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GEOLOGIC PHENOMENA OF RELEVANCE TO "NUCLEAR WINTER" SCENARIOS

by

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Although no geologic phenomena are exactly analogous to that of a so-called "nuclear winter", there are a small number of physical events which may provide constraints on modelling and information on the earth's response to large-scale atmospheric disturbances, particularly through loading with particulate matter. To be of relevance such events must occur relatively suddenly, have global or near global effects and be amenable to analysis through physical modelling combined with observational data. Examples of such events are: martian global dust storms, large-scale explosive volcanism and meteorite impact. These events are briefly discussed below.

Martian dust-storms

One of the most spectacular atmospheric disturbance events in the solar system is the occurrence of global dust storms on Mars. Each year, as Mars nears perihelion, numerous dust storms develop in the southern hemisphere and one or more may grow to global proportions, suspending micron-sized particles to heights in excess of 40 km and obscuring the surface. Several months are required before atmospheric conditions return to pre-storm conditions (Leovy *et al*., 1972). Data from the Viking 1 and 2 landing sites indicate that peak optical depths of 3 to 6 may be reached during such storms (Zurek, 1981). It is clear that these storms must affect the thermal drive responsible for large-scale atmospheric motions and, as a consequence, the general circulation of the Martian atmosphere will be highly perturbed during the storms. The response of the Martian atmosphere and climate to dust loading has been numerically simulated and discussed recently by a number of authors (e.g. Haberle *et al*., 1982; Pollack and Toon, 1982; Zurek, 1982). The principal weakness of the phenomenon of martian dust storms as an analogy to "nuclear winter" is that the martian atmospheric environment, with a mean surface pressure of 6 mbar, is considerably different from that of the earth. They do, however, supply observational data on global atmospheric loading and as such provide a mechanism to validate general atmospheric circulation models.

Explosive Volcanism

Volcanic activity on earth is, at any given time, relatively local but the effects of volcanic eruptions may be both local and wide-spread. The energies involved in major volcanic explosions are in the range of tens of megatons TNT equivalent and dense volcanic clouds develop. The mass of material in the stratosphere following explosive eruptions leads to an increase in optical depth, which for large events may be on the order of 0.1 (Pollack et al., 1976 a and b). For example, the Krakatoa explosion of 1883 may have been in the range of 25 Mt and erupted 6 to 18 km^3 of ash into the atmosphere (Lamb, 1970). Due to very high dust loadings, however, most of this volcanic ejecta is deposited locally within a few hours. Only a small portion of the erupted material reaches stratospheric heights, perhaps 10^{-2} km^3 in the case of Krakatoa, and most of this material consists of sulfuric acid rather than crustal silicate material (Toon, 1984).

Large-scale explosive eruptions, however, are known to lower the mean temperature at the earth's surface. For example, after the Tambora eruption in 1815 the mean world temperature dropped by 1°C (Lamb, 1970) and there were more severe localized effects, such as the so-called "year without a summer" in New England in 1816. Large-scale volcanic eruptions represent relatively low energy events relative to what might be expected in a major nuclear exchange (5000 Mt). Nevertheless, they do provide direct observational data on climatic changes brought about by the injection of relatively small amounts of particulate debris into the stratosphere and give an indication of the potential effects of a limited nuclear exchange. Although the optical properties of volcanic ash and sulphates are not exactly equivalent to that expected from the results of a nuclear exchange, continuing observational and modelling studies of the potential for volcanic eruptions to produce wide-spread, short-term climatic perturbations are of obvious interest to the problem of "nuclear winter".

Meteorite Impact

The energy released in large-scale meteorite impact can exceed that expected from a major nuclear exchange. Although local effects such as crater formation a fairly well understood, in part from the analysis of underground nuclear explosions, the wide-spread effects of major impacts are less well known. Unlike volcanism, impact is a relatively rare event and much of the current knowledge is based on observations from the geologic record.

One exception is the Tunguska event of 1908. This event, which is estimated to have released as much as 10^3 Mt of energy into the atmosphere, is generally considered to be the result of the explosion of a low density meteoritic body at an altitude of approximately 10 km. In addition to devastating 2000 km^2 of Siberian forest, calculations by Turco et al. (1982) suggest that the shock waves generated up to 3×10^{13} g (30×10^6 tons) of oxides of nitrogen, sufficient to deplete the ozone of the northern hemisphere by 35-45%. Furthermore, 10^{12} g of dust may have been deposited in the mesosphere and stratosphere leading to a 0.3°C cooling of the northern hemisphere.

A considerable literature now exists on the potential for large-scale impact to disrupt the global climatological and biological balance of the earth (e.g., Geol. Soc. Amer. Sp. Paper, 190, 1982). These studies were largely spurred by the geochemical evidence of an enrichment in siderophile elements, suggesting a major impact event, at the Cretaceous-Tertiary boudary 65 million years ago and the apparently contemporaneous mass extinction of much of the earth's biota (Alvarez et al., 1980; Ganapathy, 1980 and others).

Siderophile elements are depleted in the earth's crust but not in undifferentiated meteorites. Although the geochemical anomaly represents a truly global phenomenon, some scientists have argued that it represents insufficient evidence for a major impact. Recently, however, quartz grains with deformation features indicative of shock pressures of 150 kb or more have been recovered from several sites (Bohor et al., 1984). As hypervelocity impact is the only known natural physical process which can produce such pressures, they provide additional physical evidence for a major impact.

The exact relationship between such an event, with an estimated energy in the 10^7 - 10^8 Mt range, and the death of a large portion of the earth's biota is the subject of debate. In large part, the debate is generated by the incompleteness of the geologic record, the relatively imprecise nature of stratigraphic and isotopic dating for determining the exact age and duration of specific geologic events, and the methodology of detecting and defining extinctions.

A number of potential killing mechanisms have been suggested for the Cretaceous-Tertiary impact. Theoretical calculations suggest 10^{19} - 10^{20}g of dust may have been injected to stratospheric levels (O'Keefe and Ahrens, 1982), sufficient to produce initial optical depths of 10^3 - 10^4 and cause the cessation of photosynthesis and freezing conditions on land for a period of several months (Toon et al., 1982; Pollack et al., 1983). At these extremely high dust loadings, these effects are relatively insensitive to the amount of dust, although the duration depends on assumptions regarding particle coagulation and the rate of spread of stratospheric dust over the earth. Lewis et al. (1982) have calculated the atmospheric chemistry changes associated with such an event and estimate that it would result in NO_x values in excess of 100 ppm over millions of square kilometers. Such high values are toxic to many plants and animals and are sufficient to acidify surface waters killing calcareous organisms. A major uncertainty in this calculation centers on the efficiency with which the impacting body couples its energy to the atmosphere, which depends to some degree on the nature of the impacting body.

A number of other mass extinctions occur in the geologic record (Raup, 1984) and it is tempting to relate them to other large-scale impact events (McClaren, 1983). Siderophile anomalies have been recently reported at other periods: in the Devonian ~ 365 million years ago (Playford et al., 1984), at the Permian Triassic boundary ~ 245 million years ago (Yi-Ying, 1984), and at the Eocene-Oligocence boundary ~ 36 million years ago (Alvarez et al., 1982; Ganapathy, 1982). These results, however, are preliminary and any correlations with contemporaneous distruptions to the biosphere are speculative.

The potential relationship between large-scale impact events and the biosphere is an active area of research and has obvious implications for both air and ground detonations in "nuclear winter" scenarios. In detail, however, such events as the Cretaceous-Tertiary involve energies and dust loading of the atmosphere well in excess of those expected as a result of a nuclear exchange. If links are eventually established between other mass extinctions and impact events, it will still be difficult to identify actual killing mechanisms and much will be relegated to model scenarios. These events are remote in time and, due to the inherent nature of the geologic record, will lack detailed documentation. As they occurred in a world sufficiently different from the modern world, it will be difficult to separate changes which occurred as a result of meteorite impact from changes caused by other, more normal endogenic variables. If meteorite impact is to be used as a geologic analog for "nuclear winter", it might be more profitable to search for the effects of smaller events on the younger portion of the Cenozoic geologic record. That is, times that are more nearly like today, for which other variables can be more clearly evaluated and for which biological starting points are more nearly like those today.

Model calculations suggest that 10^{16} g of dust are sufficient to reduce photosynthesis to 1000 times less than normal (Gerstl and Zardecki, 1982). Such loadings can be produced by impact events in the 10^{4} Mt energy range, resulting in impact craters in the 20 km size range. Several such craters are known from the last few tens of millions of years of geologic history (Grieve, 1982). Furthermore, recent high density sampling of the δO^{18} record for ice volume history has shown a tendency for ice volume fluctuations to vary with a consistent mean and amplitude for relatively long periods of time and then suddenly shift to a new mean and amplitude pattern (Matthews and Poore, 1980; Prell, 1982 and 1984). These rapid shifts in the characteristics of the $\delta^{18}O$ temperature record may represent large scale shocks to the system or may represent the crossing of some threshold value with regard to other boundary conditions. Although no evidence of an association is presently available, it is interesting to note that some of these aperiodic events are closely associated with the age of known meteorite impact structures.

Major objectives as part of any research strategy to evaluate these Cenozoic meteorite impact events as possible geologic analogs for "nuclear winter" models should include: additional $\delta^{18}O$ data on closely spaced samples from deep sea drilling project materials as guides to locate the climatic event in numerous locations; sedimentological, chemical, and mineralogical data (identified by $\delta^{18}O$ stratigraphy) to determine any relationship between these events and meteorite impact; isotopic and biotic data to pin down the position of oceanic frontal systems before and after the event; biotic census data before and after the event to establish the effect of the event on the biosphere; interaction of the assembled geologic data with computer models. This interaction of geologic data with models could take two forms. Models could be run with before and after boundary conditions set by geologic data. Alternatively, the geologic data could be used as verification of model output.

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