Timing of CAMP magmatism in Eastern North America: Potential for Causing the Tr-J Boundary Extinction

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J. Gregory McHone, Geosciences Program, University of Connecticut

The mass extinction at the Tr-J boundary is one of the "big five" catastrophes of Phanerozoic time. Evidence for a coinciding bolide impact remains poor, and the best candidate for causing the extinction is high-volume fissure volcanism of the Central Atlantic Magmatic Province (CAMP). Unfortunately, the huge lava flows of quartz tholeiite in basins across the northern part of the CAMP appear to post-date the extinction horizon by as much as 20,000 years (Olsen, 1997), at least in northeastern North America. However, field aspects of olivine dolerite sills and dikes in the southern USA indicate an age slightly older than the northern basalts, which allows an overlap in time with the boundary extinction.

The earliest event of dike intrusions with fissure volcanism in the northern basins created large sills such as West Rock in Connecticut and the Palisades Sill in New Jersey. Hydrothermal effects of the intrusions led to physical changes of the basin strata, so that subsequent dike generations did not form sills. In North Carolina, the Durham Sill was formed from olivine tholeiite, and so that magma type must be older than non-sill-forming quartz dolerite dikes that also cut its basin. Rare cross-cutting relationships of dikes also show that olivine dolerites are older than the quartz type. Intervals between volcanic events in the northern basins were about 200,000 years or less, and so southern volcanism of olivine tholeiite probably occurred near the end of the Triassic Period, not in the earliest Jurassic. Extensive lava flows of this type still exist in basins buried under the southern coastal plain.

Sulfur in the olivine dolerite dikes and sills averages 0.067 % by weight, which is twice as high as the younger quartz dolerite average. At least 20,000 km^3 of olivine basalt (possibly much more) was extruded across 100,000 km^2 or more of the southern rift basins during this event of fissure volcanism. This is more than a thousand times larger than the Laki fissure eruption of 1783-1784, in which sulfur aerosols cooled the northern hemisphere about 1° C and caused crop failures and famine. The southern CAMP olivine basalts had the size, location, timing, and emissions to cause the mass extinction at the Tr-J boundary.

Did CAMP volcanism of olivine basalt (LTi) magmas cause the Tr-J mass extinction? Arguments and evidence:

1. Location and volume of LTi magmatism:
   - a. mainly southern USA, in central Pangaea close to the equator, covering at least 100,000 sq km.
   - b. about 20,000 cubic km present today, probably much more when it formed.

2. Types of magmas:
   - a. wide zone of NW-SE dikes of low-Ti (LTi) high-Mg olivine basalts, overlapped by a narrower N-S swarm of intermediate-Ti (ITi) quartz tholeiitic dikes.

3. Timing of LTi magmatism relative to the Tr-J boundary:
   - a. Ar dates indicate 199 Ma, within error for northern ages.
   - b. sills of olivine basalt in the south indicate LTi magmatism predates northern ITi quartz tholeiite.

4. Volatile composition of LTi magmas, and estimates of emissions:
   - a. wt. %: CO_2 = 0.091; S = 0.067; F = 0.023; Cl = 0.030
   - b. metric tons: 5.31 x10^{10} basalt; 4.832 x 10^7 CO2; 3.558 x10^7 S; 1.173 x10^7 F; 1.593 x10^7 Cl

5. Killing mechanisms:
   - a. initial cooling from sulfuric fog of 10 degrees C for years.
   - a. subsequent heating from CO_2 of 10 degrees for millennia.

6. Additional research needed:
   - a. more precise dates, such as by U-Pb analysis of zircons.
   - b. mapping of basalt flows buried beneath the coastal plain.
   - c. better correlations of buried basalts with exposed dikes.

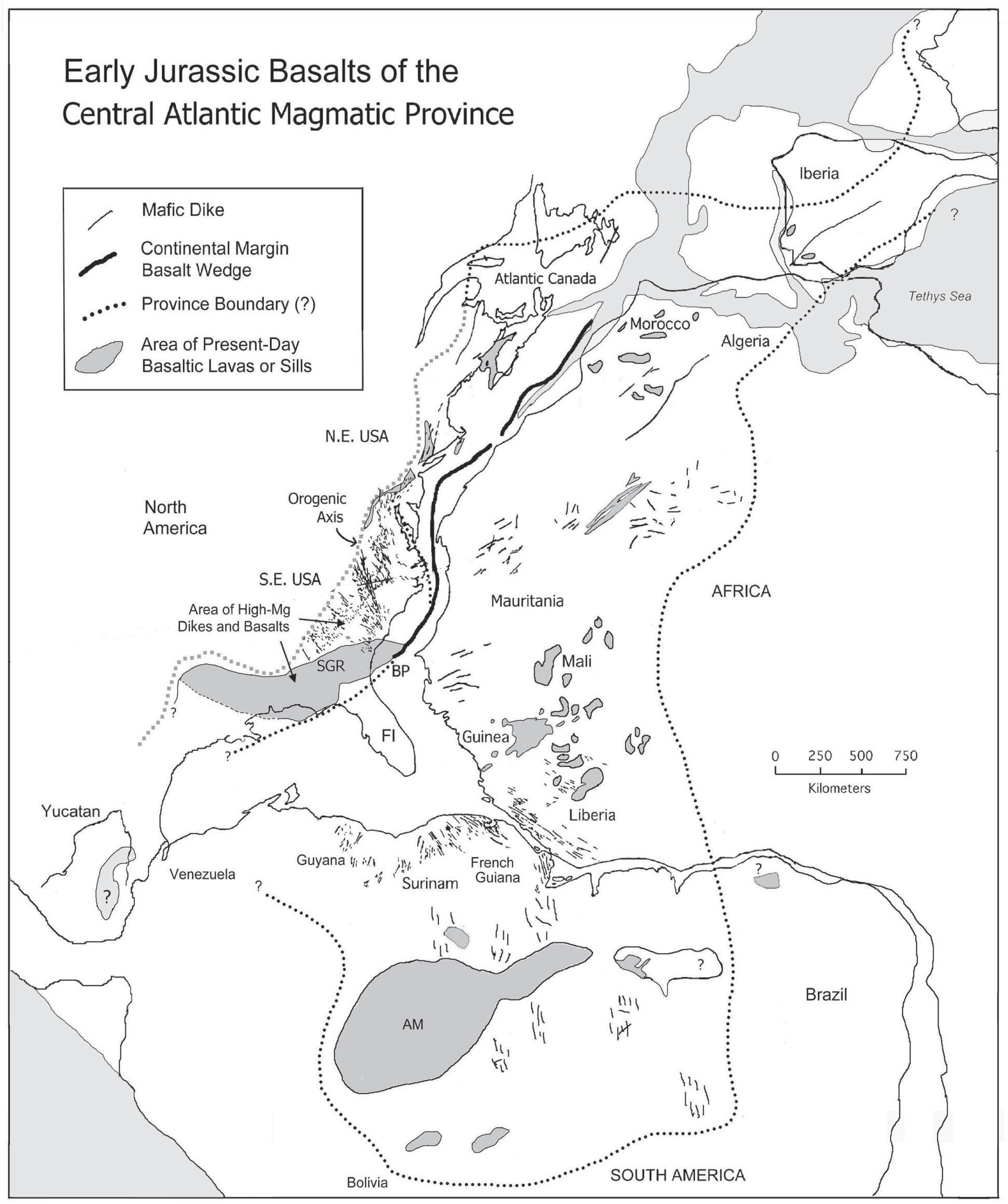


Table 4: Flood Basalt Provinces of the last 250 Ma (modified from Rampino and Self, 1990)

Province	Age (Ma)	Vol. (10^6 km^3)	Paleo-latitude	Duration (Ma)
Columbia River	16 ± 1	0.25	45ºN	~ 1 (for 90%)
Ethiopia	31 ± 1	~ 1.0	10ºN	~ 1
North Atlantic	57 ± 1	>1.0	65ºN	~ 1
Deccan	66 ± 1	>2.0	20ºS	~ 1
Madagascar	88 ± 1	?	45ºS	~ 6?
Rajmahal	116 ± 1	?	50ºS	~ 2
Serra Geral/Etendeka	132 ± 1	>1.0	40ºS	~ 1 or ~ 5?
Antarctica	176 ± 1	>0.5	50-60ºS	~ 1?
Karoo	183 ± 1	>2.0	45ºS	0.5 - 1
CAMP	200 ± 1	>2.4?	10ºS - 30ºN	~ 0.6
Siberian	249 ± 1	>2.0	45ºN?	~ 1

Table 1. Compositions of CAMP Basalts and Comparison Basalts.

	LTi Mean	LTi s.d.	LTi n	ITi Mean	ITi s.d.	ITi n	HTi Mean	HTi s.d.	HTi n	Laki glass	Roza 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].

Table 2. Sizes, Volumes, and Emissions Estimates 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	60000	700000	4500000	3500000	10160000
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)	2.18E+11	2.14E+12	1.09E+11	7.00E+11	5.44E+11	3.71E+12
avg S, wt.% (3)	0.052	0.052	0.052	0.052	0.052	0.052
Total S emission (4)	9.68E+10	9.50E+11	4.84E+10	3.11E+11	2.42E+11	1.65E+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)	1.53E+12	1.50E+13	7.66E+11	4.92E+12	3.83E+12	2.61E+13

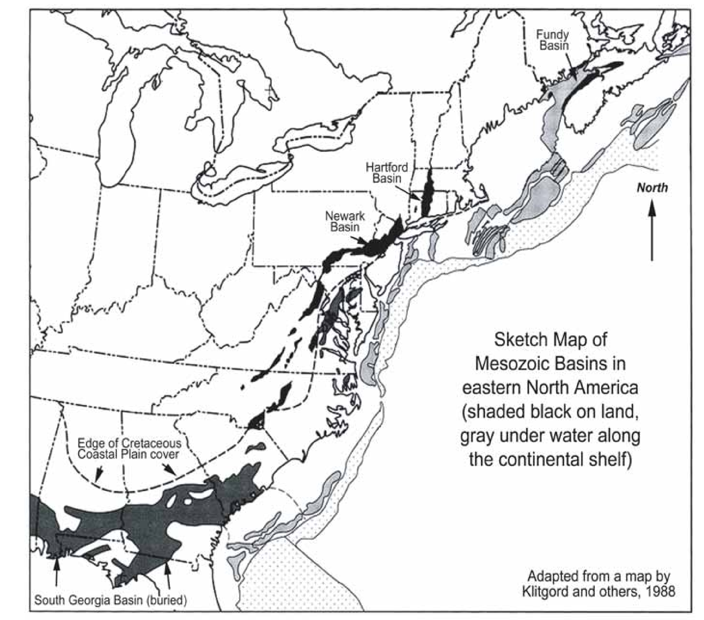
Notes: (1) assuming 1/2 CAMP area is covered with 0.2 km avg.lava thickness (ECMIP=25); (2) weighted average density of 2.655 metric tons/m3; (3) weighted averages (see text); (4) in metric tons, assuming 1/2 of volatiles escape.

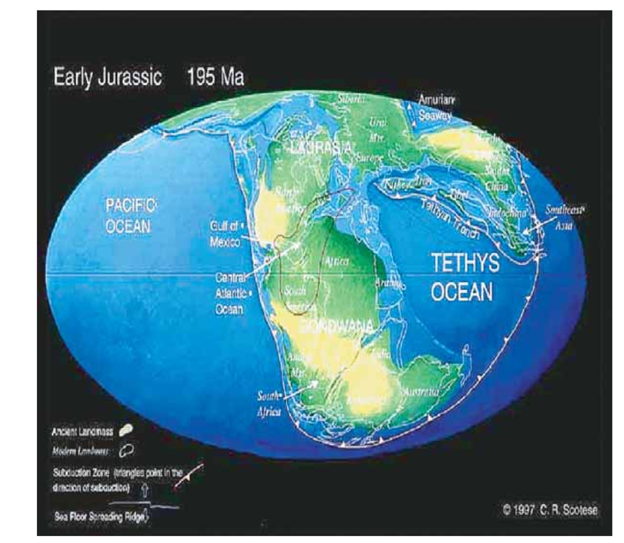
Table 3. Summary of environmental effects from CAMP volcanic features.

Feature	Mechanism	Timescale	Geography	Evidence	Effect
Halides (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	Eruption	Millennia	Local to regional	Stratigraphy	Habitat destruction

1. Location and volume of LTi magmatism:

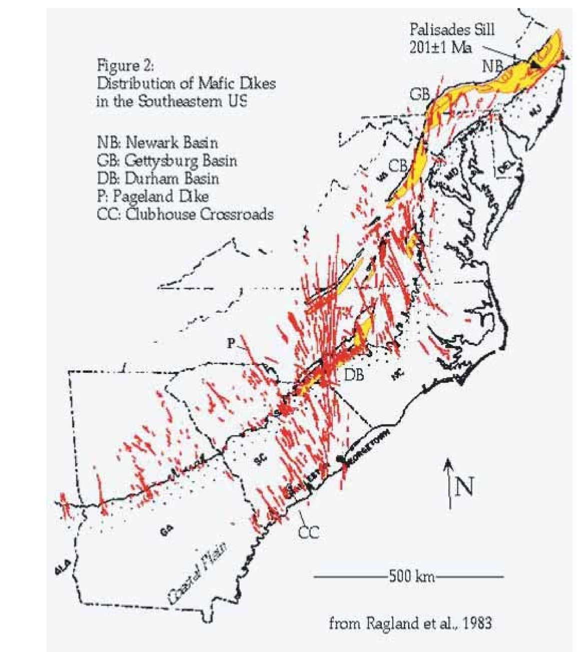
a. mainly southern USA, in central Pangaea close to the equator, covering at least 100,000 sq km.
b. about 20,000 cubic km present today, probably much more when it formed.

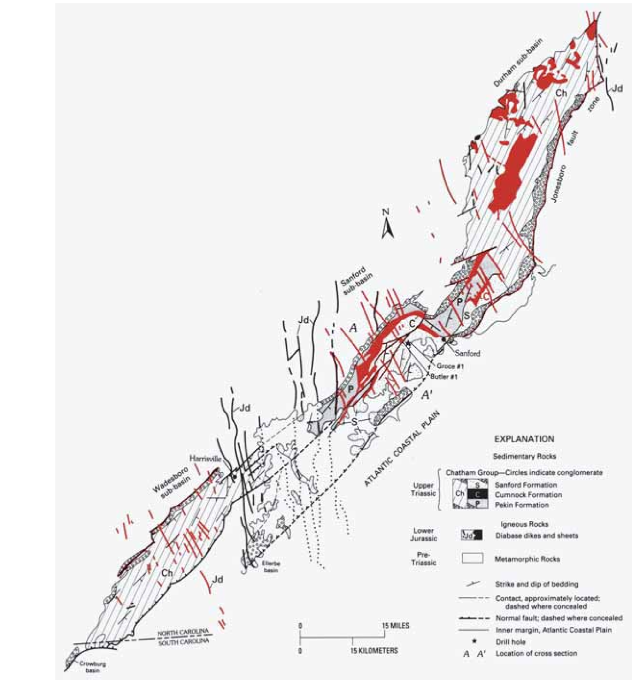




2. Types of magmas:

a. wide zone of NW-SE dikes of low-Ti (LTi) high-Mg olivine basalts, overlapped by a narrower N-S swarm of intermediate-Ti (ITi) quartz tholeiitic dikes.





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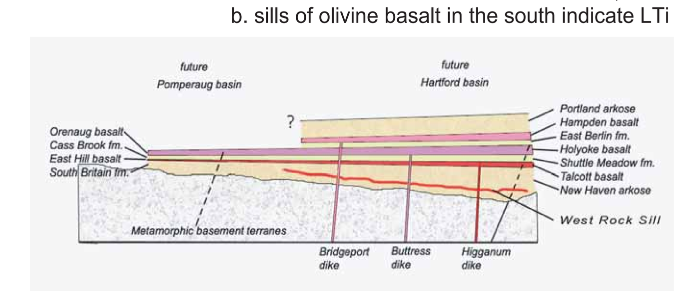
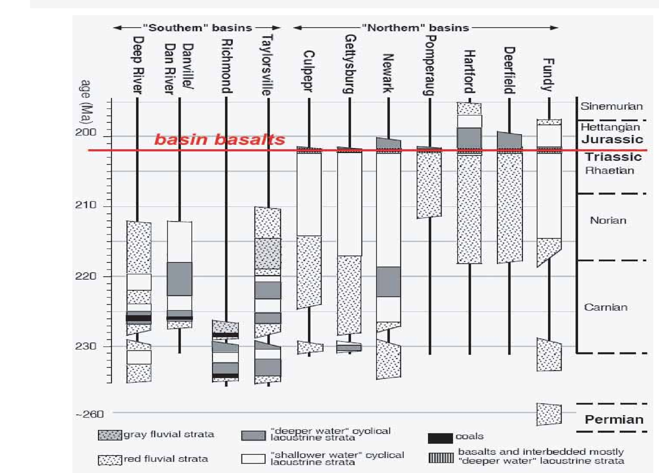
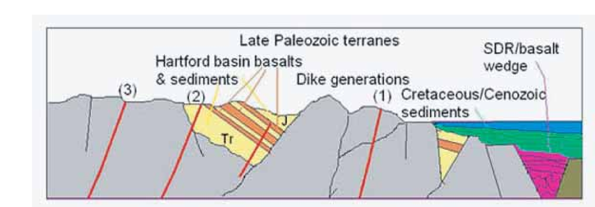
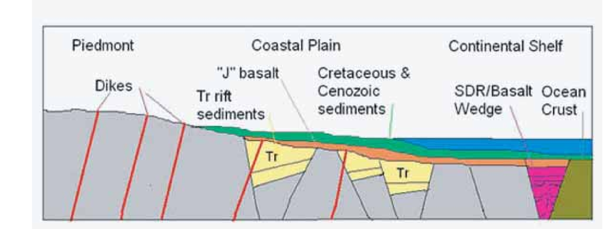






Cross section of the northeastern USA rift zone (southern New England)



Cross section of the southeastern USA rift zone (South Georgia rift)

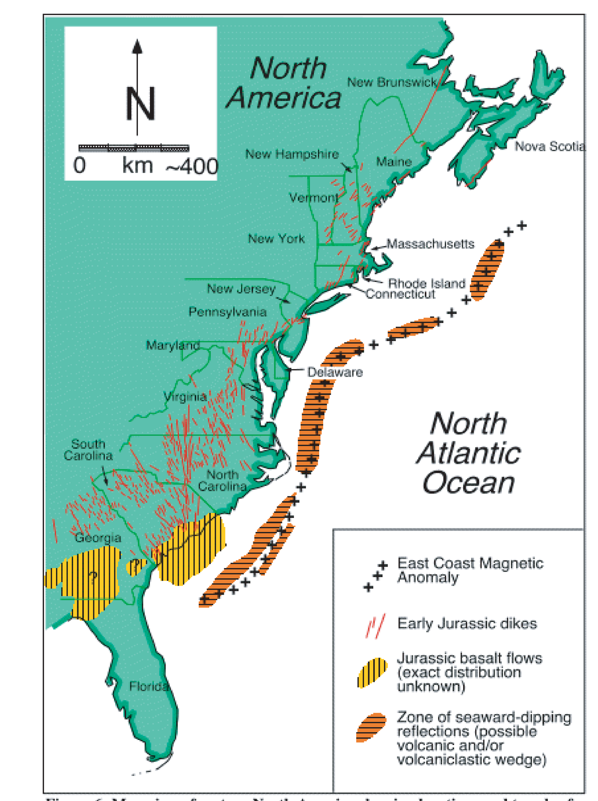


Figure 6: Map view of eastern North America showing locations and trends of dikes associated with eastern North America (ENA) magmatic activity, Jurassic basalt flows of the southeastern United States, and inferred volcanic or volcaniclastic wedge (after Dillon et al., 1983; Benson and Doyle, 1988; McHone, 1988; McBride et al., 1989; Austin et al., 1990; Sheridan et al., 1993; Keen and Potter, 1995; Oh et al., 1995).

RADIOMETRIC AGES

LTi Magmas Southeastern USA	199 ± 2 Ma	Nomade et al., 2006; Beutel et al., 2005; Hames et al., 2000
ITi Magmas Northern, Eastern, Southern CAMP (all areas except deep-south USA)	199 ± 2 Ma	Nomade et al., 2006; Marzoli et al., 2004; Marzoli et al.,1999; Deckart et al., 1997; McHone, 1996
HTi Magmas Central CAMP (Northern South America, West Africa, subsurface Florida)	193± 3 Ma	Nomade et al., 2006; de Min et al., 2003; Baksi, 2003; Deckart et al., 1997

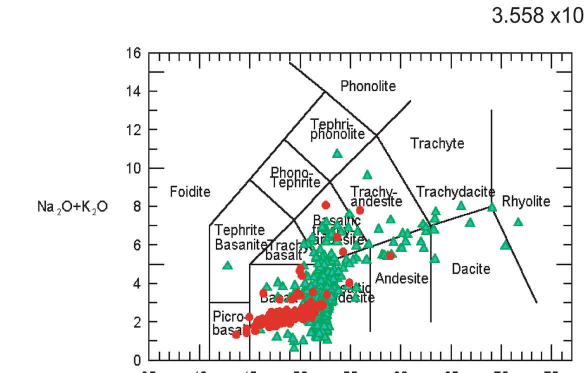
STRATIGRAPHIC AGES

ITi Magmas Northern CAMP (Northeastern USA, Northwestern Africa)	Three episodes within 600,000 years, starting >10,000 years after the Tr-J boundary.	Olsen, 1997
LTi Magmas Southeastern USA	Some are older than ITi magmas, also some possibly contemporaneous.	

Implication: the actual spread of magmatic activity for each group is much narrower (± 0.6 Ma) than the precision of radiometric dates (± 2-3 Ma). Thus, radiometric dates are not capable of distinguishing between the ages of LTi and ITi magmatic activity, which may be only a few hundred thousand years apart, and may also overlap in age.

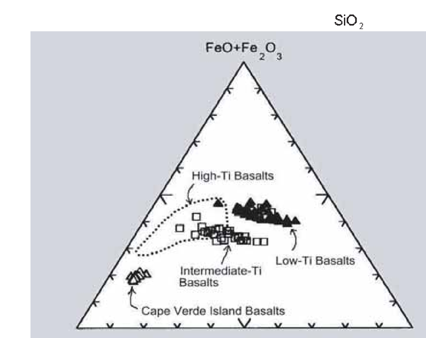
4. Volatile composition of LTi magmas, and estimates of emissions:

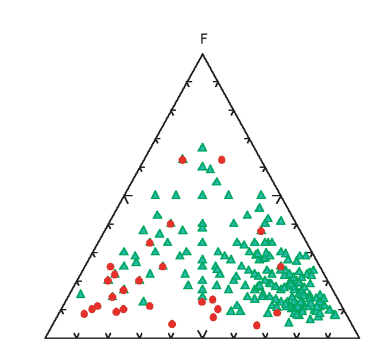
a. wt. %: CO_2= 0.091; S = 0.067; F = 0.023; Cl = 0.030
b. metric tons: 5.31 x10^{10} basalt; 4.832 x 10^7 CO2;
3.558 x10^7 S; 1.173 x10^7 F; 1.593 x10^7 Cl

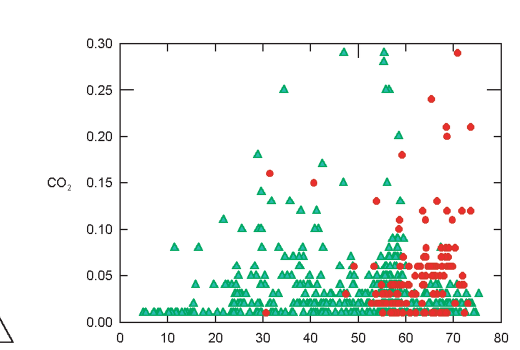


Generalized CAMP Types (averaged)

(wt.%)	ITi	LTi	HTi
SiO2	52.61	48.84	51.87
TiO2	1.26	0.62	3.21
MgO	6.72	9.46	4.11
CO2	0.124	0.091	(0.148)
S	0.034	0.067	(0.111)
F	0.030	0.023	(0.066)
Cl	0.064	0.030	(0.031)
Mg#	50.19	61.98	37.65

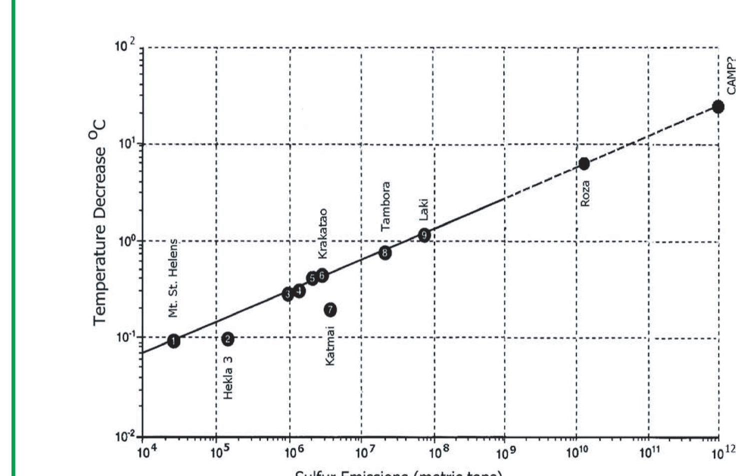






5. Killing mechanisms:

a. initial cooling from sulfuric fog of 10 degrees C for years.
b. subsequent heating from CO_2 of 10 degrees for millennia.



Total sulfur load versus temperature decrease, after Palais and Sigurdsson, 1989