Volcanic Activity and Global Change: Probable Short-Term and Possible Long-Term Linkages

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Annual to Decadal Climate Response to Volcanism

Recognition of climatic cooling following large volcanic eruptions is first attributed to observations by Benjamin Franklin following the 1783 Laki, Iceland, eruption (probably the most sulfur-rich in the past 500 years [Palais and Sigurdsson 1989]), which induced an unusually severe winter in 1783-84 (referenced by Lamb 1970 and Chester 1988). H.H. Lamb (*eg*, Lamb 1970) may have been the first modern champion of volcanically-induced climate change.

There was interest through the 1970s in the possible relationship of volcanism to the longer geologic record of climate change (Kennett [1981] provides a good summary), but interest waned toward the end of the decade, probably as a result of the rapidly growing excitement in the demonstrated likelihood of Milankovitch mechanisms to incur climate change at time scales of interest to those studying the late Cenozoic glaciations. Interest in the effects of explosive eruptions on interannual to decadal climate variations remained, however.

In the early 1980s it was realized that the sulfur aerosols were the most important attribute of large eruptions in regard to the ensuing cooling (Rampino and Self 1982; Self and King 1993). Global temperatures decline by 0.2 to 0.3°C for 2 to 5 years after large eruptions (Hoyt 1978; Self *et al* 1981; LaMarche and Hirschboeck 1984; Kelly and Sear 1984). The cooling is not evenly distributed around the earth (Robock and Mao 1992). High latitudes of the Northern Hemisphere cool by as much as several degrees following eruptions, with important consequences to snow/ice retention over the sub-polar summer (Bradley and England 1978; Stommel and Stommel 1983; Vupputuri 1992; Rampino and Self 1992, 1993; Shabbar 1993). Studies of climatic effects incurred by the El Chichon eruption of 1982 were complicated by the large 1982-83 ENSO event (Hofmann 1987), but recent work on the 1991 Pinatubo eruption has resulted in the "first unambiguous, direct measurements of large-scale volcanic forcing" (Minnis *et al* 1993, p. 1411).

Porter (1981, 1986) finds decadal-timescale influences of volcanic activity on glacial advances. He notes a time lag of 10 to 15 years between the response of a glacier terminus (an advance) to the volcanic forcing as indicated by the ice-core acidity signal. Porter (1986) concludes that sulfur-rich aerosols generated by volcanic eruptions are the primary

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forcing mechanism of climate on decadal time scales. Lamb (1970) reported that sea ice in high northern latitudes may linger long into the summer for 5 to 10 years after large eruptions. Hammer *et al* (1981) compared the acidity record of a Greenland ice core to northern Europe temperature records back to year 553 and noted the distinct correlation between the acidity level in the Greenland core and cold temperatures. In particular, Hammer *et al* (1981) emphasize that the highest levels of acidity correlate with the two coldest intervals of the Little Ice Age, between 1250-1500 and 1550-1700.

Long-Term Climatic Response to Volcanism

Volcanically-induced cooling on these relatively short time scales seems reasonably well demonstrated. The correlation to longer-term climate change is more speculative. Nearly two decades ago, Kennett and Thunell (1975; see also Stewart 1975) noticed a worldwide increase in the number of ash layers in the late Pliocene and suggested that they may be somehow associated with Northern Hemisphere glaciation. Bray, in a series of papers (1974, 1977, 1979a, 1979b), linked explosive volcanism with both hemispherical and global cooling and glacial advances. A Pacific Basin-wide summary of Neogene and Quaternary volcanism indicated larger eruptive episodes at 0-2 and 14-16 Ma, with lesser events centered near 5 and 10 Ma (Kennett *et al* 1977). Kennett *et al* (1977) suggested that there may be cooling events associated with each maximum.

Several years ago, those studying effects of volcanic eruptions adopted the "nuclear winter" arguments to their use, suggesting significant climatic effects following unusually large eruptions (Stothers *et al* 1989). Rampino and Self (1992, 1993) observed that the 74,000-year-old Toba ash in the northern Indian Ocean, marking one of the largest eruptions in the later Quaternary, occurred at the transition from warm interglacial stage 5a to cold stage 4. They suggested that the rapidity of the stage 5/4 transition was enhanced by the cooling effect of that large eruption. In fact, the observation that this large eruption occurred *after* the beginning of cooling is one argument being made to support the suggestion that ice cap formation *causes* volcanic eruptions. Presumably this is accomplished by unloading the oceans and loading the polar regions with ice. Resulting stress redistribution in the lithosphere then may trigger large eruptions in susceptible regions such as island arcs (Chester 1988; Rampino and Self 1993).

Recent Results from Ocean Drilling in the North Pacific

Recent results of Ocean Drilling Program Leg 145 to the subarctic Pacific (Figure 1) show that it may be appropriate to return to the suggestion of Kennett and Bray and their co-workers that enhanced Pliocene volcanism may be associated in a causal manner with the onset of Northern Hemisphere glaciation at 2.6 Ma. Results of that cruise (Leg 145 Scientific

Party, 1993; Rea, Basov *et al* 1993) show that the late Pliocene beginning of large-scale Northern Hemisphere glaciation, as depicted by the abrupt onset of significant amounts of ice rafting, is intimately associated with the sudden appearance of numerous thick ash layers in the sedimentary section all across the North Pacific (Figure 2). For example, macroscopic description of Core 11H of Hole 882A shows the first thick (5 cm) ash layer

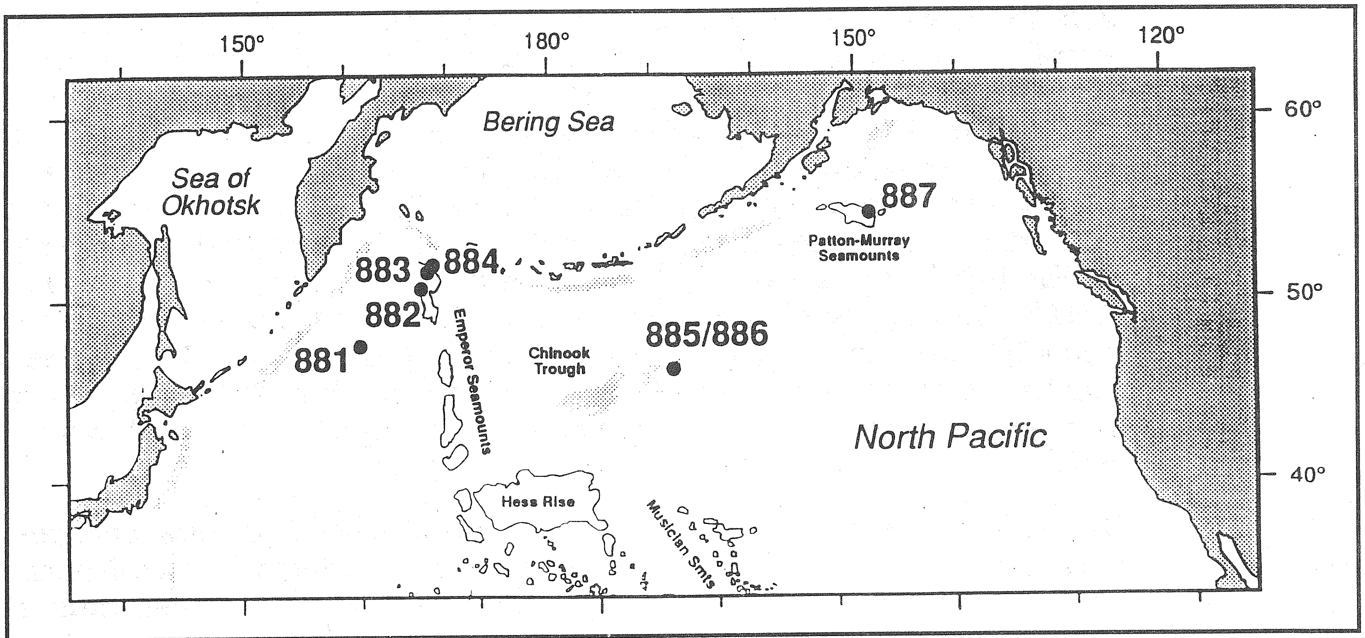

Figure 1. INDEX MAP OF THE NORTH PACIFIC SHOWING THE LEG 145 DRILL SITES

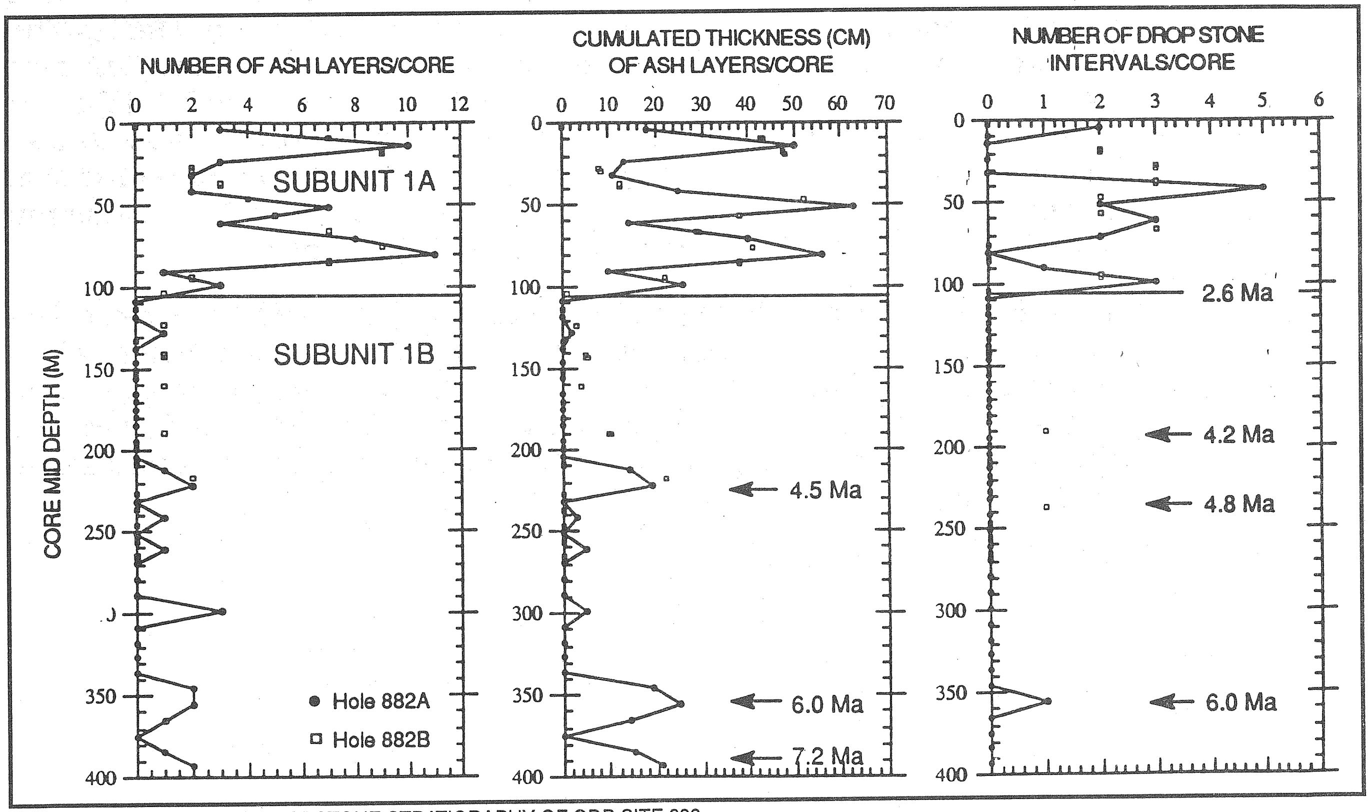

Figure 2. ASH LAYER AND DROPSTONE STRATIGRAPHY OF ODP SITE 882
Lithologic Subunit 1A is a clayey diatom ooze; 1B is a nearly pure diatom ooze. Arrows with ages point to individual ash layers or dropstones. Depth in the sedimentary section of the 2.6 Ma horizon where Northern Hemisphere glaciation begins is denoted by the horizontal line.

at Section 4, 133-138 cm; the Matuyama-Gauss magnetic reversal (at 2.6 Ma) at Section 3, 80 cm; and the first dropstone at Section 1, 88-93 cm, 4.9 meters (60 or 70 kyr) above the first thick ash layer. Similar relationships occur at other northwest Pacific sites and at the Gulf of Alaska Site 887 (Rea, Basov *et al* 1993).

At a distance of about 1000 kilometers downwind from the vent the Toba ash, thought by several authors to be the largest late Quaternary eruptive event (*eg*, Rose and Chesner 1987), is about 10 to 15 centimeters thick (Dehn *et al* 1991). At Site 882 on Detroit Seamount, a paleo-distance of about 1000 kilometers from the Kuril-Kamchatka arc, ODP hydraulic piston cores recovered by the *JOIDES Resolution* contain a dozen ash layers over 10 centimeters thick, and more than 60 distinct ash layers 1 centimeter or greater in thickness in the sequence that begins suddenly at the time of the Matuyama-Gauss magnetic reversal (Rea, Basov *et al* 1993). The suggestion arises that the enormous eruptions of the Kuril-Kamchatka-Aleutian region, which began suddenly at 2.6 Ma, provided the trigger mechanism or threshold phenomenon that rapidly tipped the Northern Hemisphere — already primed for such an event — into an ice age.

Threshold phenomena, geologically sudden responses to gradual changes, have often been called upon to explain the onset of Northern Hemisphere glaciation. One of the earlier ones was the closing of the Isthmus of Panama, resulting in the northerly diversion of warm water in the Gulf Stream. Upon reaching high latitudes, this warmer water served as a moisture source for the growing ice caps (Berger *et al* 1981). The threshold phenomenon now "on the table" is the mid- to late Cenozoic uplift of the Tibetan and American Plateaus. Plateau uplift fulfills the dual function of altering atmospheric circulation in such a way to cool the northern continents and of allowing increased erosion and chemical weathering, resulting in a draw-down of atmospheric CO_2 (Ruddiman and Kutzbach 1989, 1990; Raymo *et al* 1988; Raymo 1991).

This data- and model-based paleoclimatology may well be correct, but amidst the ongoing uplifting, cooling, and chemical weathering, all of which happen on tectonic time scales, Northern Hemisphere glaciation begins abruptly. Hence, there may remain some not yet identified critical threshold phenomenon, possibly the sudden onset of massive volcanism in the western and northern Pacific island arcs.

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