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The Study of Major Faults in Canada by Drilling: A CCDP Workshop Report

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magnetotellurics. High resolution seismic work has been done in the North Range. Data acquisition there is difficult because of terrain conditions, but useful data have been obtained. They tie in quite well with available surface and subsurface data. The Abitibi-Grenville LITHOPROBE transect that has been designed to cross the Grenville Front could also cross the Sudbury Basin. Based upon the results of that transect, a seismic reflection and refraction programme should be designed to assist in the locating of the hole (or holes) to be drilled. It was suggested that several shallow holes might be drilled in order to help solve some local geological problems before recommendations could be made regarding the location and drilling of a deep hole.

A full report of the workshop, including abstracts of the presentations, is available from the CCDP Planning Office on request (CCDP Report 88-2).

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The Industrial Associate Members of CCDP are currently: BP Canada, Bradley Bros. Ltd., Chevron Canada Resources, Esso Minerals Canada, Falconbridge Ltd., Heath and Sherwood Drilling (1986) Ltd., Inco Gold Co., JKS/Boyles Industries Inc., Longyear Canada Inc., Midwest Drilling, Newmont Exploration Ltd., Noranda Explorations Ltd., Petro-Canada Inc., Teck Explorations Ltd. and Tonto Drilling Company.

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The third of a series of thematic workshops sponsored by the Canadian Continental Drilling Program (CCDP) was held at the Pacific Geoscience Centre of the Geological Survey of Canada, Sidney, BC, 19-20 October 1988. The workshop was attended by 32 participants, drawn largely from universities and government in Canada but also with representation from industry and the United States. The principal aim of the workshop was to encourage open discussion of five proposals submitted to CCDP for the examination and sampling of fault structures by drilling. Other presentations provided background information on the geophysical response of faults, especially as regards seismic reflection profiling, and on current ideas of the importance of major faults as conduits for fluids and the loci of mineralization.

The workshop began with an outline of the objectives and progress of CCDP. James M. Hall (Dalhousie U, Halifax, Chairman, CCDP Steering Committee) described the status of the process of the review of proposals, the links CCDP had made within the geological community in Canada through recognition of its Steering Committee as a Standing Committee of the Canadian Geoscience Council, and the successful Industrial Associate program which has led to 15 major companies in the petroleum, mining, drilling and service industries becoming associated with the program.

John A. Percival (Geological Survey of Canada (GSC), Ottawa) presented his proposal for the examination by drilling of the structural break between the deep-crustal granulites of the Kapuskasing Structural Zone and greenstone-granite terrane of the Abitibi Belt to the east. The LITHOPROBE seismic profiles obtained in 1988 clearly image two zones of reflections that appear to represent listric faults dipping beneath the high-grade metamorphic terrane. Interpretation of the migrated, high-resolution seismic line in the upper one second of two-way travel time suggests that the faults corresponding to the major reflections steepen and splay toward the surface. Here a thin slice of amphibolite-grade gneiss, not correlated with either major terrane, is bounded by the steep extensions to the surface of the two faults imaged by the seismics. The western fault has a history of brittle fracture, with the production of pseudotachylites, while the poorly exposed easterly fault shows a history of more ductile deformation. In light of this new information the objectives of drilling of this structural break, proposed at an earlier workshop, would now emphasize study of mylonitic and cataclastic deformation and their inter-relationship. The results of drilling are expected to help elucidate the nature of mid-crustal delamination, as interpreted from the reflection profiles.

Ron Clowes (LITHOPROBE Secretariat, U of British Columbia, Vancouver) described refinements to seismic record interpretation that are of potential importance so far as drilling is concerned. Reprocessing of data in several areas has allowed fault traces to be followed to near surface. The Vancouver Island data has received most attention. By using a combination of pre-stacking migration and six selected shot-gathers, the Leech River Fault, for example, has been imaged to within about one kilometre of the surface. The fault surface shows the sequence of steep, shallow, then finally steep dips again as it approaches the surface. A problem of general interest is why some faults image well and others do not. Recent work by Christensen and his colleagues, using drill core samples from Brevard Zone, and by Mayrand and others has provided some information on this problem. Elsewhere in Canada there has been particular interest in imaging important structural breaks such as the Cadillac-Larder fault zone within the Abitibi Belt. Further work on these kinds of problems is planned in the near future. For example, BP Minerals has granted $50,000 toward a high resolution reflection survey in the Buchans area as part of the LITHOPROBE East work in Newfoundland.

Clément Gariépy, on behalf of a group led by J. Martignole and J.C. Mareschal (U de Montréal and U du Québec à Montréal) described a proposal to investigate by drilling several major structural breaks in the Grenville Province. The first target would be in the Grenville Front, where the GLIMPCE line has imaged a stack of slices marking extensive delamination of the crust. The aim of a carefully sited, 1-2 km hole would be to cross the boundary between two of these slices a few kilometres south of the front and sample a metamorphic inversion contrasting high T, low P, Archean amphibolite-grade schists overriden by low T, high P, Grenvillian granulites. A second target would be to test whether the Bouchette terrane consisting of homogenous anorthosite metamorphosed at amphibolite to granulite grades is allochthonous or not. Recent mapping has identified shear zones in adjacent anorthosites that suggest the presence of a tectonic break beneath the terrane, and the objective of drilling would be to seek the presence of such a break. A third area of interest provides an alternative to the second: the Panburn anorthosite terrane, which has experienced temperatures of 800-900°C, is definitely allochthonous, lying on grey gneisses. The objective of drilling would be to locate and sample completely the tectonic break. Another class of objectives is within major shear belts. Both the Renzy shear belt, with its highly deformed ultramafics of unknown origin, and shear belts in the Baskatong Zone are possible target areas. Material in these terranes has experienced very high temperatures (825-975°C) and pressures (9-11 kb) and the tectonic setting and implications of the shear belts is of current interest. A final target of interest is the Mont-Laurier terrane. Recent thermobarometric studies suggest that two lithologically similar zones with different metamorphic history are present. The objective of drilling would be to distinguish between tectonic and stratigraphic origins for the boundary between the terranes. The area is also of interest for its seismicity.

Trevor Lewis and Christopher Yorath (Pacific Geoscience Centre (PGC), Sidney, BC) reviewed knowledge of major faults on Vancouver Island and described their proposal for study by drilling of several features of one or more of these faults. In an overview, Lewis identified major faults as potential fluid-bearing conduits and discussed the properties a fault might need, such as effective thickness, in order to be imaged by seismics. It is thought that both younger faults, and many older faults in and behind the accretionary prism associated with the subduction of oceanic crust beneath Vancouver Island, could be involved in the removal of fluids resulting from the dehydration of the subducting crust. The objectives of drilling through seismically reflective faults of this type would both be to provide an explanation for their reflectivity, thus calibrating the seismic reflection technique, and to sample the unweathered alteration minerals comprising the fault zone, in order that they may be analysed to provide necessary data to model the history of such altered zones. An additional bonus might be the acquisition of rising fluids away from contamination by surface waters. An effort by a large group is proposed. The drill site would be in the vicinity of one of the on-shore, Eocene faults imaged by LITHOPROBE. It is thought that an inclined hole of not more than 2 km depth would be sufficient for this purpose. Yorath described several major faults, both in terms of their extension at depth and their surface expression. Several major fault zones on Vancouver Island, such as the Leech River and West Coast Fault Zones, are imaged seismically from the surface down to within 5 km of the top of the descending oceanic crust of the Juan de Fuca plate. It is reasonable to think of these faults as "backstops" for sediments scraped off the down-going plate and thus as likely fluid conduits. In support of this view is the recent interpretation of the "D" and "E" reflectors of the Vancouver Island LITHOPROBE survey as marking the presence of fluids, and perhaps a 450°C isothermal surface. Dramatic views of the surface expression of the Leech River Fault were shown. Its linear nature and associated broad zone of erosion are notable. Mylonitization occurs over a distance of up to 2.5 km and recent fluid movement in the fault, sometimes resulting in hot springs, has led to extensive deposition of Mg/Fe dolomite.

Nick Massey (BC Geological Survey Branch) described economic mineralization associated with major faults within the Wrangellian Terrane. These belong to the same overall crustal shortening system as the faults imaged on Vancouver Island, some of which, for example, the Tofino and West Coast Faults, are of current exploration interest. Typically, fault zones contain gold-bearing ferroan dolomite, or ankerite, and quartz. Mineralization postdates ductile shearing and predates the intrusion of quartz porphyries. With gold values of up to 8000 ppb, active exploration of fault zones is underway. Alteration, consisting of pervasive replacement by ankerite as well as discrete veins, often extends well into the country rock adjacent to faults.

Roy Hyndman (PGC) reviewed current ideas on the origin of the reflectivity of faults. This is probably only occasionally due to simple lithological contrast. Other candidate mechanisms are the presence of gouge and mylonite, the presence of fluids and their pore pressure, and, perhaps most commonly, the existence of a zone of fluid-induced wallrock alteration adjacent to a fault. This latter situation best satisfies the dual requirements of velocity contrast and sufficient effective thickness to be sensed by typical seismic wavelengths on the order of 100 m. Hyndman then described the importance of variation in pore aspect ratio in controlling reflectivity when fluids are present. Flattened pores, verging on cracks, are optimum for reflectivity and are probably important at the upper levels of faults. The review concluded with an appreciation of the value of work with synthetic seismograms and of the logging of drillholes to ground-truth models for the origin of fault reflectivity. In answer to a question, Hyndman agreed that electrical resistivity should also be of value in imaging faults but noted that the resolution of electrical methods has the disadvantage of rapid decrease with depth.

Bill Fyfe (U of Western Ontario, London, Ontario) pointed out that the importance of the release of and regular passage of large volumes of fluids through the crust had not been recognized until recently. The collision of India with Tibet, for example, must have released about 10^{18} tonnes of fluids. Another underestimated factor is the depths of up to 3-4 km at which biological activity may be important in these fluids. For the subduction of the Juan de Fuca Plate beneath Vancouver Island, subduction along a distance of about 500 km results in the release of about 4×10^{8} tonnes of fluids per year. The top of the descending slab is probably buffered by the dehydration of serpentine to produce much of this fluid, a substantial part of which is likely to return to the surface through faults, probably on a largely periodic basis. The examination by drilling of active faults in the area should have a wide range of objectives: in addition to study of the fault in the core recovered, and by downhole logging, a permanent fluid-sampling and geophysical-measurement package should be installed in the hole. Work in Japan and elsewhere suggests that fluid flow will be triggered by seismic events and the instrument package should be so designed that fluid sampling takes place automatically following an earthquake. The recovered fluids should be tested at least for volatiles, organics, salt and other inorganic ions, and ^{3}H and ^{10}B.

Ted Irving (PGC) proposed that advantage could be taken of the reduction or pseudomorphing of iron minerals associated with faults in the difficult problem of the direct dating of movement in older faults. Periods of extensive remagnetization, such as the Kiaman, might be correlated with periods of general major fluid flow through the crust. It was suggested that water from the worldwide melting ice sheets might result in such remagnetization and it was noted that Paleozoic rocks from the Sahara have a magnetic overprint dating from the recent pluvial phase.

Alan Beck (U of Western Ontario) viewed 50 years of heat flow measurements as moving toward the general recognition that local linearity in temperature gradient did not guarantee a conductive mode. Rather, widespread fluid motions provided the dominant control on many temperature profiles. The aim of temperature measurements in future drill holes might be directed to map temperature differences, flow rates and thermal properties, and changes in these with time, rather than to plan optimistically to obtain conductive heat flow. Faults would prove to be a difficult environment to characterize, several holes might be needed to do this.

Bruce Nesbitt (U of Alberta, Edmonton) then presented his proposal submitted to CCDP with Karlis Muehlenbachs and Philippe Erdmer, also of the University of Alberta. This proposal is also to investigate major Cordilleran faults by drilling, however, in this case, the faults of interest are on the mainland and are strike-slip in nature. The investigation of mineralization and its relation to fluid flow is a primary objective of the proposal. Extensive δD and $\delta^{18}O$ data show that mesothermal Au, Hg and Sb mineralization is associated with deep meteoric water circulation everywhere west of the Rocky Mountain Trench. It is only to the east of this feature that classic metamorphic fluid signatures are found. Modelling suggests that meteoric water flow penetrates the crust to depths of 10-15 km and that the return of heated fluids to shallow crustal levels is *via* strike-slip faults which appear to bottom at 8-12 km depth, in the same interval, probably in a transition from brittle to quasi-plastic deformation. Nesbitt noted that many economic deposits in the Cordillera were fault-related. However, adequate exposure or widespread exploration of thrust and extensional faults, respectively, focussed attention on the poorly exposed major strike-slip faults as targets for investigation by drilling. Three faults were suggested for potential targets, the Fraser Fault, the Pinchi Fault, with its Hg-Sb mineralization, and the active Denali Fault. As a result of expected deep contamination by surface waters, drilling would probably have to be to substantial depths, >>2 km, in order to sample fluids containing a significant fraction of heated, mineralized meteoric return flow.

The second day of the workshop began with a review by Simon Hanmer (GSC, Ottawa) of current knowledge of large-scale shear zones at depth in the crust. Such zones can occupy very large areas beneath the former brittle-ductile crustal transition (Sibson, 1977). For example, a 100×50 km triangular zone in the Shield, straddling the Alberta-Saskatchewan border, consists entirely of granulite and amphibolite facies mylonites and presumably represents the expression, within former ductile crustal levels, of a single major crustal break. Zones of this type can show evolution through time marked by uplift through the ductile-brittle transition during their formation. This is expressed by metamorphic zoning of the mylonites, with thinner zones of lower grade metamorphism succeeding more extensive, earlier, high-grade zones (Hanmer, 1988). At shallower levels, such major breaks show features of brittle failure, such as cataclastic zones and pseudotachylite veining. Hanmer considered that, at the present stage of investigation, surface studies were necessary to yield a proper appreciation of the features and history of these extensive belts of deformation. The sample provided by drill core was of much too small dimension to yield all the essential information.

Douglas Schmitt (Stanford U, Stanford, CA) described results from the DOSECC Cajon Pass drillhole. The hole was sited with the intention of providing information to resolve the so-called "Heat Flow Paradox" regarding the San Andreas Fault. This "paradox" describes the difficulty in resolving relatively low measured heat flow in the vicinity of the fault with estimates of heat generation by movement along the fault. A wide range of in-hole tests have been made; in contrast, coring was very limited. The principal conclusion to date is that the stress in the borehole and elsewhere in the vicinity is substantially different from expectations, normal faulting with an element of right lateral shear being favoured. These conclusions imply that either the San Andreas Fault is very weak or the Cleghorn Fault, located close to the drill-site, interferes with the regional stress field.

Sebastian Bell (GSC, Calgary) provided a very useful description of industry experience of drilling through faults in the sedimentary section of the Scotian and Jeanne d'Arc Basins. Features of note included deviation of the hole as the structural dip changed near the fault, change in the orientation and magnitude of the stress field, and the presence, in some instances, of overpressured zones beneath faults. In the case of the Alma-67 Hole, the changing stress field, monitored by breakout and leakoff tests down the 6.5 km hole, first favoured normal faulting, then strike-slip and finally thrusting. Bell suggested that standard oilfield methods could be used to monitor pore pressures, anticipate overpressured zones, and follow the change in other important properties in CCDP holes.

John Moore (Carleton U, Ottawa) spoke on two proposals to CCDP. The first, with Richard Brown and Randall Parrish, proposed to test by drilling a prominent reflector seen on Line 5 of the LITHOPROBE Cordilleran/Valhalla Complex Survey. This prominent E-W, relatively flat-lying, reflector has been shown through careful reprocessing to reach within 0.4 seconds of the surface before deepening again. The aim of drilling would be to test the proposed correlation of the reflector with the Gwillim Creek Shear Zone, outcropping 30 km to the north of the seismic line, to investigate the nature of the reflector and its age, and to test for the presence of North American basement rocks beneath the reflector.

The second proposal is to test both the possibly allochthonous nature of the Grenvillian Central Metasedimentary Belt of Central Ontario, and to determine the origin of a number of prominent geophysical anomalies where the Metasedimentary Belt lies under Paleozoic cover.

Alexander Colvine (Ontario Geological Survey, Toronto) described the setting of gold deposits within greenstone belts. Deposits are typically associated with major structures – ductile shear systems, but not with particular faults within such systems. The combination of ductile shearing and hydrothermal alteration is important. Such systems can extend over very considerable vertical distances. During the lifetime of such a system the brittle-ductile transition can change depth several times leading to repeated opportunities for the local development of dilational conditions, with the potential for the flow of hydrothermal fluids and consequent mineralization. Drilling can be useful in testing this model (Colvine *et al.*, 1988) for the large-scale tectonic settings for gold deposition. CCDP operations should look beyond the immediate commercial need of locating economic gold mineralization. In terms of possible targets, the Abitibi Belt should be looked at seriously. It has the advantages of scale, preservation, several LITHOPROBE seismic lines, and the $100 billion worth of gold and base metals that have been produced to date from the Belt. In addition to opportunities to investigate the nature and depth extent of ductile shear systems, research drilling in the Abitibi Belt could also be directed at identifying the nature of the reflectors that appear to mark the base of the Belt and the Blake River–Kinojévis tectonic contact.

James Monger (GSC, Vancouver) reported on his recent visit to the Soviet deep drilling operation at Yaroslawl and on discussions in the Soviet Union and Europe regarding the proposed "Globus" and "Europrobe" combined super-deep drilling and deep-seismic projects, respectively.

Jeffrey Warner (Chevron Oil Field Research Company, La Habra, CA) described his work on the sealing properties of faults within sediment sections. While the faults he is concerned with are usually on a much smaller scale than many of the major crustal breaks considered at the workshop, the relatively low effective permeability across faults when compared with efficiency of flow along them may apply generally.

Extended discussion sessions were held at the end of the formal presentation of papers on both days of the workshop. Vigorous, wide-ranging discussions took place during which much information and many ideas on the value of investigating fault systems by drilling were considered. While it is difficult to list all of the points made, a reasonable summary would be that there are several different justifications for examining faults by drilling: to measure fluid flow and related phenomena in active tectonic areas or to test models, particularly those based on seismic profiles, for example, in the Kapuskasing or Grenville Front areas. A unifying theme could be that investigations in the active or young systems of the Cordillera would help to understand the older systems of the Shield. It also becomes clear from the discussions that interest in the investigation by drilling of fault systems has led to a focussing on important, but only partly known, properties of such systems. For example, before a hole could be sited to study a young, possibly active, fault on Vancouver Island, there is a need to demonstrate that the fluids sampled would have a component that originated from the subducting plate. This led to consideration of what kinds of preliminary or site surveys would be necessary before drill sites could be located with a fair probability of objectives being met.

Discussion on the second day concluded with the adoption of several statements and recommendations regarding the potential value of the study of fault systems by drilling, and the direction that the community and the Steering Committee of CCDP might take in promoting this kind of activity. It was agreed that the drilling of carefully selected fault structures offers the opportunity to make significant contributions toward answering questions of current international interest and toward understanding the geology of Canada. The drilling of fault structures has the potential to provide information of several important kinds:

- to provide the opportunity to test large-scale structural models based on deep seismic reflection seismics and other geological and geophysical techniques.
- to make a substantial contribution to the knowledge of the expected major circulation of fluids in the lithosphere, particularly in the environment of active collision zones.
- to add to knowledge of the seismicity of active collision zones and to monitor motions and motion-related phenomena on selected faults in the collisional environment.
- to provide the opportunity to obtain important information on the means of formation of several types of economic mineralization, particularly fault-related gold, mercury and antimony deposits, believed to be deposited from circulating fluids.

Participants at the workshop strongly recommended that the Steering Committee of CCDP make every effort to include in its program the study by drilling of key fault structures in Canada. These efforts should include the identification of optimum drill sites to address the range of fault-related questions through the co-ordination of the activities of various interest groups, of appropriate preparatory surveys and, after site selection, of drilling and subsequent scientific operations.

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