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Episodes of Aleutian Ridge Explosive Volcanism

The abundance of deep-sea bentonite beds must be considered in interpreting Cenozoic volcanism.

James R. Hein, David W. Scholl, Jacqueline Miller

Recent investigators have stressed the need to understand the nature of explosive volcanism, especially with reference to its ability to affect global climate (*1–4*). Knowledge of the episodes and magnitudes of Cenozoic volcanism is also necessary before cause-and-effect relations can be ascertained with known periods of global cooling and ice ages. Explosive volcanic activity is commonly associated with volcanic arc magmatism. The Cenozoic history of arc volcanism is recorded as pyroclastic beds that are interbedded with marine deposits adjacent to volcanic centers. The Deep Sea Drilling Project (DSDP) has sampled the sedimentary sections overlying the oceanic basaltic basement adjacent to most island and continental volcanic arcs. Thus, the material needed to decipher the time and amount of explosive volcanic activity is available.

Not surprisingly, several papers dealing with the same sets of DSDP data have produced contrasting interpretations (*1–3*, *5*). In this article we discuss these contradictions and present new data on episodic volcanism on the Aleutian Ridge and Kamchatka Peninsula (Fig. 1). We also demonstrate the necessity of considering deep-sea bentonite beds (altered ash layers) when unraveling the volcanic histories in a region.

Ash occurs in deep-sea sediments as discrete layers or in a dispersed state. The lateral extent of ashfalls from volcanic centers depends on winds and the intensity of eruptions. Ash beds in deep-sea sediments can be obliterated or disrupted by reworking (currents, seafloor fauna, slumping), diagenesis (post-depositional alteration), and lithospheric plate motions (subduction). Dispersed ash may be the result of reworking or it may reflect the distance of the depositional site from the point of eruption. Under these circumstances the average amount of ash supplied to a depositional site has been equal to or less than the amount of terrigenous and biogenic material; major volcanic eruptions form discrete ash layers up to 1000 to 2000 kilometers from the source (*6*). Ash pods found in many DSDP cores are derived from ash layers that have been reworked by seafloor fauna, but some may represent thin ash beds that were deformed during the coring process.

Methods

The interpretation of the frequency of volcanic activity based on an examination of the occurrence of ash in DSDP cores is evidently not consistent among various workers. For example, it appears from the data of Ninkovich and Donn (*3*) that they counted only discrete ash layers, whereas Kennett and Thunell (*1*) included beds containing dispersed ash. Some investigators (*1–3*) do not clearly indicate the counting procedures on which they base their interpretations. Apparently, most workers consider only discrete ash layers. More significantly, earlier workers have disregarded sediment reworking and diagenesis in their interpretations. In this study, we consider not only discrete ash beds and pods as pyroclastic deposits but also dispersed ash, if it makes up more than 15 percent of the deposit, and bentonite beds (*7*, *8*). If ash pods occur in a particular core, we simply add one ash layer to the count for that core. This gives an estimate of the minimum number of ash beds originally present.

Another difficulty in comparing the results of other investigators is the variety of techniques used in analyzing and displaying the data. For example, Ninkovich and Donn (*3*) displayed their compilation of DSDP data by plotting the number of observed ash layers versus time, regardless of the greatly contrasting degrees of core recovery in the drill holes. Kennett and Thunell (*1*) used established fossil zones (planktonic foraminiferal N zones) as a basis for a temporal division of sediment sections and normalized these to the percent core recovery at N zone 22 (the Quaternary). Because N zones are not of equal duration, they also made a time-normalization correction. Stewart (*2*) plotted rates of ash production, which he obtained by finding the time span represented by each core, counting the number of ash layers in the core, standardizing this information by calculating how many ash beds this would represent per 10^6 years, and then plotting this arbitrary value of rate against time. As Stewart has emphasized, the actual number of ash layers is not as meaningful for assessing volcanic activity as the rate of ash production (*2*).

Our procedure for sediment sections from DSDP leg 19 was to divide them into intervals of 1×10^6 years (*9*) and to count the pyroclastic deposits in these intervals. The number of deposits was adjusted for the degree of core recovery, and the data were displayed as rates of ash production per 10^6 years. When enough information is available, the

Dr. Hein is a geologist, Dr. Scholl is a geologist and branch chief, and Ms. Miller is a research assistant in the Pacific-Arctic Branch of Marine Geology, U.S. Geological Survey, Menlo Park, California 94025.

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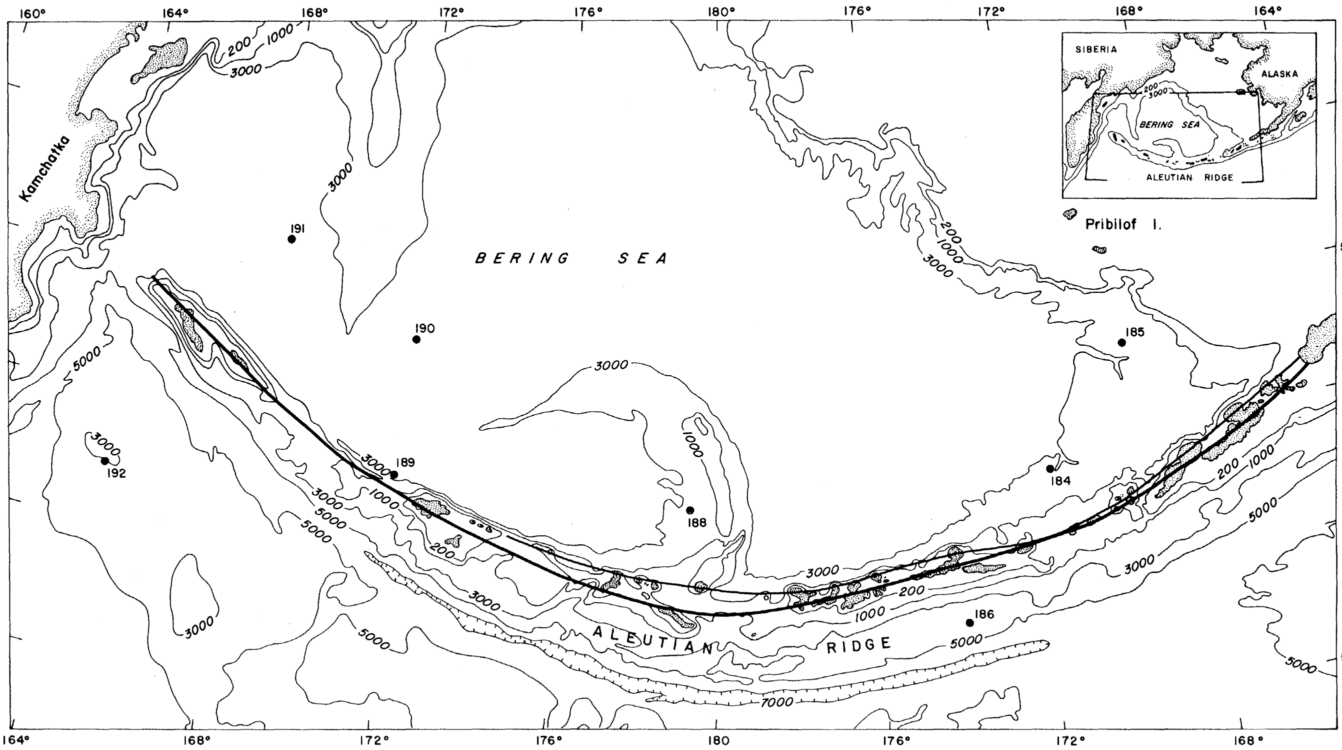


Fig. 1. Location of leg 19 DSDP sites. The axis of middle Miocene Aleutian arc is shown by the heavy line, and the line connecting the centers of Pliocene through Holocene Aleutian volcanoes by the lighter line. Active volcanism is recorded from 80 kilometers west of Buldir Island through the Alaskan Peninsula. The water depth is in meters. Modified from Scholl *et al.* (*11*).

same procedure can be used for shorter time intervals. This technique is easily applied to most DSDP cores. Its applicability, like that of the other techniques, is limited at sites where few cores were taken or where recovery was poor. However, even at some of these sites, if the cores taken are representative of the sediment sections, then trends in volcanism might be discovered.

Another major difficulty in the analysis of DSDP data is that some beds identified as sand or glassy sand in DSDP initial reports are actually ash beds. We found it necessary to spot-check these beds and make corrections. We suggest that deposits sampled at DSDP sites should be reexamined before ash layer counts are accepted.

Bentonite Beds

Bentonite beds are completely altered ash beds. Most commonly the ash alters to one of the smectite clay minerals (montmorillonite, nontronite, and saponite) and a zeolite (such as clinoptilolite or phillipsite in deep-sea deposits). In the DSDP leg 19 cores (Fig. 1), these layers formed by the diagenesis of ash derived from Aleutian Ridge volcanoes (*7, 8*). Bentonite beds are abundant in upper Miocene and older deposits but also occur at some sites in younger sedimentary beds (*8*). Evidently, under typical in situ conditions, 4 or 5×10^6 years are required for bentonite to form from unaltered ash beds (*8*). This time can vary significantly and probably depends on the composition of the ash, pore-water chemistry, geothermal gradient, and type of enclosing sediment. The ratio of bentonite beds to unaltered ash beds increases with depth in the sections.

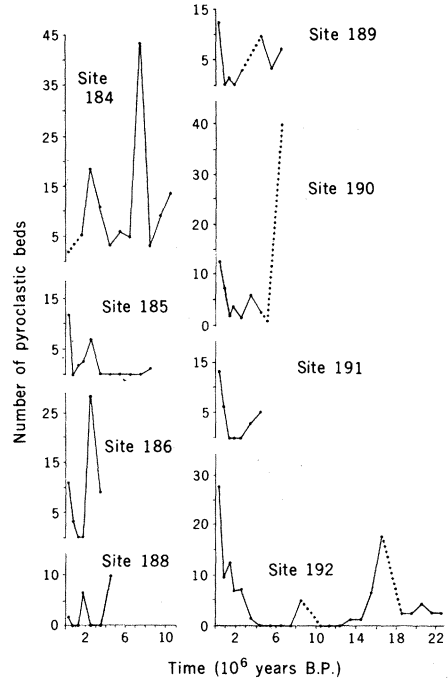
Altered pyroclastic deposits are difficult to recognize by casual inspection of the cores (*8*). Their detection often requires detailed analysis by x-ray diffraction.

Episodes of Volcanism

Figure 2 shows the number of upper Cenozoic pyroclastic beds deposited per 10^6 years for eight leg 19 sites. Because data are more complete for younger Neogene and Quaternary deposits, we use a class or plotting interval of 0.5×10^6 years for deposits 0 to 2×10^6 years old and an interval of 1×10^6 years for older deposits. With this procedure it is possible to delineate relatively short volcanic episodes that occurred during the past 2×10^6 years. This procedure decreases the amplitude of peaks (peaks represent periods of relatively greater volcanic activity) in younger deposits (0 to 2×10^6 years) relative to episodes that occurred earlier. For example, Figs. 2 and 3 show data for site 186 plotted at different time intervals.

All sites except site 184 show that volcanic activity has been increasing significantly for at least the last 10^6 years (not enough core was recovered at site 184 to permit an evaluation of the record of Quaternary volcanism there). Three sites located on or near the Aleutian Ridge (sites 184, 185, and 186) and site 192 in the far northwestern Pacific received abundant pyroclastic debris about 2.5×10^6 years ago. Sites 188, 189, and 191 show that explosive volcanism occurred around 4.5 to 5.0 (+) $\times 10^6$ years ago. Thus volcanic activity is recorded at two or more widely separated DSDP sites at approximately 5.0, 2.5, and 0.5×10^6 years ago. Minor or local pulses of activity are recorded at 5.5, 1.8, 3.5, and 1.5×10^6 years ago at sites 184, 188, 190, and 192, respectively. A major episode of volcanism equal to or greater than that of the last 10^6 years occurred between 6.5 (+) and 8.5×10^6 years ago. It is recorded at all sites where deposits of this age were recovered (sites 184, 185, 189, 190, and 192). Only sites 184 and 192 contain deposits older than this period centered near 7.5×10^6 years ago. Sites 184 and 192 recorded other pulses centered at 10.5 (+) and 16.5×10^6 years ago, respectively. A small pulse at 21×10^6 years ago is also indicated by bentonite beds at site 192. In summary, periods of increased volcanic activity recorded in leg 19 cores are clustered around 0.5, 2.5, 5.0, 7.5, 10.5 (+), 16.5, and 21.0 × 10^6 years ago, or roughly every 2.5 ×10^6 years for the last 10 ×10^6 years and every 5.0 × 10^6 years back to 21 × 10^6 years ago.

The magnitudes of the volcanic episodes that occurred prior to 5 × 10^6 years ago (prior to 3 × 10^6 years ago at site 188) are minimums because they are based on bentonite beds; as explained by Hein and Scholl (*8*), it is unlikely that all the bentonite layers in leg 19 cores were detected. Figure 3 shows the episodes of volcanism recorded at sites 188 and 192 on the basis of ash beds only. At site 192, for example, the significant volcanic pulses at 8.5, 16.5, and 21.0 × 10^6 years ago would not have been detected if bentonite beds had not been studied. Clearly, bentonite beds represent a significant part of the older volcanic record. The exclusion of bentonite beds has a less striking, but nevertheless important, effect on the magnitude and representation of volcanic pulses recorded at the other sites.



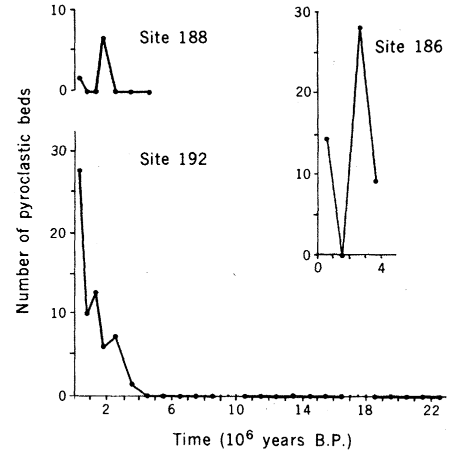


Fig. 2 (left). Periods of increased volcanic activity (peaks) on the Aleutian Ridge, Kamchatka Peninsula, and Kuril Island as recorded by ash and bentonite beds and pods at eight leg 19 DSDP sites (years B.P., years before the present). Site 186 was not analyzed for bentonite beds, but, because the oldest deposits penetrated at this site are less than 4 × 10^6 years old, it is unlikely that bentonite would have developed (see text). Solid lines with dots represent intervals at which data are plotted: at 0.5 × 10^6 year intervals for the deposits 0 to 2 × 10^6 years old and at 1.0 × 10^6 year intervals for older deposits. Dotted lines represent extrapolation in areas with no cores within the 0.5 × 10^6 or 1.0 × 10^6 year interval being considered. Fig. 3 (right). Periods of increased volcanic activity at sites 188 and 192 as recorded by ash beds and pods only; bentonite beds are not included. All relatively old pulses of volcanism are not seen by this technique. Site 186 is replotted from Fig. 2 at a uniform 1.0 × 10^6 year interval. The relative amplitudes of the peaks change slightly, depending on the time interval used to plot the data.

Discussion

A recent study of DSDP cores by Kennett and Thunell (*1*) has stimulated investigation of synchronous global volcanism and its possible effects on climate. Their main emphasis was that a major increase in explosive volcanism occurred during the Quaternary. Large quantities of dust introduced into the atmosphere at this time would have decreased incoming solar radiation and thereby triggered Pleistocene glaciation. They also suggested that lithospheric plate motions may have had some effect on the completeness of the record of volcanism as determined by deep-sea ash layers; however, they argued that this effect was not important.

Subsequently, Ninkovich and Donn (*3*), using piston core and DSDP data, delineated areas of the seafloor adjacent to volcanic arcs that contain Quaternary ash layers. They suggested that the increase in Quaternary ash layers described by Kennett and Thunell (*1*) is only apparent and is attributable to the moving of DSDP sites into areas (by plate motion) where ashfalls could be recorded. Thus, early Neogene and older episodes are not recorded at the DSDP sites because the sites of deposition were too distant from volcanic sources. Therefore, Ninkovich and Donn discounted the idea of an increase in Quaternary explosive volcanism and any primary influence it may have on climate modification.

Nonetheless, on the basis of studies of DSDP cores recovered at sites 178, 183, and 192 in the far North Pacific, Stewart (*2*) also suggested that there was an increase in Quaternary volcanism. However, there is abundant evidence for a major episode of middle Miocene volcanism and associated plutonism on the Aleutian Islands (*10, 11*), but Stewart did not note middle Miocene ash in offshore deposits. Stewart (*2*) suggested that the absence of middle Miocene ash is due to plate motion.

Kennett and Thunell (*1*) believed that diagenesis has not reduced the number of ash layers in middle and upper Cenozoic deep-sea deposits. Other workers have also not considered diagenesis in evaluating the record of volcanism (*2, 3*). A significant part of the middle and late Cenozoic ash record is obscured by diagenetic processes. Moreover, there is an increase in Quaternary volcanism in the North Pacific, as previously described (*1, 2*) and originally emphasized by Coats (*10*). This Quaternary episode, however, is not unique in duration or magnitude; it is matched, and in some cases exceeded, by late and middle Miocene episodes (Fig. 2). The apparent absence of a pre-late Miocene volcanic record at site 192 (Fig. 3) is the result not of plate motion, as previously suggested (*2, 3*), but rather of the diagenesis of ash layers. This may also be true at other DSDP sites. Leg 19 sites, other than site 192, are stationary relative to the Aleutian and Kamchatka volcanic sources and therefore have continuously recorded the volcanic activity from the adjacent Aleutian Ridge and Kamchatka Peninsula. An accurate delineation of the history of volcanism cannot be obtained from a casual perusal of DSDP initial reports; rather it must include detailed mineralogical study of the cores from each area of concern and, where possible, the volcanic record preserved at the eruptive sites themselves.

We conclude that there has been a major episode of explosive volcanism during the Quaternary as well as during the Miocene. Important volcanic pulses have occurred about every 2.5 × 10^6 years for the past 10 × 10^6 years and perhaps every 5.0 × 10^6 years for the 10 × 10^6 years before that. Ash beds in older deposits are difficult to recognize because they blend with the surrounding sediment as the result of diagenetic processes. Because older pyroclastic deposits are occult, workers (*1, 2*) have concluded that the Quaternary period of increased volcanic activity is unique. Moreover, plate motion in the far North Pacific since the early Neogene has not been great enough to move distant sites (those beyond the limits of Aleutian ashfalls) into the area where contemporary ash deposits commonly accumulate.

Regional volcanism. Two phases of igneous activity are recorded by Aleutian Island rocks. The most recent, a Quaternary phase, formed the impressive stratovolcanoes of the Aleutian Ridge. During the middle Miocene, volcanism accompanied the emplacement of granodioritic plutons (*10, 11*). The last pan-Aleutian magmatism probably occurred in middle Miocene time. More recent volcanic activity is restricted to the central and eastern Aleutian Ridge. Thus, site 188 and those sites to the east record late Cenozoic volcanism on the Alaskan Peninsula and Aleutian Ridge, whereas the western DSDP sites document late Cenozoic volcanic activity on the Kamchatka Peninsula and Kuril Islands. The middle and early Miocene pulses at site 192 record western Aleutian Ridge or Kuril Island volcanism.

Upper Cenozoic ash layers occur in deposits of the same age at western and eastern Bering Sea and North Pacific sites. This coincidence implies that volcanic pulses were synchronous in the North Pacific area along the Aleutian and Kuril-Kamchatka arcs. This synchroneity is not limited to the far North Pacific but can be traced along other parts of the Pacific rim. Volcanism broke out along the Cascade Range in Oregon at about 5.0×10^6-year intervals, centered at 1.0, 5.0, 10.0, and 15.0×10^6 years ago (*12, 13*). Equivalent episodes are recorded for the volcanic rocks of the Snake River Plain (*13*). Ninety-nine percent of the extensive flows of the Columbia River Basalt Group erupted during early and middle Miocene time (13.5 to 16×10^6 years ago) (*14*). Farther to the south, early and middle Miocene (14 to 18×10^6 years ago) volcanism was widespread in the western interior and Pacific coastal United States (*15*). Major periods of volcanism occurred in parts of the Andes of South America at about 40, 20, 14, and 10.5 to 4×10^6 years ago (*16*); the middle Miocene pulse was especially intense. Middle Miocene and Quaternary volcanic episodes appear to be especially widespread not only around the Pacific but in the central part of the plate as well (*17*). These remarkable temporal similarities imply a circum-Pacific tectonic mechanism for the episodes and a possibly cyclic nature of continental-margin and island-arc volcanism.

Interestingly, Scheidegger and Kulm (*5*) showed three periods of fluctuations in the chemical properties (Larsen differentiation index and silica content) of ash deposits recovered at site 178 (Gulf of Alaska): at 0.5, 2.5, and 5.0×10^6 years ago. These changes in chemical composition correlate with our three most recent peaks in volcanic activity. This apparent correlation of a 2.5×10^6 year long cycle of rock chemistry with episodes of volcanic activity is an intriguing one. The cycles may be related to fluctuations in spreading rates and consequent changes in the rates of plate convergence (*5*).

Probably the most popular explanation for episodic volcanism at continental margins and island arcs is changes in ocean ridge spreading rates and plate motions (*1, 5, 11, 16, 18*). The Pacific plate has rapidly accelerated relative to the North American plate during the past 15×10^6 years (*19*). If this increase in relative motion occurs in steps rather than continuously, perhaps there is a genetic relationship between volcanic pulses and pulses in plate motion. Motion of the Pacific plate relative to North America was slow prior to 15×10^6 years ago (*19*). The beginning of rapid acceleration between these two huge plates at that time may have initiated the apparently widespread Pacific margin volcanism. Increased volcanism 22×10^6 years ago may correlate with a change in the absolute rate of rotation of the Pacific plate that occurred 20 to 25×10^6 years ago (*20*). Alternatively, Jackson *et al*. (*17*) suggested that the periodicity is caused by rotational motions in the plane of the Pacific plate. Vogt (*21*) suggested that many of these periods of increased volcanism coincide with global synchronism in mantle plume convection. He argued that this coincidence may be the connection between apparent variations in plate motions and increased volcanism at plate margins.

Volcanism and climate. There is great concern about whether explosive volcanism can cause changes in climate, especially to the extent of precipitating great ice ages. Apparently, synchronous volcanic events during the past 50 millennia are closely in tune with periods of regional glacial advance (*4*). In general, volcanic pulses precede the regional glacial pulses by 100 to 300 years (*4*). However, the cause of great worldwide ice ages is unknown. Major, apparently global volcanic episodes occurred at least twice in the last 20×10^6 years. Yet, only one major glacial epoch (the Pleistocene) has occurred. One can conclude that, even though glaciation coincided with an increase in Quaternary volcanism, the increased volcanism itself may not have caused global cooling. It is possible that periods of increased volcanism are the most likely times for the occurrence of glacial epochs, but that within any volcanic period a specific combination of events is necessary. One possible combination of events that could trigger extensive glaciation might involve several major eruptions in rapid succession (that preserve the winter snow through several seasons), at the appropriate latitudes and in widely spaced locations [see (*1–4, 21*) for additional discussions].

The literature concerning the causes of glacial periods is extensive and spans a wide range of possibilities. For example, some proposed causes of major glaciations include flexure of the galaxy, supernova of relatively close stars, fluctuations in solar luminosity, changes in earth magnetism, orbital eccentricity and precession of the earth, variation of summer insolation at high latitudes, orogenesis-upwarp of continents, changes in atmosphere-ocean interactions and circulation, and volcanic episodes (*22*). The real cause could be one, or any combination of the above, or a yet-to-be proposed mechanism. Theories abound and more will come, but the materials are now available (DSDP cores) to test the significance of volcanism as a cause of modifications of the global climate. However, to decipher volcanic episodes, analysis must include detailed mineralogy in order to recognize not only volcanic ash deposits but also their completely altered counterparts.

Summary

Earlier workers have overlooked deep-sea bentonite beds when unraveling the Cenozoic volcanic history of an area. In the North Pacific, identification of Miocene and older volcanic episodes is possible only if both altered (bentonite) and unaltered ash beds are recognized. Our study, which includes bentonite beds, shows that volcanism on the Aleutian Ridge and Kamchatka Peninsula has been cyclic. Volcanic activity seems to have increased every 2.5×10^6 years for the past 10×10^6 years and every 5.0×10^6 years for the time span from 10 to 20×10^6 years ago. The middle and late Miocene and the Quaternary were times of greatly increased volcanic activity in the North Pacific and elsewhere around the Pacific Basin. The apparent absence of a volcanic record before the late Miocene at Deep Sea Drilling Project site 192 is the result not

of plate motion, as suggested by Stewart and by Ninkovich and Donn, but rather of the diagenesis of ash layers.

Major, apparently global volcanic episodes occurred at least twice in the last 20×10^6 years. Yet, only one major glacial epoch (the Pleistocene) has occurred. Therefore, even though glaciation coincided with an increase in Quaternary volcanism, the increased volcanism itself may not have been the primary cause of global cooling.

References and Notes

1. J. P. Kennett and R. C. Thunell, *Science* **187**, 497 (1975).
2. R. J. Stewart, *Nature (London)* **258**, 505 (1975).
3. D. Ninkovich and W. L. Donn, *Science* **194**, 899 (1976).
4. J. R. Bray, *Nature (London)* **252**, 679 (1974); *ibid.* **260**, 414 (1976).
5. K. F. Scheidegger and L. D. Kulm, *Geol. Soc. Am. Bull.* **86**, 1407 (1975).
6. D. Ninkovich, B. C. Heezen, J. R. Conolly, L. H. Burckle, *Deep-Sea Res.* **11**, 605 (1964); D. Ninkovich, N. Opdyke, B. C. Heezen, J. H. Foster, *Earth Planet. Sci. Lett.* **1**, 476 (1966).
7. J. R. Hein, D. W. Scholl, C. E. Gutmacher, in *Proceedings International Clay Conference*, S. W. Bailey, Ed. (Applied Publishing, Wilmette, Ill., 1976), p. 71.
8. J. R. Hein and D. W. Scholl, *Geol. Soc. Am. Bull.*, in press.
9. Time boundaries are based on diatom zones, and ages of sections lacking microfossils are determined by extrapolation of sedimentation rates, most commonly 84 meters per 10^6 years. This technique provides a first-order approximation only, and the inherent limitations should be kept in mind. Time boundaries could be refined with paleomagnetic and radiometric dates.
10. R. R. Coats, *U.S. Geol. Surv. Bull. 974-B* (1950), p. 35; in *The Crust of the Pacific Basin*, G. A. MacDonald and H. Kuno, Eds. (American Geophysical Union Monograph 6, National Academy of Sciences–National Research Council Publication 1035, National Academy of Sciences, Washington, D.C., 1962), p. 92.
11. D. W. Scholl, M. S. Marlow, N. S. MacLeod, E. C. Buffington, *Geol. Soc. Am. Bull.* **87**, 547 (1976).
12. A. R. McBirney, J. F. Sutter, H. R. Naslund, K. G. Sutton, C. M. White, *Geology* **2**, 585 (1974).
13. R. L. Armstrong, *ibid.* **3**, 356 (1975).
14. E. H. McKee, D. L. Swanson, T. L. Wright, *Geol. Soc. Am. Abstracts with Programs* **9** (No. 4), 463 (1977).
15. E. H. McKee, D. C. Noble, M. L. Silberman, *Earth Planet. Sci. Lett.* **8**, 93 (1970); D. C. Noble, *ibid.* **17**, 142 (1972); P. W. Lipman, H. J. Prostka, R. L. Christiansen, *Philos. Trans. R. Soc. London Ser. A* **271**, 217 (1972); R. L. Christiansen and P. W. Lipman, *ibid.*, p. 249; J. W. Hawkins and D. L. Hawkins, *Geol. Soc. Am. Abstracts with Programs* **9** (No. 4), 432 (1977).
16. D. C. Noble, E. H. McKee, E. Farrar, U. Petersen, *Earth Planet. Sci. Lett* **21**, 213 (1974).
17. E. D. Jackson, H. R. Shaw, K. E. Bargar, *ibid.* **26**, 145 (1975).
18. T. L. Vallier, *Initial Rep. Deep Sea Drill. Proj.* **25**, 515 (1974).
19. J. R. Hein, *Nature (London)* **241**, 40 (1973); *J. Geophys. Res.* **78**, 7752 (1973); T. Atwater and P. Molnar, in *Conference on Tectonic Problems of the San Andreas Fault System*, R. L. Kovach and A. Nur, Eds. (Proceedings of Stanford University Publications in the Geological Sciences 13, Stanford University, Palo Alto, Calif., 1973), p. 136.
20. D. A. Clague and R. D. Jarrard, *Geol. Soc. Am. Bull.* **84**, 1135 (1973).
21. P. R. Vogt, *Nature (London)* **240**, 338 (1972).
22. C. Emiliani and J. Geiss, *Geol. Rundsch.* **46/2**, 576 (1958); N. Calder, *Nature (London)* **252**, 216 (1974); J. Chappel, *ibid.*, p. 199; C. G. A. Harrison and J. M. Prospero, *ibid.* **250**, 563 (1974); P. Thompson, H. P. Schwarcz, D. C. Ford, *Science* **184**, 893 (1974); J. Chappel, *Earth Planet. Sci. Lett.* **26**, 370 (1975); J. C. Duplessy, L. Chenouard, F. Vila, *Science* **188**, 1208 (1975); G. E. Williams, *Earth Planet. Sci. Lett.* **26**, 361 (1975); J. D. Hays, J. Imbrie, N. J. Shackleton, *Science* **194**, 1121 (1976); D. W. Parkin, *Nature (London)* **260**, 28 (1976).

23. We thank R. J. Stewart and J. A. Barron for helpful discussions and C. E. Gutmacher, M. G. Jones, and C. Price for technical assistance. T. L. Vallier, E. D. Jackson, and E. H. McKee provided critical reviews. We acknowledge assistance from the staff of the National Science Foundation's Deep Sea Drilling Project and the scientists and crew of the *Glomar Challenger*.

The Biota and the World Carbon Budget

The terrestrial biomass appears to be a net source of carbon dioxide for the atmosphere.

G. M. Woodwell, R. H. Whittaker, W. A. Reiners, G. E. Likens, C. C. Delwiche, D. B. Botkin

Over the past 7 years several reviews of the world carbon budget have confirmed that there is an annual increase in the carbon dioxide content of air that is worldwide and is almost certainly man-caused (*1-7*). The source of the carbon that is accumulating in the atmosphere has been commonly assumed to be the combustion of fossil fuels. Because the amount of CO_2 accumulating in the atmosphere is less than half the total released from fossil fuels, other sinks for CO_2 have been sought. The major sink is the oceans, but mixing rates appear to be too low for the oceans to accommodate all the CO_2 that is thought to be released in excess of that accumulating in the atmosphere. The question of whether the terrestrial biota could be another sink was raised in 1970 (*1*), and the assumption was made that the biota might be a sink, especially in view of the stimulation of photosynthesis under greenhouse conditions by enhanced concentrations of CO_2. More recently the assumption that increased CO_2 in air stimulates photosynthesis worldwide has been questioned (*8-11*). So has the assumption that the biota is a net global sink for CO_2 (*3*). A series of current appraisals suggests that, quite contrary to the previous estimates, the biota is probably an additional source of CO_2 (*12-16*).

In this article we review briefly current knowledge of the world carbon budget with special emphasis on the question of whether the biota is now a source or a sink for CO_2. The analysis shows through convergent lines of evidence that the biota is not a sink and may be a source of CO_2 as large as or larger than the fossil fuel source. The issue is important because of the potential that changes in the CO_2 content of air have for changing climate worldwide (*2, 10*).

Two aspects of the world carbon budget are conspicuous at the moment because they are easily measured: the annual increase in the concentration of CO_2 in air, and the winter-summer oscillation in CO_2 concentration that is apparent in the middle latitudes, especially in the Northern Hemisphere. These variations trace the interplay among physical, chemical, and biotic factors of atmosphere, oceans, and the biota as affected by man. Although the world circulation of carbon is not well enough known to allow precise interpretation of past interactions, and predictions are still more tenuous, various analyses suggest that human activities in the near future could release large additional amounts of CO_2 into the atmosphere with results that are substantially unpredictable.

G. M. Woodwell is director and D. B. Botkin is an associate scientist at the Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts 02543. R. H. Whittaker and G. E. Likens are professors in the Section of Ecology and Systematics, Cornell University, Ithaca, New York 14853. W. A. Reiners is a professor in the Department of Biological Sciences, Dartmouth College, Hanover, New Hampshire 03755, and C. C. Delwiche is a professor in the Soils Department, University of California, Davis 95616.

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