Did the Ilopango TBJ Eruption Cause the AD 536 Event?

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Abstract

The greatest atmospheric aerosol loading event of the past 2000 years occurred in the year ca. A.D. 536. A 'dry fog' enveloped much of the earth and was followed by protracted global cooling lasting more than a decade from ca. A.D 536-550 (**Fig. 1**). Tree ring records, historical accounts, and archaeological records suggest that effects were especially pronounced in the northern hemisphere, where unseasonably cold summer temperatures and crop failures devastated societies from China to the Mediterranean to Mesoamerica. Previous studies have invoked either a comet impact or a volcanic eruption as the likely source of the A.D. 536 global dust veil event, but physical evidence to tie the climatic event to a specific geophysical source has been notably lacking. A recent revision of ice core chronologies and volcanic sulfate (SO_4) deposition records from Antarctica (DML) and Greenland (Dye-3, GRIP, and NGRIP) now point to a large tropical volcanic eruption as the probable source. Here we report data on the phreatoplinian Tierra Blanca Joven (TBJ) eruption of the Ilopango caldera in El Salvador that are consistent with the AD 536 event in terms of chronology, magnitude, and geographic location. Tephra isopach maps give a bulk tephra volume for the TBJ event of ~84 km^3, indicating an eruption magnitude of 6.9 and a VEI of 6+. We suggest that this eruption was probably the source of the AD 536 dust veil and a major contributor to the climatic disturbances that followed.

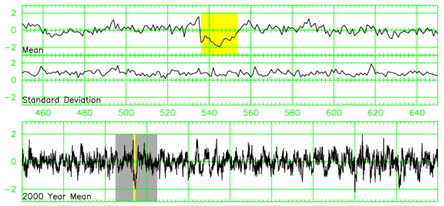

***Figure 1:** Eurasian composite tree ring temperature record from Larsen et al. 2008. yellow bar represents protracted cooling following a presumed tropical volcanic eruption that occurred in AD 535.*

The Ilopango TBJ Eruption

The largest volcanic eruption in Central America since the ~84,000 years BP Los Chocoyos eruption was the Tierra Blanca Joven (TBJ) eruption of the Ilopango caldera in Central El Salvador. Past efforts to reconstruct the impacts of the TBJ eruption have focused on the areas in central and western El Salvador that were most severely affected by pyroclastic flows and deep deposits (50 cm+) of tephra fallout, but the possible broader significance of the eruption in terms of global environmental change has not been addressed. New evidence presented here addresses two issues that until now have impeded a more complete understanding of the eruption's impacts: 1) age determination; and 2) calculation of total erupted magma and SO_2 masses.

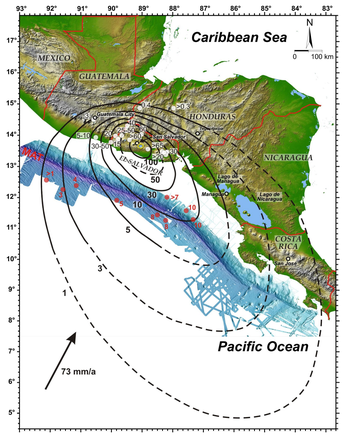

***Figure 2:** Ilopango TBJ tephra isopach map from this study, and based on* **Kutterolf, Freundt, and Peréz** *2008. All isopachs in cm.*

TBJ Erupted Volume and SO_2 emissions

The original estimates of the total erupted volume of the TBJ event were based on limited number of proximal terrestrial tephra outcrop measurements from locations within Central and Western El Salvador, and yielded an estimated total for all erupted products equivalent to ~18 km^3 of DRE, equal to a VEI 6. Over the past decade distal (>100km from source) tephra deposits from the TBJ eruption have been identified by electron microprobe and Laser-ICPMS analyses of individual tephra glass shards in core sediments from Laguna Amatitlan in Guatemala, Lago Yojoa and Laguna Petapilla (Copan) in Honduras, and importantly, from many core samples extracted along the Pacific margin of northern Central America. Also, recent TBJ tephra deposition measurements from eastern El Salvador indicate that 20-150 cm were deposited in this region which was previously thought to have had little or no ash fall from the TBJ event. Here we report a new tephra isopach map constructed from a combination of terrestrial, lacustrine, and marine sediment deposits of the TBJ tephra. All distal deposits have been matched to Ilopango by major and trace element concentrations of glass shards (**Table 1**). The new results from Eastern El Salvador and offshore constrain an erupted volume far larger than previous estimated. The tephra volume of the fallout (**Fig. 2**), including the proximal surge deposits, amounts to 65 km^3, using the integration approach of Fierstein and Nathenson (1992).

The TBJ ignimbrite has an approximately radial distribution up to 45 km from Ilopango caldera, covering most of the terrain but with great ponded thicknesses in the paleovalleys. We estimate a bulk ignimbrite volume of about 19 km^3 from the distribution map (**Fig. 3**) which includes a conservatively estimated intra-caldera volume of the thickness exposed at the caldera rim

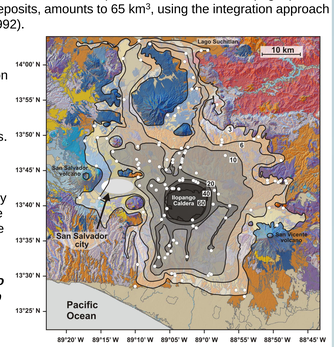

***Figure 3 (right):** Ilopango TBJ ignimbrite deposit map from this study. All depths in meters.*

Tierra Blanca Joven Tephra Chemical Compositions

Ferrometal	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO	MnO	FeO_T	Alkalis	(n)
Ilopango Caldera	4.165 ± (0.111)	0.181 ± (0.03)	12.919 ± (0.196)	77.687 ± (0.452)	2.743 ± (0.12)	1.078 ± (0.06)	0.144 ± (0.03)	0.093 ± (0.03)	1.119 ± (0.12)	6.84 ± (0.12)	20
Lago de Yojoa, Honduras	4.182 ± (0.11)	0.203 ± (0.03)	13.047 ± (0.19)	77.515 ± (0.12)	2.752 ± (0.12)	1.108 ± (0.06)	0.158 ± (0.03)	0.079 ± (0.03)	1.144 ± (0.06)	6.89 ± (0.12)	18
Lago de Yojoa, Honduras	4.192 ± (0.15)	0.203 ± (0.03)	13.081 ± (0.22)	77.506 ± (0.54)	2.738 ± (0.06)	1.108 ± (0.03)	0.160 ± (0.03)	0.079 ± (0.04)	1.144 ± (0.06)	6.90 ± (0.12)	17
Chalchuapa, El Salvador	4.177 ± (0.12)	0.202 ± (0.02)	13.045 ± (0.21)	77.543 ± (0.49)	2.746 ± (0.08)	1.102 ± (0.03)	0.157 ± (0.03)	0.083 ± (0.04)	1.141 ± (0.07)	6.92 ± (0.11)	26
Petapilla Pond, Honduras	4.168 ± (0.11)	0.212 ± (0.03)	13.065 ± (0.21)	77.398 ± (0.48)	2.729 ± (0.08)	1.111 ± (0.03)	0.161 ± (0.03)	0.079 ± (0.03)	1.168 ± (0.07)	6.79 ± (0.11)	18
Jaune de Payas, El Salvador	3.921 ± (0.11)	0.206 ± (0.02)	13.147 ± (0.19)	77.376 ± (0.47)	2.742 ± (0.06)	1.115 ± (0.03)	0.161 ± (0.03)	0.061 ± (0.03)	1.128 ± (0.06)	6.78 ± (0.12)	19
Lake Amatitlan, Guatemala	4.177 ± (0.13)	0.202 ± (0.02)	13.111 ± (0.21)	77.452 ± (0.51)	2.741 ± (0.08)	1.102 ± (0.03)	0.157 ± (0.03)	0.083 ± (0.04)	1.141 ± (0.07)	6.92 ± (0.11)	19
San Miguel, El Salvador	4.078 ± (0.14)	0.177 ± (0.03)	12.758 ± (0.26)	77.666 ± (0.56)	2.923 ± (0.08)	1.032 ± (0.03)	0.184 ± (0.03)	0.066 ± (0.03)	1.121 ± (0.07)	6.49 ± (0.12)	31
San Miguel, El Salvador	4.098 ± (0.13)	0.190 ± (0.03)	12.842 ± (0.21)	77.613 ± (0.47)	2.878 ± (0.08)	1.058 ± (0.03)	0.180 ± (0.03)	0.072 ± (0.03)	1.116 ± (0.06)	6.62 ± (0.12)	38

Tephra											
SO173-11/20-30	3.99 (0.05)	0.19 (0.04)	12.76 (0.21)	77.51 (0.41)	2.87 (0.10)	1.18 (0.05)	0.18 (0.05)	n/a	1.23 (0.05)	6.81 (0.11)	10
SO173-13/2-10:	3.83 (0.06)	0.13 (0.03)	13.26 (0.19)	77.41 (0.39)	2.99 (0.09)	0.98 (0.04)	0.14 (0.03)	n/a	1.08 (0.04)	6.92 (0.10)	31
SO173-15/22-25:	3.76 (0.06)	0.18 (0.04)	13.29 (0.18)	77.58 (0.40)	2.81 (0.09)	1.03 (0.04)	0.16 (0.04)	n/a	1.15 (0.05)	6.72 (0.07)	16
SO173-17/4-31:	3.87 (0.05)	0.19 (0.03)	12.86 (0.19)	77.40 (0.42)	3.03 (0.09)	1.13 (0.04)	0.20 (0.04)	n/a	1.12 (0.05)	6.90 (0.11)	20
SO173-18/112-115:	3.87 (0.06)	0.19 (0.04)	12.86 (0.18)	77.40 (0.42)	3.03 (0.09)	1.13 (0.04)	0.20 (0.04)	n/a	1.12 (0.05)	6.90 (0.11)	20
M66-222/13-17:	4.04 (0.11)	0.20 (0.03)	12.67 (0.19)	77.64 (0.41)	2.82 (0.08)	1.03 (0.03)	0.18 (0.04)	n/a	1.18 (0.06)	6.86 (0.12)	15
M66-223/8-14:	4.04 (0.12)	0.20 (0.03)	12.67 (0.22)	77.64 (0.36)	2.82 (0.08)	1.03 (0.03)	0.18 (0.04)	n/a	1.18 (0.06)	6.86 (0.12)	15
M66-229/8-13:	4.14 (0.12)	0.20 (0.03)	12.67 (0.21)	77.38 (0.42)	2.79 (0.08)	1.06 (0.03)	0.19 (0.04)	n/a	1.21 (0.06)	6.99 (0.12)	24
M66-228/0-6:	4.14 (0.12)	0.20 (0.03)	12.67 (0.21)	77.38 (0.42)	2.79 (0.08)	1.06 (0.03)	0.19 (0.04)	n/a	1.21 (0.06)	6.99 (0.12)	16
M66-229/29-30	3.98 (0.11)	0.21 (0.03)	12.59 (0.21)	77.51 (0.41)	2.84 (0.08)	1.11 (0.03)	0.17 (0.04)	n/a	1.17 (0.05)	6.81 (0.10)	17

***Table 3 (left):** Ilopango TBJ tephra chemical compositions, including all distal samples used to create Figure 2.*

Fallout and ignimbrite thus add to a bulk tephra volume of 84 km^3 of the TBJ corresponding to 39 km^3 DRE magma volume and 8.15*10^{13} kg erupted magma mass, which are minimum values as TBJ tephra mass hidden inside the caldera is unknown. The calculated TBJ magma volume equates to a large VEI 6 event or an eruption magnitude of 6.9. The erupted magma volume of the TBJ eruption was at least ~20% greater than the 1815 Tambora event, which would be consistent with the sulfate ice core evidence for the AD 536 trigger eruption that points to an eruption slightly larger than Tambora.

However, ice-core data relate to the magnitude of SO_2 emission rather than magma discharge. Sulfur concentrations <100 ppm in rhyolitic (~78 wt% SiO_2) TBJ melt-inclusions compared to <12 ppm S in matrix glass indicate a release of about 16 Mt SO_2 during the eruption, less than the 53-58 Mt SO_2 emitted by Tambora. However, the parental basaltic-andesitic magma of the evolved TBJ magma probably had a sulfur content of at least 1000 ppm as typical for central America (Sadofsky et al. 2008), which exsolved during magmatic differentiation [37]. Assuming that no loss of sulfurous fluid occurred prior to the TBJ eruption, a maximum output of 160 Mt SO_2 can be calculated. Thus, while the actual amount of sulfur available at the time of the TBJ eruption cannot be constrained, an up to 40% higher SO_2 discharge compared to Tambora as implied from Greenland ice-core data would have been feasible.

Radiocarbon results from previous studies

The first comprehensive data on the age of the event was published in 1983, resulting in a reported calendar age of AD 260 ± 114. Subsequent AMS radiocarbon dating of plant material killed by the Ilopango TBJ eruption has produced a tight clustering of ^{14}C ages, most falling close to 1600 ^{14}C years B.P. (**Fig. 4**).

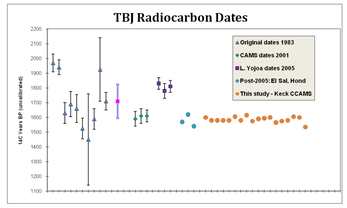

***Figure 4 (left):** All known Tierra Blanca Joven 14C dates, including new dates from this study (orange).*

Radiocarbon results from this study:

We dated a 36 cm diameter completely carbonized tree trunk (or branch), consisting of hard charcoal with well defined wood grain but no annual rings (**Fig. 5**), from a TBJ pyroclastic flow deposit. Base-resistant (1N NaOH, 60°C, 5 min) and reprecipitated base-soluble fractions from 8 samples on a radial transect yielded identical 14C ages, indicating that contaminating young humics were not present.

Due to the presence of a plateau in the INTCAL09 ^{14}C calibration curve (**Fig YY**), the death date of the tree (eruption date) cannot be unequivocally associated with the 536 AD event. **Figure 6** shows the ^{14}C data plotted over INTCAL09, for an assumed 8mm/year growth rate and a death date of 535 AD. However, the young end of the ^{14}C dataset can be placed almost anywhere within the plateau, from about 440 to 550 AD, depending on the growth rates assumed for the tree. Nevertheless, Ilopango TBJ is the *only* known large-volume eruption in this general time period with a range of possible eruption dates *consistent* with 535 AD.

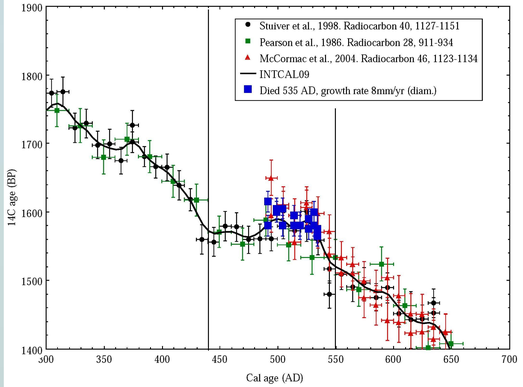

***Figure 6:** Series of 14C determinations from single tree sample from pith (left) to cambium (right).*

Regional impacts and context

The area depopulated following the TBJ eruption stretched from SE Guatemala to Eastern El Salvador (**Fig. 7**, red dashed line). Effects reverberated throughout the Maya region and beyond, and coincide with the "Classic Maya Hiatus" in the Maya Lowlands in and around Tikal (ca. AD 535-). An influx of TBJ refugees may have contributed to the rapid 6th century population increase in Copan (A). Still, other major urban centers such as the western Salvadoran city of Chalchuapa (B) were completely abandoned. TBJ ash has been found as far to the northeast as Central Honduras (C). In the area around present day San Salvador some locations contain 10 meters or more of TBJ tephra (D), and dozens of agricultural fields have now been identified under the TBJ tephra (E). Even older agricultural fields, such as those covered by the 830 BCE Plan de la Laguna tephra (F) attest to the recurring nature of volcanic hazards in central El Salvador. One surprising finding of the current study was that the trajectory of the tephra fall was dominantly S-SE, and thick deposits have been recorded throughout Eastern El Salvador (G). Plant material killed instantly by the TBJ pyroclastic flows (H) has enabled much more precise dating of the TBJ event, which resulted in the formation of the massive (9x11 km) caldera lake, Lago Ilopango (I).

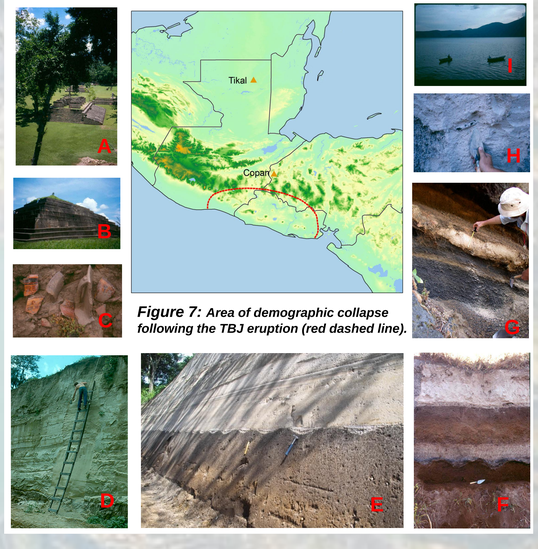

***Figure 7:** Area of demographic collapse following the TBJ eruption (red dashed line).*

Conclusion

The cause of the largest stratospheric aerosol loading event of the past two millennia has eluded researchers for decades. The sulfate deposition levels and patterns in ice core records from both Antarctica and Greenland require a large tropical volcanic eruption to explain the AD 536 event. If the VEI 6+ (~39 km^3 DRE) Ilopango TBJ eruption occurred in the year AD 535, it could have produced the AD 536 dust veil. Radiocarbon results from the TBJ event presented here constrain the timing and are consistent with an Ilopango-AD 536 linkage, though they do not unequivocally prove it. While the TBJ eruption alone probably cannot explain the entire 14+ year cold period observed in northern hemisphere tree ring records from AD 536 – AD 550, it seems now to be the best candidate for the cause of the AD 536 'mystery cloud' and a major contributor to the cold temperatures that followed

Key References:

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