Advances in Geological Science: 1980 - 1984

by Eugen Seibold

In his address to the recent 27th International Geological Congress in Moscow, the out-going President of IUGS reviewed highlights in the development of the geological sciences in the four-year period since the previous Congress in Paris. A shortened version of this "tour d'horizon" is presented here, together with citations to some of the relevant literature selected by the Editor.

Major Problem Areas

The evolution of and interrelations between the lithosphere, hydrosphere, atmosphere and biosphere have always been our key problems. To solve them, we are trained to assume the validity of physical, chemical, and biological laws with which we try to investigate, understand and explain present and past processes in these "spheres."

However, as in human history, complex and subtle interactions of many factors influence these evolutions. They may be gradual or punctuated, both in organic and inorganic aspects. They may be periodic, cyclic or steadily on-going. They may be born or killed by a sudden and unique event, even a catastrophic one.

Our first task, therefore, is to study the Earth and its relevant processes, both as they exist now and throughout their history. However, geologists should be encouraged to look at future trends as well. We should feel an increasing responsibility for providing advice on how to overcome present and future human needs. Earth scientists by profession are familiar with all regions of our planet. We see the rapid but unequal increase in the world's population, the increasingly unequal distribution of material goods, and we know from personal experience that these and other challenges are global in nature.

We also know that mankind is increasingly looking to science to resolve these questions, and that fewer and fewer people are prepared to accept acts of nature as acts of God or of fate. Thus, we are increasingly involved - and possibly even blamed - in matters like natural hazards, the guarantee of long-term supplies of food, energy and raw materials, and statements about the tolerance of nature to man's interference on a local, regional or, as in the case of climate, global scale. How, therefore, have we attempted in the past four years to increase and improve our knowledge in order to meet these challenges?

Modern science needs spectacular breakthroughs as ignition sparks to drive it forward and to obtain support from the public. Some of the scientists approached for the preparation of this paper feel that there have been no recent advances which have influenced nearly all fields of earth sciences, such as discovery of vents on mid-oceanic ridges mentioned in Paris in 1980 by my predecessor, Prof. Rudi Trümpy. Others, however, underline the great successes in planetology and the growing recognition that celestial bodies and processes

influence our earth permanently. There have also been exciting results from deep reflection seismics and from drilling into the oceanic crust. Looking backward in earth history, earth scientists have become more and more familiar with catastrophic events.

Naturally, most of the recent results are based on new or better methods and instruments, in areas such as satellite geodesy, space mapping of earth's gravity field to detect structures of the ocean floor, remote sensing, high PT experiments, and geochemical and isotope analysis down to concentrations of 10^{-9} to 10^{-10} g (Fig. 1). Tomography to define three-dimensional crust structures and deep crustal drilling are opening a new field in geology. Some enthusiastic field geologists, however, see a danger in this trend for individualists "interested to go where nothing is known or where something does not look right." However, everyone will agree that we all meet looking at geological maps, the optimum way of presenting geological information.

The Lithosphere

From the Earth's lower crust down to its core, we depend on indirect information, except for some narrow crushed lenses of ophiolites and some xenoliths as messengers from the depth. Therefore, the Earth as a planet continues to be a wide field of dispute "between paradigms and paradoxes" (Anderson, 1984).

Figure 1: Laser ranging system at Arequipa, Peru (NASA photo).

New seismic results down to some hundreds of kilometers, and geochemical indications using ratios of Rb/Sr and Sm/Nd, for example, strengthen the idea that there is no primitive, undifferentiated terrestrial mantle but that there are heterogeneities, both lateral and vertical on a variety of scales. It remains unclear how these heterogeneities are related to geoid features, to melting and differentiation processes, or to possible convection cells. Similar gaps in our knowledge concerning the properties of the "rigid" lithosphere and the "weaker" asthenosphere feed disputes about the mechanisms that drive plates and, especially, about subduction as a recycling agent to explain continental components in mantle basalts (White and Hofmann, 1982).

Two groups of results should be mentioned from studies of oceanic crust. First, the exciting discovery of ocean ridge vents (Fig. 2) has stimulated detailed geological, chemical and biological investigations (Rona et al., 1983). We now understand better hydrothermal systems and the formation of polymetallic sulphide deposits, and we have learned, for example, that microorganisms may live in environments with temperatures up to 250°C and pressures of 265 atm. New vent findings have been reported from the East Pacific Rise, the Juan de Fuca ridge and from the Mariana Basin of the Philippine Sea, and anomalous contents of ^3He in sea-water may help to detect others (e.g. Hekinian et al., 1983). Ideas about the interactions between sea-water and the oceanic crust have also been refined.

A second significant discovery was the penetration of DSDP Hole 504B of 1,076 m into 6.2 million years old oceanic basement in the Costa Rica rift, where a basaltic dike complex is overlain by effusive pillow basalts with breccias and flows (Nature, Dec. 16, 1982). On the other hand one of the open problems remaining is the nature of the oceanic plateaus that cover more than 10% of the sea floor.

As regards the less dense, buoyant continental crust in which 95% of earth history is stored, deep reflection and refraction seismics and three-dimensional tomography of the continental crust and upper mantle have resulted in a whole series of reflectors, suggesting that the continental crust is markedly tectonically layered. If so, near surface structures may no longer be extrapolated to any significant depths.

Figure 2: Artist's concept of black and white smokers and associated life forms, Juan de Fuca Ridge, NE Pacific (from GEOS, 1983/3)

There are indications of low-angle thrusts, some even crossing the Moho, which have transported thin slices of older rocks over younger ones for hundreds of kilometers, and many extensional features have also been detected. Confirmation of these and other ideas will require deeper continental drilling, as demonstrated by the Kola super-deep drillhole into the continental crust of the NW Soviet Union (Fig. 3), where no "basaltic" layer was reached in spite of seismic indications (Kozlovsky, 1982). Much more attention will have to be paid now to the role of deep fluids in rocks and to measurements in bore holes used as deep crustal labs.

Many of these exciting results are, of course, only first steps towards understanding earth processes such as involved in the evolution of the mantle and crust. Why, for example, did the break-up of Pangaea occur in the Permian? Was it caused by the insulating effects of a giant supercontinental crust, which forced heat transfers from the deeper mantle to begin convecting? And, why did it break up where it did?

During the past few years, morphological and geophysical mapping from satellites and ships has detected details down to less than 1 m on divergent plate boundaries and fracture zones. First results of satellite measurements of inter-continental distances with an accuracy of a few centimeters give us the hope that plate motions can now be measured directly. However, the origin of the magnetic stripes and reversals that we are now accustomed to use in stratigraphy remains unresolved.

Convergent plate boundaries and subduction zones, which are required if the earth is not expanding, continue to be central topics for discussion. For some earth scientists, they remain an unloved child of an unloved theory, for others the seat of the main engine, driving plate motions. Coesite, the high pressure form of quartz, was discovered as statically grown in metasediments of the continental crust, suggesting that the original sediments were subducted during continent/continent collision to depths of 90 km or more before they were tectonically uplifted again. There is also the concept of accretion of terranes, as discussed around the Pacific, now "la grande mode" in the U.S. Cordillera (e.g. Nur, 1983). Is this really one of the important mechanisms for the growth of continents, as well as one of the compensations for losses by erosion from the continents into the ocean? Is Australia really growing by ploughing into an oceanic plate full of oceanic plateaus, seamounts and island arc systems?

During the last years, we have learned to distinguish between the high-stress mode Chilean-type convergent boundary and the low-stress mode Mariana-type (Uyeda, 1983). The former has a shallow-dipping Benioff zone at a young plate border, strong earthquakes, and andesites with porphyry copper deposits, while the latter has contrasting features, such as massive sulphide deposits. But what happens in front of these downgoing plates?

And what really takes place within the plates? What causes the intraplate uplift of the Colorado plateau in the U.S.A., or the Rhenish Massif in Western Europe (Fuchs et al., 1983), or generally at the beginning of continental rifting? Intrusions of large basic magma bodies into the lower crust? Mantle diapirs with partial melts? On the other hand, what causes subsidence in continental basins or at passive continental margins? Perhaps the answer will come from basin analysis studies in which features and processes extending from 200 to 1,000 km in size can now be approached quantitatively, including diagenetic changes and hydrocarbon maturation.

The Oceans

Plate tectonic theory was born in the oceans. It was partly proven by the work of "Glomar Challenger" under the DSDP program. This ended in November 1983 after 96 legs and 624 drill sites, having trained and made enthusiastic two generations of scientists around the globe (Fig. 4). Ongoing discoveries and evaluation of core material and geophysical

data, together with computer modelling approaches, have refined our ideas about the formation and evolution of ocean basins and their sediments. As a result, marine stratigraphy, paleoceanography and paleoclimatology are presently at the forefront of world-wide investigations (e.g. Seibold and Meulenkamp, 1984).

During the Cretaceous, oceanic deep waters were apparently influenced predominantly by low latitude, warm marginal seas and seem to have been periodically anoxic in part. The shifting of continents, among other events, caused high latitude cooling resulting in a complete change in climate and in oceanic deep-water conditions during the Tertiary. This general cooling, however, was not continuous, for dramatic breaks have now been recognized as at the boundaries between the Paleocene and the Eocene, the Eocene and the Oligocene, and during the Middle Miocene. Recent work has also established relationships between sea-level variations and deep-sea erosion, leading to substantial sediment hiatuses.

Also significant are some obvious and sudden climatic changes during the Pleistocene, and the increasingly convincing indications of Milankovich cycles preserved in marine sediments up to 800,000 years old and possibly going back to the Tertiary. Variations in the CO₂ content of the atmosphere during glacial and interglacial periods are also important for the discussion of future climatic conditions.

Together with the use of magnetic reversals and the record of oxygen isotopes in calcareous shells, the dating of young marine sediments now seems to be possible with an accuracy of less than 5,000 years - an exciting promise for future work on organic evolution and biogeography (Shackleton, N.J., in Seibold and Meulenkamp, 1984). These advances enable us to draft global scenarios with extremely thin time slices - an extraordinary advance in stratigraphy. But, how do we conquer the last 600 million years as a whole, with an average of only one absolute age marker every 2 million years? And, how can we bridge the gap between this accuracy in marine sediments and the stratigraphic record from continental environments? One possibility seems to be the use of global rare events, now more widely accepted than before.

Rare Global Events

The most spectacular example is certainly the widely discussed impact of a celestial body at the Cretaceous/Tertiary boundary (Silver and Schultz, 1982). The event is marked by an unusual concentration of iridium in both marine and continental sediments. It caused mass extinction in marine planktonic and benthic biota, as well as in terrestrial flora and fauna, and afterwards new life forms replaced the extinguished ones. Another mass extinction is known from the end of the Frasnian (McLaren, 1983). A concentration of Ir (and Ni + Co) was found in metallic spherules around the 1908 Tunguska impact in Central Siberia, and a similar concentration has now also been detected in an Antarctic ice core in an annual layer deposited in 1909 (Ganapathy, 1983).

The 1883 Krakatoa eruption gave a warning for global consequences caused by volcanoes. The detailed and on-going investigations of the El Chichon eruption of April 1982 have also given exciting new insights. The latter eruption ejected fine volcanic material up to the stratosphere and circulated from there around the globe, eventually causing a temperature drop in the Northern Hemisphere of 0.25 to 1°C.

Many variations in sea level could also be grouped under sudden events, but recent studies of Holocene transgression curves demonstrated that they are not synchronous because of different effects of loading by water in different shelf environments.

Early Earth History

These new results are all related to the youngest portion of earth history. However, during the past four years very important progress has also been made in Precambrian

stratigraphy. The Upper and Lower Proterozoic can now be subdivided by classical stratigraphic methods using stromatolites and acritarchs. However, much more absolute dating is needed to prove or to disprove different ideas about the tectonic and metallogenic evolution of the Precambrian crust.

As for Precambrian life, its very origin is continuously discussed. The importance of life for geological processes is under continuous discussion. One topic has been the role of microbial benthic organisms since 3.5 Ga, another the dramatic effects of ongoing photosynthesis, finally leading to an atmosphere with permanent free oxygen some 2 Ga ago (Schopf, 1983). Perhaps, the replication of montmorillonites could become a model for the replication of organic molecules as well. In many respects, therefore, the present is not the key to the very distant past.

Further examples of the interaction between life and geology are now found in studies of soil formation and erosion. These processes are deeply influenced by organisms, as is the diagenesis of organic matter, the driving force of all biogeochemical processes, including the formation and destruction of hydrocarbons. The release of CO₂ into the atmosphere and its removal by incorporation into plant or animal tissues or carbonate shells both on land and in the sea may also be mentioned. Naturally, all these examples stress the importance of interdisciplinary approaches, and we might be well advised to follow the advice of the Russian proverb,

Figure 3: The Kola Super-deep "Well." Counter-clockwise from bottom: The main installation, north-west of Murmansk near the border between the U.S.S.R. and Norway. Inside the drill tower. The drill bit (diameter 20 cm). Examining the core.

Figure 4: The SEDCO/BP 471. The dynamically positioned drill ship that will carry out the Ocean Drilling Program, the successor to DSDP. The ship will have a drill string over 9000 m long and will be able to drill in nearly 2000 m of water. (Photo courtesy of ODP).

"Don't look for the hare in the deep forest: he is sitting at its edge."

In this connection I would like to mention one project of the International Geological Correlation Programme, which IUGS runs with Unesco, and which is one example of effective scientific cooperation crossing all kinds of political boundaries. Part of Project 156 on phosphorites has considered the evolution of soft-bodied and enigmatic metazoan Ediacaran fauna living some 670 million years ago to the Cambrian radiation event about 100 million years later, which produced so many different mineralized shelly faunas, including those of calcium phosphate. This evolution seems to be related to a very Late Proterozoic to Early Cambrian phosphogenic episode, and to a period of enhanced oceanic overturn with many phosphate traps in shallow epicontinental seas flooded by a major sea-level rise (Cook and Shergold, 1984).

Planetology

The last broad field of basic science that has produced especially spectacular, though expensive, results in recent years is planetology. Technical breakthroughs allowed the Soviet Venera 13 and 14 spacecrafts to land on Venus, a planet of Earth-like size, providing much valuable data about regional and local topography down to millimeters, and the chemistry of its atmosphere and rocks (McGill, 1983). Similar breakthroughs involving the Voyager missions (U.S.A.) allowed the study of Saturn's rings and satellites, CH₄ in the stratospheric haze of Titan, and many volcanic features including eruptions on Jovian satellite Io (Fig. 5).

Scientifically, the most important results of this work seem to me the rapidly increasing attention geologists pay to planetology and to space-earth relations in general. Examples include the impact event at the Cretaceous/Tertiary boundary, the Tunguska event, and the finding of meteorites in Antarctica that appear to have come straight from the Moon and possibly from Mars (Marvin, 1982).

These investigations are deepening our understanding that the Earth is a unique planet. One with ongoing active plate tectonics, with liquid water and therefore with oceans, with unique climatic conditions, and with life as we know it -

Figure 5: Voyager 2 mosaic of Enceladus, one of the most remarkable of the satellites of Saturn. Only 500 km in diameter, it displays evidence of extensive relatively young geological activity. (NASA photo).

altogether, a planet with a very fragile environment, the balance of which we have to protect.

Looking to the Future

We must now direct our efforts towards better hazard predictions. The seismic gap concept as used, for example, in Kamchatka, Italy, and California, has given some promising results but should be expanded in space and time. Precursor studies, including strain measurements and other methods, seem to be much more difficult to use, because earthquakes are individual and often multiple events.

Seismic monitoring, on the other hand, was very successful in predicting the Mount St. Helens eruption in 1980, after about 120 years of dormancy (Lipman and Mullineaux, 1981). Earthquake swarms accompany the present Long Valley magma intrusion near Mammoth Lake, east of Yosemite Park, "but no one knows what may happen there and when. Similarly, since 1982 the Phlegraean Field uplift, west of Naples, has been a challenge to geologists - and to its inhabitants!

Predicting the consequences of man's actions as a geological factor is even more difficult. On a world-wide scale, we consume each year a volume of oil which nature needed some million years to produce. At the rate we are burning fuel and destroying forests, the increasing CO₂ content in the atmosphere may influence our world's climate drastically during the next century. Man-made pollution of groundwater, lakes, rivers and the sea is also increasing as shown by geochemical studies in relevant sediments (e.g. Geophysics Study Committee, 1984). For example, at present, natural fluxes of Fe, Cu, Zn, and Pb into the oceans are only 10% of those due to man's input.

Conclusion

So as to meet better all these global challenges, we should first try to improve relations in basic science, especially between academia on the one hand, and industry and government on the other. The latter hide their so-called "secrets" in inaccessible data banks and files; these need to be unburied and to be evaluated more properly.

A second and widening gap is directly connected with the many new results in research summarized in this report. For most developing countries, needing food and water and trying to develop their mineral and other resources, many of these results may be irrelevant today or even tomorrow. One of the main duties for earth scientists from more industrialized nations should therefore be to cooperate with the young geologists of developing regions in solving the urgent problems of their countries, from classical field mapping to modern exploration methods.

All such progress requires well-trained and motivated geologists, and many of our problems can only be solved by international and inter-generational partnership. The ongoing fundamental task for geologists is to explore Earth history with its long time span and with its few chances to look to the future. This must be done now for the benefit of all of us and the coming generations.

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Editor's Note: Because of time constraints, it was not possible to insert all the citations into the text of this article. An additional list will be included in the next issue (vol.7, No.4) of *Episodes*.

Eugen Seibold, Past-President of IUGS, is a marine geologist well known for his work with SCOR, Unesco and a host of other international scientific bodies. IUGS Publication 14, "Stratigraphy Quo Vadis" is one recent product of his interest in the correlation of geological events at sea with those on land. As President of the Deutsche Forschungsgemeinschaft, in Bonn, one of the most important German research funding agencies, Prof. Seibold exerts a major influence on science in his own country.

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