Geoscience Canada

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Volume 20, Number 3, September 1993

URI: https://id.erudit.org/iderudit/geocan20_3icg02

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Hoffman, P. F. (1993). The Crisis in Lithospheric Research. *Geoscience Canada*, *20*(3), 91–94.

Article abstract

Lithospheric research faces a crisis. Mineral and hydrocarbon exploration (the fiscal rationale for such research) have decreased, and job prospects and undergraduate student enrollments are down. The declines are thought to be asting. Concurrently, growing environmental concerns have been a boon for funding in hydrology and the ocean, atmosphere and climate sciences. Among the environmental concerns most likely (for proper political and economic reasons) to spawn durable action are the remediation of waste dumps and the treatment of their leachates. This will require and also contribute to a greatly enhanced understanding of the physics, organic and inorganic chemistry, and geology of groundwater flow in the upper lithosphère. The knowledge gained will pay dividends in the eventual exploitation of the large portion of hydrocarbons remaining in the ground after conventional extraction. We should, therefore, expect that the emphasis inlithospheric research, which since the mobilist revolution has focussed on deep-seated processes, will shift in the direction of processes that operate from the top down. The scale and duration of groundwater migration, its control by tectonically induced topography and subsurface geological structure, and the estimated flow velocities equal to those of fast-moving lithosphericplates ensure the continuing importance of research directed at processes operating on geological time-scales.

Issues in Canadian Geoscience

The Crisis in Lithospheric Research

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ABSTRACT

Lithospheric research faces a crisis. Mineral and hydrocarbon exploration (the fiscal rationale for such research) have decreased, and job prospects and undergraduate student enrollments are down. The declines are thought to be lasting. Concurrently, growing environmental concerns have been a boon for funding in hydrology and the ocean, atmosphere and climate sciences. Among the environmental concerns most likely (for proper political and economic reasons) to spawn durable action are the remediation of waste dumps and the treatment of their leachates. This will require and also contribute to a greatly enhanced understanding of the physics, organic and inorganic chemistry, and geology of groundwater flow in the upper lithosphere. The knowledge gained will pay dividends in the eventual exploitation of the large portion of hydrocarbons remaining in the ground after conventional extraction. We should, therefore, expect that the emphasis in lithospheric research, which since the mobilist revolution has focussed on deep-seated processes, will shift in the direction of processes that operate from the top down. The scale and duration of groundwater migration, its control by tectonically induced topography and subsurface geological structure, and the estimated flow velocities equal to those of fast-moving lithospheric plates ensure the continuing importance of research directed at processes operating on geological time-scales.

RÉSUMÉ

Les recherches sur la lithosphère sont en état de crise. Le ralentissement des activités d'exploration pour la découverte de ressources minérales ou d'hydrocarbures (étant donné la logique fiscale pour ce genre d'exploration) a entraîné une baisse des possibilités d'emploi ainsi qu'une diminution des inscriptions d'étudiants en sciences de la Terre. On croit que ces ralentissement perdureront. Parallèlement, des préoccupations croissantes en matière d'environnement ont constituées une bénédiction pour les disciplines de l'hydrologie, de l'océanologie, et des sciences de l'atmosphère et des climats. Parmi ces préoccupations environnementales, celles qui sont les plus susceptibles (pour des raisons politiques et économiques évidentes) de déboucher sur des actions durables sont les mesures de restauration appliquées aux sites d'enfouissement, ainsi que le traitement de leurs lessivats. Cela nécessitera, mais contribuera également, à amélioration considérable de notre compréhension de la physique, de la chimie organique et inorganique, de la géologie et des mécanismes circulatoires des eaux souterraines dans la partie supérieure de la lithosphère. Les connaissances acquises ainsi seront profitables lorsqu'il s'agira d'exploiter les grandes quantités d'hydrocarbures abandonnées dans le sol par les méthodes conventionnelles d'exploitation. Par conséquent, nous devrions nous attendre à ce que l'intérêt des recherches lithosphériques, qui a surtout porté sur les mécanismes profonds depuis la révolution mobiliste, se déplace maintenant vers les mécanismes qui agissent du haut vers le bas. L'échelle et la durée des migrations des eaux souterraines, l'influence des éléments topographiques et des structures géologiques d'origine tectonique, ainsi que leurs vitesses d'écoulement que l'on a estimées être de l'ordre de grandeur de celle des plaques à déplacement rapide assurent l'intérêt soutenue pour la recherche portant sur les mécanismes à l'échelle géologique.

INTRODUCTION

The lithosphere is a thermal and mechanical boundary layer at the top of the Earth's silicate mantle. Its thickness ranges from approximately 2 km at oceanic spreading axes to approximately 150 km beneath Archean cratons. It includes the chemically distinct crust, a product of partial melting in the upper mantle. The lithosphere, being a solid, is a complicated recorder of Earth history, requiring investigative methods quite different from those used to study the fluid regimes above and below.

The traditional Canadian strength in lithospheric research derives from the size and geological diversity of our territory, and historical collaboration between academic researchers and government agencies mandated to make regional surveys. The LITHOPROBE project, for example, has been a triumph (Clowes *et al.*, 1992). It placed otherwise unobtainable constraints on the deep crustal structure of an active subduction zone (Vancouver Island), an intraplate megathrust (Kapuskasing), a plume-generated continental rift (Lake Superior), and diverse accretionary and collisional orogens (Cordillera, Appalachian, Grenville, Trans-Hudson). The Great Lakes (GLIMPCE) transects exploded the myth that Precambrian crust is seismically incoherent. Regional geological studies, supported by isotopic geochronology and potential field surveys, have broadly outlined the origin and evolution of the North American lithosphere through several cycles of supercontinental aggregation and fragmentation (Williams *et al.*, 1991). Innovative dating techniques and methods of determining ancient magma flow directions have unlocked the secret of giant mafic dyke swarms (LeCheminant and Heaman, 1989; Ernst and Baragar, 1992), contributing to the continuing integration of plume and plate tectonics. Such Canadian successes would not have occurred in the absence of either academic research or regional-scale government surveys.

The study of mantle xenoliths, particularly diamondiferous eclogites and harzburgites, combined with a variety of geophysical observations and high-pressure experimental data, is giving new insights into the nature and origin of cratonic lithosphere (Boyd and Gurney, 1986; Jordan, 1988; Hoffman, 1990) with profound implications for Archean plate tectonics (Helmstaedt and Schulze, 1989) and Holocene geodynamics (Peltier *et al.*, 1992). A rationale for cratonic sedimentary basins may finally be at hand with the recognition that convective mantle downwellings (supersuckers) are localized by the cold refractory roots of cratons (Peltier *et al.*, 1992). The integration of new biostratigraphic and chemostratigraphic data are lifting the veil from that most enduring enigma of historical geology by elucidating the events leading to the unique radiation of eucoelomate animals at the end of the Proterozoic that permanently changed the nature of ecological and sedimentary systems (Knoll and Walter, 1992).

Now, however, the confidence of the research community has been shaken by predicted long-term declines in domestic mineral and hydrocarbon exploration, already reflected in plummeting undergraduate enrollments. The markets for minerals are contracting globally and shifting geographically. There is no end in sight for low-cost petroleum from the Middle East and prospects elsewhere are discouraging. The needs of the exploration industries have long fuelled lithospheric research. Most graduating students were hired by industry, and governments ran field surveys to attract and nourish commercial exploration activity. LITHOPROBE, a program driven by seismic reflection profiling, a technique developed by and for the petroleum industry, looks dated. Time and site-specific earthquake prediction, once expected to drive lithospheric research, appears to be unattainable.

NEW SOCIETAL DEMANDS

New societal concerns are drawing dollars and brains to other fields of research. The threat to social welfare posed by supposedly anthropogenic greenhouse warming and ozone degradation has been a boon for climatology, oceanography, glaciology and atmospheric science. The seriousness of the former threat, which is based on numerical climate models, is still very much open to question. The critical roles of clouds, thermohaline circulation in the oceans, and the terrestrial biomass are poorly treated in the models. Measured increases in atmospheric carbon dioxide are less than predicted in models based on estimated industrial emissions. The history of warming recorded over the past 150 years correlates poorly with the history of industrial activity. The regional climatic consequences of global warming, should it occur, are conjectural. Rather than the coastal flooding predicted earlier, greenhouse warming now appears more likely to cause a lowering of eustatic sea level by increasing the Antarctic ice volume. We are in no position to know if it would be socially and economically more benign to adapt to climate change rather than to attempt to control it. The issue of potential desertification is most critical for those parts of the world where the consumption of fresh water outstrips replenishment. The danger is exacerbated by population growth and the urbanization of arable land. Irrigation accelerates soil evaporation and salination of ground waters, especially coastal ground waters.

The remediation of waste dumps and the treatment of their leachates will require huge expenditures and efforts, lasting decades. So will the control of groundwater contamination plumes generated by pesticides and leaking underground fuel and chemical tanks. A concerted effort involving hydrologists, geophysicists, geologists, organic and inorganic geochemists, and soil scientists will be required to understand the dynamics and chemical activity of continental ground waters in a myriad of situations. Policy makers will require knowledgeable and forward-looking advice.

Despite a decade of unprecedented exploration activity fuelled by tax incentives, conventional oil reserves outside the Middle East fell dramatically. It is estimated that conventional Middle East oil will be mostly pumped out in our lifetime. Undoubtedly, we will then wish to develop a technology capable of economically recovering the lion's share of the original oil, domestic and foreign, still left in the ground after secondary recovery. Detailed knowledge of reservoir properties in specific geological situations is a likely prerequisite for the successful application of such technology.

Fortunately, the knowledge gained in the remediation of waste dumps will pay dividends when the time comes for tertiary oil recovery (Abelson, 1992). Monitoring of toxic plumes may yield insights into the movement of fluids in soils and rock that will be applicable in devising efficient means of driving petroleum. The hydrophobic nature of some of the chemicals in waste sites is comparable to that of components of petroleum. Some of the chemicals are the same. The habitat of oil is deeper than that of waste dumps, which increases the geological aspect of the problem.

As scientific research seldom suffers from over-funding, areas of lithospheric research close to fields high on the socio-political agenda are likely to advance. Even in the absence of direct funding enhancements for lithospheric research, there will be a spill-over effect from the knowledge explosion concerning climate and climate change, surface processes, and the actions of subsurface fluids.

SURFACE PROCESSES AND THE LITHOSPHERE

Since the mobilist revolution, lithospheric research has fixated on deep-seated processes. Recently, however, there has been a revival of interest in the effects of surface processes, such as precipitation and erosion. Inspired by the ongoing oblique microcontinental collision expressed by the Southern Alps of New Zealand, the relationship between erosion and uplift has been investigated through field observations and numerical simulations (Koons, 1989; Beaumont *et al.*, 1991, Chase, in press). In New Zealand, the orographic effect of prevailing westerly winds is strongly imposed, with high rates of precipitation and erosion on the windward mountain slopes and low rates on the leeward slopes (Norris *et al.*, 1990). There is a feedback from the surface processes to the tectonics because the gravitational component of stress distribution within the deforming orogen depends directly on the mass transferred by the surface processes (Beaumont *et al.*, 1991). In effect, uplift trajectories are drawn toward areas of maximum erosional unloading. Quantitative investigation of processes operating on time-scales of millions of years is made possible by the kinematic framework of plate tectonics and temporal constraints from isotopic geochronology.

Initial results suggest that orographic erosion strongly influences tectonic style (Table 1). At windward orogenic fronts, high rates of erosional unloading incite rapid uplift. The resulting thermal anomaly leads to softening and reactivation of the tectonic footwall. Conversely, at leeward fronts, uplift is inhibited by low rates of erosional unloading. The models predict that a dynamically steady-state mass balance can be achieved at windward fronts (the tectonic mass flux is balanced by erosional denudation), with the result that flexural loading and foreland basin subsidence are limited. At leeward fronts, erosion is insufficient to balance the tectonic mass flux, causing increased flexural loading and propagation of the deformation front toward the foreland. Accordingly, windward basins tend to be shallow, overfilled with sediment, and dominantly progradational in depositional style; leeward basins tend to be deep, underfilled and dominantly aggradational in character (Burbank, 1992). The importance, as well as the uncertainties, of the interactions between tectonics and surface processes are illustrated by the controversy as to whether the supposed late Cenozoic rise of mountains ranges is an illusory consequence or a cause of climate change (Molnar and England, 1990; Ruddiman and Kutzbach, 1990).

GROUND WATER AND THE LITHOSPHERE

Groundwater flow is an important mechanism for heat and mass transport in the upper crust. However, there has long been uncertainty over rates (hence volumes over time), depths, sources and driving mechanisms of groundwater flow, not to mention its geochemical consequences. For example, the brines responsible for transporting metals to ore deposits were traditionally believed to be driven either by compaction and tectonic shortening of water-rich sediments, by metamorphic dehydration reactions, or by magmatically advected heat. However, the first pair of alternatives fails because inadequate volumes of brine are generated, and the last fails because convective hydrothermal cooling rapidly destroys the magmatic heat engine in most environments.

A breakthrough came with the appreciation that topographically induced hydraulic heads could drive subsurface flows of meteoric fluids indefinitely, overcoming the above problems in ore genesis (Garven and Freeze, 1984). It quickly became apparent that such groundwater systems operate on scales and at velocities comparable to those of lithospheric plates, and that they can govern secondary oil migration, formation of certain stratabound ore deposits, and regional-scale diagenetic metasomatism and low-temperature remagnetization (Bethke and Marshak, 1990). Multidisciplinary studies (geophysical, geological and geochemical), again of the New Zealand Southern Alps, provided theoretical models linking mineralization to tectonic processes through topographically driven groundwater flow (Koons and Craw, 1991). However, much remains to be learned about chemical solution and precipitation kinetics in different groundwater regimes. That topography drives ground water to depths of many kilometres and over lateral distances of hundreds of kilometres, at flow velocities on the order of 0.1 metres/year (equivalent to fast-moving lithospheric plates) is confirmed by detailed borehole geothermal data (Deming *et al.*, 1992). Also shown is the importance of aquifers and the overall geologically determined subsurface permeability structure in modulating patterns of groundwater migration. Complex feedbacks betweeen groundwater flows and geological structure are inevitable in tectonically active regions, given the well-known effect of high fluid pore-pressures on rock rheology.

SUCCESSOR TO LITHOPROBE?

The success of the Lithoprobe program leads naturally to the assumption that future research initiatives should be similarly organized. Megaprojects like Lithoprobe are effective money raisers and, if properly managed, encourage interdisciplinary communication. On the other hand, they can become wasteful, self-justifying, over-administered, unresponsive to new ideas, protective of vested interests, and safe havens for low-risk takers and modest

Table 1 Stylistic spectrum of orogenic fronts related to rates of precipitation and erosion (Hoffman and Grotzinger, 1993).

	HIGH RATES	LOW RATES
Overall depth of erosion	Deep	Shallow
Frontal metamorphic gradient	Steep	Gentle
Footwall reactivation	Extensive	Restricted
Thin-skinned thrust-fold belt	Narrow	Broad
Synorogenic detritus	Compositionally mature	Compositionally immature
Foreland basin	Poorly preserved, overfilled, fluvial to shallow marine deposits dominant, progradational stacking	Well preserved, underfilled, submarine fan deposits dominant, aggradational stacking

achievers. Big projects attract targeted funds that would not, so it is said, be available to individual researchers in their absence. But these funds do come from the overall pot that governments allot to scientific research: the more that goes to big projects the less there is for small ones. Politicans do not measure the funds alloted to science on the basis of specific research programs. They do so from the general conviction that science is good for society in the long run (the allotments fall short of our desires because other expenditures are deemed necessary in the short run). Every single scientist seeking a research grant pays for LITHOPROBE, or its successor.

Is it worth it? It can be, if the aims of the project could not be achieved without a central component that costs too much to be raised by individuals or small groups of researchers. The cost of the seismic reflection component of LITHOPROBE justified the organizational structure of the program, given that the overall objectives were worthy. Without such an organization, the work done by LITHOPROBE would never have been carried out. However, in the absence of the core seismic component, the attendant parts of the program could have been as effectively accomplished through grants to individuals and small groups of researchers. Enhanced communications, for example, could be more efficiently achieved through increased awards for conference travel to individual grant holders.

Should we seek a successor to LITHOPROBE designed to address the concerns and opportunities in surface and near-surface studies outlined earlier? I do not see that there is a core component to such studies requiring the level of funding necessary to justify a megaproject like LITHOPROBE. Furthermore, it would be unwise to freeze-in a large programmatic investment while it is still unclear what form such studies should take (by contrast, the general form and needs for LITHOPROBE were quite evident from an early stage in its evolution). It would be especially foolhardy to commit large long-term resources at a time when, because of unavoidably rising demands elsewhere in the economy, the total funding pot for discretionary research during this decade must shrink. Above all, we must preserve our ability to fund the most important new directions in scientific research, which are precisely the directions we cannot now predict with precision.

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Accepted 1 September 1993.