Text of Gerlach (1991)

About this Web Page.

I have included the full text of Gerlach's 1991 paper concerning volcanic carbon dioxide emissions because so few people who cite Gerlach's work have actually read it. This is hardly surprising, considering that until now, this paper has not been available online. Contrary to the claims of Monbiot, the USGS, and many other authors, Gerlach (1991) includes no measurements of actual submarine volcano emissions, makes no attempt at modal representation, and Gerlach's global volcanic emission estimate is based on measurements taken from only seven subaerial volcanoes (Gerlach, 1991, §4, ¶1) and three hydrothermal vent sites (Gerlach, 1991, §3, ¶3). Although a hydrothermal vent site can be a feature of a volcano, hydrothermal vent site emission and the submarine volcanic emission are two completely different measurements. To his credit, Gerlach (1991, §1, ¶4) points out the fact that the data avilable at the time was woefully inadequate to a global estimate. Although Gerlach (1991, §3, ¶3) does mention some proxy measurements for mid-oceanic ridge degassing, he also demonstrates that these are nonetheless doubtful as the degree of fractionation remains unknown (Gerlach, 1991, §3, ¶4). While he talks about "volcanos of the mid-oceanic ridge system" Gerlach (1991) neither offers nor includes emission estimates of any submarine volcano. Moreover, Gerlach (1991, §3, ¶1) asserts "There are no estimates for off-ridge volcanos ". For more information concerning why I've included Gerlach (1991) among the most misquoted and abused papers in the public domain, see http://geologist-1011.mobi.

Although I do not attempt to correct the English or the arithmetic of T. M. Gerlach (e.g. Gerlach, 1991: §3, ¶3, 1st sentence; §6, ¶1 - 2nd sentence, 1st clause), I have gone as far as to update the typesetting by:

- Eliminating the first-line indentation of paragraphs.
- Altering the page identifier to optimise clarity for online reading.
- Setting citation elements within the references to bold for ease of use.
- Change incorrect use of square brackets on references to the proper round brackets, because Square brackets are reserved for additional explanatory material added by persons other than the original author.

A list of any obviously unintended errata in the text of Gerlach (1991) can be found at the end of this web page. However, this list excludes any and all scientific assertions that may disagree with current knowledge, because such assertions remain, nonetheless, valid and correct in their historical context. This ensures that the views of the original author remain protected from over-zealous pedantry. Thus you are afforded an uncensored view of science from the perspective of the time and of the original author.

The text provided here is entirely typed in by hand from photocopied materiel. Picking off any typos will, no doubt, be an ongoing endeavour.

The photocopy I've acquired is from an edition with no specific pagination, and is spread over five mysteriously unnumbered pages, instead of the three specified by EOS as, 249, 254, and 255. For this reason, I've assembled a numbered list of sections by heading. The first section, being unnamed, I've designated as the "Introduction". Specific references to the text are thereby made by section (§) and paragraph (¶) number -from the first paragraph in the section-, which exclude headings, tables, figures, and captions.

If I receive the correct page break locations I'll paginate this copy of Gerlach (1991) accodringly.

Source

Gerlach, T. M., **1991**, "Present-Day CO_2 Emissions from Volcanoes", *EOS, Transactions, American Geophysical Union*, Vol. 72, pp. 249, 254-255.

Gerlach (1991): Main Article

Gerlach (1991, § 1)

Present-Day CO_2 Emissions from Volcanos

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 cources 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.

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 the 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 distinguish volcanic, metamorphic, and diagenetic sources of CO_2 degassing—they give an aggregate CO_2 degassing rate obtained for all sources. Since the CO_2 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 principle 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.

Gerlach (1991, § 2)

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 favour 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_2continuously 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; Allard et al., 1987; Bottinga and Javoy, 1989; Gerlach 1989a,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 emitted directly from all forms of erupting lava, as discussed below.

Gerlach (1991, § 3)

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 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 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 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 13º and 21ºN on the East Pacific Rise. The CO_2 emission rates that have been estimated for the mid-oceanic ridges from the datafor these sites are 0.6 x 10^{12} mol yr^{-1} (De Marais and Moore, 1984), 0.75 x 10^{12} mol yr^{-1} (Des Marais, 1985), and 0.7 x 10^{12} mol yr^{-1} (Gerlach, 1989b). 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 glassesfrom 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 x 10^{12} mol yr^{12} (Marty and Jambon, 1987). This value is about double that obtained from vent fluid 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_2^3 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, 1989b), 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, 1989b). 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 solubuilities could, with sufficient degassing, cause enough CO_2 and He fractionatin to account for a 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 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 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 contentof volcanic gases from transitional basalts of the Afar region suggests a ridge CO_2 emission rate in the range 0.2-0.9 x 10^{12} mol yr^{-1} (Gerlach, 1898b). Updating this estimate with new data for carbon in MORBs (Kingsly, 1989) gives a range of 0.5-0.9 x 10^{12} mol yr^{-1}, which agrees with estimates based on the CO_2 ratios of hydrothermal vent fluids.

Gerlach (1991, § 4)

Subaerial Emissions

Published 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 hotspot 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 includ 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 afte eruptions (Kilauea, Mount Etna, Vulcano). One emission rate estimate (Augustine) is based on plume measurements during a low level explosive episode.

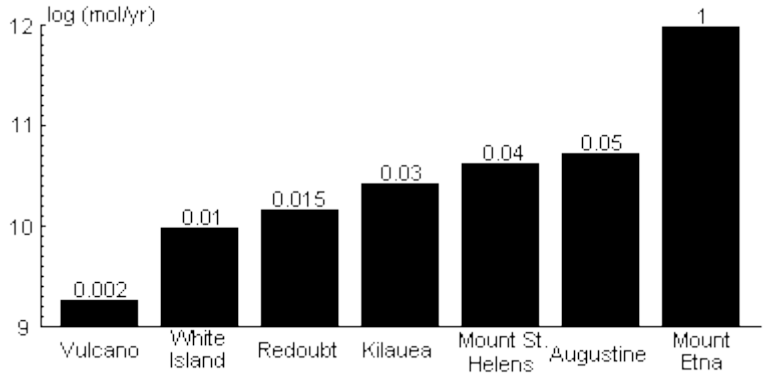

Fig. 1. CO_2 emission rates in log (moles per year) arranged in ascending order for subaerial volcanoes from Table 1. The numbers on the tops of the bars are emission rates in 10^{12} mol yr^{-1}. The median emission rate used in a calculation described in the text is 0.03 x 10^{12} mol yr^{-1}(Kilauea).The plume observations onsist of airbourne MIRAN infrared spectrophotometer measurements of above-background CO_2 concentrations, or airbourne COSPEC ultraviolet spectrophotometer measurements of SO_2 column abundancescombined with measurements ofthe CO_2/SO_2 ratio of gases supplying the plume. Most studies neglected the diffusive flux of CO_2 through volcano flanks; soil gas surveys carried out at Mount 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 Sy. Helens (Harris et al., 1981; Casadavall et al., 1983). The long-term emission rate for Kilauea (0.03 x 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 x 10^{12} mol yr^{-1}; they consider the larger 0.03 x 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 for the current east rift zoen eruption. Quiescent degassing of Kilauea's summit (Table 1) is therefore at least 10-fold greater than contemporaneous eruptive degassing at the present time. Casadawell 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 x 10^{12} mol yr^{-1}. This estimate is based on the global SO_2 output from subaerial volcanos of 0.24 x 10^{12} mol yr^{-1} (Berresheim and Jaeschke, 1983). It assumes that islandarc 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_2emission 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 x 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 emission rate of 1.2 x 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 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 x 10^{12} mol yr^{-1} indicates a global subaerial emission rate of approximately 1.8 x 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 x 10^{12} mol yr^{-1}) gives a global volcanic SO_2 output of 0.21 x 10^{12} mol yr^{-1}, which agrees well with the 0.24 x 10^{12} mol yr^{-1} estimate of Berresheim and Jaeschke (1983).

Table I. 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) Casadavall 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 November 1984 January 1985	B B B	0.03 0.0073 0.081	Rose et al. (1986) Rose et al. (1986) Rose et al. (1986)
Augustine Aleutian Volcanic Arc Alaska	convergent plate island arc andesitic-	summit plume during low-level explosive episode	April 1986	B	0.05	Symonds et al. (1991)

	dacitic magma					
Vulcano Aeolian Islands North of Sicily	convergent plate island arc trachyandesitic magma	quiescent summit plume; flux through flanks	September 1984 September-October 1988	B C	0.0015 0.0004	Carbonnelle et al. (1985) Baubon 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 Jun 1985 September 1984 June 1985	B B C C	0.58 0.58 0.46 0.46	Carbonnelle et al. (1985) Allard et al. (1987) Carbonnelle et al. (1985) Allard et al. (1987)
Kilauea North Pacific Ocean	intra-plate oceanic hot spot tholeiitic basalt magma	quiescent summit plume	9 December 1983 13 February 1984 July 1956-April 1983	A A D	0.03 0.01 0.03	Greenland et al. (1985) Casadevall et al. (1987) 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 fumarolle 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.

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 between 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).

Gerlach (1991, § 5)

Comparisons with Anthropogenic Emissions

Man's emissions of CO_2 from fossil fuel burning, cement production, and gas flaring alone not 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.

Gerlach (1991, § 6)

Conclusions

The results reviewed above suggest that constraining the global 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 6-10 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 volcanic systems such as submarine hot spot volcanos and back-arc basin spreading centers.

The avaliable data suggest that CO_2 emissions from all subaerial volcanos are probably greater than 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 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 Erubus, Nyiragongo) may produce 1-2 orders of magnitude larger contributions, if Mount Etna is any indication. On the otehr hand, Etna's large CO_2 output may be augmented by contamination from underlying carbonates (Allard et al., 1987).

Invesigations 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 modelling 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.

Gerlach (1991, § 7)

Acknowledgements

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Gerlach (1991, § 8)

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