

ture fluctuations at Summit must have been part of a larger atmospheric pattern that extended over the North Atlantic, and probably also over northwest Europe. The large number of interstadials revealed by the ice cores may be the cause of some of the confusion about the number of interstadials and their timing in northwest European climate records<sup>14–17</sup> and offer an opportunity for their interpretation.

The bottom 10% of the isotope records differ significantly. Below interstadial 22 (ref. 1) (2,700 m depth at GISP2, 2,676 m at GRIP, that is 87 kyr BP in the GRIP preliminary timescale<sup>1</sup>) layer thicknesses differ substantially; below interstadial 23 (ref. 1) (~2,750 m in both cores) the correlation between the isotope values deteriorates drastically. Taylor *et al.* report a similar breakdown of correlation between the cores for electrical conductivity measurements<sup>18</sup>. Thus, although the bottom part of both records clearly contains ice from the penultimate interglacial and beyond, the loss of a simple relationship between depth and age prevents a detailed dual-core climate reconstruction deeper than the early Wisconsin glacial. The GISP2 record of the Eemian/Sangamon interglacial period is probably affected by flow deformation and thus cannot confirm the conclusions regarding extremely high climate variability during this period that were based on the GRIP record<sup>1,2</sup>.

The excellent agreement observed above a depth of 2,700 m suggests that surface climate conditions at the GISP2 and GRIP localities were similar for both cores for the entire accumulation interval. This agrees with similar peak-to-trough  $\delta^{18}\text{O}$  values in the bottom part of the cores. The differences between the records must therefore result from flow deformation at one or both of the record localities. Inclined layering, first observed in visual stratigraphy at a depth of 2,678 m in the GISP2 core and noticed at 2,847 m in the GRIP core (see Taylor *et al.*<sup>18</sup>), may indicate such flow deformation. The location of the GRIP core at the ice divide presently protects the deep ice at GRIP from folding. Under different conditions of sea level, ice accumulation rate

and temperature during the glacial period, the ice divide may have moved 10–50 km, probably towards the east<sup>19</sup>. This would have placed both GISP2 and GRIP in a flank-flow regime, with the GRIP site downstream of bedrock slopes immediately to the east<sup>6</sup>. The greater depth at which inclined layering was reported for the GRIP core fits the predicted protection of the divide flow and suggests that the GRIP record can be interpreted climatically to a greater depth than the GISP2 record. Further work on the ice cores and the glaciology of the Summit area is needed to provide a detailed timescale for the well established glacial record down to 2,700 m, and to interpret the disturbed bottom part of the records. □

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## Endogenous growth of persistently active volcanoes

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LAVA lakes and active strombolian vents have persisted at some volcanoes for periods exceeding the historic record. They liberate prodigious amounts of volatiles and thermal energy but erupt little lava, a paradox that raises questions about how volcanoes grow. Although long-lasting surface manifestations can be sustained by convective exchange of magma with deeper reservoirs, residence times of magmas beneath several basaltic volcanoes are ~10–100 years<sup>1,2</sup>, indicating that where surface activity continues for more than 100–1,000 years, the reservoirs are replenished by new magma. Endogenous growth of Kilauea volcano (Hawaii) through dyke intrusion and cumulate formation is a well-understood consequence of the steady supply of mantle-derived magma<sup>3,4</sup>. As we show here, inferred heat losses from the Halemaumau lava lake indicate a period of dominantly endogenous growth of Kilauea volcano during the nineteenth century. Moreover, heat losses and degassing rates for several other volcanoes, including Stromboli, also indicate cryptic influxes of magma that far exceed visible effluxes of lavas. We propose that persistent activity at Stromboli, and at other volcanoes in different tectonic settings, is evidence of endogenous growth, involving processes similar to those at Kilauea.

When Europeans first visited Kilauea volcano in 1823, they found the Halemaumau crater filled by an active lava lake. In 1880, the lake had an estimated area of  $6.51 \times 10^3 \text{ m}^2$  (ref. 5). It persisted with various fluctuations until 1924 (ref. 3). Significant flank eruptions of lava took place only in 1840, 1868 and 1919–20 (refs 3, 6). The Kupaianaha lava pond which was active in the 1980s provides an analogue for the 19th century Halemaumau lava lake, although it formed part of an effusive lava system, whereas Halemaumau was located directly above a shallow reservoir at 1–2 km depth<sup>4,7</sup>. We use measurements made at Kupaianaha to estimate heat losses from the Halemaumau lake. During the period 1987–8, the surface of the Kupaianaha pond, though crusted, typically remained at a temperature of 200–300 °C, corresponding to an average radiant emittance of  $\sim 5 \times 10^3 \text{ W m}^{-2}$  (ref. 8), and a convective loss (forced or natural) of  $\sim 2 \times 10^3 \text{ W m}^{-2}$ . If these values are used for the pre-1924 Halemaumau, the inferred surface thermal losses *alone* imply a magma flux into the volcano of  $\sim 0.6\text{--}3.0 \times 10^3 \text{ kg s}^{-1}$  (depending on the enthalpy model chosen; see Table 1 and Fig. 1). When conductive losses through the walls of the reservoir and conduit<sup>9</sup>, and hydrothermal losses (not easily modelled) are considered, a much larger magma influx is indicated, greatly exceeding the time-averaged surface eruption rate of  $\sim 3 \times 10^2 \text{ kg s}^{-1}$  for the period<sup>10</sup>, but consistent with the observed eruption rate of  $\sim 10^4 \text{ kg s}^{-1}$  from Kilauea since 1924 (refs 4, 7). This in turn provides a lower bound to the rate of supply of magma to the volcano from the mantle plume powering the Hawaiian hotspot<sup>4,11</sup>.

In order to sustain the rate of heat loss from Halemaumau, we suggest that fresh magma was arriving beneath Kilauea during the 19th century at about the same rate as it has during prolonged periods of visible lava effusion in the 20th century. It follows that Kilauea was steadily 'growing'. The difference

TABLE 1 Thermal and SO<sub>2</sub> flux data for some persistently active volcanoes

Site/year of observation	Area (m <sup>2</sup> )	Effective radiation temperature (°C)	Surface heat flux (MW)	Magma influx model (A) (kg s <sup>-1</sup> )	Magma influx model (B) (kg s <sup>-1</sup> )	SO <sub>2</sub> flux (kg s <sup>-1</sup> )	Magma influx from SO <sub>2</sub> (kg s <sup>-1</sup> )	Eruption rate (kg s <sup>-1</sup> ) (period)
Halemaumau 1880 (refs 5, 6)	65,100	272	460	3,000	560	—	—	300 (1823–1923)
Kupaianaha 1987–88 (ref. 8)	2,300	272	16	110	20	—	—	—
Kilauea 1986 (refs 23, 26)	—	—	—	—	—	13.5 ± 4.6	14,000	~10,000 (Observed recent output)
Stromboli 1992 (P. Allard)	—	—	—	—	—	9.25	9,300	0.3 (?Since antiquity)
Etna 1975–1987 (ref. 31)	—	—	—	—	—	46.3 ± 9.0	46,000	~1,000 (1759–1974)
Nyiragongo 1959 (ref. 18)	13,125	650	620	4,000	750	12.6	13,000	—
Erta 'Ale 1973 (ref. 19)	7,600	573	260	1,700	320	0.58	580	—
1986 (ref. 32)	30,600	176	100	670	130	—	—	—
Masaya 1979 (ref. 21)	—	—	—	—	—	13.9	25,000	10 (since 16th C)
Erebus 1985 (ref. 22)	35,100	137	84	540	100	—	—	—
1987 (ref. 32)	—	—	—	—	—	0.59	590	—
Láscar 1987 (ref. 32)	34,200	171	110	730	140	—	—	450
1989 (ref. 33)	—	—	—	—	—	27.5	28,000	(1984–1993)

Thermal flux estimates are made mostly from satellite observations<sup>32</sup>. Effective radiation temperature is defined as  $T_e = (E/\sigma)^{0.25}$ , where  $E$  is the radiant emittance and  $\sigma$  is the Stefan–Boltzmann constant. Heat fluxes combine radiative and convective losses estimated for the given  $T_e$ , but exclude sub-surface conductive and hydrothermal losses. Magma influxes calculated from heat losses are given for models (A) and (B) of Fig. 1. SO<sub>2</sub> fluxes were determined by correlation spectrometer (COSPEC), except for Erta 'Ale and Nyiragongo which were determined by chemical methods. Errors in thermal fluxes are discussed in ref. 32. SO<sub>2</sub> fluxes are reported directly from cited references; errors are often not given. Magma influxes based on SO<sub>2</sub> data were determined for 0.05 wt% degassable sulphur in melt, as at Kilauea, except for Masaya, for which petrological data were available. Eruption rate for Láscar is dominated by the single 1993 eruption volume.

between the inferred rate of magma input and the 19th century surface output is a measure of the rate of endogenous growth.

How does endogenous growth take place? One mechanism is dyke intrusion. When Halemaumau was active, the lava lake exhibited occasional abrupt decreases in level, without flank eruptions. These events were sufficiently striking to provoke contemporary enquiries<sup>6</sup>, and indicate the intrusion of dykes into Kilauea's rift system. Some of the 'missing' lava may have been erupted on the sea floor, though there is no historical evidence for this<sup>34</sup>. During the period 1956–83, ~35% of Kilauea's input of ~10<sup>4</sup> kg s<sup>-1</sup> was extruded; the remainder was stored within the eastern and southwestern rift zones<sup>12</sup>. Dyke intrusion and rift-zone widening are accommodated by seaward displacement of the south flank of the island of Hawaii along the prominent *pali* faults<sup>3</sup> (Fig. 2).

A second mechanism of endogenous growth is the formation of cumulates, which can help drive convection in the overlying reservoir by means of crystallization and cooling. Walker suggested the progressive growth of layers of solidifying magma that maintain themselves at a level of neutral buoyancy<sup>13</sup>, an hypothesis which is supported by seismic data indicating the existence of major cumulate formations in the lower crust beneath the Hawaiian islands<sup>14</sup>. These large magmatic increments beneath the volcanoes are partly compensated by bending of the lithosphere in response to loading, leading to rapid subsidence of the islands<sup>15</sup>.

Many other basaltic volcanoes around the world display persistent magmatic activity. Although differences in scale and tectonic setting may suggest that they have little in common with Kilauea, there are some surprising similarities. Stromboli, the prime example, has been active for millenia, prompting several enquiries into the nature of its persistent activity (see, for example, refs 16 and 17). Etna has also been active throughout

history, exhibiting strombolian activity and intermittent lava effusion. Its average eruption rate between 1759 and 1974 was ~10<sup>3</sup> kg s<sup>-1</sup> (ref. 11). Both Nyiragongo (Zaire)<sup>18</sup> and Erta 'Ale (Ethiopia)<sup>19,20</sup> have probably had active lava lakes throughout historic times. Nyiragongo's lake was contained in a deep crater until this was catastrophically breached in 1977. Only minor lava flow effusion has been noted at Erta 'Ale. At Masaya (Nicaragua), a lava lake has been present intermittently over the past 450 years, although the time-averaged eruption rate is only ~10 kg s<sup>-1</sup> (ref. 21). Mt Erebus (Antarctica) contains a small, persistent lava lake of anorthoclase phonolite and has exhibited frequent minor strombolian eruptions since its discovery in the 19th century<sup>22</sup>.

We can use observed thermal and/or SO<sub>2</sub> degassing fluxes to constrain influxes of hot volatile-rich magma into sub-surface reservoirs for these volcanoes (Table 1). Magma fluxes are derived from measured SO<sub>2</sub> fluxes by assuming 0.05 wt% degassable sulphur in parental magmas<sup>23</sup>. During the sustained Pu'u O'o (Kilauea) eruption of the 1980s, the observed rate of surface lava effusion was close to the long-term rate of magma supply. Good correlations between the magma flux inferred from measured gas fluxes, and the observed rate of eruption confirms that gas flux provides a useful proxy measure of magma flux<sup>23</sup>. The discrepancies between magma fluxes derived by thermal and gas flux methods are not surprising: thermal modelling is difficult, and gas flux data are sparse and of variable quality. More important than the accuracy of individual estimates is their wider significance: fresh, volatile-rich magma from depth must continuously reach the surface, where it degasses and cools before returning to the reservoir. Magma convection within the conduit connecting the reservoir to the surface is thought to be driven by the increase in melt density that accompanies volatile exsolution<sup>24,25</sup>.

Stromboli's edifice is much smaller than Kilauea, and its time-averaged eruption rate is a mere  $0.3 \text{ kg s}^{-1}$  (refs 16, 17), but its average  $\text{SO}_2$  flux of  $\sim 10 \text{ kg s}^{-1}$  (P. Allard, personal communication) is similar to that of Pu'u O'o<sup>26</sup>, implying a comparable magma flux. Giberti *et al.*<sup>9</sup> calculated that  $\sim 200 \text{ kg s}^{-1}$  of magma must be supplied to the upper parts of Stromboli's edifice, to sustain heat losses through degassing and conduction, and to account for the inferred gas flux. They suggested that this supply might come either from a deep mantle source or from convective overturn of a large magma chamber; however, uranium-series isotopic disequilibria studies for both Stromboli and Etna suggest that the residence time for shallow magma is only several tens of years<sup>1,2</sup> indicating that their persistent surface manifestations cannot be sustained by convective circulation between surface vents and un-replenished reservoirs. Even a conservative interpretation of the thermal and gas flux data therefore implies that new magma must be supplied to these and similar volcanoes at rates of hundreds or thousands of kilograms per second. Whenever the inferred steady-state supply of mantle-derived magma exceeds the rate of eruption, formation of sub- and/or intra-volcanic intrusive complexes is indicated.

It follows that persistently active volcanoes are growing endogenously at far greater rates than their modest surface eruptions may suggest. At Kilauea, magmatic increments have been evident at the surface in recent decades, when lava has been steadily streaming into the sea, but were mostly cryptic during the last century when the lava lake at Halemaumau was the primary manifestation of magmatic activity. At Stromboli, magmatic increments appear to have been dominantly cryptic throughout history, whereas Etna has exhibited both prolonged periods of cryptic activity and occasional outpourings of lava. The typical  $\text{SO}_2$  flux for Masaya ( $14 \text{ kg s}^{-1}$  in 1979) has been interpreted as requiring a magma flux of  $2.5 \times 10^4 \text{ kg s}^{-1}$  (ref. 21), which is almost entirely cryptic.

As Kilauea demonstrates, rapid endogenous growth of volcanoes can be accommodated by minor intrusions accompanied by edifice deformation, and by formation of cumulate complexes at deeper levels. About 20% of Stromboli's edifice is composed

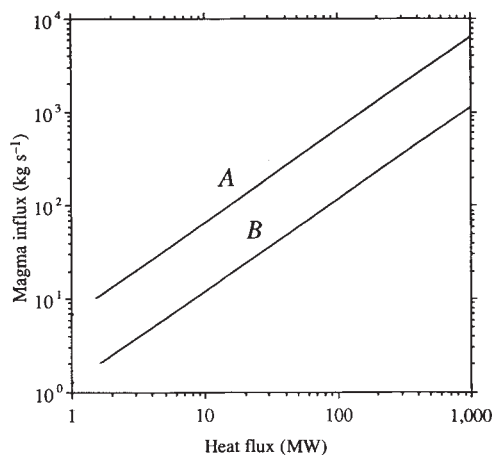


FIG. 1 Influxes of magma required to balance thermal losses from a reservoir at constant temperature and volume. Enthalpies are calculated for a parental magma that cools  $\Delta T$  (°C) and crystallizes a mass fraction  $\Delta f$  before becoming thermally isolated from the reservoir. Assuming that all the heat extracted is transferred to the reservoir, the mass influx of parental magma is given by  $q/(L\Delta f + c\Delta T)$  where  $q$  is the thermal loss (W),  $L$  is the latent heat of fusion, and  $c$  is the specific heat capacity. Two enthalpy models are given, corresponding to dykes and cumulates, respectively: (A),  $\Delta T = 50^\circ \text{C}$ ,  $\Delta f = 0.25$ ; (B),  $\Delta T = 400^\circ \text{C}$ ,  $\Delta f = 1$  ( $L$  taken as  $4.2 \times 10^6 \text{ J kg}^{-1}$ ;  $c$  as  $10^3 \text{ J kg}^{-1} \text{ K}^{-1}$ ).

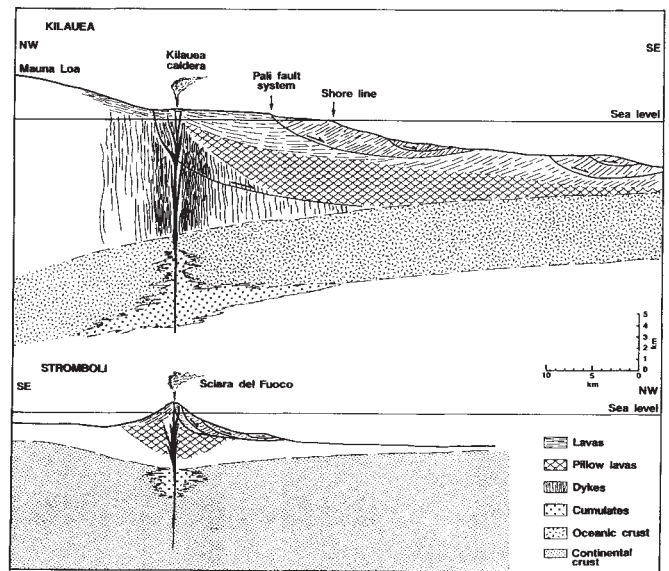


FIG. 2 Cross-sections of Kilauea (top) and Stromboli (bottom) to same scale, showing postulated overall similarities in two-dimensional internal structure, and mode of growth by flank displacement and cumulate formation. Kilauea section from ref. 13, based on seismic data; Stromboli section schematic, based on maps and sections in refs 27 and 28, and sources cited therein. The rotational faults illustrated are based on "shovel-shaped faults" first proposed by Rittman<sup>27</sup>; sub-volcanic cumulates are inferred from geochemical evidence and sections in ref. 28. Lithospheric flexure illustrated is conjectural. Stromboli's geodynamic setting is poorly understood, but the volcano is thought to be constructed on continental crust 15–20 km thick.

of minor dykes and sills<sup>27</sup>. Over the last  $\sim 10^4$  yr, its active vents have been located within the Sciara del Fuoco on the northwestern flank of the volcano, an amphitheatre-like sector bounded by faults<sup>28</sup>. We suggest therefore that Stromboli's structure and mode of growth resemble that of Kilauea, and that its endogenous growth is similarly accommodated, in part, by downward and outward movements along extensional faults that provide a stress regime favourable for minor intrusions. Loading of the lithosphere by formation of cumulate complexes in crustal reservoirs may also cause flexure similar to that observed beneath the Hawaiian islands<sup>14</sup> (Fig. 2).

Little is known about the sub-surface structures of volcanoes such as Nyiragongo, Erta 'Ale and Erebus, but all three are located in extensional environments likely to promote rifting and dyking<sup>29</sup>. Whatever the form of volcano, continued loading will lead to internal deformation, spreading and possible flank failure, as at Etna<sup>30</sup>. Lava lakes and persistent strombolian activity represent the most tangible evidence of endogenous activity, but other quiescent volcanic manifestations are also consistent with long-term growth. For example, sustained power outputs of aqueous crater lakes (such as Ruapehu, New Zealand) and lava domes (such as Láscar, north Chile) typically exceed  $10^8 \text{ W}$ . Independent quantification of the rates of endogenous growth will be difficult, and will require geophysical and geodetic monitoring. Shallow-level intrusions may be detectable through ground deformation and gravity changes, but deeper-level phenomena would be hard to detect.

More fundamental questions concern the factors that control the ratios of intrusive to extrusive volcanic activity. These must involve complex interactions between magma density and lithospheric subsidence rates. If efficient convective circulation allows extensive degassing of magma from a persistently active vent, then the resulting density increase will inhibit eruption of lavas and promote cumulate formation at depth. If lithospheric subsidence is rapid, the magma column may always be near

the surface, favouring lava eruptions; if subsidence is slow, the volcanic edifice may accumulate to such a height that ultimately only the lowest-density magmas can erupt. □

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## Deep seismic reflection evidence for continental underthrusting beneath southern Tibet

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**THE Himalaya and adjacent Tibetan plateau, constituting Earth's largest region of elevated topography and anomalously thick crust, formed as a consequence of Cenozoic collision between India and Asia—itsself considered the archetypal continent–continent collision<sup>1–3</sup>. Here we report the first results from an attempt to image the structure of the crust beneath this region using deep seismic reflection profiling. Our ~100-km-long profile, acquired in the Tethyan Himalaya, shows a mid-crustal reflection that probably marks the active thrust fault along which the Indian plate is underthrusting southern Tibet; upper-crustal reflections with geometries suggestive of large-scale structural imbrication of the upper crust; and Moho reflections from the base of the double-normal-thickness crust underlying the region. These results lend substantial support to the view that crustal thickening beneath southernmost Tibet was accomplished by wholesale underthrusting of Indian continental crust beneath the structurally imbricated upper crust comprising the Tethyan Himalaya.**

The deep seismic reflection data were collected by Project INDEPTH (International Deep Profiling of Tibet and the Himalaya), which is a cooperative programme between the Chinese Academy of Geological Sciences of the Ministry of Geology and Mineral Resources of China (MGMR) and Earth scientists from several universities in the United States. The profile was sited within the southern part of the Yadong–Gulu rift in southern

Tibet (Fig. 1). The Yadong–Gulu rift is one of a series of north–south trending Quaternary grabens that transect the Himalaya and southern portion of the Tibetan Plateau<sup>4</sup>. The portion of the Yadong–Gulu rift containing the INDEPTH survey lies within the Tethyan Himalaya, largely comprising Palaeozoic and Mesozoic miogeoclinal strata that were deposited on the north-facing continental margin of India and subsequently folded and thrust southward during Neogene collision between India and Asia<sup>5,6</sup>. Collision-related compressive deformation within the Tethyan Himalaya was apparently followed by an episode of north–south extension, manifest principally by the development of the South Tibetan Detachment (STD), a major low-angle north-dipping ductile normal fault that now forms the boundary

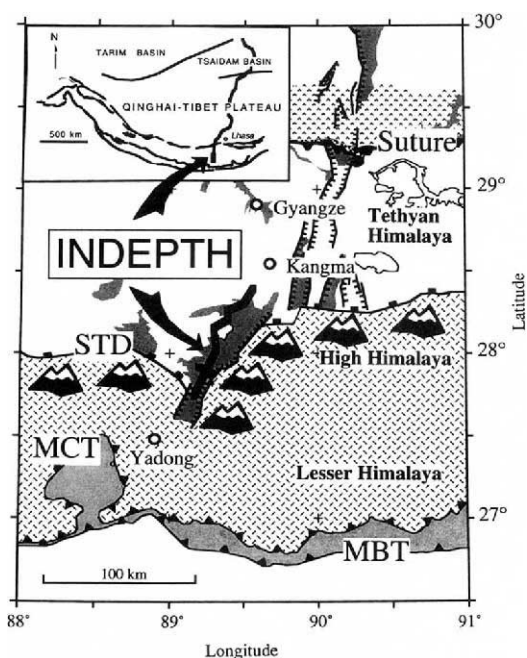


FIG. 1 Generalized geological map showing location of INDEPTH pilot deep seismic profile. MBT, Main Boundary Thrust; MCT, Main Central Thrust; STD, South Tibetan Detachment; Suture, Indus/Tsangpo suture; schematic mountains, crest of High Himalaya.

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