terrain with the DGP model, but time in EGP models is multiplied by four orders of magnitude. Appeals to destruction of surfaces by fresh lava are contradicted by the existence of igneous fossils, the preservation of such surfaces in other parts of the world, and the sheer depth of the weathering horizon that should have resulted from 10^5 years of exposure. The end of the "Pleistocene" ice age would have been approximately 10,000 years ago (end of Búði, equivalent to Younger Dryas [Björnsson, 1980, p. 206]), meaning that weathering processes would have been active for at least this long for most of Iceland. Even longer interstadials and warm periods would have existed in the more than 20 Ma widely accepted as Iceland's age. Erosion of exposed surfaces would have produced well-developed topography through multiple cycles. The eroded detritus would have been deposited as unconsolidated sediments, possibly lithified or metamorphosed by overtopping lava flows. Sediments in Iceland are a minor portion of the total and consist primarily of coarse, unconsolidated deposits and volcanosedimentary interbeds in flow successions.

Iceland is an example of the inadequacy of the EGP in igneous terranes. Similar failures of the EGP have been noted in the North American Mid-Continent Rift System (Reed, 2000b; 2002b) and the Columbia River Basalt Group (Woodmorappe and Oard, 2002). Similar EGP difficulties arise in sedimentary terranes (Lalomov, 2001; 2003; Lalomov et al., 2003; Lalomov and Tabolitch, 1996; Reed, 2002a; 2002b; 2004; Snelling, 1992). This lends credence to the thesis that *deep time is illusory*. Instead of bolstering the EGP, appeals to radiometric "dating" call these methods into question. "Dating" methods by definition depart the realm of science and enter that of history lacking a proper philosophical foundation (Reed 1998; 2000a; Reed et al., 2004). Discrepancies with these methods have been noted (Molén, 2000; Vardiman et al., 2000; Woodmorappe, 1999a; McBirney, 1993). Iceland further discredits radiometric methods, since the ages obtained by them compound the problems caused by the disparity between lava extrusion rates and inferred age.

Where Has Iceland's Mantle Plume Gone?

Iceland was an early star in the triumph of the plate-tectonics theory, appearing to confirm several of its key elements. The coincidence of the Mid-Atlantic Ridge rift and the Iceland hot spot produced enough lava to form the islands of Iceland (Jakobsson, 1980; Saunders et al., 1997; Sæmundsson, 1980). Hot spots have long been a basic component of plate-tectonics theory, resulting from relatively stationary plumes deep within the mantle, perhaps as deep as the core-mantle boundary. They "burn holes" in lithospheric plates as the plates move over them, leaving a trail of volcanic rocks that are "dated" and used to infer the direction and rate of movement of tectonic plates (e.g. the Hawaiian Islands-Emperor Seamount lineament). However, the traditional explanation for hot spots has been recently criticized (Baksi, 2001; Froede, 2001; Sheth, 2005; Stock, 2003; Tarduno et al., 2003).

Hot spots are often associated with large igneous provinces—entire regions dominated by igneous rocks on a scale not witnessed in modern environments.

Some (Simken and Siebert, 2000, p. 255; White and McKenzie, 1989) believe that these areas, particularly those covered by flood basalts, represent the initial "burn-through" of a hot spot (i.e. decompression melting as rifting is triggered), with less rapid emplacement as the hot spot "settled down." These provinces, like island chain tracks, are used as evidence for plate tectonics. Arguments for uniformitarian plate tectonics have been subsumed into catastrophic plate tectonics (CPT), which proposes highly accelerated, non-uniform plate motions during the Noahic Flood (Austin et al., 1994). While some are critical of CPT (Froede, 1998; 1999; Hohensee et al., 2002; Reed 2000b; 2000c; Baumgardner and Oard, 2002) and alternatives exist (Oard, 2001a; 2001b), CPT is probably the majority opinion in creationist circles.

Although Iceland has long been used as an example of a hot spot, recent geophysical data may call into question the existence of a narrow cylindrical plume of hot rising mantle beneath Iceland. Analysis of geophysical surface wave, receiver function and tomography data, in combination with gravitational data, indicate that the crust beneath Iceland is thicker than previously thought (Oskarsson et al., 1985), though often difficult to define (Du and Foulger, 2001; Du et al., 2002), and that a dike-like magma conduit extends no deeper than the mantle transition zone beneath Iceland's Middle Volcanic Zone (Du et al., 2002; Foulger et al., 2000; 2001; Pritchard et al., 2000). Researchers have been reticent to acknowledge it, exemplifying the "reinforcement syndrome." Foulger et al. (2001) stated:

> Much of the seismic evidence for a plume in the lower mantle beneath Iceland consists of observations of types that either are found elsewhere unaccompanied by hotspots or are not found beneath known hotspots. Many studies specifically seek a narrow, vertical, cylindrical body with a relatively strong anomaly, and the results tend to be interpreted in these terms if possible, although the observations may be consistent with other hypotheses. (p. 528.)

Helium isotope studies (Anderson, 2000; Foulger and Pearson, 2001) indicate that isotopic ratios previously interpreted as deep mantle signatures are probably related instead to relative abundances of uranium and thorium. Partial melting and changes in mineralogy, temperature, and bulk density can all affect seismic velocities (Funamori et al., 2000) and be misinterpreted as an upwelling mantle plume.

Researchers now conclude that the hot spot has not been fixed relative to a particular location on earth or to the core or lower mantle, but has rather been more or less fixed relative to the Mid-Atlantic Ridge and Iceland (Foulger et al., 2001), or has migrated eastward relative to the plate boundary (Oskarsson et al., 1985). Despite a vigorous defense by the "plumatics" against the "aplumatics" (Campbell, 2005; Parkin et al., 2007; Saunders et al., 2003; Wolfe et al., 1997), doubt has settled on the traditional plume theory in Iceland (Einarsson and Björnsson, 1980; Jakobsson, 1980), as well as at other hot spots around the world (Baksi, 2001; Christiansen et al., 2002; Sleep, 2004; Stock, 2003). While aplumatics may accept the basic concept of plate tectonics, they also entertain alternative tectonic theories (Lunde, 2001; Sheth, 2005; and others, notably Don Anderson). The arguments of the "plumatics" are invariably entangled with uniformitarian assumptions.

Perhaps the best current understanding of the Iceland hot spot consists of a magma source in the upper mantle with a north-south tabular seismic anomaly that becomes cylindrical at a depth of about 250 km. Its center is believed to lie in eastern Iceland or perhaps in the Middle Volcanic Zone northwest of the traditional center location of Vatnajökull. Complex "plumbing" feeds Krafla, Hekla, and other active volcanic centers (Allen et al., 2002; Einarsson and Björnsson, 1980; Feigl et al., 2000; Sturkell and Sigmundsson, 2000). Magma flows toward Reykjanes Ridge in the south but is blocked to the north by the Tjörnes Fracture Zone (Jakobsson, 1980). Crustal structure is relatively complex, with no distinct Moho in some locations. A "complex, unstable, leaky microplate tectonics" model has been proffered to explain the hot spot (Anderson, 2001; Foulger and Anderson, 2005) or "hotcells" rather than a traditional plume (King and Anderson, 1995), and magma forms as partial melts, possibly from decompression melting (Saunders et al., 1997). However, there are problems with these theories. Just the same, Iceland does represent a hot spot in the plainest meaning of the term–a region of unusually active volcanism (Jakobsson, 1980).

Is Iceland Coming Apart or Just Our Theories?

The "plume wars" are not the only problem Iceland presents to current theory. Palagonite and tuyas, once interpreted as evidence of glaciation, are now recognized to form in subaqueous (marine) environments, too (Jakobsson, 1980; Þorarinsson and Sæmundsson, 1980), especially shallow water (Batiza and White, 2000), challenging part of the basis for multiple glaciations. Increasing evidence of mantle heterogeneity challenges long-held suppositions underlying interpretations of isotopic ratios. Lava extrusion rates and Iceland's structure present problems for uniformitarian geochronology and plate tectonics, and offer an opportunity to test predictions of CPT.

Plate motion at the Mid-Atlantic Ridge and Iceland is "known" to be approximately 2 cm/yr of extension (Feigl et al., 2000; Hreinsdóttir and Einarsson, 2001; Jónsson et al., 1997; Sigurjónsson and Tilinius, 2001; Stesky, 1997). However, Iceland does not show a "hotspot track" in the manner of Hawaii or Reunion by which to infer plate motion. Iceland consists of a main landmass and smaller islands, with only the relatively subdued Greenland-Færöe Ridge and no series of seamounts tracking the movement of the North American and Eurasian plates. The elevated plateaus and ridges of the sea floor near Iceland are thought to result from thermal anomalies (Oskarsson et al., 1985). North American and Eurasian plate motions are inferred from radiometric "dates" and model-based speculation. Yet Iceland holds one advantage over many other spreading centers: it is above sea level. Increasingly precise distance surveys have been conducted perpendicular to the rift zones over the past three decades using global positioning system (GPS) equipment (Jónsson et al., 1997). While these data (Figure 20) indicate extension in the mid to late 1990s, this was not observed at other locations elsewhere in Iceland (Hreinsdóttir and Einarsson, 2001; Sturkell and Sigmundsson, 2000), and overall motion measurements do not support simple extension (Bjarnason et al., 2002; Foulger and Anderson, 2005). More recent data (Geirsson et al., 2006) appear to confirm the traditional view, with local exceptions, but show magnitudes of vertical motions equal to horizontal ones and nonlinear responses to earthquakes, glacioisostatic motions, and even annual oscillations. The real basis for the confidence with which plate motions are asserted is evident from the statement of Geirsson et al. (2006, p. 16): "Since the NOVEL-1A model [plate motion model] is based on geological data spanning the last few million years, it appears that plate movements outside the deformation zones are steady on timescales ranging from weeks to millions of years." Millions of years means historical inference, not geological data.

Plotted on Figure 21 are three curves: (1) a "constant" (long-term average) spreading rate based on EGP assumptions, (2) an exponentially decreasing spreading rate curve based on CPT, and (3) a stochastic (irregular or episodic) curve fit to the 1967–1994 published data. The stochastic curve has no predictive value but is simply intended to fit the observed data. Plate tectonics curves predict past spreading rates to 4,500 and 50 million years, extrapolations from the data of 150 and 1.7 million times, respectively. Even if these data were more extensive, it is questionable whether the proposed curves could be adequately assessed, since lithospheric plates are not truly rigid (Sleep, 2004). Relative plate motions must be inferred by other means.

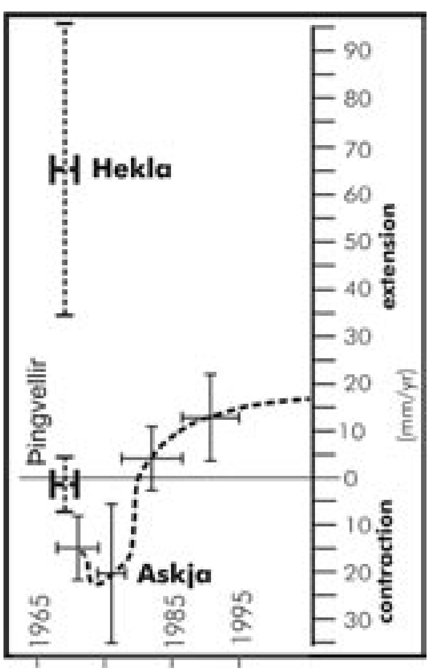


Figure 20. Observed relative plate motions for three sites in Iceland (a notable eruption occurred at Hekla in 1970.) Data from Jónsson et al., 1997; Sturkell and Sigmundsson, 2000.

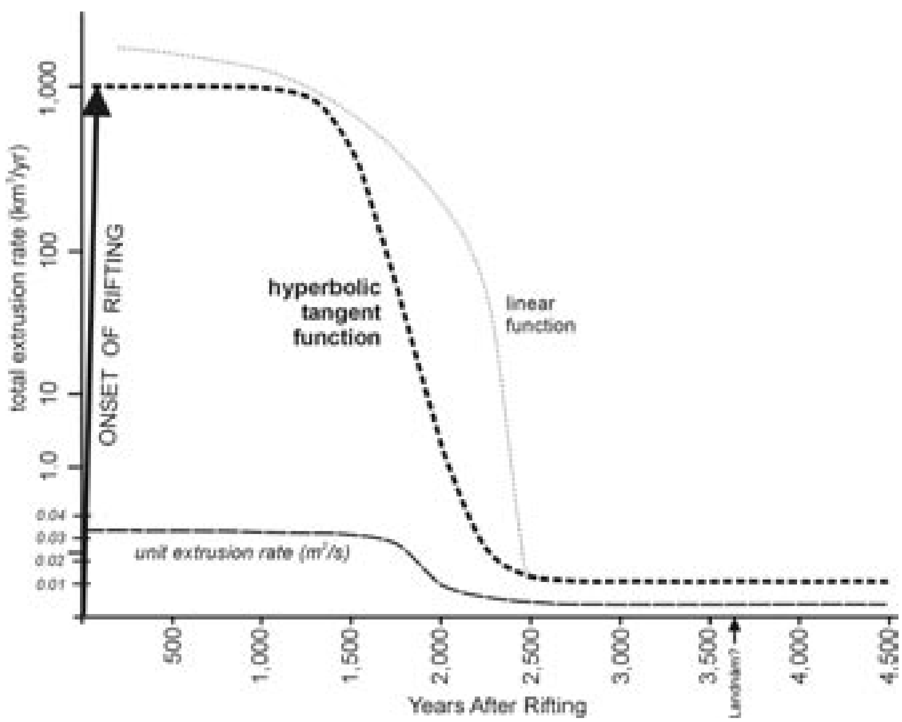


Figure 21. Comparison of three disparate historic plate motion scenarios. The accepted spreading rate between the North American and Eurasian plates is approximately 19 mm per year (Feigl et al., 2000, pp. 25, 655; Jónsson et al., 1997, pp. 11, 918), but the great disparity between this accepted value and observations has prompted some to look for a "leaky microplate" solution (Foulger and Anderson, 2005).

Commonly this is done by interpreting geomagnetic anomaly patterns on the sea floor. However, the paleomagnetic "stripes" are fraught with ambiguities (Merrill et al., 1998; Molén, 2000; Smith and Smith, 1993), the methods of analysis of the data are suspect, alternative interpretations exist (Klevberg and Oard, 2005; Merrill et al., 1998), and many if not most anomalies cannot be continuously traced to the Icelandic mainland (Kristjansson, 1980). Paleomagnetic reconstructions have proven problematic at other "hot spot" tracks (e.g. Emperor-Hawaii): "Similarly, some changes in the morphology of the geomagnetic field with time that have relied on fixed hotspots to anchor data from global sites are probably artificial" (Tarduno et al., 2003, p. 1068). Magnetic anomalies do not presently provide an adequate means of inferring plate motions, let alone rates.

Different models (Figure 22) will provide different predictions for development of a lava pile such as Iceland. Magma formed at depth will tend to move toward the surface. Where it erupts, it cools to form denser lava flows. Because of their greater density and the loss of material from the subsurface during the eruption, the flows tend to subside toward the volcanic center. Additional eruptions may deposit additional lava or tephra on the previous flows until the excess heat has been released and the magma supply is exhausted (Figure 22A). If this process occurs at a spreading center, the vertical progression will be combined with lateral displacements. If the long-term average rates of lava extrusion and plate movement are relatively constant, the lava pile will develop similarly to Figure 22B. If plate motion is constant but extrusion rates fall, the lava pile will tend to thin toward the center, where the pile is youngest (Figure 22C). If relative plate motion decreases more rapidly than extrusion, then the situation shown in Figure 22D would result. The EGP view of plate tectonics resembles

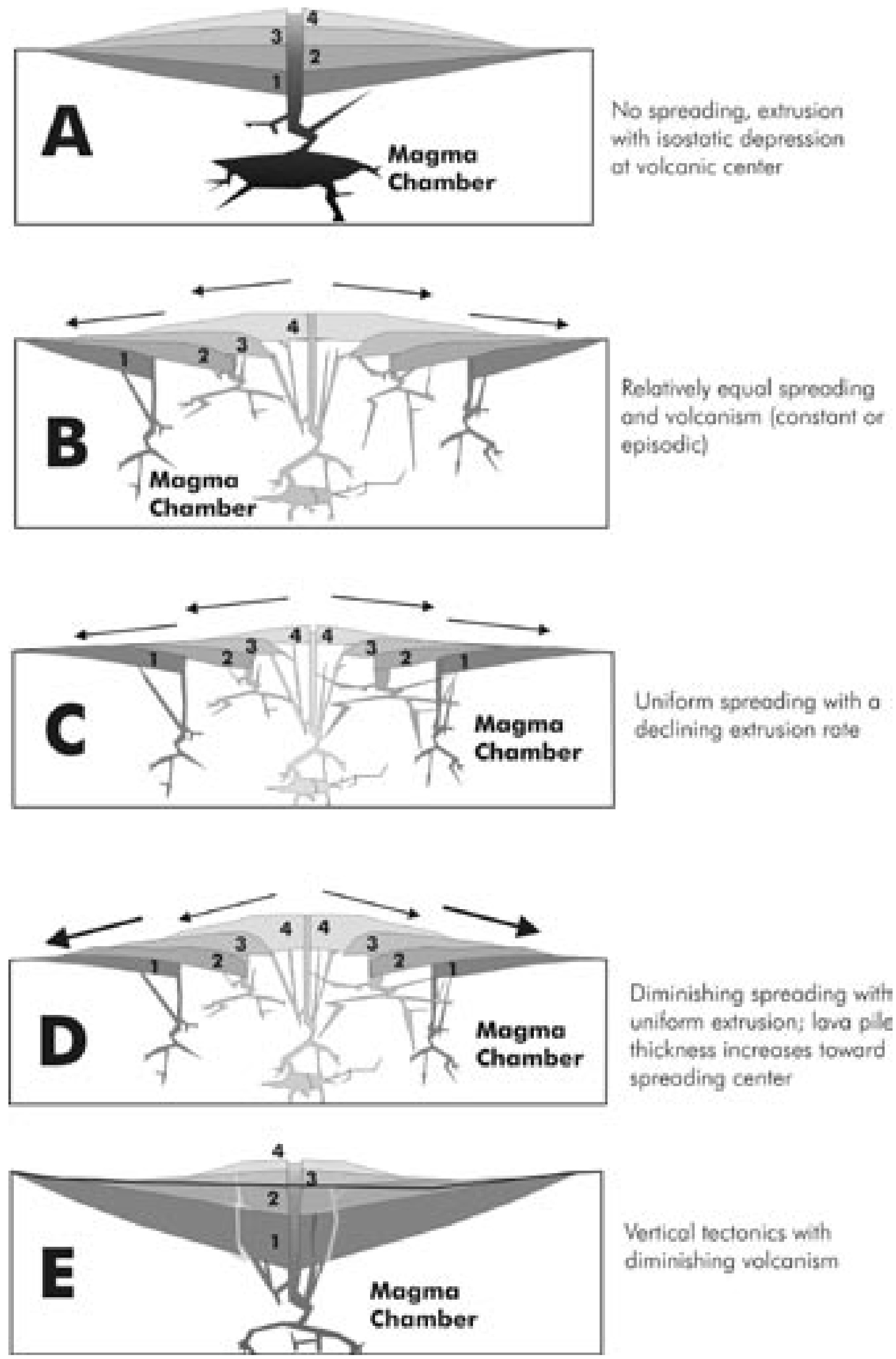


Figure 22. Different responses to volcanism and plate motion. A = lava pile formed by extrusion with isostatic depression at volcanic center; B = lava pile formed by relatively constant spreading and extrusion; C = lava pile formed by declining extrusion and relatively constant spreading; D = lava pile formed by rapidly decreasing spreading; E = lava pile formed by primarily vertical tectonics with decreasing rate of lava extrusion.

Figure 22B. CPT predictions are less clear but would probably correspond to Figure 22D. If extension and lava extrusion declined at precisely the same rate, the result would be indistinguishable from the EGP prediction, and if lava ex-

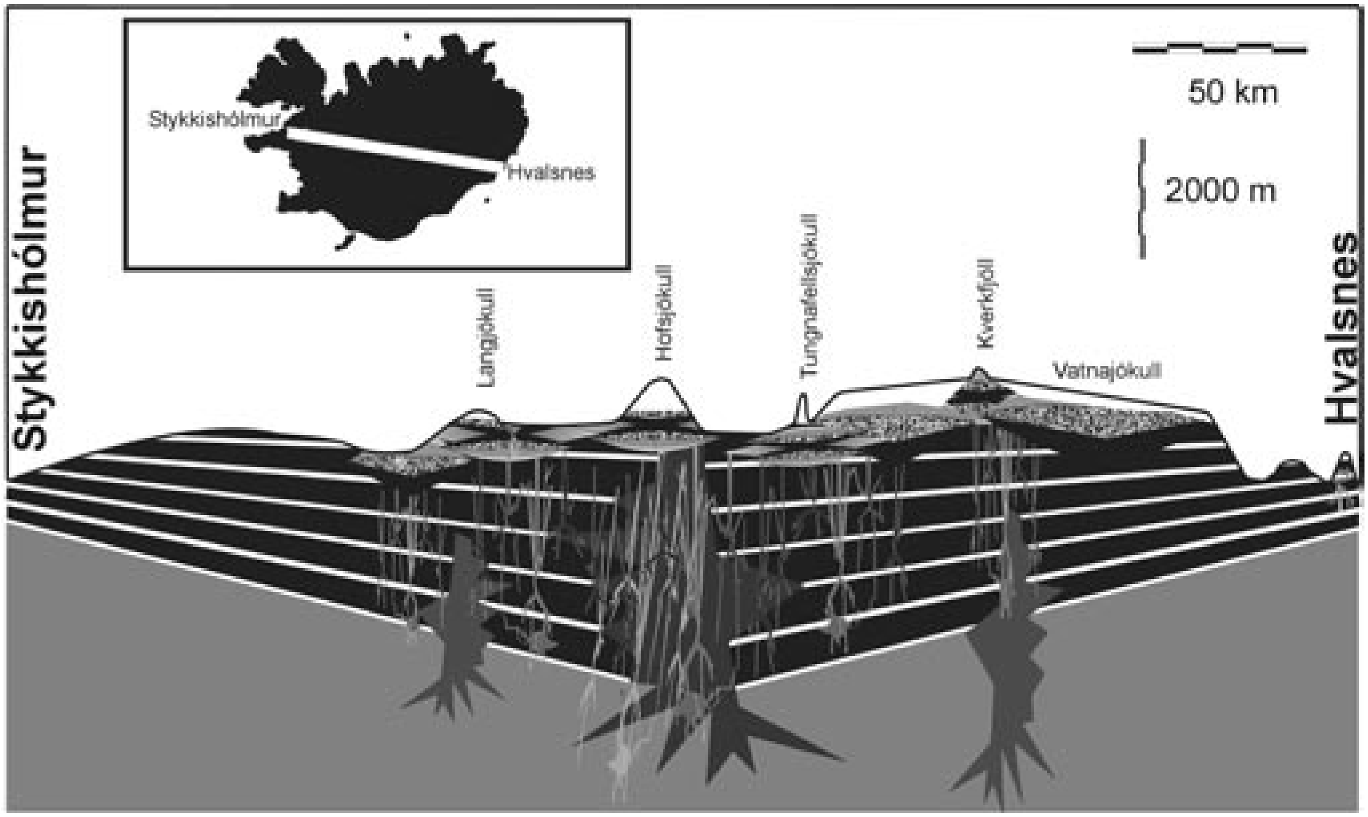


Figure 23. Simplified (cartoon) west-east section through Iceland.

trusion declined more rapidly than plate motion, the result would be closer to the situation illustrated in Figure 22C.

The actual structure of Iceland is, of course, more complex than these simple schematics. As shown in Figures 4, 5, and 23, the east, north, and west parts of the country–those most distant from the spreading center–exhibit vast flood basalt strata, while the flows near the spreading center are smaller. Flood basalts outcrop over half the country (Sæmundsson, 1980). This corresponds to neither Figure 22B nor Figure 22D. Nor does the lava pile thin in the manner of Figure 22C. Instead, the extrusion rate has fallen significantly since the flood basalts were emplaced. This, and the relatively thick crust under central and eastern Iceland (Oskarsson et al., 1985), may indicate that: (1) plate motion slowed during lava emplacement, (2) the rift and mantle plume interacted in a non-uniform fashion, or (3) plate motion was insignificant.

Figure 22E illustrates the expected lava pile structure under conditions of only vertical tectonics and a decreasing extrusion rate. According to Sæmundsson (1980, p. 136), flood basalts dip from near 0° near the top of the lava pile to about 5° to 10° toward the center of the pile at sea level, thickening conformably toward the center: "The regional tilt thus must have been imparted to the pile during its growth." This corresponds relatively well with Figure 22E.

What clearly has not occurred is the great passage of time under uniform conditions that has been the credo of most geologists over the past century and a half. Often this bias is tacit or even subconscious; occasionally it is not.

> Whatever their precise role in the history of the earth, these volcanic outbursts [flood basalts] can now take their place along with other geologic processes in the framework of uniformitarianism: the notion that the geologic past can be explained in terms of the same phenomena now shaping the earth. The unmatched scale of certain eruptions, notably the Deccan basalts, has led some workers to invoke causes outside normal earth processes–impacting asteroids, for example. But we do not think such catastrophes are required. Thick marine sequences of igneous rock, flood basalts on land and perhaps even mass extinctions–all can be explained by the interaction of familiar, ongoing earth processes (White and McKenzie, 1989, p. 71).

Despite assertions and reassurances

such as this, no extant EGP model can adequately explain the volcanic, pedologic, and tectonic features of Iceland. Uniformitarians ignore clear-cut evidence for rapid, catastrophic emplacement of the rock record and the "problem" duration of lava emplacement presents to "deep time."

Summary

Iceland provides an unusual opportunity to observe volcanic and tectonic processes usually obscured by the sea. Petrology and geochemistry, size and structure of the lava pile, and possible plate-tectonics explanations fit better with the DGP than the EGP.

While most of the lithologies of Iceland are tholeiites resembling MORB or MORB derivatives, differentiated lithologies and geochemical anomalies imply crustal recycling, fractionation in magma chambers, interaction with water, and mantle source heterogeneity. Diluvialists and uniformitarians differ primarily in the rates and relative importance assumed for these processes.

Much of the lava pile forming Iceland consists of flood basalts. These outcrop in the west, north, and east of the country. Large, conformable, inward-dipping strata indicate rapid emplacement of enormous volumes of lava. Lithologic uniformity of the flood basalts is a significant problem for uniformitarians.

> The differentiated character of such large masses of magma has presented a long-standing dilemma. Despite their great volume, the lavas were surprisingly homogeneous when erupted, and sequences of many flows maintain almost constant compositions, even though many centuries elapsed between eruptions. And yet these same flows differentiated, much in the way the ponded lavas of Hawaii have, in the periods of a few decades it took them to cool and crystallize. Eternal petrologic fame awaits the student who finds the explanation for this paradox (McBirney, 1993, p. 305).

The solution is both simple and obvious, but unacceptable to EGP adherents.

Up section and proximate to the rift are the volcanic zones, which are characterized by much smaller flows and greater lithologic diversity. EGP adherents insist on subaerial or subglacial emplacement for most of Iceland above sea level, while diluvialists can readily accommodate subaerial, subglacial, or subaqueous emplacement of all but the recent rocks. Paleontologic data fit well with a DGP interpretation.

The size and character of the lava pile and observed lava extrusion rates imply a time for emplacement of less than 6,000 years and probably closer to 4,000 years. This includes significant times for exposure of flow surfaces to erosion and soil formation. Weathering profiles, topographic development, and paleosols should therefore mark contacts. The greater the amount of time between flows, the more common and well developed these features should be. Their paucity is difficult to explain even within the biblical time frame, and virtually impossible within the EGP.

The nonlinear decrease in extrusion implied by Iceland's structure has implications for plate tectonics theories. Long-term uniformity in both extrusion and relative plate motion rates would not have generated the observed structure. Stochastic extension or plate motions decreasing less rapidly than lava extrusion could fit the geologic data. Such plate motions would be more readily accommodated by CPT, though nonuniform extrusion could be accommodated by the local interaction of the rift and mantle plume (especially with infinitely flexible plume theories). Existing rift transect survey data do not show expected plate motions. The geologic structure and transect data can be easily explained without plate tectonics, which also offers no apparent solution to the dearth of unconformities and other time indicators between flows.

Conclusions

The geology of Iceland indicates the rapid formation of its lava pile. Evidence of significant time between lava flows is lacking. Extrusion rates observed at historic eruptions provide a basis for concluding that Iceland formed in postdiluvian time within the biblical timescale. The geology of Iceland does not support deep time nor does it offer unambiguous support to plate tectonics.

Appendix A: Volcanology Primer

Igneous rocks solidify from a melt or partial melt. They are either plutonic (intrusive) or volcanic (extrusive), and rock texture usually differs between the two. Volcanic rocks are generally very fine-grained and sometimes vesicular (filled with tiny tubes formed by gases exsolving from lava). Igneous rocks can also be broadly classified by chemical composition:

- sialic: rocks rich in silica and alumina (e.g. rhyolite)
- mafic: rocks rich in magnesium and iron (e.g. basalt)
- intermediate: calc-alkaline rocks (e.g. andesite)

Igneous petrology is, of course, far more complex. A variety of minerals combine to form a plethora of igneous rock types. However, for the non-geologist, the simple classification provided here may prove useful.

The chemical composition of magma (molten rock beneath the earth's surface) strongly affects the type of eruption. Volcanic eruptions can produce tephra (material ejected into the atmosphere) and lava (molten rock that flows onto the earth's surface). Contrary to popular misconception, lavas are commonly extruded as mixtures of crystals and melt, not as a simple liquid, and thus porphyrtic lavas are not uncommon. A porphyry is a rock consisting of relatively large crystals (phenocrysts) embedded in a fine-grained matrix (groundmass).

Sialic lavas tend to be very viscous, squeezing out of vents like thick toothpaste. They tend to produce small, steep-sided domes, like that formed inside the crater of Mount St. Helens, Washington, after the 1980 eruption. Rhyolite flows are documented in the rock record, but the conditions required to form them apparently do not exist in the present. "Although very siliceous lavas are not uncommon in the geological record, no eruption of rhyolitic lava has been observed by a geologist" (Bardintzeff and McBirney, 2000, p. 81). Extensive flows must have been erupted at temperatures above or near their liquidus (completely molten), causing some geologists to conclude that rhyolite flows are rheoignimbrites, a special kind of welded tephra deposit (Peate, 1997). They may indicate the special conditions prevailing during the Deluge.

Mafic magmas tend to reach the surface in relatively quiet eruptions with relatively large amounts of lava. The earth's crust is dominated by mafic rocks. Oceanic crust consists largely of basalt. Mafic volcanoes are typically large and form shield volcanoes, with very gentle, broad slopes. The Hawaiian Islands are shield volcanoes. Basalt can often erupt from fissures, and the largest volume and highest flow rates are from fissures. Fissures typically shrink and become isolated as conduits as lava extrusion decreases and various points along the fissure erode into larger openings. Extensive basalt flows characterize the mid-ocean ridges of the North and South Atlantic Oceans and the Pacific "ring of fire." One of the most remarkable of volcanic phenomenon is large igneous provinces in which flood basalts cover entire regions, notably in the northwestern United States, Siberia, and India (Table I).

Intermediate magmas produce explosive eruptions with large amounts of tephra. They produce volcanoes with intermediate properties, typically stratovolcanoes. Examples include Mount Fujiyama and Mount St. Helens. They tend to form along continental margins, and andesite was long thought to represent melt from subducted lithosphere, though this is now a discredited concept (see McBirney, 1993, pp. 315–316).

Rates of lava extrusion are governed by many variables, including vent size and geometry, composition of the magma, temperature of the lava, volatile content, and the eruptive environment. Marine eruptions below a depth of 4 to 5 km (15,000 ft.) retain their volatiles due to pressure (Froede, 2000; also see Barndintzeff and McBirney, 2000, p. 148). A crust often forms on the top of a flow due to cooling by air or water, insulating the lava beneath and enabling it to continue to flow for considerable distances. Often the movement is concentrated in conduits in the lava flow, which may later drain to form caves called lava tubes. This is typical of pahoehoe, generally a fluid, volatile-rich basalt that produces a ropey surface texture (Figure 9). Basalt often also produces a'a, a form

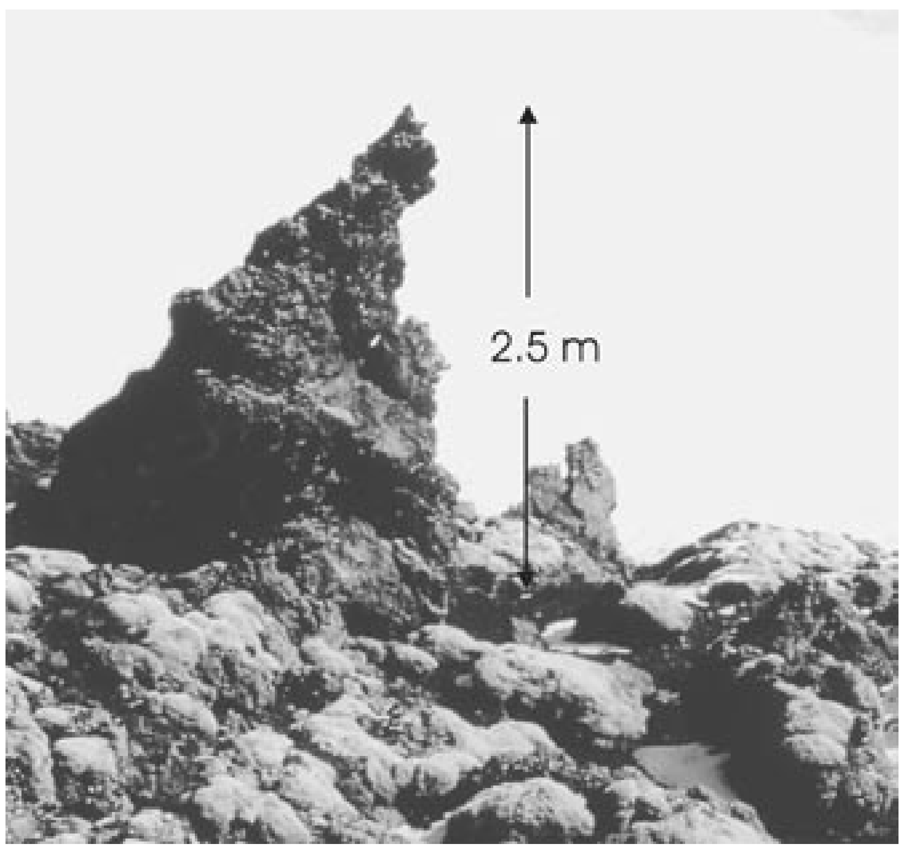


Figure 24. A'a basalt is typified by rough, jagged surfaces such as that evident on the edge of the 1947 block flow on the southwest side of Hekla.

with a very rough surface texture resulting from shearing and loss of volatiles (Figure 24). Block flows are intermediate between pahoehoe and a'a.

The emplacement environment can be partially inferred from field characteristics (Table V). Some of the characteristics formerly thought diagnostic of a subaerial environment are now known to form in a subaqueous environment (Froede, 2000).

Table V. Diagnostic Features of Lava Flows

Feature	Interpretation
Vesicles	Significant volatile content in lava which exsolved. Higher volatile content results in lower melting temperature and lower viscosity.
Phenocrysts	Lava was only partially molten. Phenocrysts may provide information useful to inferring parent composition, country rock, or other features.
A'a, blocks, pahoehoe	A'a is evidence for rapid emplacement with high shear and high loss of volatiles. Pahoehoe is evidence for low viscosity. Block flows are intermediate.
Columns	Columns indicate cooling within a single flow and the direction of the thermal gradient.
Pillows	Pillows are indicative of subaqueous emplacement.
Palagonite	Palagonite indicates quenching of lava by water or ice.
Tuff	Tuff is pyroclastic. Welded tuffs are fairly common and are typically believed to form subaerially, though subaqueous emplacement of a welded tuff is possible.
Interbeds	Interbeds of sedimentary or volcanisedimentary rocks between lava flows indicate existence of sedimentary processes between discrete volcanic events or contemporary with them.
Tuyas ("table mountains")	Generally believed to result from subglacial eruptions.

Appendix B: Estimating Time Required for Lava Emplacement

Data used for estimating maximum times required for emplacement of the lava in Iceland are shown in Tables II and VI. Assumptions used in the calculations are listed in Table VI. Volume was estimated by integrating a vertical, truncated cone with the properties listed in Table VI. I made the conservative assumption that 35 percent of the total extruded volume was lost to the sea and atmosphere.

Based on observations and geologic maps, I estimated the percentages of three types of flows: (1) flood basalts, (2) modern (generally block) flows, and (3) an "intermediate zone" with intermediate properties (and presumably flow rates). The crust beneath Iceland is complex (Du and Foulger, 2001), and precision greater than the assumptions in Table VI was not possible in this study. I made the conservative assumption that only a single fissure (initially the Mid-Atlantic Ridge) supplied all of the lava, and that the active length of this fissure declined over time. By contrast, in historic times, *en echelon* fissure systems have often been observed, and some estimate that the extrusion rate in Iceland has been twice that of the Mid-Atlantic Ridge elsewhere (Sæmundsson, 1980).

Flow rate values were derived from the data in Table II. Although the Lakagígar flows were block flows, not flood basalts, I deemed the estimated initial Laki extrusion rate to be an appropriate minimum flood basalt flow value. Icelandic flood basalts consist of overlapping shields cut by dikes that compose up to 20 percent of the rock (Walker, 2000, p. 288), so Lakagígar is a good analog. The maximum flood basalt rate is that estimated for the CRBG (Shaw and Swenson, 1970). While this estimate for turbulent emplacement of the CRBG has been criticized for assuming Newtonian fluid dynamics (Self et al., 1997), it is probably valid at the vent (Tallarico and Dragoni, 2000), though less so elsewhere (Baloga et al., 2001). Self et al. (1997) suggested a decade or more for emplacement of major CRBG flows, but Oard (1999) presented evidence for more rapid emplacement. The minimum unit extrusion rate for Iceland's modern volcanic zones is an average of the minima from the 1970 eruption of Hekla, five eruptions of Krafla between 1980 and 1984, and the 1973 eruption of Eldfell on the island of Heimaey. The maximum value for the modern volcanic zones is the upper limit of the eight-month average for Lakagígar, though this value was equaled by the 1970 eruption of Hekla and exceeded by the 1980 eruption of that volcano. The values I used for intermediate zones were the minimum Lakagígar eight-month average and maximum Lakagígar initial discharge estimate. Although the October 1980 eruption of Krafla produced a higher unit extrusion rate, the larger scale of the Laki eruption probably makes it a better analog for large events of the past. This also provides a slightly more conservative approach.

Self et al. (1997), in their effort to rein in catastrophic interpretations of the CRBG, assert that the Laki maximum unit extrusion rate approximates the average Roza flow extrusion rate in the CRBG. Others have followed suit (e.g. Rothery, 2001). If these uniformitarians look to Lakagígar to reign in catastrophic interpretations of flood basalt extrusion rates, this seems to confirm that the rates used in this study are conservative and give uniformitarians the benefit of the doubt.

It is important to note that these estimates assume that during nearly all of Iceland's history, only part of the country was experiencing emplacement of lava. Even during emplacement of flood basalts, I have assumed that individual flows were extruded at the given rates and fissure lengths presented above. This may be an overly conservative assumption, as flood basalts may well be at least an order of magnitude greater than the historic values (see Sigurdsson, 2000b, p. 276). Also, many of the flows, especially subaqueous flood basalts, probably grew by inflation, meaning that weathering processes were already active during the time the flows were being emplaced.

Table VI. Lava Emplacement Time Parameters

<table>
<tr><th colspan="4">Assumption</th><th>Value</th></tr>
<tr><td colspan="4">Land area of Iceland in square kilometers[1]</td><td>103,000</td></tr>
<tr><td colspan="4">Assume 35% lost to erosion, resulting area in square kilometers</td><td>158,462</td></tr>
<tr><td colspan="4">Equivalent radius assuming circular land mass, in meters</td><td>224,588</td></tr>
<tr><td colspan="4">Height above sea floor in meters[2]</td><td>4,000</td></tr>
<tr><td colspan="4">Average slope ratio to sea floor (horizontal:vertical)[2]</td><td>62.5:1</td></tr>
<tr><td colspan="4">Maximum fissure length (single fissure through diameter) in km</td><td>949</td></tr>
<tr><td colspan="4">Percentage of total pile that is flood basalt</td><td>75</td></tr>
<tr><td colspan="4">Percentage of total pile represented by modern volcanic zones</td><td>10</td></tr>
<tr><td colspan="4">Percentage of total pile that is intermediate between above zones</td><td>15</td></tr>
<tr><td colspan="2" rowspan="3">Maximum and minimum
effective fissure lengths as percentage
of maximum fissure length</td><td colspan="2">Flood basalts</td><td>40–100</td></tr>
<tr><td colspan="2">Modern volcanic zones</td><td>5–10</td></tr>
<tr><td colspan="2">Intermediate zones</td><td>10–40</td></tr>
<tr><td colspan="3">Flow rates in m^3/s per m of fissure length▼</td><td colspan="2">▼Basis for estimate</td></tr>
<tr><td>Flood basalts</td><td colspan="2">0.60–12.00</td><td colspan="2">Lakagígur initial maximum to CRBG maximum[3]</td></tr>
<tr><td>Modern volcanic zones</td><td colspan="2">0.01–0.03</td><td colspan="2">Hekla-Eldfell-Krafla average min. to Lakí avg.[3]</td></tr>
<tr><td>Intermediate zones</td><td colspan="2">0.02–0.60</td><td colspan="2">Lakagígur avg. min. to Lakagígur initial max.[3]</td></tr>
<tr><td colspan="4">Total estimated volume of lava pile in cubic kilometers</td><td>1,601,000</td></tr>
</table>

[1]Bridgwater, 1960, p. 622; Sigurjónsson and Tilnius, 1994, p. 133.
[2]Foulger et al., 2000, p. F1.
[3]See Table II.

Acknowledgments

Invaluable assistance was provided by Síndri Guðjónson, Guðni Jónsson, Maria Wilhalmsdóttir, Kathryn Dion, and other helpful Icelanders, especially those at the University of Iceland, Sólheimahjáleiga, and Brunnhóll. While not all may agree with my conclusions, I hope they will consider what I have presented in this paper. This research was also made possible by a grant from the Creation Research Society. The paper has benefited greatly from the comments of the editor and the other reviewers. *Deum laudo* (Psalm 104:32).

Glossary

aeolian: said of processes or sediments involving transport by wind.

dacite: a felsic, sub-alkaline (intermediate) rock containing at least ten percent quartz.

en echelon: parallel features offset diagonally.

hornito: a typically small (one to several meters) structure resembling a stratovolcano and formed by steam escaping through lava that has flowed over water or wet ground.

hot spot: generally believed to be a fixed, narrow, cylindrical plume of especially hot magma originating deep within the mantle.

hyaloclastite: coarse volcanic rock formed from quenched lava.

ignimbrite: fragmental, pyroclastic rock.

Landnám: the period beginning in A.D. 870 and extending to ca. A.D. 930 during which Iceland was permanently settled; it marks the beginning of its recorded history.

loess: open-structured silt, typically formed by aeolian deposition.

palagonite: yellowish-brown altered volcanic glass formed from quenched basalt.

paleosol: a "fossil soil profile," i.e. a soil profile preserved beneath the zone of modern soil formation.

pedogenesis: the processes of soil formation as determined by the five environmental factors mediated by the four soil-forming mechanisms (Klevberg and Bandy, 2003a; 2003b).

rheoignimbrite: an ignimbrite emplaced at high temperature, facilitating flow prior to freezing (i.e. lithification).

stratovolcano: a form of volcano composed of alternating pyroclastic and lava strata, typical of intermediate lithologies. Examples include Fujiyama, Mount Kilimanjaro, and Mount Rainier.

stochastic: said of a continuous function with an unpredictable or random path.

tholeiite: a type of basalt relatively rich in silica and iron and typical of mid-ocean ridges.

tuya: a "table mountain" or steep-sided butte of volcanic origin, characteristic of Iceland, believed to have formed by subglacial eruption.

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CENTJ: *Creation Ex Nihilo Technical Journal*

TJ: *Technical Journal (formerly CENTJ*, now *Journal of Creation)*

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