ing is especially encouraging in view of the fact that the composite cross used represents a gene pool whose diversity has been attenuated by growth for nine generations at Davis. Selections for salt tolerance made directly from the thousands of strains of barley in the world collection, followed by a breeding program, can confidently be expected to increase yields under saline conditions. Evidence already at hand (*8*) indicates that this genetic approach to saline crop production is applicable to crops other than barley. The scheme could also lend itself to the production of forage and fiber and to the generation of energy from biomass—an attractive means for the utilization of solar energy (*16*).

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Pleistocene Volcanism and Glacial Initiation

Abstract. *During the past 2 million years, major Northern Hemisphere eruptions occurred within 0.01 million years before 22 of 24 maximum-temperature dates which preceded the ten European glacial stages and 42 of 60 maximum-temperature dates which preceded the 22 cooling episodes. Massive eruptions were even more closely associated with the glacial stages and the cooling episodes. Within the errors of Pleistocene dating, major eruptions apparently occurred at the crucial moments to have triggered each of the ice ages.*

The recent increase in observational (*1*) and theoretical (*2*) evidence for the volcanic climatic hypothesis has been accompanied by suggestions that volcanic eruptions may have influenced the distribution of late Pleistocene (*3*) and Holocene (*4*) glaciation and that massive eruptions may have triggered the formation of the large Pleistocene ice sheets (*5*). In this report I will attempt to catalog the periods of rapid temperature decline and glacial advance during the Pleistocene to see if they were preceded by evidence of massive explosive eruptions.

Any correlation of episodes of rapid Pleistocene temperature decline with volcanism must be based on an understanding of the mechanism by which volcanic eruptions may trigger glaciation. Two mechanisms have so far been suggested. An early summary by Wexler (*6*) concluded that periods of increased volcanism may have reduced global temperatures and developed an increased storminess and precipitation as a result of a greater reduction in land than in ocean temperature. Glaciation would have resulted from these conditions and perhaps also from increased haziness and from a positive feedback due to a greater global albedo resulting from increased areas of snow and ice. In a more recent proposal (*5*), I suggested that massive volcanic eruptions may have been a trigger for the "instantaneous glacierization" mechanism described by Flohn (*7*) and by Ives *et al.* (*8*). According to this mechanism, if there were a survival of snow for a single summer over the subarctic plateaus, then various autocatalytic processes might have occurred which would have led to permanent snowfields and subsequent continental ice sheet formation. One or a series of several closely spaced massive eruptions may have been one means by which subarctic snow survival over a single summer was stimulated (*5*). Furthermore, the climatic effects of such massive eruptions would last, in diminishing degree, over at least several years and would thus promote snow survival in subsequent summers and enhance the feedback processes which accompany a greatly increased snow cover. If the climatic effects of one or several contiguous massive eruptions were responsible for an extensive subarctic summer snow survival leading to subsequent glaciation, then for intervals during the Pleistocene in which there were steep temperature declines followed by ice-sheet formation there should be evidence of volcanism around the beginning of each decline. It is not necessary under this hypothesis that every major eruption should be followed by glaciation, but only that every glacial age should have been preceded by one or more massive volcanic eruptions. There would be shorter to more extended periods during the Pleistocene when conditions of either climate or weather would be such that volcanic triggering could not occur. Eruptions occurring during times of ice advance or in the early or even later stages of ice retreat could not be expected to influence glaciation or have any appreciable climatic significance (*5*). Some massive eruptions would also have occurred at times when weather conditions were not favorable for a volcanic trigger mechanism—for example, during a period when the subarctic winter snowpack was thin and unlikely to survive the following summer, even during the cooler, darker, and more turbid conditions caused by volcanism.

The margin of error associated with the dating of Pleistocene events makes any comparison between dated volcanic ash layers and climatic change difficult and the results tenuous. To these errors must be added the considerable lack of agreement on Pleistocene temperature chronologies, which renders the choice of climatic curves open to bias. For this reason, I have relied on the synthesis of Cooke (*9*), who summarized eight paleoclimatic studies made between 1966 and 1971 and from these outlined, in his table 3, a European Pleistocene chronology. This chronology was based in large degree on the work of Ruddiman (*10*), and from the interpretation of Ruddiman's cores in Cooke's table 2, I have listed in Table 1 the maximum-temperature dates that were followed by major temperature declines. These dates were assumed to represent the periods in which a volcanic eruption may have been able to trigger a Northern Hemisphere ice sheet expansion and the global temperature decline which would result from such an expansion. Also included in Table 1 are the dates of the maximum temperatures which preceded temperature declines in three recent studies; they are derived from the carbonate curve from the Southern Ocean by Frakes (*11*), the Solomon Plateau curve of N. J. Shackleton and N. Opdyke as summarized in figure 1 of Calder (*12*), and the Indian Ocean sea-surface temperature curve in figure 9 of Hays *et al.* (*13*). These three curves give dates of temperature maxima preceding major minima which are similar to the dates in the synthesis by Cooke (*9*).

Table 1. Volcanic ash layers, temperature maxima that preceded major temperature minima, and temperature minima during the past 2 million years. Ocean ash data are from Hays and Ninkovich (*14*). All dates are expressed as million years ago.

Ocean ash		Land ash		Temperature maxima ($\times 10^6$ years ago)			
Date ($\times 10^6$ years ago)	Thickness (cm)	Date ($\times 10^6$ years ago)	Reference	Cooke (*9*)	Frakes (*11*)	Calder (*12*)	Hays *et al.* (*13*)
		0.018	(*21*)		0.00	0.01	0.01
0.03	8.0	0.036	(*21*)	0.03		0.04	0.04
0.04	4.0						
0.04	2.0						
0.06	2.0						0.06
		0.08 ± 0.02	(*22*)	0.08		0.07	0.08
		0.083	(*23*)				
0.10	10.0				0.10	0.10	0.12
0.11–0.12	2.5	0.11 ± 0.02	(*22*)				
0.125	5.0						
0.14	10.0	0.14 ± 0.03	(*24*)				
0.15	2.0	0.15 ± 0.04	(*24*)			0.15	
0.17	6.0			0.16		0.17	
0.17–0.18	4.0	0.18 ± 0.03	(*22*)				
0.21–0.22	2.5						
0.22	5.0	0.22 ± 0.04	(*24*)		0.23	0.21	0.24
0.24	3.7						
0.25–0.28	4.8	0.26 ± 0.08	(*24*)	0.27		0.28	0.28
0.30–0.31	2.5	0.30 ± 0.10	(*24*)				
0.33	5.0	0.32 ± 0.03	(*24*)		0.32	0.33	0.33
0.34	21.5	0.35 ± 0.02	(*24*)				
		0.39 ± 0.02	(*24*)	0.36		0.37	0.37
0.39–0.42	2.3	0.40 ± 0.02	(*24*)				
0.44	2.0	0.43	(*23*)	0.42	0.43	0.45	0.41
0.46	5.0						
0.53	10.0			0.53	0.53	0.53	
0.55	12.0	0.57 ± 0.04	(*24*)				
0.62	14.0	0.60 ± 0.01	(*25*)	0.59	0.62	0.63	
		0.69 ± 0.05	(*26*)	0.69		0.70	
0.72–0.73	4.7	0.73 ± 0.06	(*27*)				
0.74	12.0			0.76	0.73	0.74	
0.78	1.0						
0.79	2.0	0.80 ± 0.05	(*26*)				
0.82	2.0					0.82	
0.88	2.0			0.84		0.84	
0.89–0.91	1.3	0.90 ± 0.05	(*26*)	0.89	0.90		
0.92	3.0						
0.94	3.0						
0.98	3.0						
		1.09 ± 0.03	(*27*)	1.03	1.02		
1.10–1.20	5.0	1.20 ± 0.04	(*25*)	1.16	1.17		
1.14–1.18	3.5	1.20 ± 0.05	(*26*)				
1.32	6.0			1.27	1.30		
1.38–1.40	1.3	1.37 ± 0.04	(*27*)	1.36			
				1.41			
1.51–1.53	9.7	1.50	(*27*)	1.50	1.48		
				1.56			
		1.65 ± 0.05	(*26*)	1.63	1.65		
1.72	5.5			1.73			
1.81	3.5	1.80 ± 0.05	(*26*)				
		1.90 ± 0.05	(*26*)				
		1.90 ± 0.10	(*25*)				
		1.96 ± 0.05	(*25*)	1.92	1.95		
		2.00 ± 0.05	(*26*)				

The volcanic ash layers listed in Table 1 are separated into ocean and land deposits. Only Northern Hemisphere dates are included because the large Northern Hemisphere ice sheets were apparently influenced mainly by volcanic eruptions in that hemisphere (*5*). The ocean data include all the dated ash layers from the North Pacific Ocean study of Hays and Ninkovich (*14*). The North Pacific area was the most active of the world volcanic zones during the Pleistocene, as shown by figure 4 of Kennett and Thunell (*15*), accounting for more than 65 percent of the major eruptions in the Northern Hemisphere. Furthermore, the North Pacific volcanic ash, which was produced mainly in the Japan-Kurile-Kamchatka and Aleutian-Alaska areas, was in a favorable geographic position to have resulted in the increased turbidity and decreased insolation and temperature necessary to trigger snowfield survival in the subarctic plateaus. The North Pacific ash layers were dated (*14*) by interpolating from dated paleomagnetic horizons, and no margin of error can be assigned for these dates. The land ash data in Table 1 are from Japan, North America, and Europe and include only the known major eruptions in these areas. All of the ocean ash layers in Table 1 can also be considered major eruptions since they left deposits of appreciable thickness at great distances from their source. The great magnitude of the eruptions which produced these ocean ash deposits with thicknesses up to 21 cm has been stressed by Ninkovich and Donn (*16*).

It is apparent from the chronologic data in Table 1 that the intervals of maximum temperature which preceded the declines to lower temperatures and ice expansion phases were associated with volcanic eruptions. The temperature maxima which preceded the ten named European glacial stages in Cooke's synthesis occurred 1.92 to 1.95 (Biber), 1.36 (Donau I), 1.16 to 1.17 (Donau II), 0.89 to 0.90 (Günz), 0.69 to 0.70 (Cromerian), 0.59 to 0.63 (Mindel), 0.27 to 0.28 (Holsteinian), 0.21 to 0.24 (Riss), 0.10 to 0.12 (Eemian), and 0.07 to 0.08 (Würm) million years ago. Each of the series of temperature maxima preceding these ten glacial stages was accompanied by volcanic eruptions. There are 24 maximum-temperature dates in Table 1 which define the ten glacial stages; of these, 16 occurred at the same time as a volcanic eruption ($\chi^2 = 6.9$, $P < .01$) and 22 occurred up to 0.01 million years after an eruption ($\chi^2 = 11.7$, $P < .001$). Nineteen of the 24 temperature maxima which preceded the major cooling phases in Table 1 were contiguous with or closely preceded by volcanic eruptions, and in one other case (at 1.72 million years ago) the eruption followed the maxima by 0.01 million years. Of the 60 maximum-temperature dates in Table 1, excluding the present-day ones, 36 were identical with eruption dates ($\chi^2 = 4.1$, $P < .05$) and 42 followed an eruption within 0.01 million years ($\chi^2 = 4.1$, $P < .05$). These tests demonstrate a significant tendency for the temperature maxima preceding cooling phases and glacial advance to have been accompanied by major volcanic eruptions.

The association of the temperature maxima in Table 1 with volcanism is even more striking when only the massive eruptions are considered. Massive land eruptions occurred at 1.9 to 2.0, 1.8, 1.65, 1.37, 1.2, 1.09, 0.90, 0.80, 0.73, 0.69, 0.60, 0.43, 0.40, 0.35, 0.22, and 0.08 million years ago. If these eruptions are considered together with the ocean ash layers that were $\geqslant 3.0$ cm thick, then a total of 57 periods of 0.01 million years during the past 2 million years can be considered to have had a massive eruption. Of the 24 dates which define the ten glacial stages in Table 1, 14 were the same as the dates of massive volcanic eruptions ($\chi^2 = 10.6$, $P < .002$) and 21 occurred up to 0.01 million years after a massive eruption ($\chi^2 = 17.1$, $P < .001$). Twenty-eight of the 60 dates of maximum temperature in Table 1 were the same as a massive eruption date ($\chi^2 = 9.6$, $P < .003$) and 39 were accompanied or preceded within 0.01 million years by a massive eruption ($\chi^2 = 10.3$, $P < .002$). Often a glacial stage or substage was preceded by evidence of both massive land and ocean ash layers. The beginning of the Mindel around 0.59 to 0.63 million years ago was accompanied by a Yellowstone eruption around 0.60 to 0.61 million years ago (*17*) which produced more than 900 km^3 of ash and pumice (*18*) and by an ocean ash layer at 0.62 million years ago which had a thickness of 14.0 cm. The initiation of the Donau was preceded by a land eruption at 1.37 million years ago and an ocean ash layer of 6.0 cm at 1.32 million years ago. The Günz was preceded by a massive land deposit at 0.90 million years ago and an ocean ash layer of 3.0 cm at 0.92 million years ago, and the Riss by land ash at 0.22 million years ago and thick ocean layers at 0.24 and 0.22 million years ago.

If massive eruptions trigger the instantaneous glacierization mechanism, then the only time they could be expected to do so would be during an interglacial, when the subarctic plateaus are largely snow-free during the summer. These conditions would probably not be present during an interstadial, when there would be mainly permanent ice and snow cover in the subarctic. No necessary connection could be expected, therefore, between periods of Pleistocene glacial readvance and preceding volcanism. All but one of the Pleistocene readvances were preceded by massive eruptions, however, including the readvances around 0.73 to 0.76 (Günz); 0.53, 0.41 to 0.45, and 0.32 to 0.33 (Mindel); 0.16 to 0.17 (Riss); and 0.03 to 0.04 (Würm) million years ago. These results suggest that the intensity of volcanism may be related to the intensity of climatic cooling. Cooke (*9*) concluded that there were relatively few cold phases from 2.0 to 1.3 million years ago, short but severe cold phases from 1.3 to 0.9 million years ago, and much longer cold phases from 0.9 million years ago to the present. The ocean ash data in Table 1 show a mean ash thickness per 100,000 years of 3.7 cm from 2.0 to 1.3 million years ago, 4.7 cm from 1.3 to 0.9 million years ago, and 18.8 cm in the past 0.9 million years. These results suggest that the greater the amount of explosive volcanism, the more frequent and more extended were the cold periods.

The data assembled in Table 1 do not prove that volcanism has triggered glaciation, but indicate that if such a triggering is possible then eruptions appear to have occurred at the critical moments to have been climatically effective. Ninkovich and Donn (*16*) concluded that there appears to be little change in the frequency of ash layers during the Pleistocene. Such continuity of activity does not disprove a trigger connection between volcanism and glaciation since, as noted earlier, only massive eruptions which occurred at crucial climatic intervals could have been expected to act as a potential glacial trigger.

There is a tendency for the volcanic eruptions listed in Table 1 to occur toward the interglacial or interstadial periods, although the overlapping in the chronologic dates makes some of the warm peaks difficult to discern. This tendency supports the hypothesis of Matthews (*19*) that there was increased volcanic activity during the Pleistocene interglacials. Matthews stated that the K-Ar dates of the 17 younger samples of Chamalaun and McDougall (*20*) could be interpreted as indicating volcanic activity at 0.08 to 0.12, 0.18 to 0.22, and 0.29 to 0.34 million years ago, which he considered corresponded to the three major interglacials of the past 350,000 years. These three periods are represented by a greatly increased predominance of the ash dates in Table 1 and especially by some of the thicker ocean ash deposits. Over the entire 2-million-year period, however, there is no significant association of volcanic eruption with the interglacial dates in Table 1 ($\chi^2 = 1.6$, $P > .2$).

Verification of possible links between volcanism and glaciation will require more exact chronologic studies than are currently available, or perhaps ever will be available. The margins of error shown in Table 1 are such that no conclusions can be drawn about the dates of volcanic eruptions in comparison with the periods of rapid temperature decline, which themselves are not yet dated with sufficient accuracy or agreement. The importance of the possibility that massive eruptions occurred at the right times to trigger summer snow survival and glaciation should stimulate further study of the exact timing of the major Pleistocene eruptions.

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Asteroid Families: Observational Evidence for Common Origins

Abstract. *Colors of minor planets in the* UBV *system indicate compositions quite distinct from those of the field population in each of three Hirayama families. The Eos and Koronis families apparently originated from the collisional fragmentation of undifferentiated silicate bodies, and the Nysa group from a geochemically differentiated parent body.*

The recent availability of reflection spectroscopy (*1*), polarimetry (*2*), and thermal radiometry (*3*, *4*), leading to the compositional classification of a large number of minor planets (*5*), has revitalized the question of the significance of the dynamical families first recognized by Hirayama (*6*–*8*).

The dynamical families, which appear as clusterings in the orbital parameters semimajor axis, proper eccentricity, and proper inclination, are generally thought to represent fragments from the collisional breakup of discrete parent bodies (*9*). Thus the members of a single family should show identical compositions if the parent body was homogeneous, or else compositions belonging to some geochemically plausible stratigraphy if the parent body had geochemically evolved or had accreted in distinct layers (*10*). In the latter case we would now have access to the interior of a differentiated body in a way not possible for the major planets and planetary satellites.

Alfvén (*11*) and Trulsen (*12*) have suggested an alternative possibility for producing dynamical families—namely, that they are formed by the collisional focusing of unrelated field asteroids. For such an origin we would expect to find only the pattern of compositions characteristic of that region of the asteroid belt.

For the hundred or so brighter asteroids, attempts to reconstruct the progenitors of families have generally been disappointing. Chapman (*13*) has noted, for example, that there is no attractive way to reconstruct a single parent body from the S object 15 Eunomia and the C objects 85 Io and 141 Lumen. A statistical study by Hansen (*14*) based on published compositional identifications of the brighter asteroids gave rather inconclusive results. Chance orbital similarities between objects of different provenance are, of course, possible, but if such heterogeneous mixtures turn out to be the rule, then the view of families as fragmentation products is in serious jeopardy.

Figure 1 illustrates *UBV* colors for three families which show strong evidence of consanguinity. The data are preliminary results from continuing photometric surveys at the Lowell Observatory (*15*) and the University of Arizona (*16*). While *UBV* photometry is a coarse tool for elucidating compositional differences between asteroids, the ultraviolet-minus-blue ($U - B$) and blue-minus-visual ($B - V$) color indices are generally sufficient to distinguish the principal C, S, and M types and to recognize objects belonging to rarer or unknown types (*16*). Broadband colorimetry is, moreover, the only technique with which it is possible to reach almost any numbered asteroid with telescopes of modest size.

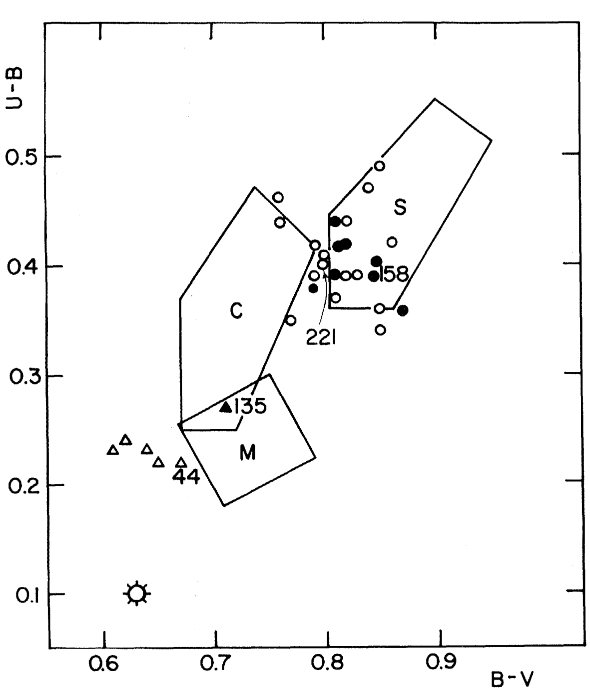

Fig. 1. Ultraviolet-minus-blue versus blue-minus-visual color indices for minor planets in the dynamical families associated with 221 Eos (○), 158 Koronis (●), and 44 Nysa (△). The M-type object 135 Hertha associated with the Nysa family is indicated by (▲). Solar colors of $B - V = 0.63$ and $U - B = 0.10$ are indicated. Family memberships are as assigned by Williams (*8*). Domains indicating the colors of the common C, S, and M asteroid types are adapted from work by Bowell (*15*) and Zellner *et al.* (*16*).

The 44 Nysa family at a mean semimajor axis, *a*, of 2.43 A.U. contains Nysa itself, a rather large, irregularly shaped object (66 by 102 km) of the very rare E type, which may be identifiable with any bright, colorless, refined silicate such as plagioclase or forsterite, but quite likely corresponds to the iron-free enstatite achondrites (*17*). The family also contains the M or metallic-type object 135 Hertha of diameter about 80 km, and a dozen numbered asteroids in the 10-km size range (*18*). At least four of the smaller objects are seen in Fig. 1 to resemble 44 Nysa closely, with colors entirely atypical of the predominant asteroid population.

The geochemical implications of the Nysa-Hertha family are more closely examined elsewhere (*19*). The configuration is strongly suggestive of the remnants of a melted, geochemically differentiated body of initially chondritic composition; 135 Hertha provides the