Note: In this version, I have revised several figures to use colour symbols. I hope they will make it easier to see the distribution of basalt groups.

Volatile Emissions From Central Atlantic Magmatic Province Basalts: Mass Assumptions and Environmental Consequences

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Mesozoic basins that contain extrusive basalts of the 200 Ma Central Atlantic Magmatic Province (CAMP) presently total about 320,000 km^2. However, CAMP dikes and sills similar to those that fed the basin basalts are also spread widely across an area greater than 10 million km^2 within four continents. In addition, basalts of the east coast margin igneous province (ECMIP) of North America, which cause the east coast magnetic anomaly, covered about 110,000 km^2 with 1.3 million km^3 of extrusive lavas. If only half of the continental CAMP area was originally covered by 200 m of surface flows, the total volume of CAMP and ECMIP lavas exceeded 2.3 million km^3. Weighted averages for the volatile contents of 686 CAMP tholeiitic dikes and sills, in weight %, are: $CO_2 = 0.117$; $S = 0.052$; $F = 0.035$; and $Cl = 0.050$. Atmospheric emissions of volatiles from flood basalts are conservatively estimated as 50 % to 70 % of the volatile content of the sub-volcanic magmas, mainly exsolved into gaseous plumes from lava curtains at the erupting fissures. Total volcanic emissions of these gases therefore ranged between 1.11×10^{12} and 5.19×10^{12} metric tons, enough for major worldwide environmental problems. Radiometric and stratigraphic dates indicate that most CAMP volcanic activity was brief, widespread, and close to the Tr-J boundary, which is marked by a profound mass extinction. More precise information about the timing, duration, and chemical emissions of volcanic episodes is needed to support a model for CAMP in the extinction event.

INTRODUCTION

The initial breakup of Pangaea in Early Jurassic time provided a legacy of basaltic dikes, sills, and lavas over a vast area around the present North Atlantic Ocean (Fig. 1). Although some connections among these basalts had long been recognized, Rampino and Stothers [1988] were possibly the first to rank them among major flood basalt provinces as a group. Marzoli et al. [1999] showed that basaltic sills of similar age (near 200 Ma, or earliest Jurassic) and composition (intermediate-Ti quartz tholeiite) also occur across the vast Amazon River basin of Brazil, and they proposed a group acronym of CAMP (Central Atlantic Magmatic Province). The province has been described by McHone [2000] as extending within Pangaea from modern central Brazil northeastward about 5000 km across western Africa, Iberia, and northwestern France, and from Africa westward for 2500 km through eastern and southern North America as far as Texas and the Gulf of Mexico (Fig. 1). If perhaps not the largest by volume, the CAMP certainly encompasses the greatest area known – possibly 10×10^6 km^2 -- of any continental large igneous province.

Nearly all CAMP rocks are tholeiitic in composition, with widely separated areas where basalt flows are preserved, and many large groups of diabase (dolerite) sills or

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10.1029/136GM013

sheets, small lopoliths, and dikes throughout the province. CAMP volcanism occurred in the middle of rifting activity of Pangaea during the lower Mesozoic, and the enormous province size, varieties of basalt, and brief time span of CAMP magmatism invite speculation about mantle processes that could produce such a magmatic event as well as break up a supercontinent [*Wilson*, 1997; *McHone*, 2000].

Throughout the Phanerozoic, the greatest mass extinctions have virtually coincided with the greatest eruptions of continental flood basalts [*Stothers*, 1993; *Courtillot*, 1994]. As the precision of radiometric dates for these events has improved in recent years, their correlation with extinctions has generally improved as well [*Courtillot et al.*, 1996; *Olsen*, 1999], to the point where some events are timed to within a few hundred thousand years [*Pálfy et al.*, 2000; *Courtillot et al.*, 2000]. This correlation includes a possible link between the CAMP and widespread faunal extinctions at the Triassic-Jurassic boundary, as suggested by Stothers [1993] and Courtillot [1996], and in new studies by McElwain et al. [1999], Pálfy et al. [2000] and Wignall [2001].

The exact mechanism by which a flood basalt could cause a mass extinction remains speculative, but the most likely scenario involves the injection into the upper atmosphere of large amounts of SO_2 and/or CO_2, causing drastic, if temporary, climatic cooling and/or heating [*Rampino et al.*, 1988; *Palais and Sigurdsson*, 1989; *McElwain*, 1999]. The heights of lava fountains at very large fissure eruptions may be 1 to 2 km, and the super-hot volatiles escaping from the vented magma can easily rise to 11 km or more [*Woods*, 1993] and enter into global circulation. The climatic cooling mechanism of sulfur aerosols has been calibrated by Rampino et al. [1988] and Palais and Sigurdsson [1989], using records of historic eruptions. Thordarson et al. [1996] applied this calibration to the Laki, Iceland flood basalt and climatic cooling event of 1783-1784, and another application for the larger Roza basalt flow of the Miocene-age Columbia River basalt province has been made by Thordarson and Self [1996]. Although they described volcanic CO_2 as a possible cause of global warming, Caldeira and Rampino [1990] concluded that CO_2 emissions of the voluminous Deccan basalts (K-T boundary age) were probably spread over too much time to produce a catastrophic increase in climatic temperature. A pertinent discussion about the timing of CAMP magmatism is presented by Baksi in this volume.

This paper is an exploration of the potential for basalts of the Central Atlantic Magmatic Province to have produced a catastrophic climate change, even if no conclusion about is yet possible. Eroded remnants of CAMP basalt that flowed onto the surface, along with their sub-fissure dike sources, are preserved in basins around the central North Atlantic Ocean, and the total extrusive mass is estimated by extrapolating a similar proportion of lava across the entire central Pangaean province. The volatile-element contents of sub-volcanic sills and dikes are reasonably well known for the Mesozoic basins in eastern North America, and through analogy with other flood basalts, become the basis for an estimate of the amounts of CAMP volatiles injected into the atmosphere. The goal is to outline such estimates, and to discuss problems that remain before the CAMP can be determined to have caused the Tr-J boundary extinction event.

CAMP BASALTS

Ages

The age precision for the main pulse of magmatism throughout the province has improved significantly from studies by Sutter [1988], Dunning and Hodych [1990], Sebai et al. [1991], Hodych and Dunning [1992], Fiechtner et al. [1992], Deckart et al. (1997], Marzoli et al. [1999], and Hames et al. [2000]. Most of the modern dates fit between 196 and 202 Ma. Olsen [1997] described stratigraphic evidence that major lavas of the northern CAMP basins were all produced within a span of 580,000 years. Similar basalts can be correlated throughout the province, and so it appears that much or most of the CAMP volcanism occurred in less than a million years around 200 to 201 Ma (beginning Jurassic). A few radiometric dates near 196 Ma in eastern North America [*Sutter*, 1988; *Hames et al.*, 2000] and western Africa [*Deckart et al.*, 1997] may indicate a smaller, later event with magmas that remain similar to the major tholeiite types. Marzoli et al. [1999] note that several dates for dikes in the central CAMP, along the future coastal region between Africa and South America (Fig. 1), are close to 192 Ma, which could be a younger age for some high-Ti tholeiites within CAMP.

Ironically, the age of the Tr-J mass extinction event is partly determined by its proximity to the oldest basalt flows in the Mesozoic basins of the northern CAMP. Olsen [1997] and his colleagues have analyzed Milankovitch climatic cycles in detail from drill cores in several basins, which show that the earliest basalt lavas of each basin are in essentially identical stratigraphic positions, and thus are identical in age. This finding agrees with the excellent petrological correlation of basin basalts [*Puffer*, 1992], which are therefore co-magmatic across the northern CAMP. The extinction horizon lies from a few meters to tens of meters beneath the basalt in several widely separated basin locations [*Olsen*, 1997; *Mossman et al.*, 1998],

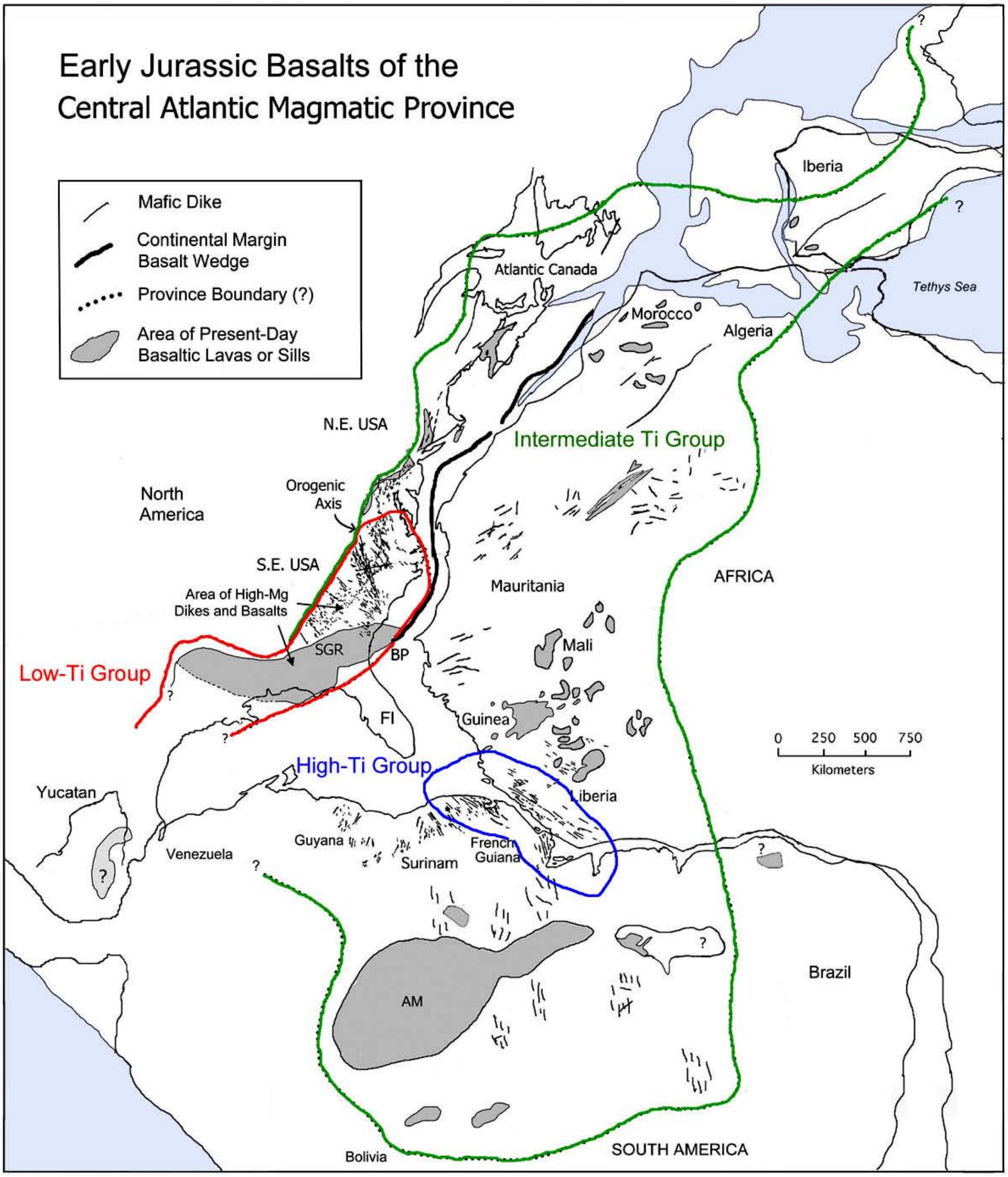

Figure 1. Distribution of Early Jurassic basalts of the central Atlantic magmatic province, adapted from McHone (2000). The predrift configuration of Pangaea is by Klitgord and Schouten (1986). The location of the North American margin volcanic wedge is from Holbrook and Kelemen (1993). Other features are from Deckart et al. [1997], Olsen [1997], and Marzoli et al. [1999], and other studies referenced in the text. Abbreviations: BP = Blake Plateau; FL = Florida; SGR = South Georgia Rift; S.E = Southeast; N.E. = Northeast. Colored boundaries correspond to basalt groups discussed in the text.

which may correspond to a few thousands to tens of thousands of years at typical rates of sedimentation. Thus, the age precision of the Tr-J boundary and extinction falls within the precision range of radiometric dates for CAMP, except that we know the boundary slightly precedes the terrestrial lavas of the northern CAMP basins [*Pálfy et al.*, 2000].

Geographic Extent

Basaltic lavas of the CAMP are best preserved within Mesozoic rift basins of eastern North America and northwestern Africa [*Manspeizer*, 1988]. Some CAMP lavas are also known over older basement terrains in Africa and South America [*Bertrand*, 1991; *Olsen*, 1997; *Marzoli et al.*, 1999], demonstrating that CAMP dikes reached the surface in places outside of the rift basins. The CAMP lavas are therefore remnants of much larger flood basalts that have been mostly removed by erosion [*Rampino and Stothers*, 1988; *McHone*, 1996; *McHone and Puffer*, 2002]. Sources for the former and present surface basalts are represented by the huge swarms of diabase dikes along eastern North America, northern South America, western Africa, and western Europe, around but also well beyond the central Atlantic rift zone (Fig. 1). Numerous large sills of CAMP basalt (such as the famous Palisades sill) occur within the rift basins, but even greater sills with volumes of 10^4 to 10^5 km^3 or more are known, with areas exceeding 10^5 km^2 in basement terrains of western Africa [*Deckart et al.*, 1997] and northern South America [*Marzoli et al.*, 1999].

Studies now suggest that dikes or flows of the CAMP occur as far as northwestern France [*Caroff et al.*, 1995; *Jourdan et al.*, this volume], the Mississippi Embayment (*Sundeen*, 1989; *Baksi*, 1997), the Gulf of Mexico (*Schlager et al.*, 1984) and west-central Brazil [*Montes-Lauar et al.*, 1994; *Marzoli et al.*, 1999]. During its formation, large sections of the CAMP extended into both the northern and southern hemispheres. The entire igneous province may stretch beyond 5000 km in length by 2500 km in width, but its actual limits are not yet known.

The total lengths of some dikes or single dike sets that fed CAMP basalts exceed 700 km (Fig. 1), and remarkably, many maintain essentially the same distinct composition along their great lengths. Others, such as the 250-km long Shelburne dike of Atlantic Canada, show variations consistent with liquid-crystal fractionation similar to surface flows [*Pe-Piper and Piper*, 1999]. In the pre-rift Pangaean region of Morocco, northeastern USA, and Atlantic Canada, at least three distinct quartz tholeiite subtypes comprise basin basalts that apparently flowed within a 580,000 year period throughout the region [*Philpotts and Martello*, 1986; *Olsen*, 1997]. Each of the three northern basalt subtypes also occurs in individual dikes that are from 250 to 700 km long in northeastern North America, adjacent northwestern Africa, and western Europe, and these dikes were certainly co-magmatic fissure sources for the basalts [*Philpotts and Martello*, 1986; *Bertrand*, 1991; *McHone*, 1996]. There may be additional sub-types, as observed in dikes that apparently have no basalts in exposed basins [*McHone*, 1996; *Pe-Piper and Piper*, 1999]. Surface basalts from most other sections of the CAMP in Figure 1 are not preserved, are poorly preserved, or are buried beneath later sediment, but based on the areas near basins, the major dike swarms are everywhere likely to have reached the surface as fissure eruptions.

The East Coast Margin Igneous Province

The widespread groups of dikes fed fissure eruptions and flood basalts that apparently preceded the initial formation of Atlantic ocean crust, which started during the Early to Middle Jurassic along sections of the central Atlantic rift [*Withjack et al.*, 1998; *Benson*, this volume]. There is also evidence for a close link between continental CAMP magmatism and a basaltic border province (volcanic rift margin) adjacent to new ocean crust along the eastern margin of North America. Austin et al. [1990] and Holbrook and Kelemen [1993] determined that sub-aerial volcanic flows comprise at least the upper section of seaward-dipping seismic reflectors, or a basalt wedge, along most of the central Atlantic continental margin. In the southeastern USA, strong sub-horizontal seismic reflectors of continental flood basalts of the South Georgia Mesozoic basin intersect or overlap the seaward-dipping reflectors [*Oh et al.*, 1995]. The SDR represents a very thick (to 25 km) basalt and plutonic cumulate wedge that is uniformly large (about 55 km wide) along roughly 2000 km of the eastern North American margin (Fig. 1), as shown by the East Coast Magnetic Anomaly and seismic reflections, and it has been referred to as the "east coast margin igneous province," or ECMIP, by Holbrook and Kelemen [1993].

Volume Estimates

Lava flows of CAMP are generally thin in comparison with other large flood basalts. The northern basins contain 1 to 3 lava units of about 50 to 200 m each, with the thickest flows (North Mountain basalt) approaching 1000 m in the center of the Fundy basin of Atlantic Canada [*Wade et al.*, 1996]. However, as demonstrated by their chemistry and other co-magmatic correlations, widely-separated northern basin basalts are derived from individual dike systems that extend between basins for 700 km or more, which strongly indicates that their lava products were also once continuous between the basins (*McHone*, 1996]. In addition, the horizon of CAMP basalt in the subsurface South Georgia rift basin is around 200 m thick, and it covers at least 100,000 km^2 of the southern U.S.A. [*Austin et al.*, 1990; *Oh et al.*, 1995]. McHone [2000] suggested that this basalt also extends westward under the southern U.S. coastal plain for at least another 100,000 km^2.

Lava flows are also preserved in other areas of the CAMP, where they flowed across older rocks outside of Mesozoic basins [*Montes-Lauar et al.*, 1994; *Baksi and Archibald*, 1997; *Olsen*, 1997; *Marzoli et al.*, 1999]. In addition, very large sills in South America [*Marzoli et al.*, 1999] and western Africa [*Deckart et al.*, 1997] comprise great volumes of basalt that were likely shallow sources for fissure volcanoes. It is apparent that great swarms of dikes and sills remain where surface flows once existed before their removal by 200 Ma of tectonic uplift and erosion. However, as pointed out by Gudmundsson et al. [1999], many smaller dikes that radiate from shallow subvolcanic magma chambers never reach the surface and must be discounted as sources for lavas. In addition, topographic highs probably existed in some sections of the Pangaean rift zone before and during CAMP magmatism, which would have precluded lava accumulations in those regions. A conservative estimate, therefore, could be that about half of the present CAMP area of 10 million km^2 was originally covered by tholeiite lava flows averaging 200 m in total thickness.

Table 2 summarizes the measurements, estimates, and calculations of CAMP magmas that were compiled into spreadsheet format for this study. Basalt types and volatiles are discussed below. Although estimates of basin areas and volumes of sills and dikes are included in Table 2, only the surface lava calculations are pertinent to the volatile emission calculations. Because very conservative assumptions were used, it is likely that greater rather than smaller amounts of surface lavas and volatiles were actually produced by the CAMP.

Geochemical Groups

Quartz tholeiites in eastern North America were initially subdivided by Weigand and Ragland [1970] into three groups based on relative compositions: 1) HTQ = "high-Ti" quartz-normative tholeiites, 2) LTQ = "low-Ti" quartz-normative tholeiites, and 3) HFQ = "high-Fe" quartz-normative tholeiites. This classification system was also followed by Grossman et al. [1991] for descriptions of their data set of 960 analyses from basins of the eastern U.S., and used for this paper. The HFQ tholeiites are now believed to represent melts derived through fractional crystallization from either of the other two quartz groups [*Ragland et al.*, 1992; *Puffer*, 1992], and for this study, the appropriate HFQ analyses were included with those of the other groups. Olivine-normative tholeiites (OLT), found mainly in the southeastern USA, form the other major division in many earlier studies, and this group has also been subdivided [see *Warner et al.*, 1985, among others]. However, as discussed elsewhere [*Ragland et al.*, this volume], the OLT and LTQ types appear to be gradational and closely related, and so they are best considered as variants of the same low TiO_2 (0.4 to 0.8 wt. %) basalt group.

The HTQ tholeiites have also been referred to as initial Pangaean Rift (IPR) tholeiites [*Puffer*, 1994], because in the Mesozoic basins of northeastern North America and northwestern Africa, the HTQ/IPR flows are the oldest in the stratigraphy. However, this group (with its derivative HFQ) is now known to be the most widespread across the CAMP, and much of it could be of a different age outside of the northeastern USA and Morocco. In fact, relative to other flood basalt provinces [*Peate and Hawkesworth*, 1996], the Ti contents of HTQ magmas (typically 0.9 to 1.5 wt. %) are not high. Other CAMP basalts with quite high TiO_2 contents (2 to 5 wt. %) are now recognized in a central region of the CAMP, particularly in Liberia, Guiana, Surinam, and possibly Brazil [*Choudhuri*, 1978; *DuPuy et al.*, 1988; *Mauche et al.*, 1989; *Oliveira et al.*, 1990; *Bellieni et al.*, 1992]. As a result, a new three-fold classification can be used for all CAMP tholeiites: *LTi* for low-Ti olivine and quartz tholeiites (old OLT + LTQ + some HFQ); *ITi* for intermediate-Ti quartz tholeiites (old HTQ + most HFQ); and *HTi* for high-Ti quartz and olivine tholeiites (Table 1).

The LTi and ITi basalt analyses that include volatiles are plotted on diagrams for this study. Figure 2 illustrates their classification on an SiO_2-total alkalies diagram [*Le-Bas et al.*, 1986], in which most LTi tholeiites plot as "Basalt" with a few samples in "Picro-basalt" (i.e. olivine rich), and ITi basalts fall along the boundary of "Basalt and "Basaltic Andesite," with some samples trending into "Basaltic Trachy-andesite" and also into higher-SiO_2 types. Selected analyses of HTi dikes (outlined by a dotted line on Fig. 2) fall within the "Basalt" field.

As a generality, LTi olivine tholeiite dikes are abundant from South Carolina to central Virginia in the southeastern USA (west-central Pangaean CAMP), LTi quartz tholeiites are common in most of the eastern USA, and the LTi type is more scattered elsewhere in the CAMP. HTi tholeiites

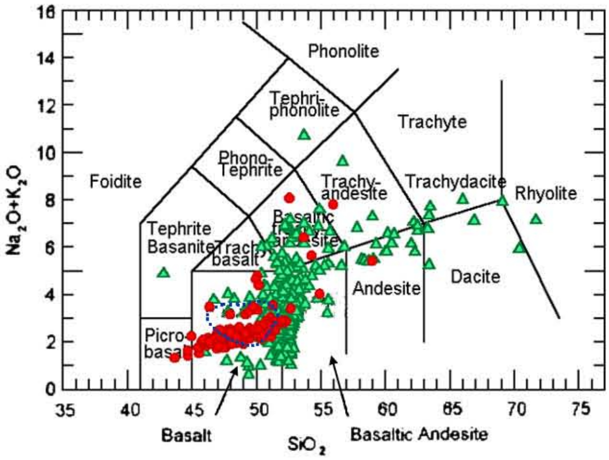

Figure 2. CAMP tholeiite groups plotted on an SiO_2-Total Alkalies classification diagram (LeBas et al., 1986). Symbols: green triangles = ITi dikes and sills; red circles = LTi dikes; dotted blue line in the basalt field encloses HTi dike analyses

are concentrated along the western Africa-northern South America margins (east-central Pangaean CAMP) and possibly into the subsurface of central Florida; and ITi tholeiite dikes, sills, and basalt flows predominate everywhere else in the CAMP. This is a semi-concentric configuration, as shown schematically in Figure 1. Some tholeiites that are intermediate between LTi and ITi are found in the transition zone between the core of LTi and outer zones of ITi within the CAMP; i.e., in central Georgia through eastern Alabama and northern Virginia through Connecticut [*Puffer*, 1992; *Ragland et al.*, 1992]. The central position of HTi rocks in Guyana, Liberia, and Surinam also invite special interest in their relationship to the other major magma types, and in their own implications for mantle geodynamics.

CAMP VOLATILES

Publications that include volatile-element analyses of CAMP basalts are uncommon. By far, the largest group of such analyses is presented by Grossman et al. [1991], which is a summary of geochemical studies by the U. S. Geological Survey from 1984 to 1990 of dikes and sills associated with Mesozoic basins in the eastern United States. Except for platinum-group elements, many of the 960 analyses listed by Grossman et al. [1991] are incomplete, but 686 examples list some combination of CO_2, H_2O+, S, Cl, and F, each in weight percent.

Field and chemical methods used for samples in the USGS data set are described by Gottfried et al. [1991]. Most major elements were analyzed via standard "rapid rock" XRF techniques [*Shapiro*, 1975]. H_2O+ (water bound in minerals) was measured by differential heated samples and filter weights as described by Shapiro [1975], and CO_2 was analyzed via a colorimetric technique of Engleman et al. [1985]. S was determined from SO_2 by combustion in a sulfur analyzer [*Kirschenbaum*, 1983]. Cl was determined as chloride by the selective ion method of Aruscavage and Campbell [1983]. Fluorine was analyzed as fluoride by the selective ion method of Kirschenbaum [1988]. Estimates of analytical precision and error are not described in detail by Gottfried at al. [1991], but essentially the oxides and volatile elements (averaged in Table 1) were rounded to two significant decimal places, in weight %. For volatiles that commonly occur only as trace amounts, such as F and S, this round off resulted in many reported analyses of 0.00, 0.01, and other values in intervals of a few hundreds percent. This commonality of values is not significant for averages of many analyses (Table 1), but it becomes more apparent in element plots of individual samples.

Using the group classification outlined by Weigand and Ragland [1970], analyses with one or more volatiles include 530 samples labeled as HTQ (high-Ti quartz-normative tholeiite); 14 samples labeled as HFQ (high-Fe quartz-normative tholeiite); 36 samples labeled as LTQ (low-Ti quartz-normative tholeiite; and 106 samples labeled as OLT (olivine-normative tholeiite). The large proportion of HTQ samples is due to an emphasis on sills and other low-angle sheet intrusions, which for an unknown reason were derived mainly from HTQ dikes in eastern North American basins. As discussed previously, the HFQ and HTQ samples are combined as the ITi (intermediate titanium) tholeiite super-group, while the OLT and LTQ samples are combined as the LTi (low titanium) super-group. Averages of these two sample groups are presented in Table 1.

To examine sample volatile distributions and possible magmatic differentiation trends, the LTi and ITi samples were plotted against Mg#'s (100xMg/Mg+Fe*) of their analyses, in which the Mg# varies mainly from olivine (in LTi) and pyroxene (in ITi) fractionation [*Puffer*, 1992; *Ragland et al.*, 1992]. The range of H_2O+ is similar in both the groups (Fig. 3A), but water contents in the ITi increase toward lower Mg#'s. CO_2 appears to have the same range of values in a total sample plot (Fig. 3B), but with a stretched Y scale, it can be seen that the LTi group has a higher proportion of higher CO_2 values than ITi group samples (Fig. 3C).

S, F, and Cl are also not evenly distributed. In Figure 4, it is apparent that S is more abundant in LTi samples in general, while Cl and to a lesser extent F are more abun-

Table 1. Compositions of CAMP Basalts and Comparison Basalts

	LTi			ITi			HTi			Laki	Roza
	Mean	s.d.	n	Mean	s.d.	n	Mean	s.d.	n	glass	dikes
SiO_2	48.84	2.27	142	52.61	2.54	574	51.87	2.04	60	49.68	51.45
TiO_2	0.62	0.29	142	1.26	0.62	574	3.21	0.48	60	2.96	3.40
Al_2O_3	16.06	1.67	142	14.06	1.62	574	14.32	1.27	60	13.05	12.80
FeO*	9.92	1.08	142	10.73	1.93	627	12.14	1.65	60	13.78	14.46
MnO	0.16	0.05	142	0.18	0.03	574	0.19	0.02	60	0.22	0.25
MgO	9.46	2.44	130	6.72	3.13	574	4.11	1.16	60	5.78	4.07
CaO	10.92	1.30	142	9.92	2.11	604	7.64	1.09	60	10.45	8.32
Na_2O	2.07	0.46	142	2.44	0.90	627	2.87	0.38	60	2.84	2.73
K_2O	0.46	0.62	142	0.83	0.64	574	1.65	0.56	60	0.42	1.36
P_2O_5	0.10	0.08	142	0.17	0.11	574	0.58	0.19	60	0.28	0.75
H_2O+	0.981	0.779	130	0.850	0.570	535	(0.19)			0.19	
CO_2	0.091	0.153	133	0.124	0.671	535	(0.148)			0.148	
S	0.067	0.041	135	0.034	0.032	421	(0.111)			0.168	0.111
F	0.023	0.055	91	0.030	0.022	411	(0.102)			0.066	0.102
Cl	0.030	0.037	37	0.064	0.086	429	(0.024)			0.031	0.024
Mg#	61.98	7.61		50.19	15.43		37.65			42.77	33.38
Density	2.683	0.037		2.647	0.045		2.652			2.713	2.695

LTi and ITi analyses are from Grossman et al. [1991], as described in the text. HTi analyses are from Choudhuri [1978], DuPuy et al. [1988], Mauche et al. [1989], and Oliveira et al. [1990], with volatiles in parentheses assumed from the Laki and Roza values. Laki (Iceland) glass inclusion data are from Thordarson et al. [1996]; Roza dike selvage data (Columbia River basalt group) are from Thordarson and Self [1996]. Components are in weight percent. FeO* is total iron as FeO. Mg# is 100xMg/(Mg+Fe*). Density is calculated on a normalized basis, using the method of Bottinga and Weill [1970].

dant in the ITi samples. This is also clear in a plot of those three volatiles against Mg#'s (Fig. 5), which indicates an increase of both Cl and F with lower Mg#'s. No such trend is apparent for S, which is generally higher in the LTi type. Averages of these elements in Table 1 support these plotted distributions.

The HTi (high titanium) tholeiites of the central Pangaean rift zone lack published analyses of volatile elements. However, their bulk compositions are similar to flood basalts of the Miocene-age Roza flow of the Columbia River basalt province [*Thordarson and Self,* 1996] and also the historic Laki flow of Iceland [*Thordarson et al.*, 1996], and for the purposes of this review, similar volatile contents have been assumed for the CAMP HTi basalts (Table 1).

In addition to measurements of aerosols at active volcanoes and in ice cores [*Pyle et al.*, 1996], several studies compare volatile contents of source dikes and magmatic glass inclusions with volatiles in the lavas from those dikes. Martin [1996] described sulfur in several dikes and flows of the Wanapum basalt of the Columbia River basalt group, with original dike S contents of about 300 to 2800 ppm in source dikes dropping to 70 to 590 ppm in corresponding flows. The average of 60 to 70 % loss was primarily at the fissure vents, with up to 2 x10^9 metric tons of SO_2 emitted per eruptive event. A study of Columbia River basalt group flows by Thordarson and Self [1996] suggests that vent emissions represented about 90 % of the original magmatic sulfur (as SO_2), 37 % of the chlorine (as HCl), and 30 % of the fluorine (as HF). Similarly, Thordarson and others [1996] found that emissions at the Laki, Iceland eruption included over 85 % of the original magmatic S, 50 % of the original Cl and F, and 80 % of the original CO_2.

Because there are no studies comparing volatiles of CAMP source dikes with volatiles in their resultant lava flows, a conservative estimate of 70 % release of S, CO_2, and H_2O, and 50 % release of F and Cl from basalt type averages in Table 1 is used for calculations of CAMP volcanic emissions in Table 2. Surface lava proportions of 70 % ITi, 20 % LTi, and 10 % HTi were assumed for the purpose of calculating weighted total emissions. Magmatic densities for the three types were calculated in Table 1, and a weighted average of 2.655 tons/m^3 was used in converting volumes into basalt mass units. The total calculated volatile emissions by basalts of the CAMP range from 1.11 x 10^{12} metric tons for F, to 5.19 x 10^{12} tons for CO_2 (Table 2). As discussed below, this total is for all volcanic events

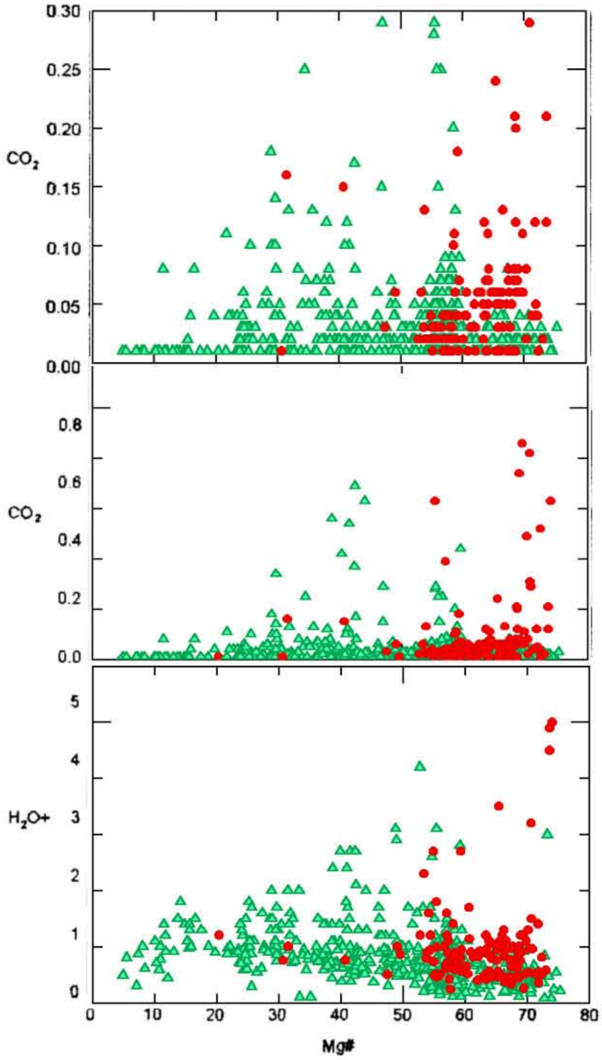

Figure 3. Mg# (100xMg/Mg+Fe*) vs.H_2O+ (A) as water bound in mineral structures, and CO_2 (B and C, scale change) as mainly in carbonate minerals, for LTi and HTi CAMP basalts of the eastern USA. Symbols are explained in Fig. 2.

spread over the entire age range of the CAMP, much of which postdates the Tr-J mass extinction.

DISCUSSION

Sulfur Emissions

The enormous scale for sulfur ejections from the CAMP encourages an assumption that they caused at least several drastic cooling events that lasted a few seasons or years each, as caused by higher optical densities of the upper atmosphere in proportion to historic eruptions (*Stothers et al.*, 1986). Cooling events would have been repeated for each episode of CAMP volcanism, with gaps between the episodes of perhaps centuries to many thousands of years. Sulfur-based aerosols diminish rapidly within a year to several years [*Pyle et al.*, 1996]. A fissure eruption on the scale of CAMP dikes would be active for months or years [*Thordarson and Self*, 1996], and could overlap in time with other eruptions across the province to cause longer periods of sulfur injections into the atmosphere. The actual amount of cooling can only be quantified by determining the precise duration and volume of each CAMP magmatic event. Alternately, evidence for or against cooling may become available through new studies of organic fossils, sediment isotope chemistry, or Milankovitch cyclo-stratigraphy.

Although the total CAMP sulfur emission of 2.31×10^{12} tons (Table 2) might imply cooling of 20 °C or more (Fig. 6), individual CAMP lava flows probably were closer in size to the Roza flow of the Columbia River basalt group [*Thordarson and Self*, 1996], which indicate releases of about 10^{10} tons of S into the atmosphere for each major fissure eruption. Such volumes, if rapidly injected during brief eruptions, could cause global cooling of between 2 and 8 °C for a few months to years if the projected extrapolation from historic eruptions is accurate in Figure 6 (essentially with the surface darkness of a moon-lit night) [*Rampino et al.*, 1988]. In addition, it is not clear whether very large volumes of sulfide aerosols are likely to cause

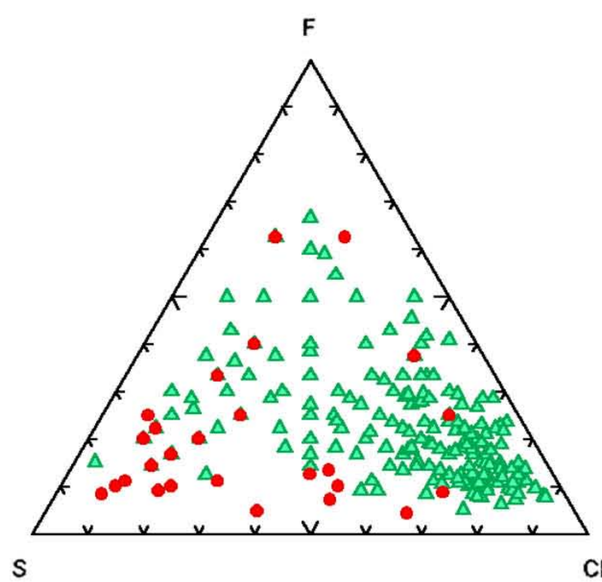

Figure 4. Ternary plot of sulfur, fluorine, and chlorine in LTi and HTi CAMP basalts of the eastern USA. Symbols are explained in Fig. 2.

the extreme temperature declines of Figure 6. The largest CAMP eruptive event may be represented by IPR lavas of northeastern North America, which covered an area about 20 times larger than the Roza flow, but only about 3 times its volume [*McHone*, 1996]. Thus, temperature declines between 2 °C and 10 °C are reasonable expectations.

Carbon Dioxide Emissions

Long-term Holocene climatic temperature changes have been closely correlated with atmospheric CO_2, especially from studies of Antarctic ice cores [EPA, 1990]. During the past 160,000 years, local Antarctic temperatures varied from -8 °C to +2 °C relative to modern temperatures as CO_2 varied from 190 to 305 ppmv (parts per million-volume). Such observations have led to suggestions that extreme global heating could have resulted from massive CO_2 emissions by flood basalts, with an example of Deccan Traps (India) volcanism causing or contributing to the K-T mass extinction [ex. *Officer and Drake*, 1985, among others]. Even a few degrees of rapid increase in climate temperatures could disrupt reproduction in reptilian animals, as well as cause other major life-cycle stress in terrestrial and marine fauna and flora.

Caldeira and Rampino [1990] estimated a total emission of CO_2 from the Deccan basalts of 2.6 to 8.8 x 10^{12} metric tons, which is comparable to CAMP CO_2 calculations in Table 2. They note that the solubility of CO_2 in basaltic magma at surface pressure is only about 0.03 weight %, so that the estimate of original Deccan basalt CO_2 of 0.2 % [*Leavitt*, 1982] requires the loss of up to 80% of that volatile during volcanic activity. However, when calculations include buffering effects from the oceans, plants, and inorganic weathering, volcanic emission time spans of 10 kyr to 500 kyr result in climatic temperature increases of only 0.7 to 0.1 °C from Deccan CO_2 [*Caldeira and Rampino*, 1990. Fig. 1].

More recently, McElwain and others [1999] studied changes in fossil plant stomata from samples around the Tr-J extinction boundary, which they interpret to indicate a 4-fold increase in atmospheric CO_2 at the boundary. Such a change might correspond to a greenhouse warming of 3 to 4 °C, which would be widely lethal to many plants and animals, and McElwain and others [1999] suggest a relationship to CAMP volcanic CO_2 emissions. The uncertainty of exact timing for particular volumes of CAMP volcanism remains a problem for modeling cause and effect, but assumptions for buffering effects as used in the calculations of Caldeira and Rampino [1990] are also imprecise. Rapid eruptions might temporarily overwhelm some buffers, or there may be triggers of reinforcing events such as releases of marine methane.

Halogen Emissions

Fluorine poisoning of livestock and acid damage to crops led to severe famine as a direct result of the Laki, Iceland eruption of 1783-1784 [*Grattan and Charman*, 1994]. Similar fluorine emission problems continue to be a major concern during modern eruptions in Iceland.

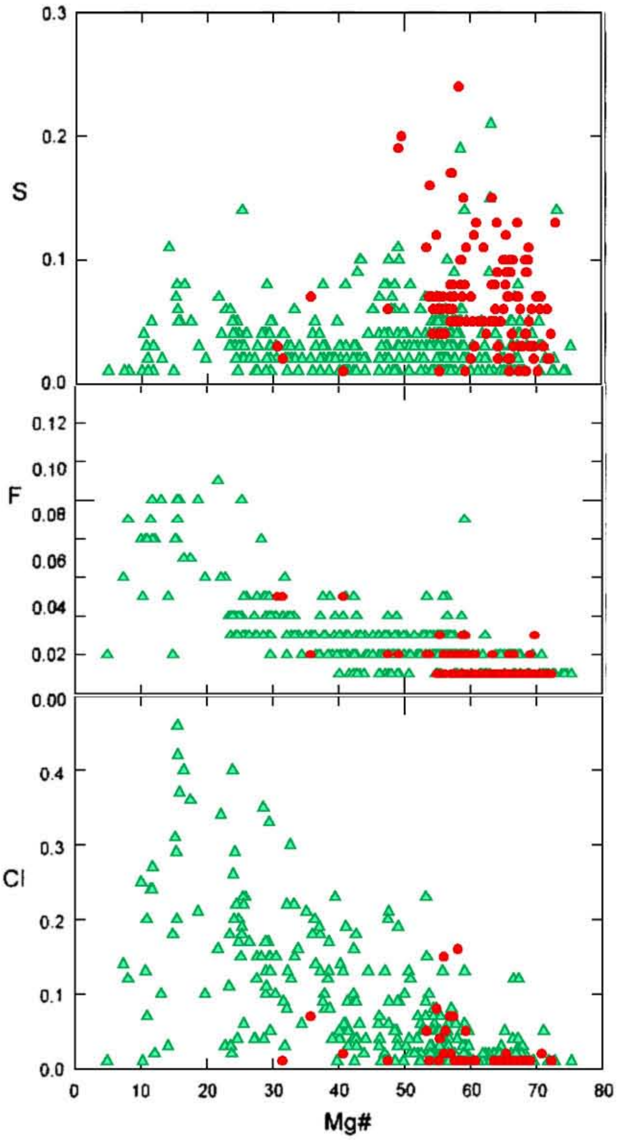

Figure 5. Mg# (100xMg/Mg+Fe*) vs. chlorine, fluorine, and sulfur in LTi and ITi basalts of the eastern USA. Symbols are explained in Fig. 2.

Table 2. Sizes, Volumes, and Emissions Estimated for CAMP

BASALT LAVAS	Basin	Basalt Type	Area km2		Avg. T km	Vol. km3
	Fundy	ITi	22500		0.4	9000
	Hartford	ITi/LTi	4500		0.3	1350
	Newark	ITi/LTi	5600		0.3	1680
	Gettysburg	ITi/LTi	2400		0.1	240
	Culpeper	ITi/LTi	22500		0.2	4500
	SoGeorgia	LTi	100000		0.2	20000
	Argana	ITi	70000		0.2	14000
	Offshore	LTi	100000		0.1	10000
	non-basin	ITi/LTi	20000		0.1	2000
LAVA TOTALS			347500			62770
BASALT SILLS	Region	Basalt Type	Area km2		Avg. T km	Vol. km3
	NE USA	ITi	17500		0.2	3500
	SE USA	LTi	2000		0.2	400
	Africa	ITi	150000		0.3	45000
	SoAmerica	ITi	1000000		0.5	500000
SILL TOTALS			1169500			548900
BASALT DIKES	Number	Length km	Total Length	Depth km	Width km	Vol. km3
Very long dikes	10	500	5000	50	0.05	12500
Long dikes	20	200	4000	50	0.04	8000
Medium dikes	100	50	5000	50	0.02	5000
Short dikes	300	20	6000	50	0.01	3000
DIKE TOTALS	430		20000			28500
EAST COAST MARGIN I.P.	Length km	Width km	Thick. km	Area km2	Vol. km3	Aerial Vol.
	2000	55	25	110000	2750000	1375000
EMISSIONS	No. Amer.	ECMIP	Europe	Africa	So Amer.	Total CAMP
CAMP area km2	1400000	1100000	700000	4500000	3500000	11210000
Lava vol km3 (1)	140000	1375000	70000	450000	350000	2385000
Lava mass tons (2)	3.72E+14	3.65E+15	1.86E+14	1.20E+15	9.30E+14	6.34E+15
avg CO2, wt.% (3)	0.117	0.117	0.117	0.117	0.117	0.117
Total CO2 emission (4)	3.05E+11	2.99E+12	1.52E+11	9.80E+11	7.62E+11	5.19E+12
avg S, wt.% (3)	0.052	0.052	0.052	0.052	0.052	0.052
Total S emission (4)	1.35E+11	1.33E+12	6.77E+10	4.35E+11	3.39E+11	2.31E+12
avg F, wt.% (3)	0.035	0.035	0.035	0.035	0.035	0.035
Total F emission (4)	6.51E+10	6.40E+11	3.26E+10	2.09E+11	1.63E+11	1.11E+12
avg Cl, wt.% (3)	0.050	0.050	0.050	0.050	0.050	0.050
Total Cl emission (4)	9.30E+10	9.14E+11	4.65E+10	2.99E+11	2.33E+11	1.58E+12
avg H2O+, wt.% (3)	0.823	0.823	0.823	0.823	0.823	0.823
Total H2O emission (4)	2.14E+12	2.11E+13	1.07E+12	6.89E+12	5.36E+12	3.65E+13

Notes: (1) assuming 1/2 CAMP area is covered with 0.2 km of lava (except ECMIP = 12.5 km); (2) weighted average density of 2.658 metric tons/m3; (3) weighted averages (see text); (4) in metric tons, with proportions as in the text.

Large ejections of halogens may also affect atmospheric chemistry, leading to ozone depletion [*Sigurdsson*, 1990]. Gaseous halogens will be converted in the atmosphere to halides such as HCl, and rainfall made acidic by Laki HCl and HF (in addition to H_2SO_4) may also have caused severe crop and tree damage in Great Britain [*Grattan and Charman*, 1994]. However, these effects must be temporary because halide aerosols are rapidly dissipated by

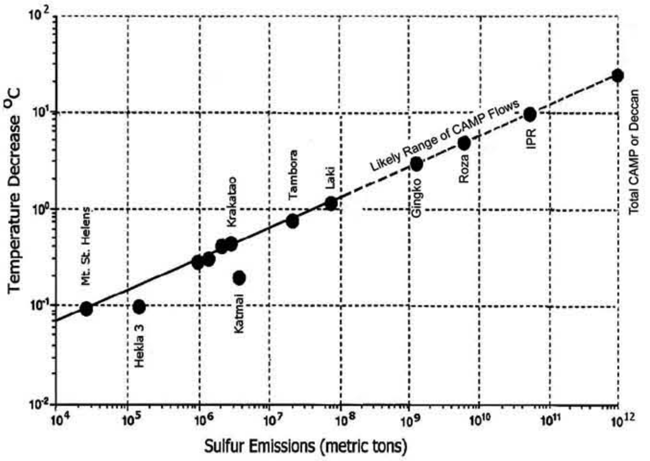

Figure 6. Volcanic sulfur vs. climatic temperature decrease, adapted from Palais and Sigurdsson [1989]. The dashed line is extrapolated from the labeled historic eruptions, and it may exaggerate the hypothetical temperature decrease. The Gingko and Roza flow data are from the Columbia River basalt group [*Martin*, 1996; *Thordarson and Self*, 1996], and the IPR basalt of northeastern North America is calculated after McHone [1996].

rainfall, and serious effects may be confined to local regions down-wind from the fissures.

Summary

Table 3 summarizes the environmental effects of volcanism. Note that the time scales involved (a few months to a few millennia) remain far smaller than age uncertainties for CAMP events (hundreds of millennia). Although the amounts of injected materials can only be estimated, and the eruptive time scales are speculative, the volcanic plume mechanisms and environmental effects are well documented in historic eruptions and studies of ice cores.

Many fossils of plants and animals, including a limited variety of tracks from the earliest Jurassic dinosaurs, are found in strata deposited between major CAMP lava flows in basins of the northern CAMP [*Olsen*, 1997]. Thus, within a few hundred thousand years after the Tr-J boundary extinction, new populations of some species had already spread across Pangaea, and they survived several subsequent volcanic events of the CAMP that are represented in the northern basins.

CONCLUSION

The enormous scale for atmospheric injections of aerosols from CAMP volcanic fissure eruptions makes it likely, although unproven, that they caused both short-term cooling events for several years or decades each, and longer-term heating events for hundreds to thousands of years. Destruction of habitat by lavas and ash falls, changes in rainfall patterns, and poisoning of plants and animals from halide precipitation were major environmental problems on a regional scale. There is also some likelihood for extensive wildfires across Pangaea from the long fissures, similar to the proposed effect from bolide impacts.

The most extreme problems that actually caused the Tr-J mass extinction must predate a large portion of the CAMP volcanic activity, as shown by basin stratigraphy in the northern CAMP areas. Unless new stratigraphic evidence in the southern regions or in buried sections of the CAMP can be found to correlate the extinction more exactly with volcanism, a cause-and-effect link must rely on better precision in radiometric dates.

Table 3. Summary of Environmental Effects of CAMP Volcanism

Feature	Mechanism	Timescale	Geography	Evidence	Effect
Halogens (mainly Cl and F)	Exsolution from magma at vent	Months to years	Local to regional	Paleontology	Poison fauna and flora
Ash and dust	Injection into atmosphere	Months to years	Regional	Stratigraphy	Light block and cooling
Water	Exsolution from magma	Months to years	Regional to global	Sedimentology, Paleontology	Wetter climate
Sulfur Dioxide	Exsolution from magma	Years to decades	Hemispheric to global	Acidic Leaching	Light block and cooling
Carbon Dioxide	Exsolution from magma	Centuries	Global	Plant stomata	Climatic warming
Lava flows	Fissure eruption	Millennia	Local to regional	Stratigraphy	Habitat destruction

Acknowledgments. Correlations and groupings of CAMP basalts are based on many years of interaction with Paul Ragland, the instrumental authority in this field. My enthusiasm for attributing the Tr-J mass extinction to CAMP volcanism has been tempered by the important work of Paul Olsen and his colleagues, whose input I greatly appreciate. Our knowledge of CAMP volatiles is due to the foresight of David Gottfried, Al Froelich, and others at the U. S. Geological Survey. An anonymous reviewer suggested important corrections to the manuscript.

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