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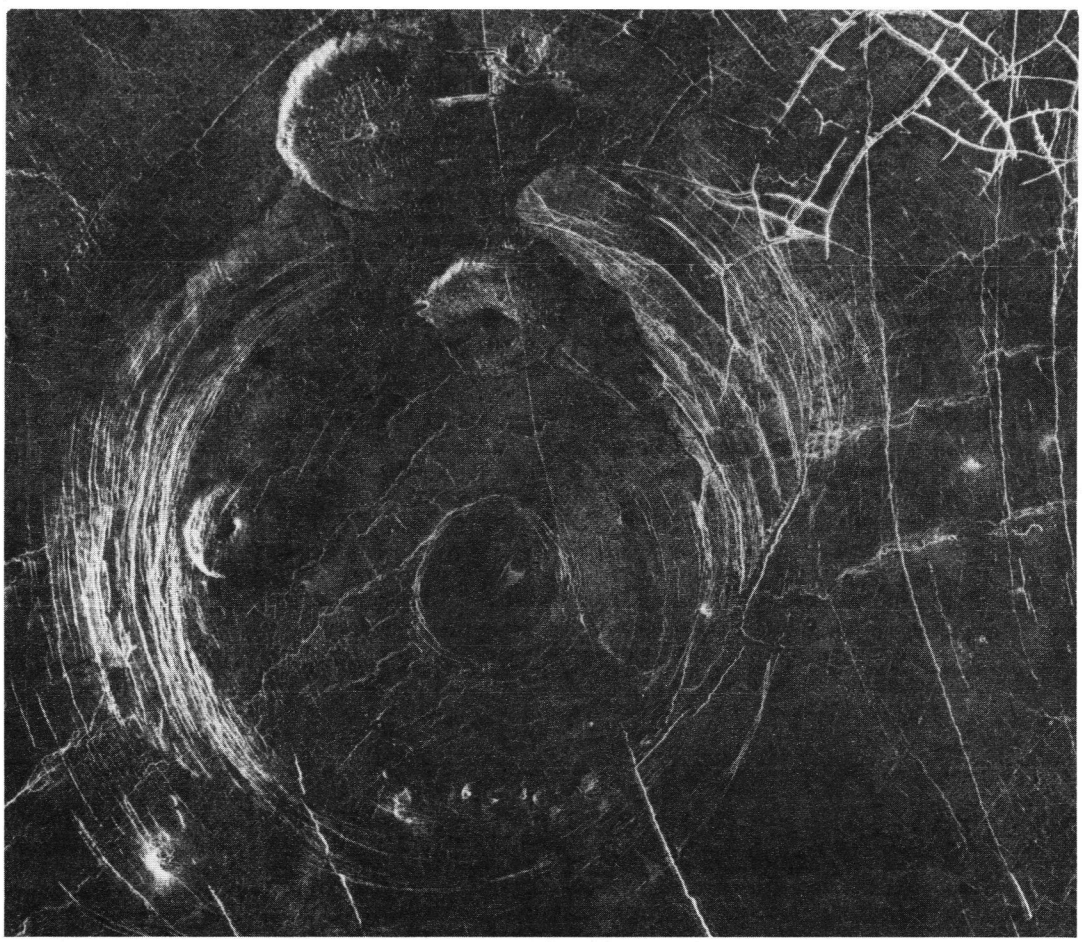

Magellan Captures 84% of Venus. *At the end of its first global mapping cycle of Venus on May 15, NASA's Magellan mission surpassed its objective of mapping 70% of the Venusian surface, according to project scientist Steve Saunders of the Jet Propulsion Laboratory. Reporting on initial Magellan science results on May 28 at AGU's Spring Meeting in Baltimore, Saunders said that 84% of Venus had been imaged during the spacecraft's first cycle of observations. This image, taken in January, shows a 200-km wide corona located in a plain south of Aphrodite Terra (59°S, 164°E). The smooth, flat region in the center of the corona is probably a relatively young lava flow. Just north of the corona is one of the flat-topped volcanic structures known as "pancake" domes, believed to have formed by the eruption of extremely viscous lava. Additional coverage of Magellan results will appear in* Eos *later this month. NASA photo (91-H-393).*

Present-Day CO_2 Emissions from Volcanos

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Terrence M. Gerlach

In an effort to better understand processes that control sources of CO_2 in the carbon cycle, the U.S. Global Change Research Program [*CEES*, 1990] identifies improving understanding of both volcanic emissions and natural sources of CO_2 in the carbon cycle as priority items for research. To implement these goals, the program plan calls for monitoring CO_2 emissions from volcanos.

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Without the resupply of CO_2 by volcanic and metamorphic degassing, removal of atmospheric CO_2 by silicate weathering, carbonate deposition, and burial of organic matter would deplete the CO_2 content of the atmosphere in 10,000 years and the atmosphere-ocean system in 500,000 years [*Holland*, 1978; *Berner et al.*, 1983]. The CO_2 content of the atmosphere-ocean system has varied in the past, but not at the rate expected if CO_2 were removed and not replenished. It is assumed, therefore, that CO_2 degassing from the Earth's interior restores the deficit from surficial processes and balances the atmospheric CO_2 budget on a time scale of 10^4–10^6 yr. Earlier atmospheric balancing calculations imply present-day (pre-industrial) CO_2 degassing rates of 6–7 x 10^{12} mol yr^{-1} [*Holland*, 1978; *Berner et al.*, 1983]; recent calculations suggest degassing rates may be as high as 11 x 10^{12} mol yr^{-1} [*Berner*, 1990].

Atmospheric balancing calculations have inherent drawbacks, however. They do not

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distinguish volcanic, metamorphic, and diagenetic sources of CO_2 degassing—they give an aggregate CO_2 degassing rate for all sources. Since the CO_2 degassing rate obtained in these calculations is the difference between several CO_2-producing and CO_2-consuming processes affecting the atmospheric CO_2 budget, it includes the accumulated error in the rate estimates for each contributing process. To minimize these problems, *Berner* [1990] suggested basing degassing rates on direct measurements, to the extent possible, in future carbon budget calculations.

In this article, I review the results and implications of past efforts to measure rates of CO_2 degassing from volcanos, and I attempt to arrive at an estimate of the global rate of volcanic CO_2 degassing. My principal aim, however, is to emphasize unsettled problems requiring further study and uncertainties due to inadequate data. I make a few comparisons between volcanic and anthropogenic CO_2 emission rates because of current concern about the buildup of CO_2 in the atmosphere.

Modes of CO_2 Degassing

Most of the data on volcanic CO_2 emissions come from active volcanos that are in a state of quiescent degassing, that is, degassing without extrusions of lava or explosive ejections of disrupted and fragmented lava. Data biased in favor of quiescent degassing are not, in my view, a serious limitation. First, the low solubility of CO_2 in silicate melts at upper crustal depths, where magmas tend to reside before erupting, causes magmas underlying volcanos to leak CO_2 continuously and to become depleted in CO_2 by diffusive loss through volcano flanks and by advective loss through fractures feeding hydrothermal fluids and atmospheric plumes [*Carbonnelle et al.*, 1985; *Gerlach and Graeber*, 1985; *Greenland et al.*, 1985; *Allard et al.*, 1987; *Bottinga and Javoy*, 1989; *Gerlach*, 1989*a*,*b*]. Second, the annual quiescent release of CO_2 from all active volcanos appears to be more than an order of magnitude greater than that annually emitted directly from all forms of erupting lava, as discussed below.

Submarine Emissions

Submarine volcanic systems provide about 80% of the present-day magma supply to the crust [*Crisp*, 1984]. Estimates of CO_2 emission rates for submarine volcanos are restricted to volcanos of the mid-oceanic ridge system, which provides about 75% of the present-day magma supply [*Crisp*, 1984]. There are no estimates available for off-ridge volcanos or volcanos on back-arc spreading centers.

Several investigators have attempted to constrain the CO_2 emission rate of the global mid-oceanic ridge system by calculating the product of the oceanic ^3He flux and measured $CO_2/^3He$ ratios of hydrothermal vent fluids and converting the CO_2 flux obtained to a mole per year emission rate. These calculations have tended to employ the original oceanic ^3He flux of 4 atom $cm^{-2}s^{-1}$ instead of the corrected value of 3 atom $cm^{-2}s^{-1}$. (The original ^3He flux assumed a mean $^3He/^4He$ ratio for injected ridge-crest helium of 11 times the atmospheric value; it was subsequently shown that ridge-crest helium has a ratio of 8 times the atmospheric value, thus reducing the oceanic ^3He flux proportionately [*Welhan and Craig*, 1983].) All CO_2 emission rate estimates based on this approach and presented below for the mid-oceanic ridge system have been recalculated for the corrected ^3He flux.

$CO_2/^3He$ data are available for hydrothermal vent fluids from only three locations, all in the eastern Pacific: the Galapagos Rift, and 13°N and 21°N on the East Pacific Rise. The CO_2 emission rates that have been estimated for the mid-oceanic ridges from the data for these sites are 0.6×10^{12} mol yr^{-1} [*Des Marais and Moore*, 1984], 0.75×10^{12} mol yr^{-1} [*Des Marais*, 1985], and 0.7×10^{12} mol yr^{-1} [*Gerlach*, 1989*b*]. Because vent fluid $CO_2/^3He$ data are restricted to so few sites, there is concern about just how representative they are of the mid-oceanic ridge system. In an ingenious attempt to obtain more representative data, *Des Marais* [1985] and *Marty and Jambon* [1987] used the $CO_2/^3He$ values of MORB glasses from many locations as proxies for the $CO_2/^3He$ ratios of ridge-crest emissions. This greatly increases the number of $CO_2/^3He$ data sets, and leads to CO_2 emission rate estimates for the global mid-oceanic ridge system that cluster around 1.5×10^{12} mol yr^{-1} [*Marty and Jambon*, 1987]. This value is about double that obtained from vent fluid data because $CO_2/^3He$ ratios for MORB glasses are about twice those of vent fluids examined so far.

The assumption that the ratio is not affected by fractionation during degassing prior to eruption on the seafloor is a critical issue in the use of MORB glass $CO_2/^3He$ values as proxies for $CO_2/^3He$ in ridge-crest emissions. Pre-eruptive degassing of CO_2 and He from MORB magma is expected to be significant [*Bottinga and Javoy*, 1989; *Gerlach*, 1989*b*], and it has been suggested that quiescent degassing from subridge magma chambers may be primarily responsible for ridge-crest CO_2 and He emissions [*Gerlach*, 1989*b*]. *Marty and Jambon* [1987] argue that because the Henry's law solubility constants for CO_2 and He in molten MORB are similar, the $CO_2/^3He$ ratios for the vapor and melt will be about equal during degassing and that the value of the ratio for MORB glasses is therefore a good predictor of the ratio for ridge emissions. However, a slight difference in CO_2 and He solubilities could, with sufficient degassing, cause enough CO_2 and He fractionation to account for the factor of 2 difference between glass and vent fluid ratios and, thereby, the factor of 2 difference in the calculated CO_2 emission rates for the ridges. This possibility and the possibility that $CO_2/^3He$ ratios of vent fluids may themselves be affected by fractionation processes (for example, differential hydrothermal solubilities of CO_2 and He, carbon precipitation, etc.) need more study.

In view of the disagreement in results thus far for constraining the mid-oceanic ridge CO_2 emission rate, alternative approaches should also be pursued. For example, a mass balance approach based on data for the carbon content of MORBs and the CO_2 content of volcanic gases from transitional basalts of the Afar region suggests a ridge CO_2 emission rate in the range 0.2–0.9 $\times 10^{12}$ mol yr^{-1} [*Gerlach*, 1989*b*]. Updating this estimate with new data for carbon in MORBs [*Kingsley*, 1989] gives a range of 0.5–0.9 $\times 10^{12}$ mol yr^{-1}, which agrees with estimates based on the $CO_2/^3He$ ratios of hydrothermal vent fluids.

Subaerial Emissions

Published data on rates of CO_2 degassing exist for only seven active subaerial volcanos (Table 1, Figure 1): five convergent plate volcanos, an intraplate continental volcano, and an intraplate oceanic island hot spot volcano.

Measurements made on quiescent volcanic plumes provide the basis for most of the CO_2 emission rates for the seven volcanos. The quiescent plumes include examples that preceded the initial explosive episode of an eruption (White Island), examples that followed the initial explosive episodes of an eruption (Mount St. Helens, Redoubt), examples that were present between explosive or dome-building episodes of an eruption (Mount St. Helens, Redoubt), and examples that exhibit long-term stability and continuity during, between, and long after eruptions (Kilauea, Mount Etna, Vulcano). One emission rate estimate (Augustine) is based on plume measurements during a low-level explosive episode.

The plume observations consist of airborne MIRAN infrared spectrophotometer measurements of above-background CO_2 concentrations, or airborne COSPEC ultraviolet spectrophotometer measurements of SO_2 column abundances combined with measurements of the CO_2/SO_2 ratio of the gases supplying the plume. Most studies neglected the diffusive flux of CO_2 through volcano flanks; soil gas surveys carried out at Mount

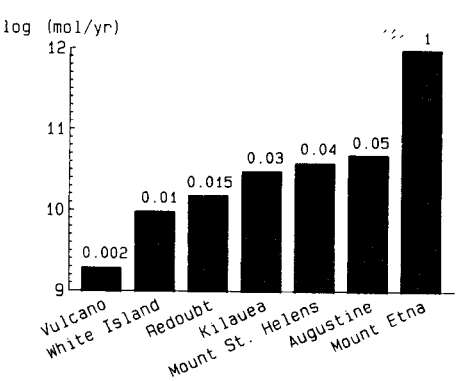

Fig. 1. CO_2 emission rates in log (moles per year) arranged in ascending order for subaerial volcanos from Table 1. The numbers on the tops of the bars are emission rates in 10^{12} mol yr^{-1}. The median emission rate used in a calculation described in the text is 0.03 x 10^{12} mol yr^{-1} (Kilauea).

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Etna and Vulcano suggest this source can be significant (Table 1).

Continuous, long-term measurements of CO_2 emission rates do not exist for any volcano. Most estimates are based on spot measurements. The only record of closely spaced measurements over several (15) months is for Mount St. Helens [*Harris et al.*, 1981; *Casadevall et al.*, 1983]. The long-term emission rate for Kilauea (0.03×10^{12} mol yr^{-1}) [*Gerlach and Graeber*, 1985] is based on the CO_2 content and average supply rate of magma emplaced in Kilauea's summit chamber from July 1956 to April 1983. *Rose et al.* [1986] suggest a long-term CO_2 emission rate for White Island of approximately 0.01×10^{12} mol yr^{-1}; they consider the larger 0.03×10^{12} mol yr^{-1} rate in November 1983 (Table 1) to be representative of degassing during periods of new magma emplacement prior to an eruption.

Kilauea Volcano provides an example of simultaneous eruptive and quiescent degassing. Lava production rates combined with estimates of the CO_2 content of the erupting lava [*Greenland et al.*, 1985; *Gerlach*, 1986; K. Hon, personal communication, 1991] give a CO_2 emission rate of $0.001–0.003 \times 10^{12}$ mol yr^{-1} for the current east rift zone eruption. Quiescent degassing at Kilauea's summit (Table 1) is therefore at least 10-fold greater than contemporaneous eruptive degassing at the present time. *Casadevall et al.* [1984] report similar eruptive CO_2 emission rates between April 2 and April 16 for the 1984 eruption of Mauna Loa Volcano, Hawaii. Unfortunately, the background quiescent emission rate is not known for Mauna Loa.

Marty et al. [1989] estimated the total output of CO_2 from island arc volcanos to be in the range $0.1–0.5 \times 10^{12}$ mol yr^{-1}. This estimate is based on the global SO_2 output from subaerial volcanos of 0.24×10^{12} mol yr^{-1} [*Berresheim and Jaeschke*, 1983]. It assumes that island arc volcanos are primarily responsible for the global SO_2 output and that the CO_2/SO_2 ratio for arc emissions is 1.5 ± 1. It is possible in principle to follow this approach in estimating the global CO_2 emission rate of all subaerial volcanos from the corresponding global volcanic SO_2 output. The difficulty in doing so is that the appropriate global volcanic CO_2/SO_2 value is unknown. Combining the total CO_2 emission rate for Etna (summit plume plus diffusive flank), which is exceptionally large and on the order of 1×10^{12} mol yr^{-1} (Table 1), with the global volcanic SO_2 output suggests that the global volcanic CO_2/SO_2 value is at least 4.2. *Williams et al.* [1990] calculated a global subaerial CO_2 emission rate of 1.2×10^{12} mol yr^{-1} from the global volcanic SO_2 output and CO_2/SO_2 data for 30 volcanos, suggesting a global volcanic CO_2/SO_2 value of 5.

Another approach to estimating the global subaerial CO_2 emission rate of volcanos is to extrapolate the rates for the volcanos in Table 1 to all active subaerial volcanos. The 5-year running average for the number of active subaerial volcanos per year is approximately 60 [*Simkin and Siebert*, 1984]. I base the extrapolation on the median emission rate of the seven volcanos (Figure 1) because the data set is small, and the median, unlike the mean, is less sensitive to outlying data. The median value of 0.03×10^{12} mol yr^{-1} indicates a global subaerial volcanic CO_2 emission rate of approximately 1.8×10^{12} mol yr^{-1}. Reassuringly, this result is larger than the rate for Mount Etna alone and similar to the estimate of *Williams et al.* [1990]. Applying the same procedure to the median SO_2 flux for the same seven volcanos (0.0035×10^{12} mol yr^{-1}) gives a global volcanic SO_2 output of 0.21×10^{12} mol yr^{-1}, which agrees well with the 0.24×10^{12} mol yr^{-1} estimate of *Berresheim and Jaeschke* [1983].

The above estimates for the global CO_2 emission rate from subaerial volcanos are based almost entirely on measurements during quiescent degassing. They are about an order of magnitude larger than the estimated annual CO_2 emission of 0.15×10^{12} mol yr^{-1} released from all forms of erupting lava [*Leavitt*, 1982]. Leavitt's estimate is based on a chronology for subaerial eruptions be-

TABLE 1. CO_2 Emission Rates for Subaerial Volcanos

Volcano	Geologic Setting	Source Characteristics	Period of Observation	Method	Rate[a] 10^{12} mol yr^{-1}	Reference
Mount St. Helens Cascades Volcano Range Western U.S.	convergent plate continental margin dacitic magma	quiescent summit plume between explosive or dome-building episodes	July 1980– September 1981	A	0.04	*Harris et al.* [1981] *Casadevall et al.* [1983]
White Island Taupo Volcanic Zone New Zealand	convergent plate island arc andesitic magma	quiescent crater plume before explosive episode December 1983; quiescent crater plume	November 1983	B	0.03	*Rose et al.* [1986]
			November 1984	B	0.0073	*Rose et al.* [1986]
			January 1985	B	0.0081	*Rose et al.* [1986]
Augustine Aleutian Volcanic Arc Alaska	convergent plate island arc andesitic-dacitic magma	summit plume during low-level explosive episode	April 1986	B	0.05	*Symonds et al.* [1991]
Vulcano Aeolian Islands North of Sicily	convergent plate island arc trachyandesitic magma	quiescent summit plume; flux through flanks	September 1984	B	0.0015	*Carbonnelle et al.* [1985]
			September- October 1988	C	0.0004	*Baubron et al.* [1990, 1991]
Redoubt Aleutian Volcanic Arc Alaska	convergent plate island arc andesitic magma	quiescent summit plume between explosive or dome-building episodes	June 1990	A	0.015	*Casadevall et al.* [1990]
Mount Etna East coast of Sicily	intra-plate continental volcano alkaline basaltic magma	summit plume during intense degassing, sometimes Strombolian; flux through flanks	September 1984	B	0.58	*Carbonnelle et al.* [1985]
			June 1985	B	0.58	*Allard et al.* [1987]
			September 1984	C	0.46	*Carbonnelle et al.* [1985]
			June 1985	C	0.46	*Allard et al.* [1987]
Kilauea North Pacific Ocean	intra-plate oceanic hot spot tholeiitic basalt magma	quiescent summit plume	9 December 1983	A	0.03	*Greenland et al.* [1985]
			13 February 1984	A	0.01	*Casadevall et al.* [1987]
			July 1956–April 1983	D	0.03	*Gerlach and Graeber* [1985]

[a]Average emission rate over period of observation.

A, measurement by airborne MIRAN infrared spectrophotometer of CO_2 content of volcanic plume.

B, measurement by airborne COSPEC ultraviolet spectrophotometer of SO_2 column abundances in volcanic plume coupled with data for CO_2/SO_2 ratio of plume or high-temperature fumarole gases supplying plume (corrected for atmospheric contamination).

C, soil gas measurements of diffusive CO_2 flux through unvegetated volcano flanks.

D, based on volcanic gas data, volatile concentrations in matrix glasses and glass inclusions, and long-term magma supply rate.

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tween 1800 and 1969, and it assumes an average eruption volume of 0.1 km^3 magma (2.7 g cm^{-3}) and a release of 0.12 wt% CO_2 during eruption. Taken at face value, this estimate implies the predominance of quiescent CO_2 degassing from volcanos, as suggested previously by *Rose et al.* [1986].

Comparisons with Anthropogenic Emissions

Man's emissions of CO_2 from fossil fuel burning, cement production, and gas flaring alone now amount to 500 x 10^{12} mol yr^{-1} [*Boden et al.*, 1990]. Contributions from man's management of the biosphere (for example, deforestation) are less well known but potentially of the same magnitude. Thus man's activities replenish the atmospheric CO_2 deficit by more than 45 times over. They are equivalent in terms of CO_2 production to turning on about 17,000 additional Kilauea Volcanos or 350–700 additional mid-oceanic ridge systems.

Conclusions

The results reviewed above suggest that constraining the global volcanic CO_2 emission rate by direct measurement is feasible. Both subaerial and submarine volcanos appear to emit CO_2 at global rates on the order of 1–2 x 10^{12} mol yr^{-1}; thus, while the global rates from subaerial and submarine volcanos are uncertain at the present time, a total global estimate of 3–4 x 10^{12} mol yr^{-1} seems reasonable and conservative. This estimate for volcano degassing is consistent with estimates of total CO_2 degassing of 6–11 x 10^{12} mol yr^{-1} based on atmospheric CO_2 balancing, and it indicates that CO_2 emissions from volcanos contribute about 35–65% of the CO_2 needed to balance the deficit in the atmosphere-ocean system. Although the present-day global emission rate of CO_2 from volcanos is uncertain, anthropogenic emissions clearly overwhelm it by at least 150 times.

The global rate of emission of CO_2 from the mid-oceanic ridge system is estimated to be in the range 0.7–1.5 x 10^{12} mol yr^{-1}. Thus, mid-ocean ridges probably account for less than half of the global volcanic CO_2 flux, despite the fact that mid-oceanic ridge magmatism provides over 75% of the present-day magma supply to the crust. Efforts should be made to reduce the uncertainty that exists presently in estimates of CO_2 degassing from the global mid-oceanic ridge system, but an equally or more important priority in submarine studies is to begin acquiring data for CO_2 emission rates at off-ridge submarine volcanic systems such as submarine hot spot volcanos and back-arc basin spreading centers.

The available data suggest that CO_2 emissions from all subaerial volcanos are probably greater than that from mid-oceanic ridges. This conclusion is at variance with the widely held view that the ridge system produces orders-of-magnitude larger emissions than do subaerial volcanos [e.g., *CEES*, 1990, p. 97]. Indeed, the output from Mount Etna alone is about equivalent to that of the entire mid-oceanic ridge system. However, CO_2 emission data for subaerial volcanos are sparse, and the global contribution from subaerial volcanos is very poorly constrained. Improving the data base for CO_2 emissions from subaerial volcanos is the highest priority for future work. The available data suggest that contributions of CO_2 in the range 0.01–0.05 x 10^{12} mol yr^{-1} can be expected from most active subaerial volcanos (Figure 1). However, alkaline volcanos (for example, Mount Erebus, Nyiragongo) may produce 1–2 orders of magnitude larger contributions, if Mount Etna is any indication. On the other hand, Etna's large CO_2 output may be augmented by contamination from underlying carbonates [*Allard et al.*, 1987].

Investigations to date suggest that most of the CO_2 emitted by volcanos is released during quiescent degassing instead of eruptive degassing. This proposition needs further investigation, however, and should be tested against more data for quiescent degassing and measurements of CO_2 emissions from volcanos during episodes of vigorous eruptive degassing. Techniques are sorely needed for making direct CO_2 emission measurements, especially during large explosive eruptions, by remote spectroscopic techniques similar to the widely used COSPEC technique for measuring volcanic SO_2 emission rates.

Berner and Lasaga [1989] have characterized the calculation of CO_2 degassing from igneous and metamorphic activity as the most vexing problem encountered in modeling the carbon geochemical cycle. In hopes of getting at least a reasonable approximation of CO_2 degassing over geologic time, modelers have coupled all degassing to seafloor spreading rates [*Berner et al.*, 1983]. This approximation is reasonable for CO_2 degassing at mid-oceanic ridges and subduction zones. The adequacy of seafloor spreading rates as a predictor of mid-plate volcano degassing rates is less clear, and it is possible that CO_2 degassing at mid-plate volcanos is outside the conceptual framework of the current carbon cycle models. The high CO_2 degassing rates for Mount Etna underscore the need to ensure that mid-plate volcano degassing is satisfactorily represented in models of the carbon geochemical cycle.

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Meteorite Impact and the Early Earth Workshop

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Scientists trying to decipher the early history of the Earth are like people who arrive late for a movie, after the basic story line and characters have been established. Like tardy moviegoers, geologists are frustrated by the absence of any preserved geological record from the Earth's early years, the "Hadean Interval," which extended from about 4.6 billion years ago, when the solar system formed, to about 3.8 billion years ago, when rocks started to be preserved.

It is in this Hadean Interval that much of the basic character of the Earth was established. A metal core formed, a magnetic field developed, the first lavas erupted, continental nuclei possibly formed, and there may have been the first stirrings of plate tectonics. Oceans and an atmosphere formed, prebiotic chemical evolution took place, and the first primitive life forms may have appeared.

In the absence of a preserved geological record, study of these events has been largely a free-form debate. However, a recent workshop on "Meteorite Impact and the Early Earth" (Perth, Australia, September 21–22, 1990), attended by 50 scientists from 11 countries, produced a rich collection of information to support a major role for large extraterrestrial impacts in the development of the early Earth. The workshop also illuminated some challenging questions, provided a focus for discussions between scientists from a wide range of disciplines, and identified a host of exciting next steps for research on a problem that involves both the Earth and its neighboring terrestrial planets. The major results are summarized here, with the names of the first presenters of key papers given in parentheses.

Two broad areas of agreement emerged from the 28 papers presented at the workshop. First of all, there was a consensus that intense bombardment by large extraterrestrial objects was a major process during the origin and early development of the Earth. In the last 25 years, meteorite impacts have been increasingly recognized as a significant, if sporadic, process in the modern (<2 billion years) geological evolution of the Earth. About 110 preserved impact structures, formed in the last 600 million years, have so far been recognized (R. Grieve, P. R. Weissman), as well as two large older structures of probable impact origin, Sudbury (Canada) and Vredefort (South Africa), both about 2 billion years old (W. S. Shanks, W. U. Reimold). A more recent biological dimension has been added by the increasing evidence that the impact of one or more sizeable objects (up to 10 km in diameter) was responsible for the great Cretaceous-Tertiary (K-T) extinction.

During the same 25 years, explorations of other planets have established that meteorite bombardment is a far more fundamental process in planetary formation and evolution than we could have known from studying only the Earth. Extensive cratering observed on old planetary surfaces, like that of Mercury, the southern hemisphere of Mars, and the highlands of the Moon, indicates that the bombardment rate was many times more intense in the early years of the solar system than it is today.

The heavily cratered lunar highlands, in fact, preserve a critical piece of information: evidence of the intense bombardment that affected both the Moon and Earth soon after both had formed. Between about 4.5–3.8 billion years ago, the lunar highlands recorded a bombardment more than 500 times as intense as that in later geologic time (G. Ryder, N. G. Barlow, W. K. Hartmann, C. R. Chapman, and G. W. Wetherill), including the creation of more than a dozen lunar basins ranging in size from hundreds of kilometers to over a thousand kilometers across. The nearby Earth could not have escaped such a bombardment; indeed, it would have probably been struck by even more large objects. R. Grieve estimated that more than 200 impact basins greater than 1000 km in diameter formed on the Earth during the period recorded in the lunar highlands.

The workshop's second major area of agreement was that the energy added by such impacts to the near-surface regions of the Earth provides a major force for geological, atmospheric, and biological change. A 10-km asteroid, traveling at 20 km/sec, deposits 10^{20}–10^{21} J of kinetic energy in the Earth's atmosphere and upper crust. A rarer 100-km object generates 10^{23}–10^{24} J. (For comparison, the current release of internal energy from the Earth is 10^{21} J/yr.) This intense and localized spike of energy can produce major regional and global effects. An immediate result is near-surface heating and the production of large volumes of impact melts from the target rocks (R. Grieve, A. Y. Glikson). In areas of high geothermal gradients, which were probably widespread during the Hadean period, such impacts may have triggered intense volcanism and helped to form the first continental nuclei.

Above bedrock, large impacts would also have had major effects, both constructive and destructive, on oceans, atmosphere, and life. New atmospheres would be produced from the water and other volatiles contained in the impacting bodies (A. M. Vickery), but this process would be overshadowed by the loss of existing atmosphere through blast and ejection effects associated with the impact (A. M. Vickery). The energy released would result in intense global atmospheric heating and would produce boiling and reprecipitation of the oceans (Y. Abe). In this process, any established life could be destroyed by so-called "impact frustration" (K. Zahnle), although new life could subsequently arise, possibly fueled by carbonaceous compounds surviving from the impacting object. One consequence of these ideas is that terrestrial life, instead of developing smoothly from a single point, may actually have had several starts, stops, and restarts.

Unanswered Questions

Beyond this general two-part consensus, workshop participants were sharply divided on several fundamental questions. One of these was: How did the ancient impact rate vary with time? The lunar highlands present a unique and critical record of the ancient impact rate in the Earth-Moon system, but exactly what was the rate, and how did it vary with time? Did the intense bombardment recorded by the lunar highlands represent a gradually declining sweep-up, from the whole solar system, of the original planetesimals that formed the other planets (G. W. Wetherill, D. H. Grinspoon, and W. K. Hartmann)? Or did it reflect special conditions in the Earth-Moon region following the catastrophic origin of the Moon by the impact of a Mars-sized body on the primordial Earth? Or is much of what we see on the Moon the

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