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LARGE NATURAL GEOPHYSICAL EVENTS: PLANETARY PLANNING

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LARGE NATURAL GEOPHYSICAL EVENTS: PLANETARY PLANNING

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ABSTRACT

Geological and geophysical data suggest that during the evolution of the earth and its species, that there have been many mass extinctions due to large impacts from comets and large asteroids, and major volcanic events. Today technology has developed to the stage where we can begin to consider protective measures for the planet. Evidence of the ecological disruption and frequency of these major events is presented. Surveillance and warning systems are most critical to develop wherein sufficient lead times for warnings exist so that appropriate interventions could be designed. The long term research undergriding these warning systems, implementation, and proof testing is rich in opportunities for collaboration for peace.

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ABSTRACT

The hazards from comets and asteroids, volcanoes, and earthquakes are described, and compared with the dangers of a nuclear war. A comprehensive program of scientific and engineering studies to fully evaluate the natural hazards and develop reliable methods for prevention could ultimately require resources comparable to the current technical effort devoted to nuclear weapons. Collaboration between the superpowers to provide protection for the whole planet would give hope to a fearful world.

A comet should strike the Earth on average every few hundred years, and indeed one exploded over the Tungusska river, Siberia, with 20 Megatons of energy in 1908. Some of the 12 major extinction events in the fossil record are now related to impacts, and the energy associated with the Cretaceous-Tertiary event is estimated at 100 million Megatons, i.e. 10,000 times greater than the combined nuclear arsenals. Much more research is needed to establish the frequency and possible periodicity of impacts. We propose establishment of international agencies to coordinate (a) expansion and improvement of the present instruments for detection of comets and asteroids, (b) development of optimized search procedures and orbital predictions, and (c) design and construction of spacecraft systems for deflection or destruction of a body in collision orbit.

Approximately 1300 volcanoes have yielded 6000 eruptions in the past 10,000 years. Volcanic eruptions in the past century have been small, and [illegible] larger ones have occurred in the past: e.g. the caldera (basin) west of Naples results from an eruption 36,000 years ago which sprayed 80 cubic kilometers of ash from Naples to Sicily and Crete. Even small eruptions from Vesuvius have been catastrophic to Pompeii and Naples. At the moment, calderas at Mammoth Lake (California), Rabaul (Papua New Guinea) and the above one near Naples are causing concern. There are many records of poor harvests after volcanic eruptions, and a sulfuric acid aerosol in the lower stratosphere may be responsible for modification of weather systems. We propose establishment of an international agency to coordinate (a) deployment of instruments on the ground and in orbit to measure gas emission, change of shape, and earthquake activity of the potentially dangerous volcanoes (approx. 700), (b) measurement of the dust and aerosol clouds emitted by volcanoes, and the relation to the temperature, chemistry and wind velocity of the atmosphere, (c) evaluation of possible measures to control volcanic activity including drilling into magma chambers and pumping of groundwater from calderas.

For earthquakes, we propose establishment of an international agency to coordinate (a) deployment of seismic and laser-ranging arrays to provide a detailed 3D distribution of the strained regions in active earthquake regions, (b) exploratory discussions of methods to release strain in potentially dangerous regions.

Finally, we emphasize that all measures to protect the earth from impacts and volcanoes will be imperfect, especially in the early stages, and that it would be prudent to stockpile food and essential supplies to cover the possibility of poor harvests for several years after a major event. This proposal must be discussed carefully because of its sensitivity in relation to civil defense against nuclear war, and to famines and population pressure on food supply.

INTRODUCTION: GENERAL

Massive extinctions have occurred on Earth; indeed most species are now extinct, and many of them disappeared in short periods associated with major impacts (Alvarez et al., 1980, Nitecki, 1984; Raup and Sepkoski, 1984; Silver and Schultz, 1982). Earthquakes and volcanic eruptions have caused many deaths, and the geological record testifies to much greater events prior to human history. Until now, mankind was unable to control such assaults on the life support system of the Earth, and any destruction was accepted as an Act of God. Today, however, technology has developed to the stage that we can consider protective measures against large geophysical events. In particular, the technology of space surveillance and rendezvous permits detection and either deflection or destruction of asteroids and comets in collision orbit with the Earth (unpublished report of Spacewatch Workshop, July 1981, Snowmass, Colorado). Protection against volcanic eruptions and earthquakes is more difficult, but some progress is possible.

Mankind could use its intelligence, knowledge and resources to protect itself from these natural hazards if the nations of the world, particularly the superpowers, entered into suitable collaboration. We already know that we must eliminate the very serious hazard of a nuclear war. Let us also recognize that doing nothing about the large geophysical hazards will leave us at the mercy of random events which must ultimately occur. All science and engineering is two-faced with potential for either good or bad. Let us devote our scientific and engineering skills towards protection of the Earth and its species so that future generations of homo sapiens will look back with admiration to the pioneers of the twentieth century. In particular, let us begin to collaborate in protection of the world against the great natural hazards, and use this positive approach and experience to guide us towards collaboration for peace.

In the next three sections, we shall consider the hazards from comets and asteroids, volcanoes, and earthquakes. Then we shall consider ways to detect and define the hazards, together with possible methods of prevention.

ASTEROIDS AND COMETS: DESCRIPTION

Perhaps your initial reaction is that the chance of a destructive impact from a comet or an asteroid is too small to be taken seriously, and that there are more urgent problems facing the human race. But consider that a bolide (meteor) exploded 8 km high in the air over the Tungusska river in Siberia, SSSR on June 30, 1908 (Krinov, 1966; Dolgov, 1980; Shoemaker, 1983). The fireball was seen at 1000 km (600 miles). Trees were knocked down up to 40 km (25 miles) and dry timber ignited at 15 km (10 miles). The kinetic energy was comparable to that of a 10-30 Megaton (Mt) nuclear explosion, and some millions of people would have died if the meteor had struck a major city. It is difficult to estimate the frequency of such impacts, but once per 100 to 1000 years seems reasonable in relation to the entire body of knowledge on impacting bodies (Shoemaker, 1983). Of course, only 10% of the Earth has a significant density of population. The Tungusska meteor was only 60 meters across (about the size of a football field), and may have been a fragment of Comet Encke.

There is a wide range of bodies in orbits which may ultimately intersect the Earth. These bodies are the remnants of planetesimals produced from the dust-gas cloud of the primordial solar nebula (Smith, 1982). Earth and Venus cleaned up the planetesimals in their part of the solar nebula within the first few hundred million years. A continuous supply of new bodies comes from two sources: the <u>main belt of asteroids</u> between Mars and Jupiter, and the <u>cloud of comets</u> at the outer edge of the solar system. Gravitational forces kick out an asteroid or a comet into a path which may lead to the Earth. The details are complex and not completely understood (reviews: asteroids, Gehrels, 1979; comets, A'Hearn, 1984; Wilkening, 1982; comets, asteroids and meteorites, Delsemme, 1977). Only the larger and stronger bodies can survive passage through the atmosphere, and most break up in the air. Although most impact craters have eroded away, 103 impact craters with diameters of about 1 to 100 kilometers have been found (Grieve, 1982).

In the fossil record of the past 250 million years, there are 12 major extinction events (Raup and Sepkoski, 1984), and some are now demonstrated to be associated with major impacts. The world-wide clay layer at the Cretaceous-Tertiary boundary (65 million years ago) has a noble-metal anomaly (Alvarez et al., 1979) consistent with impact of a body 10 km across, or a comparable cluster of bodies, composed of primitive solar material. Such a body would have a kinetic energy near one hundred million Mt compared to about ten thousand Mt for all the weapons in a full-scale nuclear war. Just as for "nuclear winter," it is impossible to make a reliable prediction of the physical, chemical and biological consequences of the impact of such a body, but the effects would be very severe. The biological extinctions in the fossil record demonstrate that the higher forms of life are more susceptible than some of the primitive forms which can tolerate large changes of temperature. If you are w rried about the effects of a hypothetical "nuclear winter," you should ally take seriously the possible effects of an impact with ten thousand times more energy than for a nuclear war.

Before looking at the chance of a large impact, consider some of the properties of comets and asteroids. The bright gas-dust stream allows detection of a few comets each year as they pass the Sun. A new comet from the Oort cloud at about 10,000 astronomical units from the Sun accelerates up to 60 kilometers per second as it crosses the orbit of the Earth. Accidental gravitational forces coupled with gas loss move some comets into smaller orbits with a shorter period (e.g. Halley's comet with a 76-year period). Although Whipple's dirty snowball model of a comet is popular, it is likely that future studies will demonstrate a wide range of properties. Some micrometeorites which produce flashes in the sky (meteor showers) were once dust grains in comets. Because some comets lose their ices but do not disappear completely, it is certain that they have a mechanically stable core of solid material. Such dead comets become part of the population of earth-crossing asteroids.

As the main-belt asteroids circulate between Mars and Jupiter they change orbit in response to gravitational forces. Most of the changes are random, but asteroids which resonate with Jupiter are perturbed systematically and ultimately kicked out to produce the Kirkwood gaps. Very rarely, pairs of asteroids collide to produce fragments. Orbital calculations are very difficult (Wisdom, 1983), but there can be no doubt that a tiny fraction of the material of the main belt of asteroids is migrating past Mars into earth-crossing orbits. There is no agreement on what proportions of the Apollo, Amor and Aten families of near-Earth asteroids are derived from comets or main-belt asteroids; Zimbelman (1984) estimated that 3-9% of the large craters on the terrestrial planets result from impacts by long-period comets. It is certain that there is a wide range of reflectivities of both the earth-crossing and main-belt asteroids (Gehrels, 1979), and that there is a diverse set of meteorites (Dodd, 1981).

An Earth-crossing asteroid is defined as a body of asteroidal appearance at the telescope whose orbit occasionally intersects the orbit of the Earth as a result of distant perturbations by the planets (Shoemaker, 1983). About 80 Earth-crossing asteroids are known with estimated diameter (d) of 0.2 to 10 km and with brightness expressed as the absolute visual magnitude (V) of 14 to 20. Shoemaker estimates that only 2-3% of the asteroids with V greater than 18 have been detected. This corresponds to a diameter of 1-2 km for the darker C-type and 0.7-1.3 km for the brighter S-type. Orbital calculations indicate a collision probability with the Earth of $\sim 2.5 \times 10^{-9}$ per year, and a collision rate of about 3 per million years for asteroids brighter than V = 18. This rate is roughly comparable with the observed number of large impact craters when adjusted for land-sea area, etc.

So far it has been assumed that the motions of the earth-crossing asteroids and comets are governed by orbital perturbations which yield random impacts on the Earth. This assumption is now being questioned because of new indications of periodicity in biological extinctions and crater ages. Raup and Sepkoski (1984) found that the 12 extinctions of marine vertebrates, invertebrates and protozoans in the past 250 million years have a periodicity of 26 million years at the 1% probability level, but they recognize some problems in the statistical analysis including uncertainty in geological dating. A further analysis of 8 extinction maxima of marine animals over the past 268 million years (Sepkoski and Raup, 1985) reinforced their proposal of a 26 $\pm$ 1 My periodicity. Particularly important is the phase which indicates that we are now in the middle of a cycle with the implication that there would not be another large impact-induced extinction for about 10 to 15 million years. Analysis of the ages of large impact craters is difficult because only a dozen or so have been dated accurately. Several workers (Alvarez and Muller, 1984; Rampino and Stothers, 1984) have concluded that there may be a periodicity, and Raup and Sepkoski (1985) prefer 27 to 28 My. There are three small clusters of craters at ~38, ~67 and ~98 My which can be correlated with mass extinctions (Shoemaker and Wolfe, 1984). Just to illustrate the uncertainty: Rampino and Stothers (1984) suggest that we are not in the middle of a cycle, and are closer to a possible major impact than the implication from the Raup-Sepkoski cycle.
correlated with mass extinctions (Shoemaker and Wolfe, 1984).

No process within the planetary region has been invented to explain a periodicity of 26-28 My, and the three suggested astronomical causes are highly controversial: transit of the solar system through spiral arms of the Milky Way Galaxy (50 My period); vertical oscillation of the solar system through the plane of the Galaxy (33 My for each half-oscillation); passage of an unobserved companion star through the Oort comet cloud (Davis et al., 1984; Whitmore and Jackson, 1984).

Whatever the outcome of these statistical studies and astronomical speculations, there can be no doubt that there are earth-intersecting asteroids and comets, and that there is a continuing flux of meteorites. It would be prudent to conclude that at least some impacts of asteroids and comets are random, and to take into account the possibility that some biological extinctions result from random impacts. To provide a valid basis for planning defenses against impacts by asteroids and comets, it is necessary to foster the purely scientific studies such as those described above. Cooperation between experts covering geology and astronomy is necessary to reduce uncertainty in the present observations and interpretations; indeed, new types of observations and theories will appear as old ideas are invalidated. The new data and conclusions will provide a fundamental basis for the proposals in the next section.

ASTEROIDS AND COMETS; PROTECTIVE MEASURES

We shall now describe how the science and technology used in the design and construction of weapons and delivery systems could be transformed into an international effort for protection of the Earth from impacts. There are three needs: (a) expansion and improvement of the present instruments used for detection of comets and asteroids, (b) development of mathematical procedures for optimization of search procedures, data handling and prediction of orbits, and (c) design and construction of space-craft systems for deflection or destruction of a body in collision orbit. None of the proposals here is fundamentally new, and all have been discussed to some degree in other forums, but only briefly in the context of a nuclear war (Smith, 1983).

We propose that an international agency be established to coordinate efforts to achieve these three goals. The agency could be associated with the International Union of Geodesy and Geophysics and the International Council of Scientific Unions. A special International Geophysical Decade on Prevention of Impacts might be declared.

The international agency would

(a) organize a workshop each year to bring together the experts on detection, tracking and recording of comets and asteroids. The participants would evaluate the current status of these activities, and make recommendations for experimental and theoretical activities.

(b) organize a second workshop each year on the design of space-craft systems for deflection or destruction of dangerous bodies.

Because of the direct relationship of some of the technology in (b) to nuclear war, it may be desirable to keep these workshops separate to allow more freedom for the participants of (a).

Implementation of the suggestions from these workshops might require careful diplomatic negotiations. One possibility would be an agreement between the nuclear powers to devote significant resources made available in an equitable funding process to protect the planet and its inhabitants against natural hazards including impacts. A small fraction of the resources would go to the international agency to cover administration and the workshops, and the remainder would be spent directly on contracts in each donating country.

We suggest the following specific actions among many others:

(a) Systematic exploitation of the success of the Infrared Astronomical Satellite (IRAS) in detection of moving objects in the Solar System. The prototype infrared satellite (Netherlands/UK/USA), which was launched on January 26, 1983, discovered six comets and also located five known comets (Davies et al., 1984). The infrared emission is from heated dust, and the detection limit corresponds to V near 17. Two new Apollo asteroids were detected. Further development of the detection systems should allow discovery of asteroids somewhat smaller than 1 km diameter. Simultaneous observations from several IR satellites in optimized orbits should improve the efficiency of detection.

(b) Major improvement of the optical telescopes devoted to comet and asteroid searches. The 46-cm Schmidt camera at Palomar revealed 12 new planet-crossing asteroids in 6 years (Helin and Shoemaker, 1979) and 4 were found early in 1984; however, the great majority of the Apollo, Amor and Aten asteroids remain undetected. The new telescopes (including the Space Watch Camera) at the Steward Observatory, Arizona, should improve the rate of discovery of asteroids and comets, but even a discovery rate of 20 asteroids per year would be inadequate. It is possible that at least ten new telescopes will be needed for a comprehensive search for just the larger of the potentially dangerous asteroids. Optimized search procedures (e.g. Taff, 1984) should be developed further.

(c) Detailed evaluation of possible ways for detection of small comets and of the smaller near-Earth asteroids with a diameter of 1 km down to 100 m. This will be a severe technical challenge even with the best optical telescopes with electronic scanning (Gehrels, 1981) and it may prove possible to detect the smaller bodies only when they are dangerously close to the Earth. To obtain enough sensitivity, it may be necessary to place the telescopes on orbiting spacecraft or on the Moon.

(d) Development of a data center to process the incoming data and make predictions of orbits. Optimization of the search and recovery procedures would be another important duty of the center.

(e) Systematic exploration of comets and near-Earth asteroids by fly-by and rendezvous missions. Considerable experience will be gained by the space craft which will explore Halley's comet in 1986 (Neugebauer et al., 1979; The International Halley Watch, 1980; Gombosi, 1983). The two Soviet spacecraft (Vega) will be coordinated with the European Space Agency Giotto spacecraft and a Japanese spacecraft to obtain the first close-up observations of a comet head and tail. The spacecraft will encounter Halley's comet at about 70 km/s, and it is anticipated that the Giotto spacecraft will fly through the dust cloud and be destroyed as particles ultimately penetrate the bumper shield. At least one dozen comets should be explored by spacecraft using instruments optimized to take advantage of the experience from earlier missions. Ultimately, it will be necessary to develop a rendezvous mission to allow a close-up examination of a comet head, and comet Kopff may be a suitable target for a launch in 1990 (Swenson et al., 1984). This will require an advanced propulsion system including an ion-driven rocket engine.

(f) Development of detailed plans for deflection of comets and asteroids which are heading for the Earth, and ultimately actual construction of appropriate spacecraft. The technical problems are very severe, and we have not seen any thorough assessment in the open literature. The proceedings of a Spacewatch Workshop held at Snowmass, Colorado, July 1981, should provide the basis for serious discussion when they are published. It would be highly desirable to control asteroids by a motor driven by solar energy, but it appears that a more powerful source of energy is needed. A controlled collision of an asteroid with the Moon is almost certainly impractical or too dangerous; even if a successful collision were achieved, the shower of debris might be dangerous. Currently it seems necessary to rendezvous with an asteroid or comet, and let off an explosive charge to deflect it sufficiently. The closer the body is allowed to approach the Earth before it is deflected, the greater will be the required explosive energy. Current calculations indicate that only a small explosive charge (< one kiloton) may be sufficient for early detection and deflection of a small body, and about one Megaton for late detection and deflection of a large body. The risk of fragmentation would increase for a larger explosion and a more fragile body; perhaps a series of small explosions may be needed for a comet head. A simple solution cannot be expected, especially for comets. Only 2 to 4 weeks time would be available from detection to deflection or destruction of some bodies, and it appears that nuclear explosions would be needed: hence, international agreements would be needed for design and construction of protective systems. Of course, it would be highly advantageous if an asteroid could be manoeuvered into a safe orbit as part of a project for economic exploitation (O'Neill, 1975, 1977).

It is quite certain that there are huge technical challenges in prevention of impacts from comets and asteroids, and we believe that a comprehensive program could ultimately reach a size comparable to the effort now devoted to nuclear weapons.

VOLCANOES: DESCRIPTION

This section is brief because a detailed description is given in a companion paper (Smith, 1984). Volcanic phenomena are extremely complex (Williams and McBirney, 1979) and predictions of activity are of variable reliability. Approximately 1300 volcanoes have been active over the past 10,000 years, and 6000 eruptions have been described (Simkin et al., 1984). New physical and chemical studies are revolutionizing our understanding of volcanoes but there is a long way to go because most of the needed information is still inaccessible (e.g. the deep plumbing system).

Particularly dangerous to the local inhabitants are the volcanoes which emit large amounts of hot ash in ground-hugging flows or in the air. Vesuvius is a good example: the destruction of Pompeii by a pyroclastic flow in AD 79 is well-known, but the partial destruction of Napoli in AD 472 by a rather small Plinian eruption is known mainly to professional volcanologists (Rosi and Santacroce, 1983). Even for such a well-known volcano with geological records back to 17,000 BC, prediction of future activity is uncertain (Santacroce, 1983; Sheridan and Malin, 1983). However, it is certain that the building of new houses up the flanks of Vesuvius increases the danger from any hot ash flow.

Even more dangerous to Napoli, and indeed a considerable part of the Mediterranean region, is the basin-shaped caldera at the Phlegrean Fields, west of Naples. About 36,000 years ago, a huge eruption (Campanian) ejected about 80 cubic kilometers of an alkali-trachyte ignimbrite (i.e. fiery ash cloud) which produced an ash deposit 20 cm thick from Napoli to Sicilia and 1 cm as far away as Crete (Cornell et al., 1983; Rosi et al., 1983). Four minor eruptions have occurred since the Campanian eruption, and there is current concern about the recent inflation of part of the caldera at Pozzuoli. Two other calderas at Mammoth Lakes, California and Rabaul, New Britain, are also inflating.

In addition to the calderas, there are many potentially dangerous volcanoes with a wide range of physical and chemical properties. Documentation is given in Smith (1984). The "Ring of Fire" around the

Pacific Ocean is well known; e.g. in northwest U.S.A. there is a string of volcanoes, one of which (Mount St. Helens) burst sideways ir 1980. Other volcanoes occur at hotspots; e.g. in the Hawaiian Islands and Iceland. Those volcanoes which frequently emit small flows of a non-sticky lava of basaltic composition are only of local danger (e.g. Kilauea). It is the volcanoes with long repose times and viscous lava which are of danger to the entire world; they literally build up a head of gas and blow their top in rare but massive eruptions. There are huge thicknesses of ash in southwest U.S.A. and elsewhere which are the product of such eruptions. A thick ash blanket can be dangerous over thousands of square kilometers, but after one day most of the ash has fallen. Current research indicates that it is not the ash but the sulfur-rich gases from volcanic eruptions which affect the climate. Large volcanoes can inject the sulfur-rich gases up to 25 km high in the stratosphere where they react with water to form sulfuric acid droplets. The resulting haze absorbs and scatters incoming sunlight, and persists for up to two years. Ultimately most of the acid returns to the Earth, but there appears to be an intermediate stage in which the haze survives over the polar regions. A lot of research is needed, but we suggest that this haze may result in a greater stability of the wave patterns in the atmosphere with development of greater excursions of temperature about a mean temperature which is affected little by the volcanic haze. Extremes of weather, including cold snaps in summer and long droughts, are harmful to agriculture. Whatever the mechanism, there is considerable evidence for poor harvests in the next two years after major volcanic eruptions, as exemplified by historical records for the Mediterranean region (Stothers and Rampino, 1983). The eruption of a sulfur-rich volcano, El Chichon (Mexico), in 1982 is providing valuable data on the climatic effect of volcanoes (Pollack et al., 1983), and further study of ice-cores (Hammer et al., 1980) and tree rings (LaMarche and Hirschboeck, 1984) should allow more detailed characterization of past climatic effects of volcanoes. It should be emphasized here that it is difficult to disentangle the effects on the climate of volcanoes, solar variability, and greenhouse effects from CO_2 and other gases (Lamb, 1982; Gilliland and Schneider, 1984), and that the human race should consider all factors in discussions about hazards to the climate.

VOLCANOES: PROTECTIVE MEASURES

Whereas it was easy to define the problem of defending the Earth against comets and asteroids, it is much less easy to focus on the hazards of volcanic eruptions. Although considerable progress has been made with volcanic forecasting (Tazieff and Sabroux, 1983; Dekker, 1978), predictions on a day-to-day basis are useful only for certain well-studied volcanoes such as Mount St. Helens (Swanson et al., 1983) and Kilauea (Klein, 1984). Of critical importance is a great expansion in the study of volcanic phenomena to augument present knowledge (UNESCO, 1971) and to establish the basis for new ideas.

Only then will it be possible to make realistic plans for protection against volcanic hazards. The World Organization of Volcano Observatories was established in 1982 to achieve these goals, and it needs strong support. It must be recognized by the general public that scientists are not miracle workers, and that important advances in earth sciences develop in response to systematic collection of data and testing of theoretical models.

We propose cooperative studies on an international basis which would include the following:

(a) monitoring of the shape and height of all recognized volcanoes using laser altimetry from earth-orbiting satellites. The Laser Geophysics Satellite (LAGEOS) launched in 1976 is capable of measurements to about 2 cm, and further improvement is planned. A huge expansion of effort is needed to exploit this technical possibility.

(b) deployment of seismometers, tiltmeters and gas detectors on volcanoes to monitor seismic activity, deformation and the emission of gases which might presage an eruption. Cheap standardized units could be built which would tolerate hard landing from an aircraft, and which would telemeter data from remote volcanoes to a receiving satellite.

(c) thorough field study of erupting volcanoes and of the debris from recent eruptions. Teams of scientists should be given facilities so that rapid deployment is possible for an imminent eruption.

(d) three-dimensional seismic profiling of volcanoes to obtain information on the structure of the plumbing system. The deductions would be tested against the chemical evidence in the erupted lavas, ashes and gases.

(e) monitoring of the world-wide distribution of aerosols, dust and various chemical species (OH, SO_2, CO, CO_2, CH_4, odd nitrogen compounds) in the troposphere and lower stratosphere. Monthly flights by high-flying aircraft from the north to the south poles plus associated launches of balloons at a dozen latitudes should be established.

(f) further detailed chemical analyses of polar ice cores and tree rings using new techniques (e.g. synchrotron X-ray fluorescence) to establish the types of emission from past volcanic eruptions.

(g) on the basis of (e) and (f), study of the correlations between volcanic phenomena and the weather patterns to test models of climatic changes.

(h) preliminary discussion of ways to alleviate or obviate volcanic eruptions. These might include drilling into magma chambers to allow harmless escape of lava. Draining of lakes in calderas might minimize explosive interaction of water with subterranean lava. Such programs might be coordinated with development of geothermal power. If these discussions appear promising, experiments might be started on remote volcanoes. Easy technical solutions cannot be expected.

EARTHQUAKES: DESCRIPTION AND PROTECTIVE MEASURES

We shall pursue this topic in detail elsewhere. Let it suffice that scientific research on earthquakes is still in an early stage (Kanamori and Boschi, 1983). There is a wide range of earthquakes which includes those at the fault boundaries of plates sliding past each other (e.g. San Andreas fault system in California); earthquakes in the center of a plate which is being splintered by a collision (e.g. China where the Eurasian plate is being compressed by the India plate at the Himalayas); earthquakes at the center of a plate which almost split along a rift (e.g. Missouri region of the U.S.A.); earthquakes associated with volcanic eruption (e.g. Mount St. Helens). Earthquake forecasting and warning (Rikitake, 1982; Ward, 1978) is in an active state of research and development and some, but not all, earthquakes have been predicted. We propose that present resources be increased greatly in an international program. In particular, we suggest that deployment of two-dimensional arrays of seismic detectors around seismically-active regions should allow mapping of the constituent rock formations and the three-dimensional strain patterns (this could be an extension of present two-dimensional seismic profiles; Oliver, 1982). Systematical drilling would allow testing of the conclusions from the seismic data. Proposals for lubricating plate boundaries to promote many small quakes instead of rare catastrophic ones could be tested in an unoccupied region such as parts of Alaska.

CONCLUSION

We urge that comprehensive programs of scientific and engineering studies be established to evaluate the natural hazards which threaten the human race, and to develop reliable methods for prevention. In particular, we have discussed the hazards from comets and asteroids in detail, and from volcanoes and earthquakes in brief, and have not considered other geophysical hazards involving the atmosphere (e.g. severe storms) and the oceans (Landsberg, 1978). After the spectacular advances of the last 30 years, geoscientists can now provide accurate statements on what should be done about natural hazards so that money can be spent efficiently and wisely. There are no quick fixes, and the human race should recognize that the scientific and engineering programs proposed here must be continued and expanded into the indefinite future. Furthermore, we must accept that complete protection against natural hazards is not possible by engineering means, and that it would be prudent to stockpile food and essential supplies to compensate for poor harvests after a major event. Of course, such stockpiling must be discussed carefully because of its sensitivity in relation to civil defense against nuclear war, and to famines and population pressure on food supply. Protection against natural hazards must become part of our life, just as we must find a solution to the hazards of war. Let us try to solve the two problems at the same time so that the collaborative projects of protection against natural hazards provide a basis for hope in the avoidance of the man-made hazard of nuclear war. The geosciences can show the way to safety if we can get together around the world. Three Italian proverbs, loosely translated, can be our mottos:

L'unione fa la forza (Union gives strength)
Uomo avvisato e mezzo salvato (Warning leads to safety)
Finche c'e vita c'e speranza (Where there is life there is hope).

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REFERENCES

A'Hearn, M.F., 1984, Chemistry of comets, Chemical and Engineering News, May 28, 32-49.

Alvarez, W. and R.A. Muller, 1984, Evidence from crater ages for periodic impacts on the Earth, Nature, 308:718-720.

Alvarez, L.W., W. Alvarez, F. Asaro and H.V. Michel, 1979, Extraterrestrial cause for the Cretaceous-Tertiary extinction, Science, 208:1095-1108.

Cornell W., S. Carey and H. Sigurdsson, 1983, Computer simulation of transport and deposition of the Campanian Y-5 ash, Journal Volcanological and Geothermal Research, 17:89-109.

Davies, J.K., S.F. Green, B.C. Stewart, A.J. Meadows and H.H. Aumann, 1984, The IRAS fast-moving object search, Nature, 309:315-319.

Davis, M., P. Hut and R.A. Muller, 1984, Extinction of species by periodic comet showers, Nature, 308:715-717.

Dekker, R.W., 1978 State of the art in volcano forecasting, in Geophysical Predictions, National Academy Press, Washington, D.C.

Delsemme, A.H., editor, 1977, Comets, Asteroids and Meteorites, University of Toledo Press, Toledo.

Dodd, R.L., 1981, Meteorites: A Petrologic-Chemical Synthesis, Cambridge University Press, New York.

Dolgov, Yu.A., editor, 1980 [Interaction of Meteoritic Material with Earth], Nauka, Novosibirsk.

Gehrels, T., editor, 1979, Asteroids, University of Arizona Press, Tucson.

Gehrels, T., 1981, Faint comet searching, Icarus, 47:518-522.

Gilliland, R.L. and S.H. Schneider, 1984, Volcanic, CO_2 and solar forcing of Northern and Southern Hemisphere surface air temperatures, Nature, 310:38-41.

Gombosi, T.I., editor, 1983, Cometary Exploration, Hungarian Academy of Sciences, Budapest.

Grieve, R.A.F., 1982, in Silver and Schultz, 1982, 25-37.

Hammer, C.U., H.B. Clausen and W. Dansgaard, 1980, Greenland ice sheet evidence of post-glacial volcanism and its climatic impact, Nature, 288: 230-235.

Helin, E.F. and E.M. Shoemaker, 1979, The Palomar planet-crossing asteroid survey, 1973-1978, Icarus, 40:321-328.

Kanamori, H. and E. Boschi, 1983, Earthquakes: Observation, Theory and Interpretation, North-Holland, Amsterdam, 698 pp.

Klein, F.W., 1984, Eruption forecasting at Kilauea volcano, Hawaii, Journal Geophysical Research, 89:3059-3073.

Krinov, E.L., 1966, Giant Meteorites, Pergamon, Oxford.

LaMarche, V.C. Jr. and K.H. Hirschboeck, 1984, Frost rings in trees as records of major volcanic eruptions, Nature, 307:121-216.

Lamb, H.H., 1980, Climate, History and the Modern World, Methuen, London.

Lansberg, H.E., 1978, Geophysical Predictions, National Academy Press, Washington, D.C., 215 pp.

Neugebauer, M., D.K. Yeomans, J.C. Brandt and R.W. Hobbs, 1979, Space Missions to Comets, NASA Conference Publication 2089.

Nitecki, M.H., editor, 1984, Extinctions, University of Chicago Press, Chicago.

Oliver, J., 1982, Probing the structure of the deep continental crust, Science, 216:689-695.

O'Neill, G.K., 1975, Space colonies and energy supply to the Earth, Science, 190:943-947.

O'Neill, G.K., 1977, The High Frontier: Human Colonies in Space, William Morrow, New York.

Pollack, J.B., O.B. Toon, E.F. Danielsen, D.J. Hoffman and J.M. Rosen, The El Chichon volcanic cloud: an introduction, Geophysical Research Letters, 10:989-992.

Rampino, M.R. and R.B. Stothers, 1984, Terrestrial mass extinctions, cometary impacts and the Sun's motion perpendicular to the galactic plane, Nature, 308:709-712.

Raup, D.M. and J.J. Sepkoski, Jr., 1984, Periodicity of extinctions in the geologic past, Proceedings National Academy Sciences USA, 81:801-805.

Rikitake, T., 1982, Earthquake Forcasting and Warning, Reidel, Amsterdam, 400 pp.

Rosi, M. and R. Santacroce, 1983, The A.D. 472 "Pollena" eruption: volcanological and petrological data for this poorly known, plinian-type event at Vesuvius, Journal Volcanological and Geothermal Research, 17:249-271.

Rosi, M., A. Sbrana and C. Principe, 1983, The Phlegrean Fields: structural evolution, volcanic history and eruptive mechanisms, Journal Volcanological and Geothermal Research, 17:273-288.

Santacroce, R., 1983, A general model for the behavior of the Somma-Vesuvius Volcanic Complex, Journal Volcanological and Geothermal Research, 17:237-248.

Sepkoski, J.J., Jr. and D.M. Raup, 1985, Periodicity in marine mass extinctions, in D. Elliott, editor, Dynamics of Extinction, Wiley, New York.

Sheridan, M.F. and M.C. Malin, 1983, Application of computer-assisted mapping to volcanic hazard evaluation of surge explosions: Vulcano, Lipari, and Vesuvius, Journal Volcanological and Geothermal Research, 17:187-202.

Shoemaker, E.M., 1983, Asteroid and comet bombardment of the Earth, Annual Review Earth Planetary Sciences, 11:461-494.

Shoemaker, E.M. and R.F. Wolfe, 1984, Crater ages, comet showers, and the putative "death star", Proceedings 47th Annual Meteoritical Society Mtg.

Silver, L.T. and P.M. Schultz, editors, 1982, Geological Implications of Impacts of Large Asteroids and Comets on the Earth, Geological Society of America, Special Paper 190.

Simkin, T., L. Siebert, L. McClelland, D. Bridge, C. Newhall and J.H. Latter, 1981, Volcanoes of the World, Hutchinson Ross, Stroudsberg.

Smith, J.V., 1982, Heterogeneous growth of meteorites and planets, especially the Earth and Moon, Journal of Geology, 90:1-48.

Smith, J.V., 1983, Geophysical and geochemical consequences of nuclear explosions, Eos, Nov. 15, 930.

Smith, J.V., 1984, Relationships of volcanic phenomena and the effects of nuclear explosives, Proceedings Fourth International Seminar on Nuclear War, Erice, Sicily.

Swanson, D.A., T.J. Casadevall, D. Dzurisin, S.D. Malone, C.G. Newhall and C.S. Weaver, 1983, Predicting eruptions at Mount St. Helens, June 1980 through December 1982, Science 221: 1369-1376.

Swenson, B.L., P. Tsou, A. Friedlander and A.C. Mascy, 1984, A proposed Giotto/Comet Coma sample return mission. Proceedings 47th Annual Meteoritical Society Mtg.

Stothers, R.B. and M.R. Rampino, 1983, Volcanic eruptions in the Mediterranean before A.D. 630 from written and archaeological sources, Journal Geophysical Research, 33:6357-6371.

Taff, L.G., 1984, Optimal searches for asteroids, Icarus, 52:259-266.

Tazieff, H. and J.C. Sabroux, editors, 1983, Forecasting Volcanic Events, Lange and Springer, Berlin, 636 pp.

The International Halley Watch, 1980, Report of the Science Working Group, NASA TM 82181.

UNESCO, 1971 The Surveillance and Prediction of Volcanic Activity, a Review of Methods and Techniques, Paris, 166 pp.

Whitmore, D.P. and A.A. Jackson, 1984, Are periodic mass extinctions driven by a distant solar companion?, Nature, 308:713-715.

Wilkening, L., editor, 1982, Comets, University of Arizona Press, Tucson.

Williams, H. and A.R. McBirney, 1979, Volcanology, Freeman and Cooper, San Francisco.

Wisdom, J., 1983, Chaotic behavior and the origin of the 3:1 Kirkwood gap, Icarus 56:51-74.

Zimbelman, J.R., 1984, Planetary impact probabilities for long-period comets, Icarus, 57:48-54.