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RITUAL RESPONSES TO CATASTROPHIC VOLCANISM IN VIKING AGE ICELAND: RECONSIDERING SURTSHELLIR CAVE THROUGH BAYESIAN ANALYSES OF AMS DATES, TEPHROCHRONOLOGY, AND TEXTS

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ABSTRACT

Surtshellir, a 1,600-meter-long lava cave in the interior of Iceland, contains a unique Viking Age archaeological site located nearly 300 meters from its entrance and more than 10 meters below the surface of the Hallmundarhraun lava field. Since the 1750s, the site has been interpreted as an outlaw shelter, yet in the 12th-13th century it was associated with actions directed towards an elemental being – Surtr – for whom the site was named and who, according to medieval Icelandic accounts of Viking Age mythology, was present at the world's creation and would destroy it after the battle of Ragnarök. Archaeological fieldwork inside Surtshellir in 2001, 2012, and 2013 produced 20 new AMS dates that, combined with three earlier radiocarbon and tephrochronological dates, provide the basis for Bayesian analyses which suggest (1) that the cave formed in the first major volcanic eruption directly witnessed by northern Europeans (2) that this took place shortly after the Norse colonization of Iceland began, (3) that people entered the cave soon afterwards, (4) that for 80-120 years they deposited the fragmented bones of slaughtered domestic animals in piles stretching 120 meters through the cave's "dark zone", burning others at high temperatures in a dry-stone structure built deep inside a raised side passage, and (5) that these activities ended shortly after Iceland's conversion to Christianity. Surtshellir provides important new insights into Viking Age ritual practice, Iceland's settlement and conversion, and the cultural responses of Iceland's newly arrived settlers to the existential challenges posed by previously unimagined catastrophic volcanism.

KEYWORDS:
Calibration, AMS dates, Bayesian statistics, Viking Age, Iceland, Ritual sites, Volcanism

1. INTRODUCTION

Late in the 9th century AD, Viking Age settlers colonized Iceland unaware that they were settling one of the world's most geologically active land masses. Sitting atop the Iceland plume, a volcanic hot spot carrying magma up from the mantle (Bijwaard and Spakman 1999; Helmberger et al. 1998; Steinberger et al. 2019; Wolfe et al. 1997), and straddling the Mid-Atlantic Ridge, Iceland is home to 30 active volcanic systems that have erupted at least 205 times since the first Norse settlers arrived (Thordarson and Larsen 2007).

Medieval texts, archaeological evidence, isotopic and paleo-genomic data concur that Iceland's settlers arrived from Scandinavia and Scandinavian settlement areas in the British Isles that were

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among the world's most tectonically stable regions (Ebenesersdóttir et al. 2018; Hayeur Smith et al. 2019; Helgason et al. 2000, 2009; McGovern et al. 2007; Pálsson and Edwards 1972; Price and Gestsdóttir 2006; Smith 1995). The last volcanic eruption in northern Europe had been the Laacher See eruption, 13,000 years ago (Riede and Kierdorf 2020), and yet the myths of the Viking Age Norse, as preserved in the 13th century Icelandic *Prose Edda* (Sturluson 1987) and the poems of the *Poetic Edda* (Hollander 1962), held that the world would end when Surtr, an elemental being present at the world's creation, would kill the last of the gods in the battle of Ragnarök and then engulf the world in flames. Another early medieval Icelandic poem, the *Hallmundarkviða*, makes it clear that Surtr was believed to direct fire giants, in caves below the earth, to cause volcanoes to erupt (Hjartarson 2014; Jónsson 1953; Nordvig 2015; Taggart 2017), suggesting that the world's end would come in Surtr's volcanic flames.

In 1905 Bertha Philpotts argued that the specific beliefs about the end of the world incorporated within the *Prose* and *Poetic Eddas* were not brought to Iceland from Scandinavia by its Norse settlers but were, instead, framed in Iceland by the colonists' first encounters with, and responses to, volcanism (Philpotts 1905). She noted that Surtr's name was undocumented elsewhere in Scandinavia and in Iceland was exclusively associated with Surtshellir, a massive cave in western Iceland's Hallmundarhraun lava field. Earlier, in the 19th century, Finnur Magnússon had speculated that this cave had been a site of the "cult of Surt" (Magnússon 1828), and earlier still the 13th century Icelandic Book of Settlement, *Landnámabók*, linked Surtr specifically to this cave, recounting the story of a chieftain's son, Þorvaldr holbarki[4] Þórðarson, who traveled through Iceland's desolate interior to perform a ritual act at *hellisins Surts* (Surtr's cave), chanting a poem of praise (*drápa*) there to the giant who lived inside (Pálsson and Edwards 1972:94).

However, *Landnámabók* (Pálsson and Edwards 1972) and *Harðar Saga og Hólmverja* (Hreinsson 1997) also mention outlaws briefly taking refuge in unnamed caves within the Hallmundarhraun around AD 975 (Ingvarsson 1986:398). Later folktales and stories collected and written down in the 18th-20th centuries localized these and other outlaws in Surtshellir, and today these stories are the dominant narratives about the cave (Árnason 1902; Arngrímsson 1979; Konráðsson 1946; Laxness 1969; Miles 1854; Ólafsson and Pálsson 1772).[5] Surtshellir therefore has two origin stories – one focusing on outlaws' brief use of unnamed caves in the Hallmundarhraun and another suggesting that Surtshellir, specifically, was a site of unusual and potentially ritual activity undertaken by Viking Age elites to influence its occupant, a cosmogenic being whose actions could destroy the world.

In 2001, 2012, and 2013 we documented architectural features, cultural deposits, and a unique suite of Viking Age material culture in an extensive archaeological site located 300 meters into Surtshellir's "dark zone",[6] approximately 10 meters below the earth's surface. After our first brief field reconnaissance in 2001, we interpretated Surtshellir as an outlaw shelter (Ólafsson et al. 2004, 2006, 2010). However, new work at the site in 2012-2013 showed that it was much more complex than we had originally believed and provided new data, including an expanded suite of radiocarbon dates, for re-assessing Surtshellir's archaeological record and origin stories.

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[4] Holbarki ("hollow throat") suggests a chanter or someone recognized for his loud and sonorous voice.
[5] In the 18th century, legends connected Surtshellir to young priests who became murderers and thieves during the 15th century (Árnason 1902; Ólafsson and Pálsson 1772) and in the late 19th century a work of fiction about outlaws in this region during the Viking Age was written using medieval and post-medieval sources (Konráðsson 1946).
[6] That part of a cave into which no natural light penetrates, producing total and constant darkness that can "instil feelings of blindness, fear, hesitancy, and disorientation" (Skeates 2016) in those entering, contrasted with bright and "twilight" zones near caves' entrances and near-surface passages where some light is present (Dowd and Hensey 2016).

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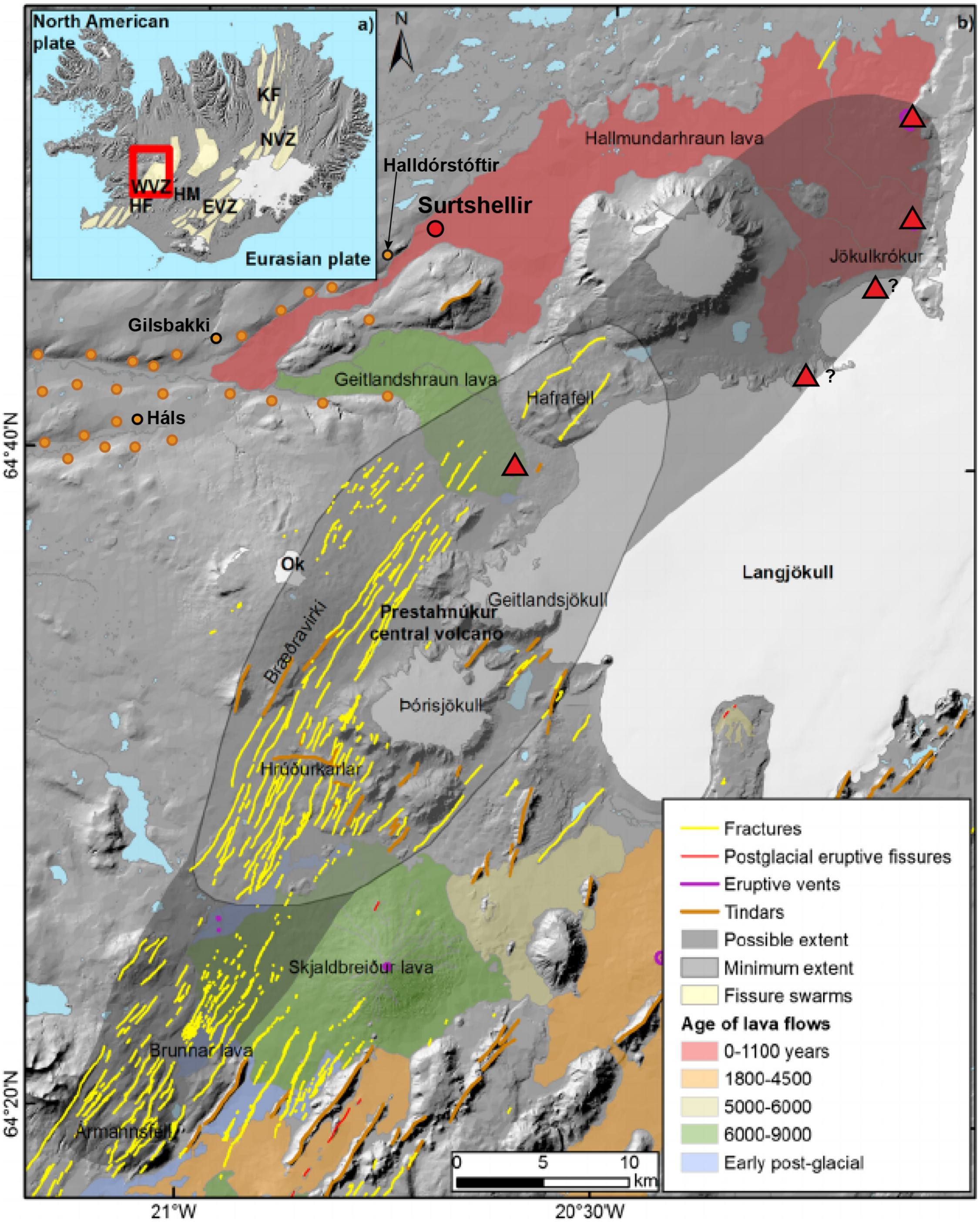

Figure 1: a) Location of the Prestahnúkur volcanic system within Iceland's Western Volcanic Zone (WVZ) and b) the location of Surtshellir in relation to the Hallmundarhraun lava field (pink) and other major features of the Prestahnúkur volcanic system. The four northernmost red triangles adjacent to, and beneath, Langjökull identify vents thought to be responsible for the 10th century Hallmundarhraun eruption (Hjartardóttir et al. 2015; Piper 1973; Sinton et al. 2005); while the southernmost vent was the source of the mid-Holocene Geitlandshraun flood basalt. Orange circles identify the locations of farms settled before AD 930 according to *Landnámabók*; three with black rims are sites confirmed by archaeological research to be of this age (Ólafsson 2020; Smith 1995, 2005, 2009). Base map modified from Hjartardóttir et al (2015: 8744) with cartographic data from the Land Survey of Iceland (Landmælingar Íslands).

2. SURTSHELLIR

2.1 SURTSHELLIR AND THE HALLMUNDARHRAUN ERUPTION

Surtshellir is located within western Iceland's Hallmundarhraun lava field, which was formed by the third-largest effusive eruption to have occurred in Iceland since its settlement (Sinton et al. 2005). This lava shield eruption began when at least two, and possibly four, vents opened at the northern end of the Prestahnúkar volcanic system in Iceland's Western Volcanic Zone, just below and under the edge of the 920 km^2 Langjökull glacier (Piper 1973; Sinton et al. 2005; Hjartarson 2014, 2015; Hjartardóttir 2015). Lava from these vents flowed more than 50 kilometers through the valley of the Norðlingafljót river to its confluence with the Hvítá river, covering more than 240 square kilometers of once-fertile upland grazing land, birch forests, and lowland in smoldering black basalt (Figure 1).

Estimates of the amount of lava produced by the Hallmundarhraun eruption vary from 5-8.5 km^3 (Sinton et al. 2005; Thordarson and Larsen 2007; Sæmundsson 2019). Although the Hallmundarhraun eruption itself has received little direct study, Icelandic shield eruptions' lava production rates are generally considered to be relatively low, ca. 5-10 m^3/sec, with large eruptions of this type lasting for years or even decades (Sinton et al 2005; Thordarson and Höskuldsson 2008; Thordarson and Sigmarsson 2009; Larsen and Guðmundsson 2019; Sæmundsson 2019), although Thordarson and Larson (2007: 131) suggest maximum production rates could approach 100 m^3/second. Both the length and size of the lava tubes in the Hallmundarhraun suggest that this eruption saw episodes of both very high and considerably lower flow, but at average flow rates of 5-10 m^3/sec the eruption would have lasted 16-54 years to produce the 5.0-8.5 km^3 Hallmundarhraun lava field, with lava flowing across its surface at times of high production and emerging at its margins from subterranean lava tubes. Even at Thordarson and Larsen's highest estimate (≤100 m^3/sec), the eruption would have lasted 4.5 years, its fronts advancing much more rapidly with surges of lava flowing from its caves.

The twenty known caves that formed in the Hallmundarhraun once these lava tubes emptied include some of the largest in Iceland(Hróarsson 2006:382–456). Eight or more have archaeological records (Hróarsson 2006: 383-455), but only three—Hallmundarhellir (Gestsson 1960; Pálsdóttir and Smith 2019; Smith et al. 2019), Víðgelmir (Ólafsson 1998), and Surtshellir (Ólafsson et al. 2004, 2006, 2010)—have been archaeologically investigated. Surtshellir contains the most extensive and complex suite of archaeological remains.

2.2 ARCHAEOLOGICAL FEATURES WITHIN SURTSHELLIR

Surtshellir is the 1.6-kilometer-long "downstream" portion of the ~5 kilometer-long Surtshellir-Stefánshellir-Hulduhellir system (Hróarsson 2006; Stefánsson and Stefánsdóttir 2016; Wood et al. 2008). For most of its length (Figure 2), the cave is a single tunnel, 10-15 meters high and 9-13 meters wide, meandering towards the west-southwest. However, two passages cross-cut the main tunnel 250 meters into the cave and 5-6 meters above its floor. These passages, each about 7-8 meters wide and 3-5 meters high, have been known since the mid-18th century as Beinahellir (the "bone cave") and Vígishellir (the "fortress cave").

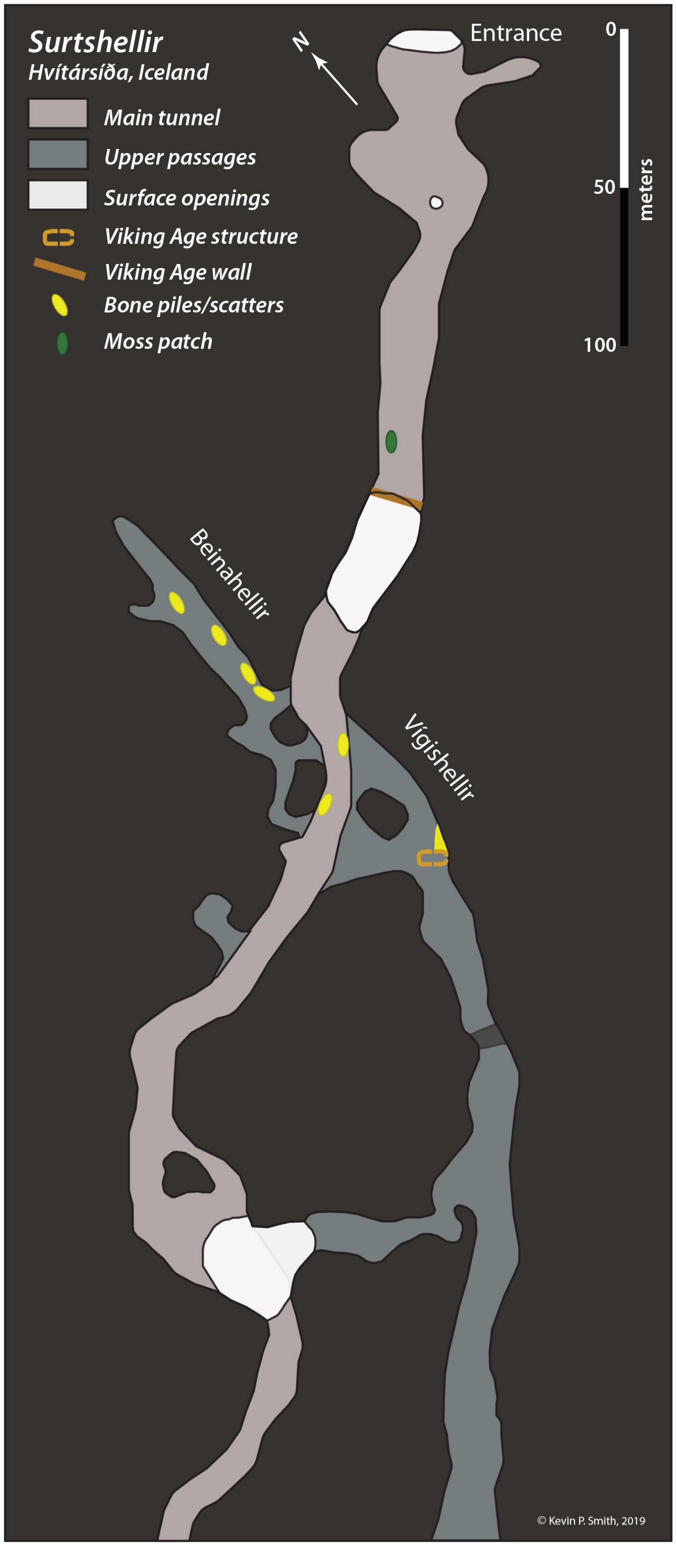

Figure 2: Surtshellir, northern end, rescaled and modified from Hróarsson 2006 to correct tunnel lengths by reference to measured and satellite imaged distances between surface openings. While the sizes of the bone piles in Beinahellir and Vígishellir and the moss patch in the main tunnel are not to exact scale, the structure and bone pile in Vígishellir are to scale.The darker gray zone in Vígishellir is a low (0.7 m high), squeeze separating the chamber with the structure from its farther passages.

Archaeological features in these upper galleries, including a low, boat-shaped[7] stone enclosure and piles of bones, were first described by Eggert Ólafsson and Bjarni Pálsson following their visit to Surtshellir in August 1753 (Ólafsson and Pálsson 1772). Although explorers and geologists noted these features for more than two centuries, they were not archaeologically investigated until 2001, except for a brief description by Matthías Þórðarson (Þórðarson 1910).

In 2001, following reports that visitors were removing bones from the cave, we mapped the structure in Vígishellir, excavated part of what remained of the once-massive bone pile beside it, and obtained two radiocarbon dates on *Bos taurus* bone fragments from its base (AAR-7412, AAR-7413). These confirmed that this feature dated to the Viking Age (Ólafsson et al. 2004). We returned in 2012 and discovered that a thin layer of grit inside the structure and at its entrance, thought since the 1750s to be sterile, was actually a thin, man-made pad of crushed basalt containing Viking Age beads, burned bone, and other artifacts.

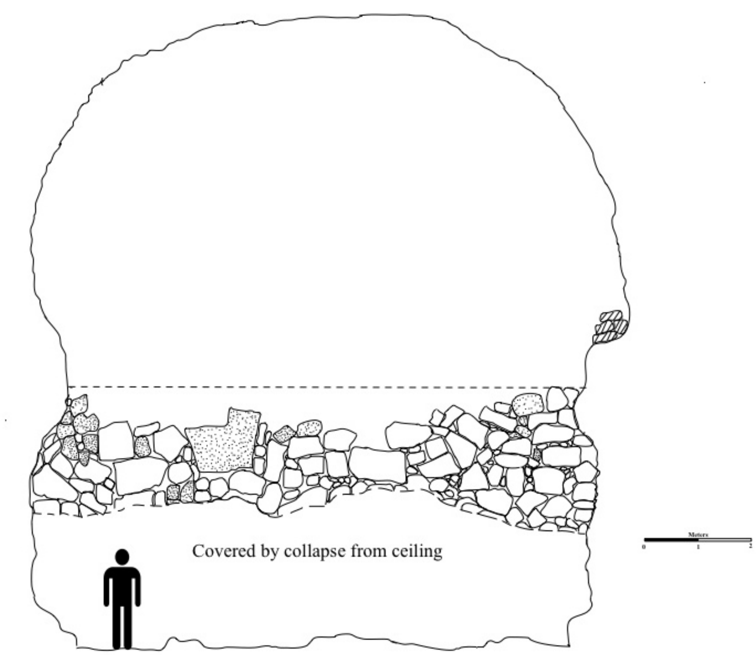

Figure 3: The wall inside Surtshellir's main tunnel. Stippling identifies blocks set with dripstone projections facing forward. Dashed line identifies inferred height of the original wall. Drawing by K.P. Smith and G. Ólafsson, 2012.

We excavated this deposit in 2013 and documented additional features within Vígishellir, Beinahellir, and Surtshellir's main tunnel. These include a massive stone wall, 10.5 meters long and originally perhaps 4.5 meters high, that blocks the main passage 175 meters from the cave's entrance (Figure 3). Behind this, 250-300 meters from the cave's entrance are the remains of seven concentrations or piles of unburned, fragmented bones: two beneath blocks of roof collapse on the floor of the main tunnel below the openings of Beinahellir and Vígishellir, remnants of four similar but once-larger piles of unburned and fragmented bones in Beinahellir, and the

[7] Viking Age buildings are characteristically built with curved walls, narrowing towards the ends, and are often referred to as boat-shaped.

remains of the largest bone pile located 50 meters into Vígishellir beside the boat-shaped stone structure.[8] This last covered an area of 8.75 m^2 (2.5 m x 3.5 m) and was described by Ólafsson and Pálsson in 1753 as "a great bone heap" (*en stor Beendynge*) which they partially dismantled looking for artifacts (Ólafsson and Pálsson 1772: 245). Since their visit, this heap has been almost completely depleted by visitors taking bones as souvenirs; yet organic staining and fragments of bone still adhering to the cave's wall confirm that the pile was originally 0.8 meters high (Ólafsson et al. 2004).

The structure beside it is a bowed-walled, dry-stone enclosure with narrow openings in the middle of its side walls and three niches built symmetrically into its side walls and eastern gable (Figure 4). A thin (<1.0-1.5 cm), man-made pad of crushed basalt fragments and burned bones, located in the center of the structure and extending just beyond its northern entrance, contained a unique assemblage of more than 200 jasper and chalcedony fire-starter fragments; thousands of burned bone fragments; 63 glass beads including types known from mid-to-late 10th century AD Scandinavian archaeological contexts (Callmer 1977; Eldjárn 2000; Hreiðarsdóttir 2005, 2014) as well as previously undocumented forms similar to tiny beads from the 10th century Fjallkonan grave in Iceland's interior (Bergsteinsson 2005); four fragments of schist and sandstone hones; 12 fragments of orpiment – an arsenic sulfide ore obtained from eastern Turkey never before found in Iceland[9] and otherwise known in Viking Age contexts only from the late-10th century royal burial mound at Jelling, Denmark and perhaps the Gokstad ship (Krogh et al. 2007; Marxen and Moltke 1981); and a set of lead scale weights, including one in the shape of a cross, placed at the center of the structure (Figure 5).

[8] All of the bone piles in Surtshellir have been damaged by tourists and explorers taking souvenirs away since at least the 1750s; virtually every explorer's account of the cave mentions removing bones for various purposes. Our work in 2012 was in response to reports of accelerating tourist activity and damage to the site's archaeological record. The National Science Foundation (US) funded excavation of the remaining cultural deposits, other than the remnants of the remaining bone piles, in collaboration with The Cultural Heritage Agency of Iceland (Minjastofnun, permit 2013080010) and with the gracious permission of the site's landowners. Collections from this project are curated at the National Museum of Iceland (Þjóðminjasafn Íslands).

[9] Orpiment forms in low temperature hydrothermal veins, hot springs, and fumaroles rich in arsenic-antimony minerals, often in association with stibnite (Sb_2S_3], realgar [AsS], calcite, barite, and gypsum (Anthony et al. 1990; Lazaridis et al. 2011; Webster and Nordstrom 2003), raising questions of whether it could be of Icelandic origin rather than imported. However, Iceland has one of the world's lowest concentrations of As in geothermal water (~0.10mg-0.15/kg) due to low concentrations of arsenic in the island's basalt host rocks (Olsen et al. 2010; Webster and Nordstrom 2003) and neither orpiment nor other alteration minerals of As have been identified in Icelandic geothermal surface environments (Kaasalainen and Stefánsson 2012).

Figure 4: The boat-shaped structure inside Vígishellir, looking towards its eastern gable following the removal of the thin crushed basalt pad in the 2013 excavation. The natural lava floor of the cave can be seen to have been protected by the pad. Three niches were built into the walls – the largest of which is visible in the gable with fire damage from 19th-21st century tourists. Two others are located in the opposed bowed side-walls closest to the camera. The scale bar lies between two narrow doorways, the one on the left leading out towards the cave's main tunnel and entrance; the one on the right opening towards a low (0.7 m high), mouth-like squeeze 40 meters farther into the cave, beyond which Vígishellir's deeper passages of continue. Photograph © Kevin Smith, 2013.

Figure 5: Set of lead scale-weights from the structure in Vígishellir. The cup- and cone-shaped weights (first and second from left) have close parallels in 10th century Norse Ireland and Kaupang, Norway (Pedersen 2007; Wallace 2014), while the cross-shaped weight at right is unique. All have been pecked or shaved to calibrate the set to a combined weight of ~26 grams, the ounce unit (*øre, eyrir*) used in Scandinavia into the 10th century (Brøgger 1921; Kilger 2007; Pedersen 2007), as well as in Viking Age Ireland, Wales, and parts of England (Kruse 1988; Sheehan 2011; Wallace 1987). Photograph by Ívar Brynjólfsson, courtesy of The National Museum of Iceland (Þjóðminjasafn Íslands).

The cave's faunal assemblage, composed of bones from full-grown and fetal domestic animals (sheep/goats, cattle, horses, pigs in descending order of frequency), is unique within Iceland (Ólafsson et al. 2006: 398). McGovern's analysis of faunal remains from the bone pile adjacent to the structure suggested these animals were killed during the late winter/early spring birthing season rather than during the normal fall slaughter.[10] Butchery and cut marks from axes, large knives, and blunt instruments suggest they were dispatched and dismembered in ways that differ from standard Icelandic butchery patterns (Marengère et al. 2019; McGovern 2002; Ólafsson et al. 2006:398–402) but may reflect practices similar to those used to sacrificially slaughter bulls at Hofstaðir, a Viking Age feasting hall in northern Iceland (Lucas 2009; Lucas and McGovern 2007). The presence of horse remains in the deposit is consistent with its age; horses had been sacrificed during pre-Christian times and while eating horse flesh was one of the main concessions allowed to Icelanders at the time of the country's conversion to Christianity it was soon forbidden by medieval Iceland's law code, *Grágás* (Dennis et al. 1980:49; Grønle 2006:9,50). Leifsson has documented that horses were slaughtered and dismembered at grave-side sacrifices in Viking Age Iceland in ways that differed from the ways oxen were dispatched at Hofstaðir (Leifsson 2018); yet practices of violent slaughter and dismemberment connect both with evidence for the dismemberment and sequestration of livestock at Surtshellir.

[10] On-going work at Laval University by Véronique Marengère on calcined and unburned bones from the thin, crushed basalt pad inside the enclosure largely supports McGovern's taxonomic identifications and insights on the age structure and seasonality of the faunal assemblage, including the recovery of fetal animal bones, but have also identified a small number of bird bones (n < 10) of unidentified galliform species, domestic fowl or possibly wild ptarmigan (Marengère et al. 2019).

3. DATING SURTSHELLIR

3.1 MATERIALS AND METHODS

Twenty AMS and two standard radiocarbon dates, as well as one tephrochronological date, are now available for estimating the age of Hallmundarhraun lava field and identifying the periods when Surtshellir was in use. Table 1 presents the laboratory and field numbers, materials dated, locations within the cave, measured ages, $^{13}C/^{12}C$ ratios, conventional radiocarbon ages, 1- and 2-sigma calibrated ranges, internal probability ranges, and median ages for all 22 radiocarbon dates from the site.

Two of these are standard radiocarbon dates run in the 1960s. In 1966, the volcanologist Kristján Sæmundsson ran a radiocarbon date (H2453-1857; 1190±100 bp) on peat buried beneath the Hallmundarhraun's lava just north of Surtshellir (Sæmundsson 1966) and in 1968 the Nobel Prize-winning novelist Halldór Laxness dated a cow bone (K-1435; 1010±100 bp) that he removed from cave while researching a novel about Viking Age outlaws (Laxness 1969). These dates suggested that the Hallmundarhraun lava flowed about the time Iceland was discovered and that the bone pile in Vígishellir dated to the first centuries of Iceland's settlement, but their large standard deviations limited inferences regarding the eruption's date or the duration of human activity in the cave.

However, in 1988, Haukur Jóhannesson showed that the Hallmundarhraun's lava had flowed over the Landnám tephra layer (LNL), now dated in Greenland's ice cores to 877±1 AD (Grönvold et al. 1995; Batt et al. 2015; Schmid et al. 2017, 2018).[11] Its presence immediately beneath the lava demonstrated that the eruption began around the time of Iceland's settlement, leading Jóhannesson to suggest that the lava flowed shortly after 900 AD (Jóhannesson 1989:8).

Our work in 2001, 2012, and 2013 provided 16 new AMS dates on domestic animal bones and teeth from Vígishellir (n=11), Beinahellir (n=3), and the adjacent floor of Surtshellir's main tunnel (n=2), along with one AMS date on felt recovered deeper into Vígishellir, one on a fragment of candle wax from the wall of the cave in Vígishellir, and two on moss from the floor of the main tunnel near the massive stone wall.

3.2 CALIBRATING SURTSHELLIR

With the exception of the wax fragment, all of the radiocarbon samples came from short-lived (<1-8 years) taxa: *Bos* or ovicaprine bones and teeth, wool, and moss. $^{13}C/^{12}C$ ratios, obtained for all bone and tooth samples but K-1435, are consistent with values from terrestrial Icelandic herbivores (Ascough et al. 2014; Hayeur Smith et al. 2019), and combined with consistent nitrogen isotope ratios for three ovicaprid bones (Beta-359530, Beta-359535, and Beta-417367: +2.9 ‰, +2.9 ‰, +3.4 ‰, respectively) indicate that these animals fed on terrestrial grasses without seaweed fodder (Blanz et al. 2020). Given these results and the cave's location 55 kilometers from Iceland's coast, the dates were calibrated using OxCal v4.2.4 (Bronk Ramsey 2020) and the r:5 IntCal13 atmospheric curve (Reimer et al. 2013).

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[11] The "Landnám tephra layer" (LNL), found over much of Iceland, provides a robust geochronological horizon marker for the initial settlement of the country. Initially dated to 871±2 AD in Greenland's GRIP ice core (Grönvold et al. 1995), its subsequent identification in the GISP2 ice core led to two minor revisions of its age to 877±4 AD and, later, 877±1 AD (Baillie and McAneney 2015; Schmid et al. 2017, 2018; Sigl et al. 2015). Only a handful of archaeological features in southwestern Iceland have been found beneath the LNL (Roberts 2001, 2003; Schmid et al. 2018).

Lab number	Field number	Material	Location	Measured age	C^{13}/C^{12}	Conventional radiocarbon age	1 sigma calibration	2 sigma calibration
Beta-474884	Candle stub	Paraffin	**Vígishellir** above bone pile	22580±70	-28.0	22530±70	27027-26694 BC	27149-26545 BC
Beta-359357	Peat sample 3	Moss	**Main cave** before wall	106.6±0.4pMC	-23.1	106.2±0.4pMC	2005-2007 (68.3)	2004-2008 (93.5) 1956-1957 (1.9)
Beta-359356	Peat sample 2	Moss	**Main cave** before wall	127.0±0.5pMC	-23.9	126.7±0.5pMC	1980 (44.1) 1981 (24.1)	1979-1981 (85.6) 1962 (2.8) 1959 (7.1)
Beta-359529	2013-77-S122	Bone Ovicaprid	**Vígishellir** Wiii, near beads	100.7±0.3pMC	-23.0	100.4±0.3pMC	1954-1955 (68.3)	1954-1956 (95.4)
Beta-350954	2012-66-033	Felt	**Vígishellir** Deeper tunnel	101.0±0.4pMC	-16.0	70±30	**1879-1916** (36.4) 1817-1834 (13.1) 1699-1722 (18.7)	**1810-1924** (71.1) 1691-1730 (24.3)
Beta-359534	2013-77-S137	Bone Ovicaprid	**Surtshellir** main, below Beinahellir	920±30	-22.0	970±30	1138-1149 (8.4) **1088-1123** (31.4) 1021-1048 (28.3) ***1091***	**1016-1155** (95.4) ***1091***
OxA-37473	2013-77-384 #3	Bone *Ovis aries*	**Vígishellir** Grab sample N of structure		-21.1	981±28	1141-1147 (4.7) 1094-1120 (24.5) **1018-1046** (39.0) ***1063***	1077-1154 (47.4) 994-1055 (48.0) ***1063***
Beta-359758	2013-77-S125	Bone Ovicaprid	**Beinahellir** middle locus	950±30	-22.0	1000±30	1110-1116 (4.3) **993-1040** (63.9) ***1026***	1135-1152 (5.2) 1082-1128 (19.2) **983-1051** (71.0) ***1026***
K-1435	Laxness	Bone *Bos*	**Vígishellir,** bone pile, top?	1010±100		1010±100	**953-1156** (63.2) 901-921 (5.0) ***1026***	**776-1220** (94.5) ***1026***
Beta-359532	2013-77-S126	Tooth Ovicaprid	**Vígishellir** Uii, near beads	980±30	-22.0	1030±30	**989-1023** (68.3) ***1005***	1109-1116 (0.7) **962-1041** (91.9) 901-920 (2.8) ***1005***
Beta-359531	2013-77-S124	Bone Ovicaprid	**Beinahellir** deepest locus	980±30	-21.4	1040±30	**986-1021** (68.3) ***1000***	**951-1033** (90.2) 901-921 (5.2) ***1000***
Beta-359535	2013-77-S138	Bone *Bos*	**Surtshellir** main below Vígishellir	1020±30	-21.7	1070±30	**968-1016** (58.8) 905-916 (9.4) ***977***	**940-1021** (74.5) 895-928 (20.9) ***977***
Beta-380955	2013-77-S128	Bone Ovicaprid	**Vígishellir** Mi, near ingot	1020±30	-21.0	1090±30	**952-988** (44.4) 901-921 (23.8) ***957***	1008-1011 (0.6) **937-996** (59.9) 893-931 (34.9) ***957***
Beta-417367	2013-77-S131	Bone Ovicaprid	**Vígishellir** Div	1030±30	-20.8	1100±30	**944-985** (40.4) 898-925 (27.8) ***946***	**887-1013** (94.5) ***946***
Beta-359533	2013-77-S132	Bone Ovicaprid	**Vígishellir** Mi, near ingot	1060±30	-21.6	1120±30	**893-970** (68.3) ***930***	**863-995** (91.8) 826-841 (1.4) 809-815 (0.5) 778-790 (1.7) ***930***
Beta-338044	2012-66-030	Bone Ovicaprid	**Beinahellir** main pile	1110±30	-20.7	1180±30	853-887 (24.6) 801-847 (31.9) 777-793 (11.7) ***839***	921-951 (7.2) **769-901** (87.5) 730-736 (0.7) ***839***
AAR-7413	Surt-S2	Bone *Bos*	**Vígishellir** bone pile		-21.9	1197±36	**775-877** (68.3) ***826***	923-947 (3.8) **764-899** (82.9) 708-746 (7.9) 695-702 (0.7) ***826***
AAR-7412	Surt-S1	Bone *Bos*	**Vígishellir** bone pile		-20.8	1214±41	**769-880** (63.2) 727-737 (5.0) ***810***	929-939 (1.3) **685-895** (94.1) ***810***
OxA-37506	2013-77-275 #1	Bone Ovis aries	**Vígishellir** Aiv		-21.3	1189±27	**800-880 (57.2)** 778-793 (11.0) ***832***	928-940 (2.1) **768-895 (92.2)** 729-736 (1.0) ***832***
OxA-37505	2013-77-275 #1	Bone Ovis aries	**Vígishellir** Aiv		-21.5	1225±27	837-867 (19.2) 790-830 (25.8)	**762-884 (69.7)** 691-748 (25.7)

							767-779 (9.1) 721-741 (14.1) ***798***	***798***
Beta-359530	2013-77-S123	Bone	**Vígishellir** Dii, NW corner	1210±30	-21.9	1260±30	*761-770* (8.9) *690-751* (59.3) ***733***	*838-865* (4.2) *791-829* (5.9) 669-779 (85.3) ***733***
H2453-1857*	Sæmundsson	Charcoal	**Beneath lava and LNL**	1190±100	--	1190±100	919-965 (12.9) **765-903** (46.5) 713-744 (8.8)	**662-1016**

Table 1: Calibrated radiocarbon dates from Surtshellir and the Hallmundarhraun, prior to Bayesian analysis. Boldface figures within the last two columns identify the internal peaks with highest probability within each calibrated date's 1-sigma (68.4%) and 2-sigma (95.4%) probability ranges. Red numbers identify date ranges within individual samples' internal probability distributions that pre-date the 877±1 AD "Landnám tephra" layer found beneath the Hallmundarhraun lava field; single numbers in bold italics identify median dates for each calibrated sample.

Two samples (Beta-359356 and Beta-359357) from the base of a moss deposit on the main tunnel's floor adjacent to a massive area of roof collapse produced post-bomb carbon values indicating that growth began there late in the 20th century as year-round snow drifts and "ice lakes" described at this location by 19th and early 20th century explorers melted away. In 1674 Þorkell Arngrímsson noted a small hole forming in the ceiling here (Arngrímsson 1979) and these dates suggest, with Arngrímsson's account, that the cave was roofed until the post-medieval period. During the Viking Age, therefore, travel into Surtshellir's deeper recesses would have been undertken in total darkness.

Three of the dates document 18th-20th century visits: a felt insole (Beta-350594) from the 18th-19th centuries, a partially cooked sheep bone (Beta-359529) from the mid-1950s, and a candle stub with a date of 22,580±70 bp (Beta-474884), indicating that it was made from petrochemicals. Parafin candles were first produced in the 1850s but only became widely available after the 1890s. No dates or archaeological specimens from the cave can be assigned to the period 1100-1670.

Fifteen dates from Vígishellir, Beinahellir, and Surtshellir's main tunnel span the 10th and early 11th centuries AD. Split samples from a single sheep bone (OxA-37505 and OxA-37506) were merged using OxCal's R_Combine function before being integrated into further analyses as OxA-37505/37506 (1207±20 bp). After calibration, the fourteen resulting dates, run by four independent labs (University of Copenhagen, Aarhus University, Beta Analytic, and Oxford), are consistent with typological assessments of the ages of the artifacts recovered from the structure inside Vígishellir.

However, one date (Beta-359530) on a fragment of medium terrestrial mammal bone from Vígishellir, is a clear outlier with 1- and 2-sigma calibrated ranges that predate the age of the Landnám tephra. Its $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios are consistent with others from the site and do not suggest post-deposition contamination. Recent research has documented that freshwater reservoir effects in some parts of Iceland produce radiocarbon ages much older than their tephra-constrained ages, due to dietary uptake of plants, animals, or surface water enriched with ancient carbon from volcanic sources (Sayle et al. 2016). If this bone came from an animal raised in such an area, isotopic studies might provide insights into the distances across which animals were transported to the cave. However, given that the cave formed after 877 AD, and in the absence of analyses to resolve this issue, Beta-359530 was excluded from further analyses as an outlier.

3.3 Refining Surtshellir's Chronology Through Bayesian Analysis

Bayesian statistical analyses, using functions in OxCal v4.2.4 (Bronk Ramsey 2009, 2017, 2020), were employed to refine the site's chronology and assess interconnected questions regarding the relationships of the activities undertaken in the cave to the timing of the Hallmundarhraun eruption, Iceland's conversion to Christianity, and the site's alternate origin stories. Focusing on these three issues provided frameworks for assessing when the Hallmundarhraun eruption took place, when people entered the cave, the span of time over which bones were brought to the cave, whether bone piles in different parts of the cave were created simultaneously or sequentially, and whether the termination of these activities coincided with Iceland's conversion.

Bayesian modeling allowed pre-existing knowledge about the site's geological context, tephrochrological dates, and historical records to be integrated with its radiocarbon sequence (Bayliss 2009; Otárola-Castillo and Torquato 2018), creating posterior information in the form of Highest Probability Density ranges (HPDs) to help constrain, narrow, or refine interpretations about the site's radiocarbon data set (Bayliss 2009). Although Surtshellir's archaeological deposits were too thin to create a stratigraphic model, a sequence model with five phases was developed for the site as a whole by integrating existing knowledge about the relative ages of dated samples beneath the lava and the lava flow itself with dates from inside the cave and medieval and post-medieval descriptions of it. The boundary between Phases 1 and 2 relies on tephrochronology, the boundary between Phases 2 and 3 relies on the distribution of AMS dates and inferences from volcanological research about the eruption's potential duration, while the boundaries between Phases 3, 4, and 5 rely on AMS dates and texts relating to the dates of Iceland's conversion and the first pre-modern description of the site.

Phase 1 represents the period prior to the Hallmundarhraun eruption. Kristján Sæmundsson's (1966) date on peat beneath the lava and the LNL's date of 877±1 AD were included in Phase 1 to set a *terminus post quem* for the start of the Hallmundarhraun eruption.

Phase 2 represents the eruption itself and the time required for the cave to cool down enough for people to enter it. The Hallmundarhraun eruption is not described directly in any historical sources and current estimates of the eruption's age range from shortly after AD 900 (Jóhannesson 1989; Sinton et al. 2005) to ca. AD 930-940 (Hjartarson 2014, 2015) and ~950 AD (Thordarson and Larsen 2007). Since this was an effusive eruption whose geochemical signature has not yet been identified in Greenland's dated ice cores, Bayesian analysis was employed to define a window within which the eruption could have taken place, using the LNL and the dates from inside the cave.

Different estimates of shield volcanoes' lava production rates suggest that the eruption could have lasted as long as 16-54 years or as little as 4.5 years. Estimating the time required for a cave of its size to cool down enough to enter safely (<40°C) is difficult due to a paucity of relevant studies. When analyzing the potential for generating energy from residual heat inside lava produced by the 1973 Heimaey eruption, Sveinbjörn Björnsson calculated that lava flows 20 meters thick would become too cold for energy generation (<100°C) after 12.5 years, although the earth beneath them would still be 190°C, and noted that geologists used the mouths of caves as saunas on the island of Surtsey more than two decades after its 1961 eruption (Björnsson 1987). Since the lava surrounding Surtshellir is at least 20-25 meters thick, Björnsson's observations suggest it could have remained too hot to enter for 10-15 years after the eruption ended. We used an estimate of 30±5 years for the time required for the lava to flow and cool sufficiently and 880 AD as the earliest date that lava could have flowed near the cave to establish a theoretical date (910±5 AD) employed in some models to constrain the end of Phase 2 and initiate Phase 3.

Phase 3 represents the period of Viking Age activities in Vígishellir, Beinahellir, and Surtshellir. To assess whether these activities ended as a result of of Iceland's conversion to Christianity, or was independent of that process, a constraint was incorporated into some models reflecting the time when pre-Christian rituals were to be abandoned following Iceland's conversion in AD 1000. Both *Íslendingabók* (AD 1122-1133) and *Kristni Saga* (13th century) state that sacrifices to the Norse gods were allowed to continue out of sight for some time after the Conversion and *Heimskringla* (13th century) suggests that such practices were banned after 1016 (Sturluson 1945:77, Sturluson 1964:292) but this date is not attested in other medieval sources. To avoid a sense of spurious accuracy, a date of AD 1020±15 – approximately one generation after the conversion – was integrated into Phase 4 in some models to constrain the end of Phase 3. Other models incorporated this date within Phase 3 to assess how much later the modeled period of activity in the cave would extend if this date was not used as a *terminus ante quem*.

Phase 4 represents the period during which historical records suggest the cave was abandoned. Aside from the description of the chieftain Órækja Snorrason's mutilation inside Surtshellir in 1236 (McGrew 1970; Thorsson 1988), no historical sources or artifacts suggest Surtshellir was visited between the Viking Age and the Early Modern period.

Phase 5 represents the Early Modern, Modern, and Contemporary periods during which explorers, tourists, and others returned to the cave. Since Þorkell Arngrímsson's 1674 description of Surtshellir's interior is the earliest known account of its investigation, we incorporated the date 1674±1 into the start of Phase 5 to constrain the end of Phase 4.

3.4 Defining the Models

These five phases were used to create a basic sequence model constrained only by the LNL and Arngrímsson's 1674 account (Model 0). Four refinements to the model (Models 1-4) were then developed by integrating variable constraints for the end of the Hallmundarhraun eruption and Iceland's conversion to Christianity (Table 2). These allowed correspondences to be examined between modeled date sequences, phase boundaries, phase durations, and individual dates' ranges under four alternative models defined by the presence or absence of both primary and variable constraints.

The primary constraints incorporated into all of the models were:

(1) the date of the Landnám tephra (877±1) in Phase 1, setting a *terminus post quem* for Phase 2.
(2) the date of Arngrímsson's description of the cave (1674±1) in Phase 5, setting a *terminus ante quem* for Phase 4.

The variable constraints were:

(3) the estimated date for the end of the Hallmundarhraun eruption (910±5 AD), included at the end of Phase 2 in Models 2 and 4 to impose a constraint consistent with the eruption taking 30±5 years to flow and cool down. This was not incorporated into Models 1 and 3 to assess when the models would independently initiate Phase 3 in the absence of any prior constraints.
(4) the estimated date (1020±15 AD) after which pre-Christian rituals would not have been tolerated, included at the start of Phase 4 in Models 3 and 4 to constrain Phase 3. This was folded into Phase 3 in Models 1 and 2 to allow their HPDs to establish Phases 3 and 4 independently.

	Eruption end not set	**Eruption end set**
Conversion date not set	Model 1	Model 2
Conversion date set	Model 3	Model 4

Table 2: The four models, defined by two variable constraints on dates from Phases 2-5.

4. Results

Our base model (Model 0), run without any constraints except the Landnám tephra (877±1 AD) and Arngrímsson's visit (1674±1 AD), used all 14 AMS and standard dates from Phase 3, with the proxy date for the end of pre-Christian rituals incorporated into Phase 3. Model 0 yielded marginally acceptable levels of agreement between the radiocarbon dates and prior information (A_{model} = 67.6; $A_{overall}$ = 60.7, where A ≤ 60 is rejected), suggesting that activity began within Surtshellir circa *calAD 873-897* (68.3%, or *calAD 873-933* at 95.4%; median, *calAD 883*) and ended circa *calAD 1028-1057* (68.3%), with a median date for the start of Phase 4 at *calAD 1045* (Table 3).[12] Phase 3's duration was estimated at *131-186* years (68.3%; *93-224* years, 95.4%; median, *159* years), after which the cave was abandoned and avoided for more than 600 years.

However, Model 0 provided very little time between the LNL and the start of Phase 3 for the eruption to have taken place because three of the earliest dates from the site, all from well-excavated contexts, had very low rates of correspondence with the model. These included two samples (AAR-7412 and AAR-7413) from the base of the bone pile in Vígishellir and one (OxA-37505/37506) from the crushed basalt pad on the floor of the boat-shaped structure.

Parameter	Base Model (Model 0)
	- Eruption phase - Conversion Early dates out: 2013-77-S123 (outlier)
# dates for VA	14 + conversion
Passes	878,000
A_{model}	66.7
$A_{overall}$	62.8
Boundary, start Phase 1	*833-880* (1s) *654-883* (2s) ***863***
Boundary, Phase 2 (eruption) / Phase 3 (VA use)	*874-883* (1s) *870-929* (2s) ***879***
Duration of Phase 3: Interval (1s)	 *147-183* yrs

[12] In accordance with current protocols, Bayesian *modeled* dates and estimates are given in italics throughout.

Interval (2s) median	*109-238* yrs ***166***
Boundary, Phase 3 (VA use) / Phase 4 (abandonment)	*1028-1059* (1s) *1019-1110* (2s) ***1046***
Dates with poor correspondence to the model	AAR-7413 = 48.9 AAR-7412 = 41.9 OxA-37505/37506 = 37.3

Table 3: Base model for Surtshellir's Phase 3 dates, incorporating all 14 radiocarbon dates and the proxy date for the end of pre-Christian rituals included, without any constraints except for the LNL tephra at the end of Phase 1 and the date of Thorkell Arngrímsson's visit in 1674 at the start of Phase 5. Median dates in bold italics.

To assess these three dates' roles on the model's performance, the samples with the lowest correspondence were removed sequentially until Model 0's A_{model} and $A_{overall}$ indices exceeded 70.0. After the removal of two dates (OxA-37505/37506 and AAR-7412) the revised model had significantly improved indices of agreement (A_{model} = 79.8, $A_{overall}$ = 77.3) and, having neither constraints for the eruption nor for the conversion, this became Model 1, the first of the four models in Table 2.

Model 1 provided a window of 53-76 years between the start of the eruption and the beginning of Phase 3 (*calAD 875-931*, 68.3%; *calAD 873-948*, 95.4%) – long enough to accommodate theoretical estimates of 16-54 years for the eruption and a maximum cool-down period of 12-15 years. Phase 3 was estimated to have begun before *calAD 931* (median estimate, *calAD 904*) and to have ended in the mid-11th century (*calAD 1027-1060*, 68.3%; *calAD 1018-1120*, 95.4%; median, *calAD 1046*), implying that bones were deposited in the cave for at least 68 years, with a median estimated duration of *148* years.

In **Model 2**, the estimated prior date for the end of the eruption and its cool-down period (910±5 AD) was included as a constraint for the start of Phase 3, but no constraints were used for its end. The same dates (OxA-37505/37506 and AAR-7412) had to be removed to achieve comparable levels of agrement (A_{model} = 71.7, $A_{overall}$ = 70.7). Model 2 placed the beginning of the eruption between *calAD 878* and *calAD 906* (68.3%; *calAD 875-913*, 95.4%; median, *calAD 894*), and suggested that people could have entered the cave by *calAD 923* (*calAD 909-934*, 68.3%; *calAD 902-952*, 95.4%). The duration of the eruption and cool-down phase was estimated at *7-74* years (68.3%; *0-63*, 95.4%) with a median of *30* years. Phase 3 ended before *calAD 1043* (*calAD 1027-1055*, 68.3%; *calAD 1016-1098*, 95.4%), with its duration estimated at *97-141* years (68.3%; *71-179* years, 95.4%; median, *121* years).

Model 3 removed the pre-set eruption phase but incorporated the model's date (1020±15) for the abolishment of pre-Christian sacrifices at the start of Phase 4. This model only achieved comparable levels of agreement (A_{model} = 80.3; $A_{overall}$ = 81.3) after the three earliest dates (OxA-37505/37506, AAR-7412, AAR-7413) were removed, leaving 11 AMS and standard dates to inform the model. Model 3 produced a median estimate for the start of human activity in Surtshellir at *calAD 922*, leaving a 40-45 year window for the eruption and the cave's cooling. Phase 3 was estimated to have lasted a bit more than a century (median, *111* years; *83-151* years, 68.3%; *56-125* years, 95.4%) and to have ended before *calAD 1031* (*calAD 1022-1041*, 68.3%; *1006-1052*, 95.4%).

Finally, **Model 4** constrained both the start and the end of Phase 3 by incorporating the models' dates for both the end of the eruption phase and for the legal abolishment of pre-Christian rituals. This model also only achieved comparable levels of agreement (A_{model} = 78.8, $A_{overall}$ = 79.5) after the three earliest dates in the sequence were removed. Model 4 suggested that Phase 3 began before *calAD 931* (*calAD 910-946*, 68.3%; *calAD 905-966*, 95.4%) after an eruption and cool-down phase of *13-63* years (68.3%; *0-93*, 95.4%; median, *41* years). Phase 3 was estimated to have ended before *calAD 1031* (*calAD 1022-1041*, 68.3%, *calAD 1008-1051*, 95.4%), implying that bones continued to be carried into Surtshellir for 80-120 years.

All models concurred that the cave was abandoned for nearly 650 years after Phase 3 ended. Their results are summarized in Table 4.

Parameter	Model 1	Model 2	Model 3	Model 4
	- Eruption phase - Conversion Early dates out: 2013-77-S123 OxA-37505/37506 AAR-7412	+ Eruption phase (910±5) - Conversion Early dates out: 2013-77-S123 OxA-37505/37506 AAR-7412	- Eruption phase + Conversion (1020±15) Early dates out: 2013-77-S123 OxA-37505/37506 AAR-7412, -7413	+ Eruption phase (910±5) + Conversion (1020±15) Early dates out: 2013-77-S123 OxA-37505/37506 AAR-7412, -7413
# dates included for Phase 3	12 + conversion	12 + conversion	11	11
Passes	911,000	1,837,000	860,000	4,116,000
A_{model}	79.8	71.7	80.3	78.8
$A_{overall}$	77.3	70.7	81.3	79.5
Boundary, start Phase 1	*796-880* (1s) *564-883* (2s) ***840***	*817-880* (1s) *640-883* (2s) ***850***	*804-880* (1s) *612-883* (2s) ***842***	*830-880* (1s) 686-881 (2s) ***855***
Boundary, Phase 1 / Phase 2 (eruption)		*878-906* (1s) *875-913* (2s) ***894***		*877-903* (1s) *875-912* (2s) ***893***
Duration of Phase 2 Interval (1s) Interval (2) Median		 *7-47* *0-63* ***30***		 *13-63* *0-93* ***41***
Boundary, Phase 2 (eruption) / Phase 3 (VA use)	*875-931* (1s) *873-948* (2s) ***904***	*909-934* (1s) *902-952* (2s) ***923***	*877-951* (1s) *875-963* (2s) ***922***	*910-946* (1s) *905-966* (2s) ***931***
Boundary, Phase 3 (VA use) / Phase 4 (abandonment)	*1027-1060* (1s) *1018-1120* (2s) ***1046***	*1027-1055* (1s) *1016-1099* (2s) ***1043***	*1023-1042* (1s) *1009-1052* (2s) ***1032***	*1022-1043* (1s) *1008-1051* (2s) ***1031***
Duration of Phase 3: Interval (1s) Interval (2s) median	 *99-181* yrs *68-252* yrs ***148***	 *97-141* yrs *71-179* yrs ***121***	 *83-151* yrs *56-165* yrs ***111***	 *82-123* *0-137* ***98***
Boundary Phase 4/5			*1026-1678* (1s) *1023-1679* (2s)	*1025-1677* (1s) *1022-1677* (2s)
Dates with poor agreement (< 60.0)	2012-66-030 = 40.5 AAR-7413 = 28.9	2012-66-030 = 32.5 AAR-7413 = 21.7	2012-66-030 = 32.3	2012-66-030 = 27.3

Table 4: Outcomes of the final four models. Modeled dates and ranges in italics; bold italics identify median dates.

5. Discussion

Bayesian analyses of Surtshellir's radiocarbon and tephrochronological dates provide far better control over the site's chronological contexts than we had after the 2001 investigations and require revisions to our initial interpretations of the site. The four models were, overall, consistent and robust regardless of which constraints were introduced, confirming the coherence of the underlying suite of dates. Boundaries, ranges, and median dates for Phases 2, 3 and 4 were rarely more than 15-30 years apart, regardless of which model was run. Multiple iterations of each model produced consistent results and while removing dates with correspondence <60.0 improved the models' A_{model} and $A_{overall}$ indices this ultimately effected only minor changes to the phases' boundaries, dates, or duration.

Table 5 documents overall consistency in the models' median dates for the boundaries of Phases 2, 3, and 4 and for the duration of Phase 3. As expected, Models 2 and 4, incorporating prior dates for the eruption's end, produced later dates for the Phase 2/Phase 3 transition, while Models 3 and 4, which constrained the end of Phase 3 suggested earlier dates for the end for Phase 3. Without any constraints, Model 1 provided the widest estimates. Overall, however, the differences are minor: two models suggest that people entered the cave during the second decade of the 10th century; the others are slightly earlier or later. All models suggest that activity stopped inside the cave by the second quarter of the 11th century.

	Without Eruption end set	**With Eruption end set (910±5 AD)**
Without Conversion date set	Phase 2/3 boundary: **904** Phase 3/4 boundary: **1046** Duration of Phase 3: **148** **Model 1**	Phase 2/3 boundary: **923** Phase 3/4 boundary: **1043** Duration of Phase 3: **121** **Model 2**
Conversion date set (1020±15 AD)	Phase 2/3 boundary: **922** Phase 3/4 boundary: **1032** Duration of Phase 3: **111** **Model 3**	Phase 2/3 boundary: **931** Phase 3/4 boundary: **1031** Duration of Phase 3: **98** **Model 4**

Table 5: Comparison of estimated median dates for the initiation, end, and duration of Phase 3 under each of the four final models.

Model 3, which had the highest agreement scores among the four models, forms the basis for most of the following illustrations, with information from other models integrated as needed to explore variability in the discussion of results. Figure 6 graphically represents the highest probability distributions for all of the dates from Phases 1-5, as defined by Model 3. Table 6 provides one- and two-sigma HPDs for the dates from Phase 3, based on Model 3.

Lab number	Field number	Location	Model 3 1 sigma	Model 3 2 sigma	Agreement with model
Phase 3 / Phase 4 Boundary			*1023-1042 (68.3)* ***1032***	*1009-1052 (95.4)* ***1032***	
Beta-359534	2013-77-S137	**Surtshellir** main, below Beinahellir	*1015-1037 (68.3)* ***1024***	***991-1041*** *(95.4)* ***1024***	93.2%
OxA-37473	2013-77-384 #3	**Vígishellir** Grab sample N of structure	*1013-1035 (64.9)* *999-1002 (3.3)* ***1022***	*990-1040 (95.4)* ***1022***	112.5%
Beta-359758	2013-77-S125	**Beinahellir** middle locus	*995-1029 (68.3)* ***1014***	*985-1037 (95.4)* ***1014***	122.7%
Beta-359532	2013-77-S126	**Vígishellir** Uii, near beads	*990-1021 (68.3)* ***1003***	*967-1032 (95.4%)* ***1003***	106.5%
Beta-359531	2013-77-S124	**Beinahellir** deepest locus	*987-1019 (68.3)* ***1000***	*953-1031 (95.4%)* ***1000***	105.6%
K-1435	Laxness	**Vígishellir,** bone pile, top?	*963-1028 (68.3)* ***989***	*907-1038 (95.4)* ***989***	124.9%
Beta-359535	2013-77-S138	**Surtshellir** main below Vígishellir	*967-1015 (68.3)* ***984***	*939-1022 (88.5)* *903-926 (6.9)* ***984***	107.4%
Beta-380955	2013-77-S128	**Vígishellir** Mi, near ingot	*943-998 (68.3)* ***970***	*903-1017 (95.4)* ***970***	102.0%
Beta-417367	2013-77-S131	**Vígishellir** Div	*939-993 (68.3)* ***965***	***903-1012*** *(95.4)* ***965***	101.0%
Beta-359533	2013-77-S132	**Vígishellir** Mi, near ingot	*936-984 (68.3)* ***957***	*895-994 (95.4%)* ***957***	104.6%
Beta-338044	2012-66-030	**Beinahellir** main pile	*928-968 (68.3)* ***944***	***917-982*** *(87.9)* *881-900 (7.6)* ***944***	32.3%
Phase 2 / Phase 3 Boundary			*906-951 (50.8)* *877-892 (17.5)* ***922***	*875-963 (95.4)* ***922***	

Table 6: Phase 3 dates, with ranges redefined under Model 3. Boldface text in "Location" column identifies the principal segment of the cave system from which the samples were recovered, followed by excavation unit (e.g. Uii). Internal probabilities under each modeled date's 1-sigma (68.3%) and 2-sigma (95.4%) curves are shown; as in previous tables, bold italic numbers identify median dates.

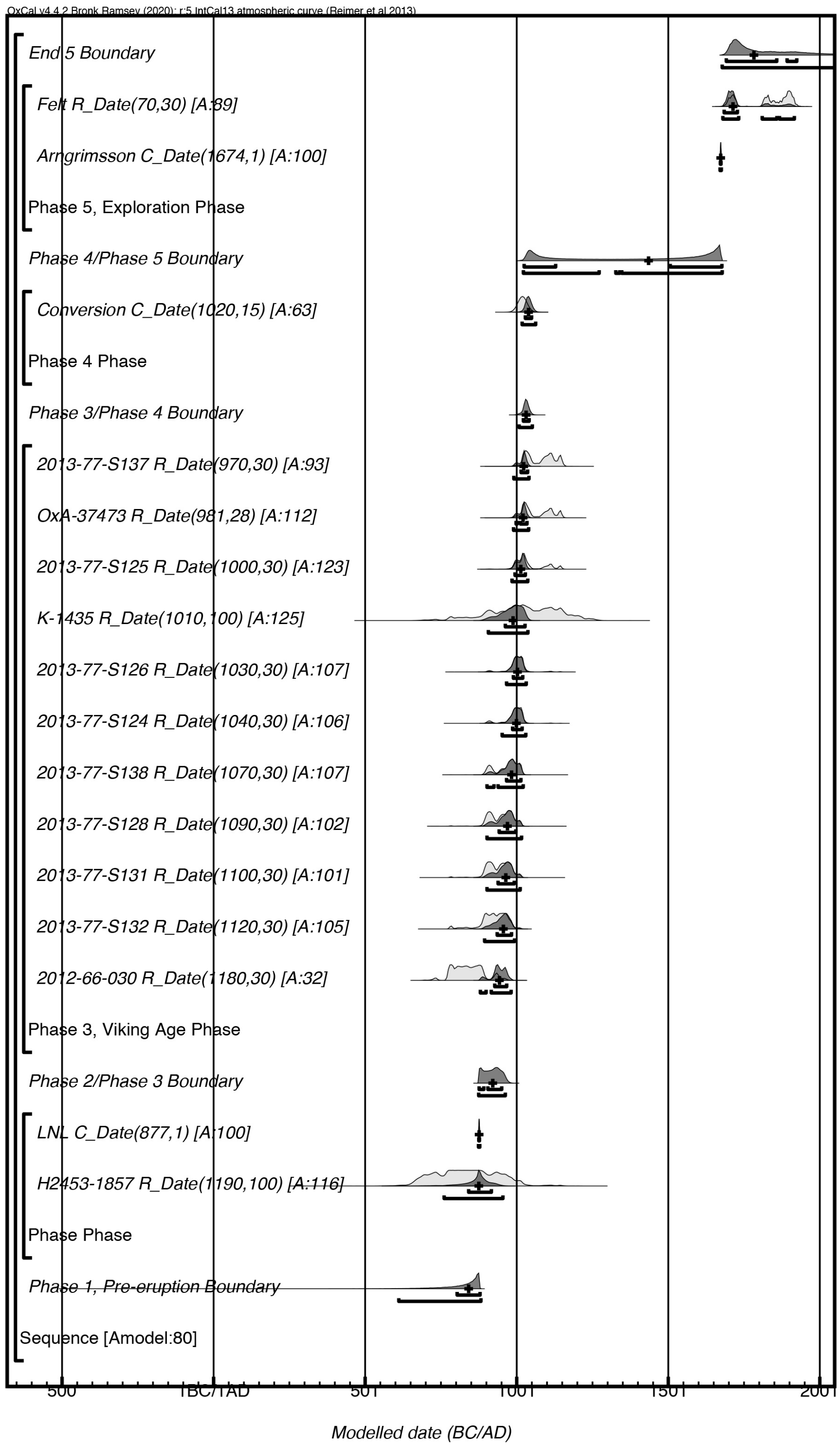

Figure 6: Surtshellir's calibrated dates and boundaries under Bayesian Model 3. Gray outlines show probability distributions for each calibrated sample (R_Date) or calendric date (C_Date) in the model; dark-shaded zones are the recalibrated HPDs. Bars beneath each curve identify 1-sigma (68.3% probability) 2-sigma (95.4% probability) ranges, and median dates (crosses) for each modeled date. Brackets at left margin document the model's structure. Comparable graphic representations for Models 0, 1, 2, 3, 4 are provided as Supplementary Material for this article.

IMPLICATIONS OF THE MODELS

5.1 The Hallmundarhraun Eruption: Tephrochonological dating indicates that the eruption began after AD 877 while Model 3 suggests that people may have entered the cave by *calAD 922*. Model 2, which included the 910±5 AD prior estimate for the end of the eruption, produced a nearly identical date (*calAD 923*) for the Phase 2/3 transition. If cool-down took 12 years, the eruption would have begun around 880 and ended around 910; if it cooled faster the eruption may have begun in the first decades of the 10th century, ending shortly before AD 920. All of the models confirm that the Hallmundarhraun eruption took place within the first decade(s) after the Norse arrived in Iceland and most likely ended before 930 AD, as Jóhannesson suggested based on his stratigraphic analyses of the Landnám tephra's position beneath the lava field (Jóhannesson 1989; Sinton et al 2005).[13] All of the models imply that the Hallmundarhraun eruption would have been one of the first, if not the first, volcanic event that Iceland's Norse settlers witnessed and the first major effusive eruption directly witnessed by northern Europeans.

5.2 The settlement of Iceland: Surtshellir's dates contribute to ongoing debates about the age of Iceland's settlement. Several sites in Iceland have produced calibrated dates 200-300 years older than tephrochronological or typological indicators would suggest for the contexts dated, leading to arguments that Iceland's settlement occurred around 700-750 AD (Hermanns-Audardóttir 1991; Hermanns-Auðardóttir 1992; Theodórsson 1998, 2009). Four of Surtshellir's dates (Beta-338044, AAR-7412, AAR-7413, OxA-37505/37506) had 2-sigma ranges extending back into the late 7th century, but since the cave hadn't formed until after the Landnám tephra fell in 877±1 AD, the earlier part of these dates' calibration curves can be dismissed with great confidence.

Paired dates on animal bones and charcoal from Víðgelmir cave, 5 km west of Surtshellir in the Hallmundarhraun (Ólafsson 1998), confirmed that dates on charcoal from early Icelandic sites can be problematic due to settlers' use of old wood from bogs or from forests and driftwood on beaches that had never been harvested (Smith 1995:324–326; Sveinbjörnsdóttir 2010; Vilhjálmsson 1991:171–172). The dates from Surtshellir demonstrate that a centuries-long plateau in the radiocarbon calibration curve extending from calAD 790-880, with flanking reversals at calAD 730-790 and calAD 880-940 (Figure 7), also limits the value of using terrestrial mammal bones to date sites from the time of Iceland's settlement, at least in the absence of Bayesian analyses incorporating tephrochronological constraints or datable objects such as coins (Manning et al. 2020; Schmid et al. 2017, 2018; Sveinbjörnsdóttir et al. 2004; Theodórsson 1993).

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[13] Jóhannesson assigned the eruption to the first decades of the 10th century based on the lava's position relative to the Landnám tephra, then dated to AD 900, in his soil profiles (Jóhannesson 1989:6). Thordarson and Larsen (2007) assigned the eruption to ~950 AD, presumably based on an estimate of the time required for a 0.3-0.5 cm layer of silt to accumulate in some of Haukur Jóhannesson's profiles between the Landnám tephra layer and the base of the lava. Hjartarson (2015) dated the eruption to AD 930-940 on the assumption that a reference to a burning glacier in the 13th century poem *Hallmundarkviða*, which he otherwise feels describes the Hallmundarhraun eruption (Hjartarson 2014), must have been seen by the poet during the Eldgjá eruption (ca. 934 or 939, Oppenheimer et al. 2018).

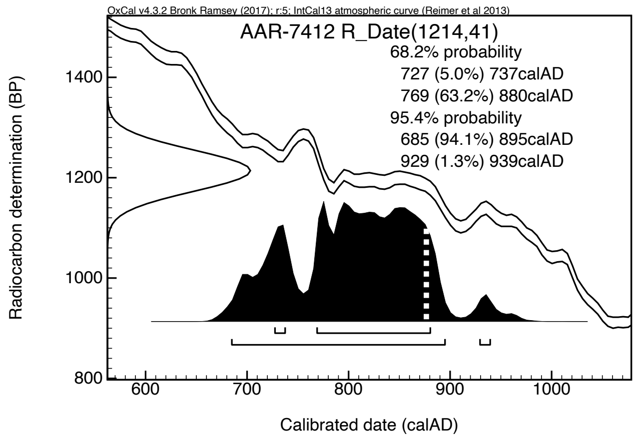


Figure 7: Probability distribution for sample Surts-S1 (AAR-7412) prior to Bayesian analysis, illustrating the effect of the plateau in the calibration curve between calAD 790-880, and its two flanking reversals (calAD 730 - 790 and calAD 880-940). The dotted white line at AD 877±1 represents the age of the Landnám layer (LNL) beneath the Hallmundarhraun. The earlier portions of the sample's probability curve, extending from calAD 685-877, as well as two apparent zones of low probability between calAD 737-769 and calAD 895-929 are artifacts of the plateau and reversals in the calibration curve rather than evidence of occupation of the cave before its formation, post-877 AD or of lower frequencies of the bone deposition, calAD 895-929.

5.3 Surtshellir in the Viking Age: The modeled dates from Phase 3 form a coherent sequence that spans the 10th through early 11th centuries AD rather than clustering into sub-phases suggestive of episodic or short-term uses. The dates at the ends of this sequence (AAR-7413 and Beta-359534) are not equivalent at any statistically meaningful confidence level (X^2 t-test; T=23.577, 1 df). However, temporally adjacent dates are statistically equivalent and overlap their neighbors, indicating that this sequence reflects activities recurring regularly over a span of at least 50-60 years and probably more than a century.

While Models 2 and 3 suggest that Phase 3 began around *calAD 922-923*, either two or three of the earliest dates (OxA-37505/37506, AAR-7412, AAR-7413) from the cave had to be removed from each of the models to obtain indices of agreement greater than 70.0. Two of these samples (AAR-7412, AAR-7413) were excavated from the base of the bone pile in Vígishellir while the third (OxA-37505/37506) came from the crushed basalt pad on the floor of the adjacent structure. Given their contexts, these dates are extremely important for understanding the site's chronology. As Figure 7 shows, their lack of correspondence with the models is due to their intersection with the centuries-long plateau on the atmospheric calibration curve described above. Before Bayesian modeling, their median calibrated C14 ages were 11-29 years older than Beta-338044 (which could be incorporated into all four models), and the calibrated median of OxA-37505/37506 was nearly identical to that of AAR-7413, which could be incorporated into Models 1 and 2 with median age estimates of *calAD 937-942*. Since AAR-7412 and OxA-37505/37506's calibrated C14 ages were 10-30 years earlier than AAR-7413 and Beta-338044, it is likely that they document that bones began to be left inside Surtshellir during the 930s or possibly the 920s.

The models' median estimates of Phase 3's duration range from *98-148* years, with an average estimate of 120 years. This is too long for Surtshellir's archaeological record to be attributed solely to outlaws' activities. Few of the many outlaws described in Iceland's medieval sagas survived more than five years and Grettir Ásmundarson, the outlaw said to have survived longest, stayed in few places more than a few years or seasons during his 25 year outlawry (Scudder 2005). Information about outlaw bands is even less common. The *Saga of Hord and the Hólmverjar* describes a large band who survived for two years on an island before they were defeated, after which seven fled to an unnamed cave in the Hallmundarhraun (Hreinsson 1997). No sagas suggest that outlaw bands were tolerated for more than a few months or years. These sources, written 200-300 years after the events they describe, cannot be considered literal accounts but indicate that medieval Icelanders accepted 25 years as an extreme limit for outlaws' survival and that outlaw bands were a threat to be eliminated quickly. While Phase 3's duration is inconsistent with an archaeological record attributed solely to outlaws' activities, a brief occupation similar to that documented in Víðgelmir (Ólafsson 1994, 2000, 2004) could potentially fit into Phase 3 without being easily identifiable within Surtshellir's assemblage.

5.4 Spatio-temporal patterning within Surtshellir: All of our models indicate that the actions responsible for the unique assemblages in Vígishellir, Beinahellir, and the Surtshellir's main tunnel spanned several generations. This not only implies that new caretakers had to be trained to maintain the site and its practices in the decades after the site was established, but also that one or two new generations of officiants would have had to be instructed in how, where, when, and why to undertake these activities within the cave. The seven piles of fragmented domestic animal bones are among the most archaeologically visible components of those activities, and the spatial patterning of dates from these piles and Vígishellir's structure provides insights into the site's development (Figure 8).

Vígishellir, Beinahellir, and Surtshellir's main tunnel were clearly components of a single site, yet each segment was characterized by a different depositional sequence. The earliest dates are from the crushed basalt pad on the floor of the structure in Vígishellir (OxA-37505/37506) and the base of the adjacent bone pile (AAR-7412, AAR-7413). Vígishellir's continuous sequence of dates, its spatially concentrated assemblage of material culture, and its specially built structure indicates that it was the primary focus of activity in the cave from the late 10th through the early 11th centuries. However, Beinahellir's dates are statistically equivalent to those from Vígishellir, indicating that bones were added to both side caves simultaneously from the beginning until the end of the cave's use. Here, four smaller piles of bones were created, possibly sequentially, in a line from the passage's mouth into its depths, yet no structures were built, no bones were burned, no fires were made, and no material culture was deposited in Beinahellir. Dates from the two concentrations of bone on the floor of Surtshellir's main passage, on the other hand, fall close to the time the site was abandoned, suggesting that an effort was made to complete a line of bone deposits stretching 120 meters from the structure inside Vígishellir into the deepest part of Beinahellir before the cave was abandoned.

5.5 Christianity, Conversion, and the end of the Viking Age in Iceland: All four models indicate that bones began to be piled inside Surtshellir, that Vígishellir's boat-shaped structure was built 60-80 years before Iceland's conversion to Christianity, and these activities continued uninterrupted through the 10th century and for at least two decades after Iceland's conversion. All four models' median dates indicate that the site was closed or abandoned before *calAD 1030-1045*; and incorporating a constraint of 1020±15 at the start of Phase 4 only shifted the median dates for the Phase 3/Phase 4 boundary by a decade or so.

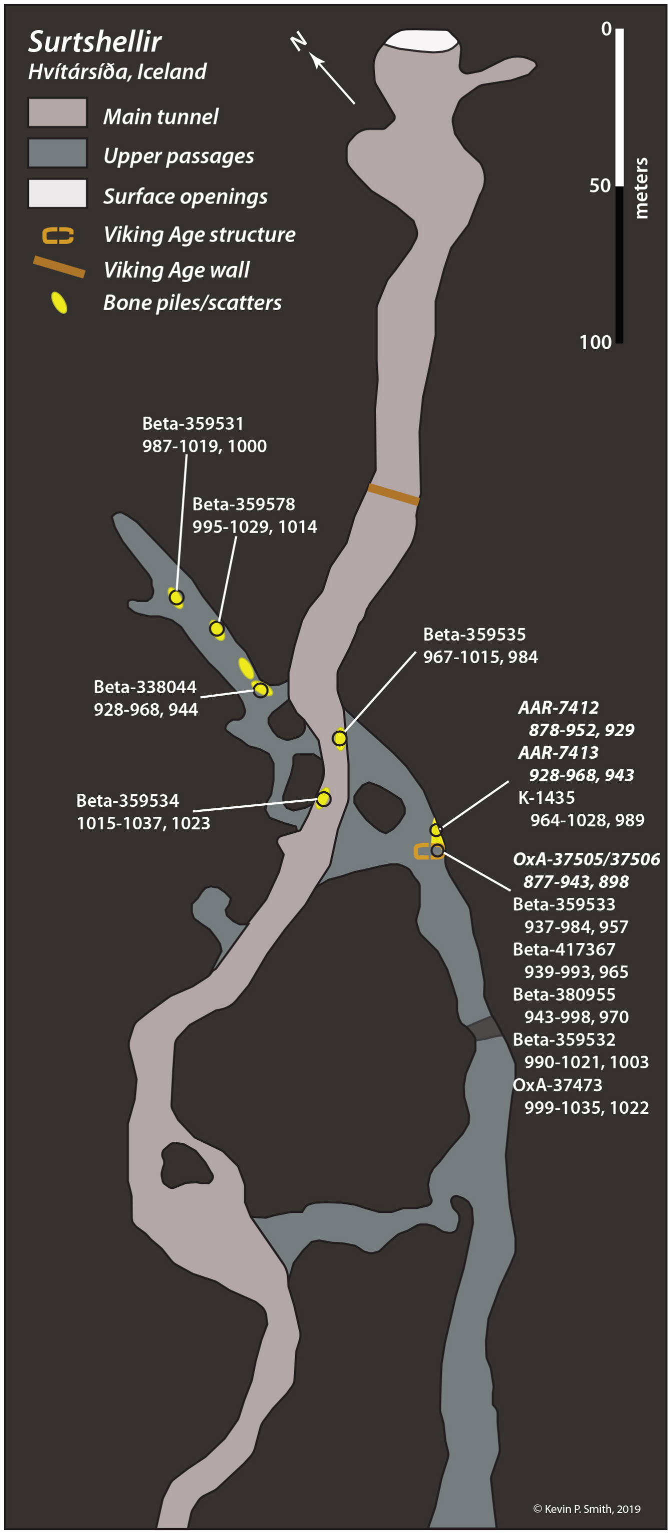
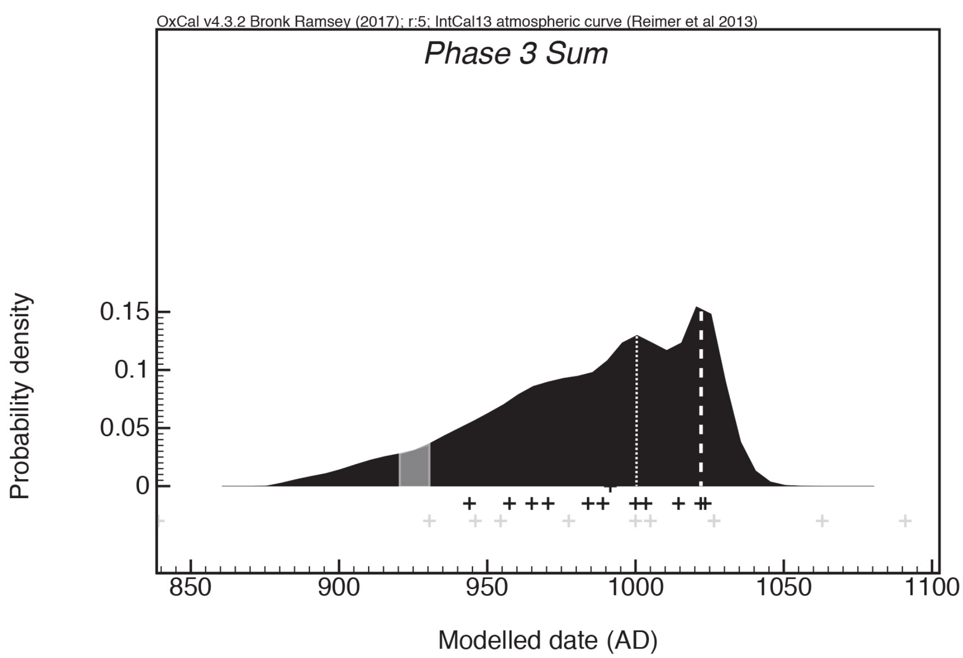


Figure 8: The distribution of dated Phase 3 samples within Surtshellir's main tunnel and the upper passages Vígishellir (right) and Beinahellir (left). Dates are shown with 1-sigma ranges and medians from Model 3, except for AAR-7413, AAR-7412 and OxA-37505/37506 (in italics) which are from Model 0 for reference, since these were excluded from Model 3. Post-medieval surface openings have been removed to give a sense of the site's original configuration.

This indicates that Surtshellir was abandoned around the time that medieval Icelandic sources indicate pre-Christian ritual practices were forbidden by law (Grønle 2006). Our dates suggest that these practices continued somewhat longer here than 1016 (Sturluson 1964:292), yet only two samples had modeled median dates later than AD 1020, all seven of the site's latest dates incorporate the period AD 1000-1020 at one standard deviation, and no samples' probability distributions preclude the possibility they could have been deposited before AD 1020 (Table 6).

Re-interpreting Surtshellir as a place of sacrifice and rituals linked to pre-Christian beliefs and practices is supported by evidence that the site was formally closed, and ritually sealed, through actions that included placing a set of lead weights, with one in the form of a Christian cross (Figure 5), in the center of Vígishellir's boat-shaped structure. Here, fires had been raised with sustained temperatures hot enough (≥ 600-900°C) to cause thermal damage to jasper and chalcedony fire-starter fragments and to fully cremate or calcine bones (Figueiredo et al. 2010; Jew and Erlandson 2013; Pérez et al. 2017; Shipman et al. 1984). Since lead melts at 327.5°C, these weights would not have survived had any further fires been raised in this location, suggesting they were consciously placed as a termination deposit.

Figures 9a and 9b plot the summed marginal posterior distributions of Phase 3's dates, based on Bayesian Model 3. Figure 9a indicates that bones were brought into Surtshellir shortly after the cave became accessible and reached a relatively steady state of accumulation after AD 950. However, this curve underestimates the actual density of dates prior to AD 950 since the three earliest dates from Vígishellir (OxA-37505/37506, AAR-7412, and AAR-7413) were removed from Model 3. With those dates restored (Figure 9b), the decades immediately after the cave became accessible appear to have seen the most intense activity inside Surtshellir.[14] Two peaks around AD 990-1000 and AD 1020-1030 also suggest that activity in the cave intensified around the time of Iceland's Conversion and then again just before the site was abandoned.



[14] While the destruction of the upper portions of the main bone pile in Vígishellir could have biased age estimates towards the site's earliest periods of use, only 3 of the 15 dated samples from Phase 3 came from this feature.

Figure 9a: Summed marginal posterior distributions of dated events in Phase 3, based on Model 3. The gray shaded area between AD 920-930 represents the most-likely time by which Surtshellir had cooled enough for humans to enter. The dotted and dashed white lines identify two peaks of more intense activity focused on the date of Iceland's official conversion to Christianity (1000 AD) and approximately 1020-1030, after which activity ends.

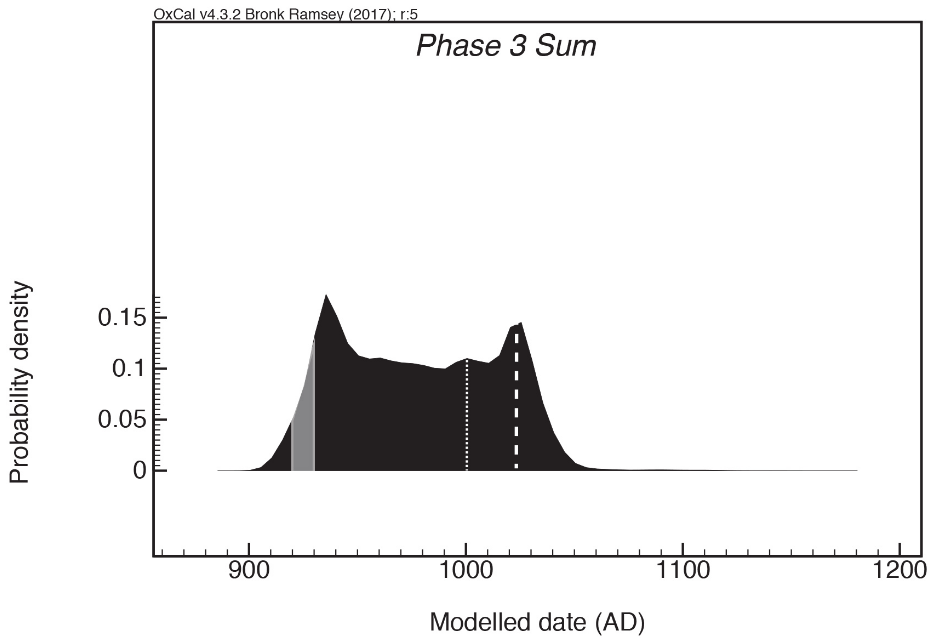


Figure 9b: Summed probability curve for Model 3 with early dates OxA-37505/37506, AAR-7412, AAR-7413 added. With these dates the most intense period of activity inside Surtshellir appears to have been immediately after the cave became accessible. By calAD 950, activity levels became relatively constant through the course of the 10th century before rising around AD 1000 and peaking again, circa 1020-1030.

5.6 Surtshellir after the Viking Age: All four models indicate that Surtshellir was abandoned and avoided for 600-650 years after Phase 3 ended. No dates or material culture document activity in Surtshellir between the early 11th and the late 17th centuries. However, coins from the 17th-19th century, placed much deeper in the cave by generations of explorers (Grossmann 1894; Hróarsson 2006), a felt boot liner recovered deeper within Vígishellir (Beta-350954), and recent garbage strewn throughout the cave document visits from the 17th century to the present.

6. Conclusions

Surtshellir is a unique Viking Age archaeological site located below the surface of the Hallmundarhraun lava field in the interior of western Iceland. A massive drystone wall and a boat-shaped structure were built, and seven piles of domestic animal bones were created, here during the Viking Age, 175-300 meters from the cave's entrance and fully within its dark zone.[15]

[15] The massive wall in Surtshellir's main tunnel was first noted as an archaeological feature during our work in 2001 (Ólafsson et al. 2004), when snow banks that formerly filled the cave to half its height, year-round, melted after several sequential warm summers. We assign it to the Viking Age based primarily on inferences from medieval sources. A wall large enough to be identified as a "fortification" (*vígi*) inside Surtshellir is mentioned in *Sturlunga saga*'s account of the mutilation of Órækja Snorrason, son of the chieftain Snorri Sturluson, who was captured by his enemies in June 1236 and taken "up onto the wall" in Surt's cave (*Þá fara þeir í hellin Surt ok up á vígit*) where he was blinded, castrated, and left to die. As there are no other walls inside Surtshellir that could be mistaken for a fortification, this

Investigations in 2001, 2012, and 2013 documented Surtshellir's material culture, faunal remains, and archaeological features. Twenty new AMS dates, complementing three earlier radiocarbon and tephrochronological dates from the cave and its surroundings, allow us to constrain the date of the Hallmundarhraun eruption, reassess the age of the cave's archaeological remains in relation to significant events in Icelandic history, including the Conversion, and assess two different origin stories about the cave and its inhabitants.

Bayesian modeling of radiocarbon dates from the cave, constrained by the presence of the Landnám tephra beneath the lava flow itself indicates that the Hallmundarhraun eruption had ended, and the cave had cooled down enough for humans to enter, by AD 920-930. This eruption most likely began between AD 880 and 910 and would almost certainly have been the first major volcanic eruption directly observed by northern Europeans since the Late Pleistocene.[16] Its lava ran more than 50 kilometers down from ice-shrouded highlands into newly settled valleys, burying 240 km^2 of valuable upland grazing land and fertile lowland valleys beneath black, smoking basalt. *Landnámabók* suggests that farms were being established throughout these valleys in the early 10th century (Figure 1) and archaeological investigations at Halldórstóftir, Gilsbakki, Háls, and Reykholt confirm this (Guðrún Sveinbjarnardóttir et al. 2012; Ólafsson 2020; Smith 1995, 2005, 2009). Hjartarson (2015:22-24) suggests that five farms mentioned in *Landnámabók,* whose locations are unknown today, may have been buried under the lava.

If the Hallmundarhraun's lava was produced at the lowest rates suggested for shield eruptions, it may have continued for more than 50 years; at the fastest rates it could have advanced more than a kilometer a month, burning and swallowing everything in its path in less than five years. However, whether of longer or shorter duration, the impacts of this eruption must have been unsettling, posing existential challenges for Iceland's newly arrived settlers. It may have been possible to adapt day-to-day activities in response to an eruption flowing slowly for decades, yet the fear and dread of living with something so destructive for much of a lifetime, not knowing whether it would ever end, must have been extremely challenging. On the other hand, experiencing an eruption capable of covering 240 km^2 of land in just a few years would have revealed almost unfathomable levels of destructive power to anyone living in its vicinity. The advance of the lava would not have been the only challenge these early settlers faced since shield eruptions release massive amounts of toxic gases (SO_2, CO_2, H_2S, HF, HCl) that can flow into low-lying valleys, accumulating in low-lying depressions, hollows, and caves, poisoning the air, killing vegetation, livestock and people, and damaging land far beyond the eruption's immediate vicinity (Guðmundsson and Larsen 2016; Thordarson and Larsen 2007; Weinstein et al. 2013).

We do not yet know what Iceland's settlers did while the eruption was flowing, but once it stopped, circa AD 920-930, people entered Surtshellir and built the structure inside Vígishellir. This low, roofless, boat-shaped stone structure served as a defined space within which some

architectural feature must have been built before the 13th century and since there is no evidence for activity in the cave after the second quarter of the 11th century, we feel confident that it dates to Phase 3.

[16] Two other eruptions in the first decades of Iceland's settlement are documented by tephrochronology– as noted in fn 12, the Landnám tephra sequence, produced by explosive/phreatic eruptions two southern Icelandic volcanoes, lies beneath early settlement sites across much of Iceland but overlies a handful of man-made features in southwestern Iceland, suggesting that distant ashfall from this eruption may have been experienced by early Norse explorers or seasonal hunters in Iceland (Einarsson 2011; Frei et al. 2015). The Katla-R tephra, dated ~920 AD, another ash layer from an explosive eruption in south-central Iceland would either have been pene-contemporaneous with, or slightly later than, the Hallmundarhraun eruption (Haflidason et al. 1992). Median and highest probability dates for the Hellnahraun eruption, a smaller early historic effusive eruption in southwestern Iceland are AD 947 and calAD 949-992 (Einarsson et al. 1991)

bones were burned in the flesh at high temperatures[17] (Marengère et al. 2019) on a prepared surface of crushed basalt. Unburned bones were added to the pile outside this structure and simultaneously to four separate piles in Beinahellir over a span of 80-120 years.

What kind of site was Surtshellir? Both the unburned bones deposited on piles and the bones burned inside Vígishellir's structure came from prime livestock killed and dismembered in the early spring with knives, axes, and blunt instruments like hammers (McGovern 2002). The site's material culture assemblage is specific, unique, and non-domestic in nature, incorporating one of the largest suites of imported glass beads known from Iceland, orpiment – a toxic arsenic ore from eastern Turkey, otherwise only known as a pigment from the highest elite contexts in Viking Age Scandinavia,[18] and a unique set of lead scale weights. These were unusual, exotic, and valuable materials deployed in deliberate acts that were undertaken for a century or more under difficult conditions, outside the reach or sight of most members of Iceland's developing society.

One of the main activities that we can document archaeologically involved bringing in bones of domestic animals that had died on distant farms or driving animals to the cave to be slaughtered and dismembered there, with their fragmented remains distributed throughout three separate passages in a restricted portion of the cave. These actions were certainly just part of a larger set of performances that gave meaning to acts involving not only slaughtering but dismembering animals, breaking their bones, and adding them to piles deep in the darkness and stillness of a cave named for Surtr.

These actions continued throughout the 10th century and into the first decades of the 11th with three apparent periods of intense activity – just after the eruption ended, at the time when Iceland adopted Christianity, and just before the site was closed. These latter spikes echo findings from Hofstaðir, a Viking Age feasting hall in northern Iceland, which was also closed with special termination deposits 20-30 years after the Conversion and where three out of five dated skulls of sacrificed bulls produced calibrated ages of 980-1015 suggesting intensified activity around the time of the Conversion itself (Lucas 2009; Lucas and McGovern 2007). They also resonate with medieval Icelandic sagas' portrayals of the decades immediately before the Conversion as a time of tension and competition between elites legitimated through pre-Christian belief systems, Christian converts, and missionaries (Schach 1982); accord well with medieval Icelandic sources' statements that pre-Christian rituals were allowed to continue out of public view for some time after the Conversion to ensure the peace (Aðalsteinsson 1998; Aðalsteinsson and Jónsson 1999); and document that Iceland's conversion was a process, not an event.

By *calAD 1020-1030 AD*, seven piles of fragmented animals' remains stretched in a line extending more than 120 meters from the boat-shaped structure in Vígishellir, down onto the floor of the main tunnel, and up again into Beinahellir's deepest recesses. No evidence of Viking Age activity has been found any further into the cave than this line, suggesting that it divided the cave between an outer zone that could be entered by a few people on very specific business and a deeper zone where humans never traveled during the Viking Age.

Surtshellir was visited for more 80 years, which would have required sharing knowledge across generations and training new officiants in how to find the cave's entrance; what to bring to it;

[17] This conclusion is based on experimental data combined with detailed taphonomic analyses of burned bones from the crushed basalt pad in Vígishellir's structure and will be explored further in a separate publication. Preliminary information presented as a poster at the 2019 meeting of the Canadian Archaeological Association is accessible through this link: Marengère et al. 2019.
[18] Detailed descriptions, analyses, and discussions of the beads, orpiment, and weights from Surtshellir are subjects of papers currently being prepared for publication.

how to enter it, traverse it, and reach its upper galleries; what to do before making this subterranean journey; what to do once there; and why these actions had to be repeated again and again over a span of 80-120 years.

The sequestration and destruction of valuable resources through repetitive and patterned actions differing in season and practice from normal activities, undertaken in a specially prepared and unique structure built in a setting accessible to only a few, accessible only with risk in a location with special natural or supernatural associations at a liminal boundary between the world of normal experience and areas into which humans did not travel are consistent with behaviors responsible for producing archaeological records of ritual activity (Barrowclough and Malone 2010; Insoll 2005; Kyriakidis 2007; Renfrew 1985, 2007; Renfrew and Bahn 2004:416–417). They are also consistent with increasing evidence for caves' active use as ritual spaces during the early medieval period in the North Atlantic, especially in areas with a significant Norse presence (Bergsvik 2017; Bergsvik and Dowd 2017; Connolly et al. 2005; Dowd and Hensey 2016; Kaiser and Forenbaher 2014; Moyes and Clottes 2014).

Shortly after the last bones were added to these piles, special deposits, including a set of scale weights with one in the form of a Christian cross, were carefully placed in the center of the structure in Vígishellir. After this, the cave was avoided for more than six centuries, becoming known as a place of dread, entangled in tales of mutilation, outlaws, murder, and terror. Surtr was remembered as its occupant into the 19th century and Surtshellir, itself, was reimagined in Christian contexts as the place where Satan would emerge on Judgment Day (Miles 1854).

Surtshellir's radiocarbon dates indicate that the archaeological features in its dark zone are parts of a single, coherent Viking Age archaeological site that was a focus of repeated, non-domestic activities consistent with archaeological signatures of ritual. People entered the cave and created a space for these activities shortly after the Hallmundarhraun eruption had ended. The structures they built in Surtshellir's darkness are among the largest stone constructions known from medieval Iceland, and the things they brought to the cave and sequestered inside it included valuable prime livestock and rare objects obtained through trade networks that spanned the Viking world. Surtshellir's archaeological record implies the organization, wealth, connections, and activities of Iceland's elite, concentrated in the cave's darkness.

It is hard not to conclude that the actions undertaken inside Surtshellir were initially done in response to the existential challenges that the Hallmundarhraun eruption presented to Iceland's newly arrived Norse settlers. Bertha Philpotts's and Finnur Magnússon's suggestions that Surtshellir was the site of a cult devoted to Surtr, rather than efforts done to constrain him, may have missed the mark; yet the conclusion that the site and its assemblages were produced through ritual responses to this cataclysmic, volcanic event seems inescapable. These activities continued within the cave for more than a century after the eruption ended, long after the lava cooled, until pre-Christian practices were abolished by Iceland's elite. Perhaps, once begun, they were maintained for political as well as sacral reasons, as Iceland's chieftains established their secular positions through participation in sacred acts. However, continuity of practice may simply have seemed warranted, for as long as sacrifices continued underground, out of sight, this volcano remained quiet.

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CRediT author statement

Kevin P. Smith: Conceptualization, Investigation, Funding Acquisition, Project Administration, Writing – Original Draft, Review, and Editing; Visualization;

Guðmundur Ólafsson: Conceptualization, Investigation, Funding Acquisition, Resources, Writing – Review & Editing.

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