melane glass implies that rapid quenching occurred, perhaps within steam clouds above the vent on the sea floor.

A final surprising implication of the paleomagnetic results is that the cooling units of the breccia are at most a few meters thick. Paleoinclinations of the matrix are random between pieces of core rather than uniform as they should be had the deposit welded as a single cooling unit. If the samples had been uniformly magnetized upon deposition at 31°N during the Matuyama reversed epoch, then they all would be inclined $-50° \pm 5°$. Paleoinclinations are not expected to be affected by drilling rotation. In contrast, no two adjacent pieces of core have the same inclination, and many pieces are overturned. Inclinations of the matrix do agree within one 20-cm-long core and within five of seven minicores ($10\ cm^3$); these data indicate that samples at these scales belong to the same cooling unit. The maximum distance between adjacent randomly oriented cores is 2.5 m, so that cooling units are at least that thin.

The paleomagnetic heterogeneity shown by the matrix may have been caused by welding within the eruption column, or on the steep slopes of a small sea floor cinder cone. Welding may be more likely in a submarine than subaerial eruption column because dispersal is less rapid and fragments can be convectively reentrained while hot, even though they are quenched (*18*). In this interpretation, matrix domains acquired their remanent magnetism in the eruption column and landed randomly. Alternatively, rapid mass wasting of agglutinated cinders during the eruption could result in the random orientations encountered. In this interpretation, welding occurred during deposition on the sea floor and the randomness reflects subsequent slope instability. The absence of similar breccia at Site 790 only 2.4 km away is consistent with the inference of a small steep-sided edifice, but the available evidence is inconclusive about where welding occurred.

In summary, the matrix of this scoriaceous basaltic breccia suggests explosive eruption, hot deposition, and thin cooling units despite eruption at >18 MPa. The obvious clasts appear to be accidental. The occurrence in deep water of these phenomena, which usually are associated with subaerial eruptions, result from the high water content of backarc tholeiitic basalt magma. Although H_2O is much more soluble than CO_2 in magma and has a smaller work function at these pressures, the recycling of much more H_2O than CO_2 at subduction zones creates the potential for deep explosive eruptions. Terrestrially, the association of high magmatic water with eruption at confining pressures >18 MPa is characteristic of backarc basins.

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21. This serendipitous, multi-disciplinary discovery was possible because of the Ocean Drilling Program. Shipboard chemical analyses, thin sections, and photographs were provided by ODP staff, especially B. Domeyer, K. Kuroki, and C. Galida. B. Houghton, H. Staudigel, and D. Clague provided helpful reviews.

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A Comparison of the Contribution of Various Gases to the Greenhouse Effect

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The current concern about an anthropogenic impact on global climate has made it of interest to compare the potential effect of various human activities. A case in point is the comparison between the emission of greenhouse gases from the use of natural gas and that from other fossil fuels. This comparison requires an evaluation of the effect of methane emissions relative to that of carbon dioxide emissions. A rough analysis based on the use of currently accepted values shows that natural gas is preferable to other fossil fuels in consideration of the greenhouse effect as long as its leakage can be limited to 3 to 6 percent.

THE GREENHOUSE EFFECT OF A CERtain amount of a greenhouse gas in the atmosphere can be estimated with radiative transfer calculations. Even though considerable uncertainty is associated with calculations of an expected increase in temperature, the relative contribution of various gases can be determined more accurately (see Table 1).

The effect of 1 mol (or 1 kg) of CO_2 in the atmosphere depends to some extent on the prevailing concentration of CO_2. At present, high atmospheric concentrations of CO_2 already prevail and the effect of additional CO_2 is less. No corresponding saturation effect has yet occurred with the other greenhouse gases. The values in Table 1 are based on current CO_2 levels; consequently, future comparison values for the various gases will be somewhat greater.

When these relative values are scaled according to the currently observed increase in concentrations in the atmosphere, the relative contributions of the gases to the greenhouse effect are obtained (Table 2). The percentage contributions are uncertain because of uncertainties in both the values in Table 1 and the observed rate of increase. The latter uncertainty is particularly true for ozone (O_3) in the troposphere. The total effect is expected to cause an increase in the average global temperature of 1.5 to 4.5 K sometime around the middle of the 21st century (*1*). Although CO_2 is the least efficient gas on a per mole basis, it is responsi-

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Table 1. The contribution, relative to CO_2, of various greenhouse gases to the greenhouse effect per mole or per kilogram in the atmosphere; CFC, chlorofluorocarbon. The values show the effect of the amount of a given gas in the atmosphere (as opposed to the amount emitted) (*7*, *8*).

Species	Mass basis (kg^{-1})	Mole basis (mol^{-1})
CO_2	1	1
CH_4	70	25
N_2O	200	200
O_3*	1,800	2,000
CFC-11	4,000	12,000
CFC-12	6,000	15,000

*In the troposphere.

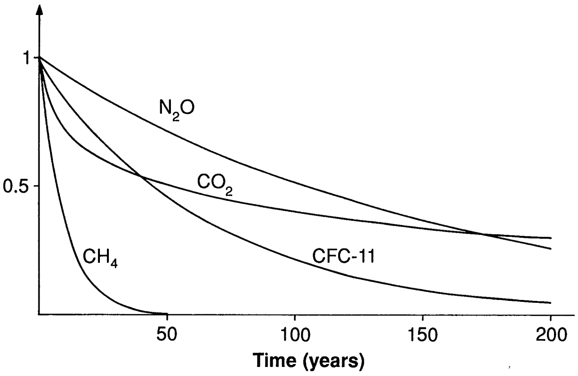

Fig. 1. Approximate decay history for a unit release of various gases to the atmosphere. The decay of CO_2 is taken from the model calculations by Siegenthaler and Oeschger (*2*). The other curves are exponential decays with time scales as given in Table 3.

ble for about half of the observed effect because of its high absolute increase in concentration.

In order to compare emitted amounts with each other, two factors must be considered: (i) different gases have different decay times in the atmosphere, and (ii) a certain emission of one gas may affect also the concentrations of other greenhouse gases. To illustrate these points, consider the emission of 1 kg of a gas into the atmosphere. For most gases, it can be assumed that the decay occurs exponentially with time (Fig. 1), at a time constant (the half-life divided by 0.7) equal to the turnover time of the gas. For CO_2, a fraction disappears relatively fast (within a few years), whereas the rest decays much more slowly (*2*). The turnover time of CO_2 in the atmosphere is often quoted as being 3 to 4 years only. Although such a short time scale is a correct measure of how rapidly CO_2 is exchanged between the atmosphere and the biota and the ocean surface, respectively, it has no direct relation to the decay time of CO_2 in the atmosphere.

The decay time for methane, CH_4 (10 years) (Table 3), is calculated on the basis of concentration measurements and the estimated flux of this gas (*3*). The decay time for CH_4 molecules emitted in the future will probably be somewhat longer than the value estimated in Table 3, however, as a result of an ever slower breakdown (*4*).

One way of comparing the emissions of the gases from the point of view of the greenhouse effect is to define the accumulated greenhouse effect as the integral of the greenhouse effect over time. This concept corresponds to dosage in radiology. Considering the emission of 1 kg of a certain gas i, we can write

$$AG_i = \int_0^T k_i M_i(t)dt = k_i \int_0^T M_i(t)dt \qquad (1)$$

where AG_i is the accumulated greenhouse effect of an emission of 1 kg over the time period T, $M_i(t)$ is the amount remaining in the atmosphere after time t, and k_i is the greenhouse effect per kilogram in the atmosphere.

The question arises what time scale T one should use in this integration. If the main concern is the long-term effect of a climate change, for example, sea level rise, it would be reasonable to extend the integration over a century or more. On the other hand, it might well be justified to stop the integration after some decades for someone most concerned with the rate of temperature change. As a compromise, I have chosen, somewhat arbitrarily, T to be equal to 100 years. If another value had been chosen, the quantitative conclusions would need to be modified accordingly.

Table 2. The estimated contribution of various gases to the anthropogenic greenhouse effect, based on the currently observed increase in the concentrations in the atmosphere (*9*); ppbv, parts per billion by volume.

Species	Concentration (ppbv)	Rate of increase (% per year)	Relative contribution (%)
CO_2	353×10^3	0.5	60
CH_4	1.7×10^3	1	15
N_2O	310	0.2	5
O_3*	10–50	0.5	8
CFC-11	0.28	4	4
CFC-12	0.48	4	8

*In the troposphere.

Table 3. Decay time for an additional emission of greenhouse gases to the atmosphere. The decay of CO_2 does not follow a simple exponential relation (see Fig. 1). The decay time given for CO_2 represents the time taken for the added mass to decay to 37% (1/*e*) of the initial value.

Species	Decay time (year)
CO_2	(120)
CH_4	10
N_2O	150
O_3*	0.1
CFC-11	65
CFC-12	120

*In the troposphere.

We can thereby use Eq. 1 to compare the accumulated greenhouse effect of a given emission with an emission of CO_2 (Table 4). In addition to its direct effects on the greenhouse, CH_4 reacts photochemically to produce O_3, CO_2, and water vapor, which also have a greenhouse effect. These indirect contributions are comparable to the direct effect of CH_4. This idea is based on the estimate that every emitted mole of CH_4 results in the formation of 1 mol of CO_2, about 0.7 mol of O_3, and a certain amount of water vapor (*5*). Considerable uncertainty is associated with the values in Table 4, in part because of uncertainties in, for example, the amount of O_3 formation caused by CH_4 emissions and the decay rate of the various gases, especially CO_2.

The emission of CO_2 per megajoule of usable energy is 92 g for coal, 78 g for oil, and 56 g for natural gas on average for Sweden (*6*). Switching from coal (or oil) to natural gas would therefore, in theory, reduce the emission of CO_2. Any spillage of natural gas, which consists primarily of CH_4 ($\approx$90%), would reduce the benefits of the switch with respect to the greenhouse effect, because the decrease in CO_2 emissions would be counteracted by emission of the spilled CH_4. How large would the spillage have to be to completely nullify the decrease in CO_2 emissions resulting from a switch from oil to natural gas?

Table 4. The contribution of various gases, relative to CO_2, to the greenhouse effect. Calculations are based on emitted amounts, and consideration has been given to the gases' decay in the atmosphere. The entry for O_3 refers to amounts formed rather than to amounts emitted.

Species	Relative contribution	
	Mass basis (kg^{-1})	Mole basis (mol^{-1})
CO_2	1	1
CH_4 (direct effects)	15	5
CH_4 (including indirect effects)	30	10
N_2O	300	300
O_3*	3	4
CFC-11	4,000	11,000
CFC-12	8,000	20,000

*In the troposphere.

Assume that we produce 1 MJ of energy from natural gas and that a fraction x of the natural gas leaks out before combustion. The emission of greenhouse gases to the atmosphere would then be 56 g of CO_2 (or 1.27 mol) from the combustion and $1.27\,[x/(1-x)]$ mol of CH_4 from the leakage. Each mole of emitted CH_4 is assumed to result in a greenhouse effect corresponding to ten times that of 1 mol of CO_2 (see Table 4). The total greenhouse effect, converted to the equivalent CO_2 emissions, would thus be

$$1.27\left(1 + \frac{10x}{1-x}\right)\text{mol of } CO_2 \text{ or}$$

$$56\left(1 + \frac{10x}{1-x}\right)\text{g of } CO_2$$

The advantage of converting from oil to natural gas would thus be completely nullified if

$$56\left(1 + \frac{10x}{1-x}\right) = 78, \text{ that is, } x \approx 4\%$$

If the spillage of natural gas can be held to 4% or less, there is a net gain in switching from oil to natural gas. This value will actually be higher because CH_4 is also released during the extraction and refining of oil. In consideration of the uncertainties in the calculations of this study, a "break-even" value for natural gas spillage of 3 to 6% is reasonable when comparing oil and natural gas combustion. If the time of integration in Eq. 1 (T) was chosen to be much less than 100 years, the "break-even" value could be even smaller than 3%.

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Defensive Spray of the Bombardier Beetle: A Biological Pulse Jet

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The defensive spray of the bombardier beetle *Stenaptinus insignis* is ejected in quick pulses (at about 500 pulses per second) rather than as a continuous stream. The pulsation may be a consequence of intermittency in the explosive chemical process that generates the spray. The ejection system of the beetle shows basic similarity to the pulse jet propulsion mechanism of the German V-1 "buzz" bomb of World War II.

BOMBARDIER BEETLES, WHEN DISTURBED, emit a jet of defensive spray (Fig. 1A). The fluid stems from two large glands that open at the tip of the abdomen. The abdominal tip acts as a revolvable turret that enables the beetles to aim the spray in all directions (*1*). The ejections appear as a fine mist and are accompanied by audible "pops." The spray effectively deters vertebrate and invertebrate predators (*1*, *2*). Its active principles are *p*-benzoquinones (*3*).

The quinones are not stored as such in the glands but are produced explosively at the moment of ejection by the interaction of hydroquinones and hydrogen peroxide with oxidative enzymes (catalase, peroxidases) (*4*). The glands are essentially binary weapons. Each consists of two confluent chambers in which the chemical reactants are separately stored (Fig. 2). Hydroquinones and hydrogen peroxide are stored in the larger, inner chamber of each gland (the reservoir) and the oxidases in the smaller, outer chamber (the reaction chamber). The reservoir is thin-walled, enveloped by muscles, and compressible; the reaction chamber is thick-walled and rigid. A tight valve ordinarily keeps the juncture between the two compartments sealed. Ejections are presumably effected by brief compression of the reservoir. This compression forces reservoir fluid through the inlet valve into the reaction chamber, where the catalytic events leading to quinone formation are initiated.

Thermodynamic calculations had predicted that spray formation should be accompanied by substantial liberation of heat. This was verified empirically: the spray of bombardier beetles is ejected at 100°C (*5*), confirming the observation of early naturalists that seizing large bombardier beetles by hand can be painful (*6*). We report here that the bombardier beetle spray is emitted not as a continuous stream but as a pulsed jet, in analogy with fluid delivery systems known from technology but not from animal glands. Our data were obtained with one species of bombardier beetle, the relatively large (body length ≃ 2 cm) *Stenaptinus insignis* from Kenya.

The first clue to the pulsed nature of the spray stemmed from acoustical recordings (*7*) of the detonations that mark the discharges. Spectrographs (*8*) from these recordings showed that the sound contains a broad range of frequencies (essentially "white noise," as is typical for turbulent, explosive processes) (*9*) and that it is dis-

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