Construction of stress analysis models of the earth's crust requires definition of boundary and initial conditions. These include: stress field, rock mass properties, fault strength and geometry, and boundary stress or displacement constraints. By comparing model behaviour to observations, the mechanical compatibility of various geological hypotheses can be tested. Our work focuses on assessing the stability of major structures in southern Ontario with the objective of providing input to the assessment of seismic risk. Analysis of triaxial stress data from the nearby Sudbury Structure shows a linear relationship between the major and minor principal stress magnitudes, suggestive of a strength limited state of stress. The computed Mohr-Coulomb strength parameters ($c = 5.4$ MPa, $\phi = 14^{\circ}$) are relatively low, with the frictional component indicative of a clay or gouge material. This suggests that the strength of the upper brittle crust in that region is limited by the strength of major faults. It also indicates that the crust is likely at a state of limiting equilibrium so that a small increase in stress may exceed the effective strength of the crust and induce seismicity. The same apparent strength was obtained from a large set of triaxial stress measurements at similar shallow depths (< 2 km), but from a mine in the Chilean Andes. This indicates that the upper brittle crust may evolve to a common state of low strength limited by the strength of accumulated gouge in faults. The similarity between the stress data at the two different locations suggests that other areas in a compressive tectonic stress regime (such as southern Ontario where triaxial stress measurements aren't available) may also be in a state of limiting equilibrium. Evidence of stress rotations in southern Ontario from the general orientation of the stress field with respect to the major structural features (thrust faults, accreted terranes etc.) would support this hypothesis. In addition to near surface stress measurements, the orientation of stresses in the deeper ductile crust may be inferred from shear-wave splitting data. Variations in direction of these inferred deep stresses with the near surface stress field may give some indication of the amount of rotation due to fault slip, and possibly seismicity, that occurred during the evolution of the stress field. The significance of the stress data and the potential for the brittle crust in southern Ontario being in a limiting state of equilibrium with tectonic driving forces, is that seismicity in such a system will differ significantly from one in which faults do not limit the state of stress. Numerical modelling will be used to test these ideas.

S31A CC: 516 A Wednesday 0830h

POLARIS: Electromagnetic Methods and Results *(joint with GP, SA, T, SEDI)*

Presiding: **I Ferguson,** University of Manitoba**; C Samson,** Carleton University

S31A-01 0830h INVITED

Transformation of MT Resistivity Sections into Geologically Meaningful Images

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Earthscope offers an unprecedented opportunity for interdisciplinary studies of North America. In addition to a continent-wide seismic study, it includes the acquisition of magnetotelluric (MT) data at many of the Bigfoot array sites. Earthscope will thus provide a uniform 3-D MT survey over regional scales when completed. MT interpreters will be able to include 3-D regional effects in their models for the first time whether they are interpreting local studies. However, the full value of the interdisciplinary nature of Earthscope will be realized only if MT sections and maps are useful to other earth scientists. The standard final product from any 2-D or 3-D MT interpretation is a spatial distribution of electrical resistivity. Inference of the physicochemical state from bulk resistivity is complicated because a variety of factors influence the property including temperature, intrinsic conduction of silicates, and small amounts of interconnected conducting materials (e.g., graphite, metallic minerals, partial melt, fluid). Here, I use petrophysical measurements and a petrological model to transform a resistivity section into cross sections of temperature and partial melt fraction in the mantle beneath the Sierra Nevada. In this manner, I am able to separate the contributions of increasing temperature and melt fraction to the bulk resistivity. Predicted melt fractions match observations from xenoliths relatively well but temperatures are systematically 200C higher than those observed. A small amount of dissolved hydrogen (70 ppm H/Si) lowers the predicted temperatures to match those from the xenoliths, however. I conclude that while this transformation is a simple first step based on many assumptions, initial results are promising.

S31A-02 0855h

POLARIS Magnetotelluric Overview and Update - Spring 2004

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The Canadian POLARIS project includes an important component of electromagnetic studies. As part of this project, magnetotelluric (MT) equipment has been acquired to develop an infrastructure for electromagnetic soundings over depths ranging from the uppermost crust to depths of several hundreds kilometers into the asthenosphere. A key innovative feature of the POLARIS project is that MT instruments are being used in association with teleseismic techniques for imaging the Earth's structure, and for investigating seismogenic structures. MT soundings are in progress and, at the end of the project, will have been made at most of the 90 POLARIS observatory arrays on the Slave craton in the Northwest Territories, in the Casacadia region of southwestern British Columbia, and in the Precambrian Grenville Province in southern Ontario. MT equipment is also being used in studies of geomagnetically induced currents (GICs) on powerlines and pipelines. To carry out soundings at different target depths, the POLARIS MT equipment includes: audio-frequency (10^4 to 10 Hz) MT (AMT) systems for imaging the upper crust; broadband (10^2 to 10^{-3} Hz) MT (BBMT) systems for imaging the middle and lower crust; and long-period (1 to $<10^{-4}$ Hz) MT (LMT) systems with specialized ring-core fluxgate magnetometers required for imaging at mantle depths and for geomagnetic hazard studies. More specifically, the AMT-BBMT equipment consists of six MTU-5A systems that have been procured from Phoenix Geophysics Ltd. and the LMT equipment of twenty-five ring-core NIMS systems on order from Narod Geophysics Ltd. A subset of the POLARIS MT equipment consisting of the AMT, BBMT, and fifteen of the LMT instruments is designed to be moved progressively through the POLARIS arrays providing MT responses over a broad frequency range. The remaining ten LMT instruments are to be deployed at carefully selected POLARIS sites in satellite-telemetered observatory configuration to provide ultra-deep imaging of the mantle and monitoring of temporal conductivity variations. POLARIS MT soundings have been completed using both the new equipment and alternative LMT systems. In 2002, LMT soundings were done at eleven sites on the Southern Ontario array. In 2003, LMT soundings were done at 40 sites on and adjacent to the Cascadia array and a four-station GIC survey was done in the Ottawa River Valley, Ontario. Field-work planned for 2004 includes: the deployment of MT telemetered observatories and the acquisition of AMT-BBMT data in the Slave craton; AMT-BBMT soundings on the Southern Ontario array; and deployment of MT observatories on the Southern Ontario and Cascadia arrays.

S31A-03 0910h

Deep electrical conductivity structure of the Cascadia subduction zone in Southern British Columbia

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Long period magnetotelluric (MT) measurements were made in southwestern British Columbia in 2003 to investigate the electrical structure of the Cascadia subduction zone as part of the POLARIS project. Data were recorded in the period range 1 to 25000 seconds at 36 field sites using long-period MT systems with fluxgate magnetometers.
The instruments used were the Geological Survey of Canada LIMS systems and University of Alberta NIMS systems. MT data were collected at many locations in the Canadian Cordillera during the Lithoprobe project, but the new MT data are the first to give the long period data needed for imaging deep structure. The stations were concentrated on a profile that extended from Port Renfrew on Vancouver Island to Shuswap Lake. Some MT stations were located in Washington State to investigate the 3-D effects of the low resistivity salt water in the Strait of Georgia and Puget Sound.
The MT impedance data have been analyzed with 2-D inversions and the models reveal the following features:
(1) The data on Vancouver Island detect low resistivities above the subducting Juan de Fuca plate, similar to previous results on a profile to the northwest. This anomaly corresponds to an area of high seismic reflectivity ('E-reflector') and low seismicity, and may be related to fluids originating from the oceanic plate.
(2) A zone of low resistivity is present beneath the volcanic arc at a depth of 15-20 km below the surface.
(3) The Intermontane and Omineca Belts are characterized by high resistivities in the upper crust and low resistivity in the lower crust, similar to models of previous studies such as Lithoprobe. The lower crustal resistivity decreases to the east, as also indicated by vertical magnetic transfer functions. Further analysis of these data are in progress to determine the resistivity of the underlying upper mantle and to evaluate the depth of the astenosphere.
A second deployment of the NIMS instruments in summer 2004 will extend the line across the Rocky Mountains into the Foothills of Alberta, and will produce a continuous long-period MT profile across the entire Canadian Cordillera.

S31A-04 0925h

Telluric currents in pipelines

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Inductive coupling of the varying geomagnetic field to pipelines produce low-frequency ac-currents which can affect their operation. The presented approach to the mathematical modeling of the geomagnetically induced (telluric) currents in pipelines was as follows. First is to evaluate the induction effect in general. This has been done by application of Maxwell's equations to model induction in the infinitely long multilayered cylinder under plane electromagnetic wave excitation. Important results were obtained by calculating the transfer function relating the total electric current in the steel to the non-disturbed (in the absence of the cylinder) electric field. It is shown that this function depends on the frequency as well as on the electromagnetic properties and sizes of the multilayered cylinder. However, it is constant for most of the geomagnetic frequency range (0.01 mHz to 80 mHz) and the typical values of the pipeline electromagnetic properties and size. Hence, for the geomagnetic frequency range one can expect that when the non-disturbed electric field in time-domain is known, induced currents can be calculated in the time-domain by applying a constant scaling factor. Next step is to provide the non-disturbed electric field. Using the same plane wave assumption and layered earth conductivity model, the geomagnetic field was converted to the geoelectric field. The frequency response here shows more power at high frequencies and cannot be approximated by a constant. The last step in the evaluation of the modeling is comparison with pipe-to-soil potential variations (PSP)produced by telluric currents on a few pipelines. Comparisons show that linear correlation coefficients vary from 0.6 to 0.9, depending on the distance from the pipeline recording site to location of the geomagnetic observatory. These correlations confirm the similarity of the frequency content of PSP fluctuations to the electric field variations. For the modeling of the amplitude changes in PSP along the pipeline, distributed source transmission line model can be applied with a spatially non-uniform electric field as an input. The non-uniform electric field can be found by further detailed 2-d modeling of the earth ground conductivity along the pipeline route, which is the subject of further investigations.

S31A-05 0940h

Acquisition of Magnetotelluric Data for Studies of Pipe-to-Soil Potentials on Pipelines: Preliminary Results From the 2003 Ottawa River Valley Survey

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A long-term study has been initiated as part of the POLARIS project to investigate the effect of Earth resistivity on pipe-to-soil potentials (PSPs) on pipelines. The pipeline chosen for investigation is a natural gas pipeline extending from the Alberta/Saskatchewan border to Quebec and Vermont. A previous study of this pipeline revealed large PSPs variations near the contact of the Precambrian Shield and Paleozoic sedimentary rocks of the Ottawa Embayment in eastern Ontario. The POLARIS Ottawa River Valley Survey was done in October 2003 to investigate the PSPs. Objectives included: (1) magnetotelluric (MT) soundings to define the sub-surface resistivity structure; (2) simultaneous recording of MT and PSP time-series; and (3) field-testing MT instruments acquired for the POLARIS project. Remote-referenced MT soundings were made at four sites spaced 25 km apart along a NNW-SSE line parallel to the pipeline and perpendicular to the geological contact. Recordings were made using audiofrequency and broad-band equipment allowing the MT impedance to be defined between 10,000 Hz and 0.001 Hz and providing continuous electric and magnetic field time series with 15 Hz sampling frequency for time segments of up to 12 hours duration. During the MT survey, the pipeline was instrumented with 5 dataloggers measuring PSPs at a sampling rate of 1 Hz. This survey may be the first one in which simultaneous and co-located MT and PSP recordings have been made. The MT responses sampled the Earth resistivity at depths ranging from tens of metres to tens of kilometres. The results reveal that the most conductive responses occur at site ORV003, at the margin of the Paleozoic sedimentary rocks. However, the enhanced conductivity at this site is not caused by the Paleozoic rocks. Modelling of the data from ORV003 indicates a contribution to the response from a 30 m thick, conductive (2 ohm.m) surface layer of glaciomarine and marine silt and clay sediments and also a contribution from conductive rocks of the Precambrian basement at depths exceeding 5 km. The next step in quantifying PSP fluctuations consists of combining electric field data with a model of the pipeline based on a distributed-source transmission line model. The PSP modeling results will be further refined using the 2-D resistivity model defined by the MT data.

S32A CC: 516 A Wednesday 1030h

Advances in Seismic Event Location and Source Characterization

Presiding: **D McCormack,** Geological Survey of Canada**; K Chun,** University of Toronto

S32A-01 1035h INVITED

Prospects for Widespread Implementation of Better Methods for Source Location

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Many seismologists are becoming more familiar with techniques for estimating source locations that improve very significantly upon the standard procedure of locating events one-at-a-time from phase pick data. As the new techniques (reducing model error by use of multi-event location algorithms, and reducing pick error by use of waveform cross-correlation) become more prevalent, assessments are needed of (a) what practical steps can be taken to facilitate the new methods, and (b) what fraction of seismicity in a given region can foreseeably be better located with new procedures. We comment upon (a) and (b) in light of several studies already completed or still underway in East Asia and North America. Of great importance for (a), is attention to operating stations continuously for long periods of time (decades) without change and maintaining easily accessible waveform archives. Systematic efforts to obtain reference events are necessary to convert high quality relative locations to absolute locations. As for (b), there are large regions for which most of the routinely detected and located events can be relocated by the new techniques, to substantially improve source locations in existing catalogs, and additionally for events soon after they occur.

S32A-02 1050h INVITED

Remarks on Several Non-standard Location Methods

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In this study, several non-standard location procedures are reviewed, contrasted, and compared. Though independently developed, two methods among those been tested, the "Induced Perpendicular Bisector" [IPB] (or,equivalently, the "Yin Zhong Zian" [YZX] in Chinese) method and Jih's (PEPI, 1999) "J0" method, appear to be extremely similar in concept. For several decades, i.e., since before the advent of digital computers, Asian seismic network operators have been locating earthquakes by triangulation using the IPB technique. In the ideal case where two seismographs happen to report identical arrival times of the same seismic phase, then under the assumption of a uniform earth structure, the hypocenter should lie on the perpendicular bisector of the line segment (great circle) which connects these two specific seismographs. Depending on the epicentral distances, the perpendicular bisector itself could be a great circle along the Earth's surface or a normal section cutting through the Earth. If two or more such perpendicular bisectors are available, then the hypocenter or epicenter can be determined via triangulation. The challenge lies in how the perpendicular bisector is derived for the more general situation when arrival times vary from station to station, which is more typically the case. An advantage of the technique is that it can be used when waveform data are not available, thus rendering techniques based on full waveforms (such as correlation analysis, polarization analysis and frequency-wavenumber [FK] technique) not applicable. The so-called YZX algorithm, is a variation of IPB procedure, in which one computes an IPB (via interpolation) for each group of three seismographs. Also relying on azimuth triangulation for seismic location, Jih (1999) proposed a procedure J0 to derive the backazimuth with a large aperture network where all seismographs are on one side of the event. Any standard Geiger-type of least-squares inversion routine can be applied to determine the backazimuth easily. Two or more such skew networks would suffice to derive two backazimuths for triangulation purpose. It has been demonstrated that this simple, hybrid procedure is particularly suitable for the seismic location problem at regional distances when [1] the crustal model is not known, [2] the seismic network is not calibrated, and [3] the azimuthal coverage of recording stations is poor. In this paper the procedure J0 is compared against the YZX method, to relocate earthquakes and explosions of known or well-constrained locations. It is shown that, at regional distances, the J0 algorithm outperforms the YZX method, simply because the backazimuths used by J0 method are more reliable and stable. On the other hand, the YZX method provides very intuitive insight into the uncertainty ellipse, which neither J0 nor the standard least-squares based Geiger inversion offers. The old Watatsu formula, which determines the origin time by regressing the Pg arrival times on the Lg-Pg differential arrivals, turns out to be very robust in improving the location and stablizing the Geiger inversion procedure at local and regional distances - especially when most or all the stations persistently, faithfully report both Pg and Lg phases. Data from the Montenegro Network provide an excellent basis for comparison of the techniques.

S32A-03 1105h

Detection of Energy Emission by Micro-events Below the Detection Threshold

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Conventional practice in the detection, location, and characterization of small local events entails the use of single-channel arrival detection, the association of multiple-station detections, and the location and characterization of each event, based on these associated arrivals. At smaller magnitudes, arrivals are lost in the noise, and insufficient detections are obtained to identify and locate an event. Thus each network has a magnitude below which only a small fraction of events are detected and catalogued. Two strategies are available for lowering this network threshold. [1] Single-instrument (1 or 3 channels) data processing to lower the single-instrument detection threshold; [2] All-station processing, to utilize the multichannel time series. We show numerical experiments in which migration-stacking of data flow from the Anza network is used to create subsurface 3-d images of seismic emission. Any experiment involves a specified time window. When the window is a few seconds, the experiment is scanning for individual events... thus looking at events which are just below the usual detection threshold. Windows of minutes to hours can be used, and the stacking generalized to entail stacking over such windows. Thus, detection of the emission of seismic energy by large numbers of micro-events is achieved by this time averaging. A reliable velocity model of the subsurface is required, as with conventional event detection. Implementation involves a variety of discretionary analysis options for noise balancing, bandpass selection, and stacking. It represents a fruitful area for exploratory data analysis. Following studies by Archambeau, we have detected emission from a pre-event time window, from the location of a well-detected m1.5 event. The seismic energy studied represents a portion of the noise window with partial coherence across the network. We conjecture that this represents in effect a proxy monitor of creep in the tectonically active subsurface.

S32A-04 1120h

A Maximum Likelihood Perspective on the Influence of Data Correlations and the Precision of Event Locations

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The objective of earthquake location is to find the earthquake's focus with the greatest probability of being correct. Specifically, one should find the maximum in the joint probability distribution of the data, d, and location parameters, m, given equations, G, relating m to d, $P(d, m|G)$. Inverse theory proves that if the data have a Gaussian error distribution and are weighted by the inverse of the data covariance matrix, then the focus found is the maximum likelihood solution. Successive application of Bayes theorem gives $P(d, m|G) = P(G|m, d)P(d, m) = P(G|d, m)P(d|m)P(m) = P(G|d, m)P(d)P(m)$ when the probability distribution of the arrival times are independent of the location. The first term includes, for example, the probability distribution for the velocity, a factor rarely included in conventional locations. The third term is the a priori distribution for the location. The second component is the significant part. Arrival times are correlated when stations are close or, equivalently, when the travel paths of phases are similar. For correlated phases, $P(d) = P(d1|d2, d3, -)P(d2, d3, -)$ etc., where $d = (d1, d2, d3, -)$. For example, the probability distribution for an S and P phase at one station should be highly correlated, giving a narrowly defined $P(P|S)P(S)$, or $P(S|P)P(P)$ and consequently a significantly more precise location. In conventional location equations, this is equivalent to properly including the off diagonal elements in the weighting matrix, Cov(d). SVD inversion of Cov(d) from a pair of P and S phases is equivalent to reformulating the location phases as an S-P phase and an S+P phase. A similar analysis for JHD, where the correlation among arrivals is directly related to the separation of the events, shows how maximum likelihood formulation provides the locations with a more accurate assessment of location precision.

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