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Q for Eastern North American Lg is a DECREASING Function of Frequency: Contamination by Sn is to Blame for the Increasing Function Most Researchers Have Found.

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Most researchers working on S-wave attenuation in eastern North America have derived frequency-dependent models like $Q = 700f^{0.35}$ when $R^{1/2}$ is assumed for far-field (D > 200 km) geometric spreading. Such Q models are important because they are applied to correct close-in data to derive source properties (e.g. for spectral shape) and used to modify the strong ground motion relations needed for hazard in the distance range 50-200 km. We find that a significant mistake has been made, and that the correct Q for Lg along most, if not all, paths FALLS from >2000 at 1 Hz to <1400 at 15 Hz, i.e. is a DECREASING function of frequency, contrary to most published results. Previous results were severely contaminated by Sn, which dominates the S-wave train for high frequencies and large distances.

We assert: For large distances and high frequencies, the S-wave energy in the Lg-wave window is almost entirely derived from Sn. The observed Q for Sn behaves as an increasing function of frequency in a manner similar to that derived (and mis-applied to Lg) by previous authors. All Sn energy is originally derived from leakage of Lg, so not only must the effective Q's for Sn and Lg differ greatly, but they must behave in entirely different ways as functions of frequency. The actual Q in the upper mantle is uncertain, because the observed Q represents a Q-related diminution PLUS a frequency-dependent enhancement by progressive leakage from Lg (and at its expense) as distance increases. The hazard implications will be discussed.

Contemporary Seismic Hazard from Reactivation of Faults of the Canadian Shield—Which Faults will Rupture, and Does It Matter?

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Exposed continental shields are cut by numerous Precambrian faults which might be reactivated during M>6 earthquakes tomorrow. A deterministic hazard analysis requires identifying both the recently reactivated faults (say, age <1 Ma; to distinguish which faults have moved and how often), and the faults that may rupture "soon" (say, next 10 ka). This is difficult, since: 1) faults as short as 5 km can cause damaging earthquakes; 2) no "active" fault in the shield of northern Ontario has yet been identified; and 3) even if all the "active" surface faults were identified, the problem of unexposed faults at depth remains, and 4) an "inactive" fault might rupture instead. Thus we consider hazard-elimination schemes that "identify and avoid the active faults" to be dubious.

To estimate low-probability seismic hazard for northern Ontario we use its short 50-year seismicity record together with the average rate of 0.004 p.a. for M>6 earthquakes per 10^6 km^2 derived from analogous shields worldwide. About 20–40 M>6 earthquakes might have occurred in Ontario since deglaciation (10-14 ka); perhaps 5–20 (dependent on assumptions) would have a surface rupture, and so an example might soon be discovered and confirmed in Ontario. ("Neotectonic" faulting with "seismotectonic implications for metropolitan Toronto and the nearby nuclear facilities" has been claimed (Geology, v20 p1006), but not confirmed.) However, unless geologists can identify the majority of future-active seismogenic faults, emphasizing the few known sources misdirects attention from the many unknown sources. Instead of relying on incomplete or chance discoveries, robust hazard estimates should be made probabilistically using available seismological/geological information. Such conclusions would not automatically require adjustment should a reactivated fault be found nearby.

"The Earthquake Cycle"—Anticipating, Capturing, Responding to, and Learning from Significant Earthquakes

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From the seismologist's perspective, one way to look at the earthquake cycle is described in the title. For each region of the country, we are learning what we can from small earthquakes, interpreting them as well as possible in terms of seismic hazards, and ensuring that building codes reflect this understanding. In regions where we anticipate large earthquakes, modern seismographs are in place, field teams are ready, and emergency and media contacts are identified. When the earthquake occurs, there is capture of the data, preliminary analysis, and rapid notification to emergency services; aftershock and geological field teams are deployed; seismologists in the field are providing a media presence and assisting to alleviate local psychological trauma; and a thorough understanding for the earthquake is being gained. Back in the office afterwards, new hypotheses are formulated to explain this significant earthquake; models for seismic hazard assessment are revised; and we learn from all aspects of the earthquake cycle that has just been experienced in order to respond better to the next significant event.

The Hamilton-Burlington Fault at the Western End of Lake Ontario

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The Southern Ontario Seismic Network (SOSN) consists of 6 three-component short period stations located mainly in the Toronto-Hamilton-Niagara area of Ontario, Canada. The network is operated by the University of Western Ontario for Ontario Hydro and has been in operation since 1991. Over the past 6 years over 50 local small earthquakes (magnitudes 1.0-3.5) have been detected by this network with a location precision of ±2 km. An examination of the seismicity map shows that a definite pattern of events is now beginning to emerge. Most of these are scattered about mainly along the southwestern part of Lake Ontario and New York State east of Niagara Falls. There does, however, appear to be a line-up of 11 events starting just south of Hamilton Ontario and extending about 25 km to the NE. This possible relatively active earthquake fault may align with the regional crustal structure as determined from past Lake Ontario seismic reflection surveys. The origin of the fault is still not known. If the events are very shallow, they may be related to the movements of fluids in the sedimentary layers. If the foci are deeper within the rocks of the Canadian Shield, they may have a more significant tectonic origin and may be related to regional stresses.

Regional Seismograms from Historical Earthquakes in Southeastern Canada

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Regional seismograms from four historical earthquakes of M 5.8 to 7.2 that occurred in southeastern Canada in the first half of this century were digitized. Instrument-corrected Fourier spectra of the shear-wave portion of the signal were computed, for the frequency range from approximately 0.05 to 2 Hz. These spectra were corrected for the effects of regional attenuation to obtain apparent source spectra for each of the four events. The apparent source spectra for all events strongly support the empirical source model of Atkinson (1993), and show that the Brune point-source model, as applied in most eastern ground motion prediction relations, grossly overpredicts intermediate-frequency spectral amplitudes.

Evaluation of Models for Earthquake Source Spectra in Eastern North America

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There have been several relations proposed in the last few years to describe the amplitudes of ground motion in eastern North America (ENA). These relations differ significantly in their assumptions concerning the amplitude and shape of the spectrum of energy radiated from the earthquake source. In this paper we compare ground motions predicted for these source models against the sparse ENA ground motion database. The source models evaluated include the two-corner models of Boatwright and Choy (1992), Atkinson (1993), Haddon (1996), and Joyner (1997), and the one-corner model of Brune (as independently implemented by Frankel *et al.* (1996) and by Toro *et al.* (1997)). The database includes data from eight ENA mainshocks of M>4 and four historical ENA earthquakes of M>5.5, for a total of 117 records, all recorded on rock. We conclude that all of the proposed ENA source spectral models overpredict the observed motions at long periods (>2 seconds). At short-to-intermediate periods (0.1 to 2 seconds) the Atkinson source model, as implemented by Atkinson and Boore (1995), provides the least-biased predictions, overpredicting ground motions by 10% to 30%. The Joyner source model also provides relatively unbiased predictions within the period range from 0.1 to 2 sec. The Frankel *et al.* and Toro *et al.* relations overpredict the motions by less than 40% for periods of 0.1 to 0.2 sec and by 70% to 300% for periods of 0.5 to 2 sec. The Haddon model overpredicts the recorded ground motions for all periods by more than 100%. The Boatwright and Choy source model underpredicts amplitudes for T < 0.5 sec, while overpredicting longer period amplitudes. In summary, most recent ENA ground motion relations significantly overpredict the amplitudes of the existing ENA ground motion database at long periods. The Atkinson and Boore (1995) relations are consistent with the database for periods <= 2 seconds.

Comparisons of Signal and Noise Characteristics of Broad-Band Sensors Recording at Palisades, NY

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Sensors at Lamont's PASSCAL Instrument Center are routinely tested by continuously recording for 3-7 days in the Palisades, NY vault along with a Streckeisen STS-2 "reference" seismometer on a concrete pier built on bedrock. Using the test data, we compare noise levels and signal characteristics of several broadband sensors: CMG-40T, CMG-3ESP (both with natural period at 30 seconds), CMG-3T, and STS-2 (both with natural period at 120 seconds). These comparisons will supplement information about bandwidth and noise performance provided by manufacturers' specifications and can provide additional guidance for selection of sensors: e.g. designing experiments with PASSCAL portable instrumentation or planning regional and national network changes.

Large teleseisms are precisely recorded by all three of the Guralp (CMG series) sensors, when compared to the STS-2 reference. Smaller, more distant teleseisms are well-recorded by all but the noisiest of the CMG-40T sensors. Not surprisingly, the least expensive of the broad-band sensors, the CMG-40T, has the highest levels of instrument noise; because of increasing interest in this sensor for regional networks, we focus on it in this paper. At a site with low levels of ambient background noise, the CMG-40T noise levels exceed background noise except for the period range from about 1 to 7 seconds, the bandwith of peak microseism energy. At Palisades, where cultural noise (>1 Hz) levels are relatively high, the CMG-40Ts record background noise in the bandwidth from around 7 seconds out to ~5 Hz. We are currently examining the CMG-40T data to measure the range of instrument noise, and by using teleseismic and local signals evaluate instrument performance.

A New "Robust" Seismic Hazard Assessment for Canada

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For production of the fourth generation seismic hazard maps of Canada, earthquake sources are defined for two complete source zone models covering the entire country, one which is biased toward clusters of historical seismicity, and one which is biased toward geological controls of source boundaries. A deterministic Cascadia subduction earthquake (a repeat of 1700 AD) is added to the southwestern Canada models. The mapped hazard is the greater of the values determined from these three sources: a "robust" approach to hazard mapping that has found approval in the Canadian engineering community. A comparison of the hazard in major cities west and east, for both peak acceleration and spectral accelaration at 0.2 seconds, shows the hazard in the Vancouver region to be similar to the hazard in the Montreal region. For spectral accelerations in the 0.5 to 1.0 second range, the hazard in Vancouver is a factor of two to three higher. The Cascadia earthquake dominates the 5% damped spectral hazard only along the coast of Vancouver Island.

Another Moderate Earthquake Near Ste-Agathe-des- Monts, Quebec: 24 May 1997

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On 24 May 1997 a moderate earthquake (m_{bL_g} 4.3) occurred near Ste- Agathe-des-Monts, Quebec approximately 20 km to the southeast of the epicenter of a magnitude 4.4 earthquake that occurred on 14 March 1996. Both earthquakes were felt in the Laurentians and the Ottawa-Montreal region. An oblique-thrust mechanism was determined for the 1997 earthquake from P and S first motions recorded by eastern Canadian seismograph stations. Although this mechanism differs in detail from that determined for the 14 March 1996 earthquake, both are typical of western Quebec earthquakes in that one of the nodal planes implies primarily thrust faulting on a northwest striking plane. The P axis is consistent with the regional stress field which is dominated by northeast-southwest compression. A portable instrument was deployed near the epicenter on 25 May 1997 and operated until 6 June. It recorded several local blasts but no aftershocks. Nor, to date, have any aftershocks been recorded by the permanent network. The mainshock triggered a digital strong-motion instrument operated by Hydro-Québec at Grand-Brûlé located 40 km from the epicenter. The maximum vertical acceleration was 0.021 g. Peak horizontal accelerations were 0.017 g (radial) and 0.010 g (tangential). These values are smaller than but proportionally similar to those recorded during the 1996 event, which was closer to the station.

Re-Evaluation of Source Parameters of Large Historical Earthquakes in Eastern Canada Using Modern Waveform Analysis Techniques

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In terms of seismic hazard, the few largest earthquakes in any region are usually the most important. In most eastern North American seismic zones, the largest earthquakes occurred prior to the 1960s when standardized data sets became more readily available and prior to the development of modern waveform analysis techniques. Thus, often little has been known about the most important earthquakes for hazard assessment. However, by applying modern methods to historical seismograms, much can be learned about these earthquakes. The re-analysis of five earthquakes will be discussed: 1925 Charlevoix (Mw 6.2), 1929 Grand Banks (Mw 7.1), 1933 Baffin Bay (Mw 7.3), 1935 Timiskaming (Mw 6.1) and 1944 Cornwall-Massena (Mw 5.8). The Timiskaming and Cornwall-Massena earthquakes are typical of earthquakes in the western Quebec seismic zone in that they have northwest striking thrust mechanisms and occurred at mid-crustal depths. The mechanism of the Charlevoix earthquake (northeast striking thrust faulting) is similar to that of many smaller, recent earthquakes in the region, but analysis of a large data set shows that the earthquake was smaller than previously believed. The Baffin Bay and Grand Banks earthquakes have primarily strike-slip mechanisms although both occurred in regions believed to be dominated by thrust faulting. Additionally, there is sufficient evidence to show that the Grand Banks earthquake was, in fact, an earthquake and not a landslide as had been hypothesized.

Shear-Wave Velocity Survey of Seismographic Sites in Eastern Canada

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Reliable information concerning the predominant site effects on ground motions can be obtained from low-cost shear-wave refraction surveys using a sledgehammer as an energy source. For the south and south-east Ontario region, the velocity structure can be determined to a depth oapproximately 70 m. Near-surface shear-wave velocities of hard-rock sites range from 1.7 to 3.1 km/sec, with an average value of approximately 2.6 km/sec. Typical soil sites have shear-wave velocities of 250-700 m/sec near the surface.

Empirical methods of determining the relative values of frequency-dependent amplification are commonly employed.These methods fit the observed earthquake spectra with a regression model that decomposes the recorded spectrum into source, path, and site terms. By regression analysis of large amounts of recorded data, the average site term for a particular station can be determined. We calibrated such an empirical technique against the theoretical responses based on the velocity structure obtained from a field survey. The empirical-regression approach and the theoretical-response approach provide reasonably consistent estimates of amplification at hard-rock sites. We conclude that the amplification for an average hard-rock site is about a factor of 1.3. At soil sites, empirical-analysis and theoretical-response results agree as to the frequency of the fundamental resonance peaks. The maximum theoretical amplification values generally exceed those indicated from the empirical analyses; theoretical amplifications by as much as factors of 6 and 7 were calculated, while empirical amplifications were below a factor of 3. Thus use of theoretical site responses may be conservative.

Global and Regional Seismicity, Long-Term and Short-Term Prediction

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Long-term prediction is based on the detection of the global component of seismicity, on the harmonic approximation and the extrapolation of the series of seismicity (S) and the series of the non-uniformities of the daily rotation of the Earth which are characterized by changes in the angular velocity of rotation (R).

These processes (1891–1985) have had almost the same harmonic components: S—63, 58, 31, 22, 17, 13, 7y, R—60, 34, 23, 19, 15, 11, 7 years. The correlation (–r) of seismicity (m ≥ 7.0) with the speeds of rotation (v) for the intervals averaging T_j years are given below:

T_j, y	1	3	5	7	9	11
v	0.42	0.57	0.62	0.66	0.68	0.70

One must expect insignificant activation of strong earthquakes (m ≥ 7.0) in 2005–2008, and also earthquakes (m < 7.0) in 1985–1991, 1999–2003, and in 2013–2017. The forecast can be checked on the data for 1985–1991.

Short-term regional and local prediction is based on the theory of brittle destruction and require the space-time monitoring of seismic signals related with the tidal influences of celestial bodies and the terrestrial preface stress-strain processes and foreshocks.

There is an equation for the first impulse of the growth of a critical crack: $1 = N_0 \exp(K_C\sigma_b / \sigma^*)^{1/2}$. The number of the impulses has the maximum value N^* when an earthquake happens: $N^* = \exp\,[(K_C)^{1/2} - (K_C\sigma_b/\sigma^*)^{1/2}]$, where σ_b is the beginning stress when the first emission impulse happens, σ^* is the critical stress, K_C is the stress intensity critical coefficient, and A is the regional coefficient. The solving of the system of similar physical-empirical equations allows us to estimate N^* and the time of a future earthquake.

Emergency Preparedness Response in Canada and the United States

Mike BRAHAM, Director of Emergency Programs and Exercise, Emergency Preparedness Canada

In the emergency field, as in most areas, Canada and the United States have many approaches in common and many that are different. This presentation will contrast the two national approaches to both emergency preparedness and the response after one happens.

Seismic Behavior of Unreinforced Masonry Buildings—State-of-knowledge and Seismological Parameters of Significance

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The seismic hazards posed by existing unreinforced masonry (URM) buildings have long been recognized. However, this awareness is relatively new in Eastern North America (ENA). While recent damaging North American earthquakes have accelerated current efforts to implement mandatory seismic-resistant design requirements through-out the Eastern United States, in Canada, where such requirements have been in place for over 20 years, they have rather prompted some owners to fund seismic retrofitting projects, and others to seriously contemplate the possibility. Not surprisingly, old URM buildings are the prime target.

To determine if, and what level of, retrofitting is required for an existing structure, an engineering analysis must first be performed. In the absence of legislation prescribing how, or against which basis, this structural assessment is to be accomplished, engineers are free to establish both. At first, this may appear to the designer as an ideal situation. However, in ENA, the long return period of major earthquakes, the absence of interim perceptible seismic activity, and/or the often small to moderate predicted intensity of the maximum credible earthquakes, shed a new and different perspective on the problem. For example, the real "threshold" of damage of a given URM structure may only be slightly exceeded during a short duration Magnitude 6.0 earthquake, but a conventional engineering assessment based on code procedures may be incapable of predicting this satisfactory performance, labeling instead the building as seismically unsafe. Better quantitative assessments of seismic demand uncertainty are also needed in that perspective.

A number of common failure modes of URM buildings have repeatedly been observed following earthquakes. These can be regrouped in the following categories: (1) Lack of anchorage; (2) Anchor failure; (3) In-plane failures; (4) Out-of-plane failure; (5) Combined in-plane and out-of-plane effects, and (6) Diaphragm-related failures. In-plane and out-of-plane failures of the rocking type, the most frequent and dangerous failures, depend on the pulse-content, or sudden energy release, of the seismic ground excitation, as well as the number of repeated such pulses. Photos from earthquake reconnaissance visits and research analytical and experimental results will be used to illustrate the influence of the above seismological parameters.

The Potential Use of an Energy-Based Motion Parameter for Probabilistic Seismic Hazard Analysis

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The amplitude and duration of ground motion are important considerations for engineering analysis. However, the duration of shaking is not modeled routinely in probabilistic seismic hazard assessments. We are examining the potential use of a parameter based on the square root of the elastic input-energy spectrum. This is attractive because it has many similarities to the familiar pseudo-relative velocity (PSV) spectrum, yet it depends upon the duration of shaking as well as the amplitude of motion. The energy-based prediction model may have application in the identification of scenario events for dynamic analysis, assuming that the energy spectrum can be predicted as a function of magnitude and distance and that statistical variability is comparable to that associated with peak motion measures or response spectra ordinates.

This study involves development of regression models for predicting the elastic input-energy spectrum using strong motion data from western US earthquakes. The emphasis of the study is on comparison of those results with PSV response spectra derived from the same data set, using identical processing procedures. Preliminary results indicate that similar regression models can be used for PSV spectra and equivalent velocity spectra derived from the absolute and relative input-energy spectra. The energy-based models exhibit a stronger dependence upon earthquake magnitude, compared to the PSV models: that is, the ratio of the equivalent velocity spectral amplitudes to the PSV amplitudes is an increasing function of magnitude.

Grey System Theory: A New Method to Predict Future Earthquakes From Past Earthquake Records

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This paper presents a new method to predict future earthquakes from past earthquake records. The method utilizes grey system theory to process the data from historical earthquake catalogues. Using grey system theory, six different grey forecasting models are developed to predict future earthquakes of different magnitude, and occurring at different location as well as different times.

We provide three examples to illustrate how to use these forecasting models and interprete their results. One example uses historical earthquake records from Chile while the other two use earthquake records from California.

The new method was tested for earthquakes which have already occurred using data only up to the time period before the event and matched well for the California region. The new method can potentially be used in earthquake forecasting.

P-WAVE PRECURSORS FROM INTERMEDIATE DEPTH EARTHQUAKES IN SUBDUCTION ZONES

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A small amplitude precursor before an impulsive P arrival is consistently observed from intermediate-depth subduction zone earthquakes in local, regional, and teleseismic distances. This small amplitude precursor has been identified as a P-wave train from the particle motion and polarization analysis. Time separations between the two P arrivals can be a few to several seconds which appear to be proportional to the traveling length of the seismic waves inside the subducting slab. A preliminary two-dimensional crustal and upper mantle velocity model including a 60° dipping slab was designed to investigate the relationships between the propagation of high-frequency seismic waves and the internal structure of the subducting slab. Synthetic P-wave seismograms at surface stations of various distances from the trench axis assuming earthquake sources at various depths and different parts of the subducting slab were calculated using a two-dimensional finite-element method. Although it is still very preliminary, results of the modeling suggest that earthquakes at intermediate-depth showing two P arrivals are most likely located in the upper portion and not in the central or lower portions of the subducting slab. The small amplitude first P arrival can be interpreted as a P wave train traveling deeper into the central portion of the slab where seismic wave velocity is higher than that in the upper and lower portions of the slab. The impulsive large amplitude second P arrivals may represent a P wave train traveling along the upper portion of the slab where velocity and thermal gradients are the highest. Basically the second P waves are traveling along a well-developed wave guide near the upper portion of the slab where velocity is slower than that toward the inner portion of the slab. The multipathing effect becomes apparent only when P waves are traveling beyond certain length inside the slab along up-dip direction such that the arrival times of the two P wave trains become separable.

Seismic Hazards in Southern Ontario—Characterization of Uncertainty

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We present a probabilistic seismic hazard model for the southern Ontario and surrounding region. In developing the model emphasis was placed on quantifying the current level of scientific uncertainty in seismic hazard assessment: selection of appropriate ground motion attenuation models, specification of the appropriate boundaries of regional sources, identification of potential local sources, and characterization of the frequency, spatial distribution, and size distribution of future earthquakes. The seismic hazard model was constructed using a logic tree formulation with 19 levels of uncertainty that provided a convenient framework for examining the impact of uncertainty in the various scientific issues on the hazard at sites in southern Ontario. Issues addressed include the use of geology versus seismicity to develop regional source zonation, the location of the boundary between extended and non extended crust, the potential extension of the St. Lawrence rift system into the Lake Ontario region, and the potential that such features as the Niagara-Pickering linear zone, the Rouge River fault, the Georgian Bay linear zone, and the Toronto-Hamilton seismic zone represent distinct seismic sources. The analysis of the resulting seismic hazard model is described in the companion paper by R.R. Youngs, S.-J. Chiou, and K.J. Coppersmith. The study was sponsored by the Atomic Energy Control Board of Canada.

Mine induced seismicity of the M zone at Sigma Mine, Val-d'Or, Québec

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CANMET installed a seismic system at Sigma Mine in 1994. This system recorded over 1500 events over a 36 months period. Statistical analysis and correlations between seismic parameters, geological features and mining parameters have been performed on the M zone of this mine. These show that the seismicity related to mining is in most part due to geological features. Concentration of seismic activity is found near the intersection of two major structures or at the intersection of a structure with the mine openings. To some extend, the correlations show that mining methods and the extracted volume influence the number of seismic events that occured.

Beside this qualitative aspect, a seismic potential assessment was performed using the Energy Index concept by G. van Aswegen and A.G. Butler. This parameter gives mine operators the likelihood of a specific area to experience a large event in the near future.

Both the quantitative and qualitative aspects help us design guidelines for mining in burst prone areas of a narrow vein type mining operation.

The Seismic Network AcQuisition System (SNAQS)

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The Canadian National Seismograph Network (CNSN) consists of 25 three-component broad-band and 47 single- or three-component short-period seismograph stations for a total of 136 channels. Packets of seismic data from these stations are transmitted in real-time via satellite, radio or telephone links to GSC offices in Ottawa and Sidney. In Ottawa the data are collected, processed and archived by dual-redundant systems running the Seismic Network AcQuisition System (SNAQS) software. The SNAQS software is also used at the Charlevoix and Yellowknife sub-networks to concentrate multiple input stations into one output channel before forwarding it to Ottawa. The SNAQS software is also used at several "data on demand" dial-up stations which allow data to be retrieved across regular phone lines, thus avoiding expensive dedicated communication links.

The SNAQS software was designed and written in-house to run on Sparc workstations running the Solaris operating system. The SNAQS is a collection of multi-threaded programs and utilities which perform the following tasks: collect continuous data from stations, store data in 24 hour ring buffers, monitor and control station operation, archive data on optical disks and local disks, run a first level event detector on selected stations, run a beam former and detector on Yellowknife array data, concentrate multiple input channels into one output channel, forward data in real-time to the IDC, and "drive" helicorder devices.

Waveform data and detection lists output by the SNAQS are used by subsequent automatic programs that analyze and associate raw detections and autolocate events. Waveform data can also be extracted from the SNAQS for use by seismologists. Long-period data can be generated from broad-band data. Output files can be in several formats, including SEED, and can have customized station lists and arbitrary start and end times.

Future versions of the SNAQS will receive and send seismic data across the Internet, handle non-CNSN data formats (ie. EarthWorm), allow multiple concentrator outputs and will be ported to linux.

Earthquake Preparedness in Canada

Ann DEBEAUPRÉ, Program Coordinator, Emergency Preparedness Canada

From first principles to the completion of a national plan, the enhancement of emergency preparedness for earthquakes has followed a lengthy road. This presentation will explain the National Earthquake Support Plan, describe how the plan was developed and approved, and outline upcoming activities.

NEONOR: Neotectonics in Norway

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The traditional view that Norway and the stable Baltic Shield do not exhibit major earthquakes or large crustal surface deformations have obscured the fact that several observations have documented the contrary, albeit not on scales comparable with plate margin deformations. A detailed geologic mapping over the last two decades in selected regions has revealed several sites of recent or contemporary surface deformations, but still this type of information is poorly integrated and emphasized in the scientific community. Also more recent studies of earthquake occurrences have revealed several regions of unexplained high seismic activity, but an undisputed correlation between earthquakes and surface deformation is still pending.

Geological investigations in Norway, Finland and Northern Sweden have revealed a set of neotectonic faults of which the Stuoragurra fault near Masi is the one best mapped in Norway. These faults indicate that very strong earthquakes (magnitudes 7-8) may have occurred repeatedly in Fennoscandia immediately following the deglaciation about 9000 years ago. In northern Norway there are now documented post-glacial faults in Beiarn, K&fjord and Masi, and remarkable recent earthquake sequences in Mel%y and Steigen. Since, until now, the seismic activity in Norway has been monitored only by means of regional seismic networks, there are no sites where observed seismicity is tied to mapped faults with mapped recent displacements, except for the Stuoragurra Fault in Masi.

The Stuoragurra fault is relatively continuous for 80 km in a NE-SW direction, with a vertical displacement as high as 7 metres. Earthquakes have been recorded in a linear zone 30 km wide, parallel to the fault trace on the southeast side. The January 21, 1996 earthquake (M4.0) in the Masi area was almost certainly located on the Stuoragurra Fault at a depth of c.10 km. Fault plane solutions from this, and three lesser earthquakes are consistent with oblique reverse faulting.

Catastrophic 97 and Earthquake Scenario Exercises

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The Catastrophic 97 exercise brought together emergency managers from seven states and the U.S. government to exercise a scenario of a catastrophic earthquake on the New Madrid Fault. This presentation will review this exercise and describe other recent earthquake scenario exercises.

Paleoseismicity: Seismicity Evidence for Past Large Earthquakes

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Clusters of earthquakes in continental intraplate regions are used to estimate the times and magnitudes of past earthquakes in a model we call "paleoseismicity". The time of a past earthquake is estimated from an Omori-law decay of aftershocks with time, while the magnitude of the earthquake is inferred from the length of the current zone of seismic activity. The aftershock decay rates of a number of recent continental, intraplate earthquakes from North America and Europe were determined. While some of the events had relatively active aftershock sequences and others had few aftershocks, the range of aftershock decay rates are similar to those reported from California. Using parameters derived for average aftershock decays, we find that the earthquake activity in the main New Madrid seismic zone and in the Charleston, SC areas could be regarded as aftershocks of the major events in 1811-1812 and 1886, respectively. We have applied the paleoseismicity model several localities in northeastern North America and in western Europe to estimate the possible dates and magnitudes of past strong events.

Shake Table Facility at Ecole Polytechnique: Research Activity and Seismological Needs.

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The recently acquired earthquake simulation facility at Ecole Polytechnique in Montreal has been used extensively on various experimental research projects. This presentation describes the basic features of this unique equipment in Canada and briefly highlights the seismological needs to improve the confidence in shake table testing. The 1,000,000$CAN uniaxial earthquake simulation facility at Ecole Polytechnique has plan dimensions of 3,4m × 3,4m with a specimen payload capacity of 15 tons. The shake table is driven by a 250 kN fatigue-rated hydraulic actuator fed by a 730 l/min hydraulic power supply. The actuator can induce a peak horizontal acceleration of 1,0 g for the fully loaded table condition The workable frequency range of the system spans from 0 to 50 Hz. A key feature of the system is it's advanced digital control algorithms to improve drive signal reproduction which can be expressed in terms of displacement or acceleration time-histories. This facility is used to evaluate seismic code requirements for new structures, to evaluate the seismic behaviour of existing structures and test retrofit measures, to proof-test non-structural elements and equipment, and to increase the awareness of the public towards seismic hazard and risk. Shake table studies can provide meaningful results only if representative earthquake ground motions are used as drive signals. There is an urgent need for the elaboration of site specific horizontal ground acceleration time-histories in Canada. Only when this seismological data is widely available that shake table testing could reach its full potential.

Seismic Images of Grenville Basement and Appalachian Cover: Southeastern Ontario to Northern New York State

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Seismic images from Lake Ontario and the adjacent Central Metasedimentary Belt clearly show a Grenville basement characterized by easterly dipping, folded, imbricated and overlapping structures. Truncated antiforms characterize upper crustal reflection geometry. A strong northeast continuity is apparent between exposed Central Metasedimentary Belt structures and Paleozoic-covered basement seismic structures beneath Lake Ontario. Wide-angle reflections and distinct northeast trending magnetic and gravity anomalies link exposed terrane boundaries characterized by ductile shear to prominant reflective zones beneath Lake Ontario. Late tectonic pluton emplacement may explain local correlations between distinct circular magnetic highs and antiformal reflections. Interpreted Grenville structure includes major northeast trending, easterly dipping, crustal-scale tectonic boundaries and secondary features in the form of: (i) a 30-40 km-wide zone beneath Lake Ontario (traversed by 3 reflection lines) marking the southwest continuation of the Elzevir-Frontenac boundary zone (EFBZ) separating Elzevir and Frontenac terranes exposed to the north. (ii) an interpreted shear zone beneath eastern Lake Ontario (no clear exposed counterpart) (iii) an interpreted ductile shear zone extending beneath western Lake Ontario and eastern Lake Erie representing the southwest continuation of the Central Metasedimentary Belt boundary zone. (iv) the Iroquoian High, a zone of thinned and disrupted Paleozoic strata overlying the EFBZ beneath central Lake Ontario. The structure of the Iroquoian High is variable, featuring consistent up-to-the-east apparent offsets beneath central Lake Ontario and a crestal area flanked by thickening Paleozoic strata benath southern and western Lake Ontario. The Iroquoian High helps explain the peninsular extension of Prince Edward County into Lake Ontario and the Precambrian inliers in Prince Edward County. (v) east of the Iroquoian High the near Lake Bottom structure is hummocky in contrast to relatively undisturbed strata to the west.

Geotomography Velocity Survey of a Destress Blast

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Destress blasting is one of the means used by the mining industry to reduce the potential of rockbursts associated with highly stressed areas. The objectives of these blasts are to reduce the level of stress observed in loaded areas by modifying the rockmass properties at these areas. In practice, it is a carefully designed blast to fracture the rockmass, by firing a series of closely spaced blast holes.

Destress is achieved by allowing the dissipation of stored strain energy under relatively controlled conditions, which may be otherwise violently released as a rockburst. In the longer term, it is achieved by reducing the rigidity of the rockmass. However, there is also a risk associated with this technique as its effect is highly site dependent and its design is largely based on experience. If it is too strong, it may trigger a rockburst; and if it is too weak, it may not be able to release enough energy.

To evaluate the potential of the technique in its ground control program, the Sigma Mine, a gold producer in Québec, owned by Placer Dome Canada Ltd., carried out a field test in January 1996, with a very comprehensive monitoring program. The test site was a sill pillar adjacent to an abandoned stope, located approximately 1500 metres below the surface.

Geotomography survey was used as a qualitative means to assess the change of rigidity of the site by comparison of the velocity images of the site before and after the blast. The survey shows that the velocity in the survey area decreased by 2% on the average after the blast. The major reduction in velocity, about 3%, took place in the central part of the survey area where the blast holes were located. There was little change at the boundary of the survey area. Since the survey area was highly stressed, the change in velocity of 2 or 3% is a reliable indication of a substantial decrease in stress and the rigidity of the pillar.

The actual stress measurement shows that the average maximum stresses before the blast were 104 MPa at the centre of the pillar, and 34 and 64 MPa at the west and east ends, respectively. After the blast, the average stress at the centre decreased to 59 MPa at the centre. At the west and east ends of the site, it established itself at 42 and 19 MPa respectively.

A particular advantage to use the tomography survey in this study is that it provides a clear picture of the distribution of the effect of the destress blast.

Microseismic Monitoring in Mines

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The purpose of this paper is to describe in-mine microseismic monitoring and how information from such monitoring can assist in mining engineering decisions. Monitoring seismicity continuously in a mine gives observational information of rock failure in the vicinity of the mine. When rock fails in a brittle manner, seismic waves are emitted into the surrounding rock. Information about the failure is contained in wiggle-trace recordings of the seismic waves from the event, even though the failure may have occurred

tens of meters, even kilometers, from the recording instruments. The ability to obtain information about remote sites without the need to visit the remote site is an important feature of seismic monitoring. Basic analysis of the seismic signals tells the mine operator when and where rock is breaking in the vicinity of the mine and gives an estimate about the size of the failure zone. If the seismic data are of sufficient quality, advanced analysis can provide information about the mechanism of failure but in many instances, seismic sensors are too few to get accurate results.

Prediction of seismic events or roof-falls has so far proved to be an unattainable goal, at least in potash mines, although statistical estimates of seismicity over time are possible. No mechanical device, data acquisition system, computer system, etc., can reliably predict when and where a seismic event or roof-fall will occur. Only intelligent interpretation of seismic data, together with other information, provides useful results. Routine monitoring of seismicity gives specific, systematic observations of the circumstances associated with a rock failure hazard, (such as roof-fall) which can be analyzed in detail in the context of other similar observations.

Seismic monitoring in a mine may have several objectives which depend on the nature of the seismic problem in the mine, the quality of the seismic monitoring system, the technical skills of the seismic system operators, and the expectations of the mine managers. All of these factors interact, but the main requirement for a successful seismic monitoring program is the will of the mine manager. If the manager perceives that a seismic system is useful, the technology is available to make it so.

We consider that there are three main uses of a seismic monitoring system: 1) to identify and locate large seismic events for rescue or damage control; 2) to identify areas of seismic activity and interpret ground stability in an active mine; and 3) to evaluate the performance of mine design. The three uses overlap to some extent.

The first use, to identify and locate large seismic events, is probably the most basic application of seismic monitoring systems. In many mines there is a real possibility of generating an earthquake of substantial energy release, often by activating a pre-existing fault near the mine. If a large seismic event occurs, the mine engineers need to know when and where it occurred, and if workers might be in danger or if there might be damage to the mine. In mines subject to large rockbursts this is an important application. In Saskatchewan potash mines no workers have ever been injured by rockburst but some large water inflows are associated with mining induced earthquakes.

The second use, to identify areas of seismic activity and to interpret ground stability, is common in many mines. Small seismic events, as well as large ones, can be mapped to observe the rock response to any change in the mining pattern, or to any unusual geological situation that the operator may cut into. Microseismic activity is often observed near geological anomalies such as faults, folds, or intrusions. Roof-falls are a serious hazard in any mine. Microseismic data may provide key information to the thinking engineer who hopes to predict such hazard by using all of the seismic and other information at her or his disposal. The objective is to use the data to identify areas where there might be a problem and to take some action, such as adding roof support. In potash mines, mined out areas become inaccessible within a few months after abandoning them, and the seismic systems are the only practical means of maintaining day-to-day monitoring of such areas.

The third use, to evaluate performance of mine design, is perhaps the most demanding. A seismic event of any size is evidence that mining-induced stress has exceeded the strength of the rock. If a seismic event occurs in an area where finite element analysis has predicted that none should occur, then the finite element model must be incorrect. The seismic performance of a specific mine plan may be used to modify the mine plan and to reduce stress concentrations and seismic hazard.

Information provided by seismic monitoring gives observational confirmation of the success or failure of the management of rock stress and stress concentrations in the mine. Routine seismic monitoring is an integral part of the long-term ground control and rock mechanics program at some mines. Engineering staff able to determine when, where, and on what scale rock is breaking in the vicinity of their excavation will have a better understanding of mining effects on the surrounding host-rock than engineers without access to such data. This requires continuous seismic monitoring, 24 hours every day.

Small scale seismic events are common at underground mines, occurring regularly whether the operator is aware of them or not. They are free, they cost nothing. Why not use the information provided by this seismicity to gain understanding of how mining is affecting rock about the mine?

Asymetrical, Episodic Rupture but Normal Stress Drop: A Detailed View Inside the *Mw* = 4.5 Mont-Laurier Earthquake with Insight into the Rupture Process.

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High-frequency ground motions from the mbLg 5.0 Mont-Laurier earthquake of 19 October 1990, in Quebec Canada, exceeded values anticipated for an event of its size by a factor of 3; observations attributed by some to a stress drop of over 500 bars. We derive detailed fault slip models to fit waveform and spectral characteristics of the regional data. We establish that the effective rupture stress was normal (about 100 bars), that the fault rupture developed asymmetrically, and that the average slip time for points inside the rupture area (approx. 0.1 s) was significantly less than that associated with the standard Brune (1970) source spectral model. The rupture area developed in at least three distinct episodes during 0.66 s, each extending the previously ruptured area for a final total of about 1.3 km*km. The apparent rupture velocity (equivalent radius/half total duration of rupture) is less than 60% Beta even though the actual rupture velocity needed in the modelling was 95% Beta. Thus we believe that such complexity, as observed in this and the mbLg 6.5 Saguenay earthquake of 1988, makes the standard Brune spectral model an unreliable basis for the interpretation and prediction of strong ground motion, and that care needs to be taken in interpreting 1-km-scale zones with "slow" rupture velocities as special "nucleation regions" for larger earthquakes.

Crossing the Border: Assessing the Differences Between New Canadian and American Seismic Hazard Maps.

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The Geological Survey of Canada has produced a new suite of seismic hazard maps. These maps are intended to form the basis of seismic design codes in the year-2000 edition of the National Building Code of Canada. The USGS has released a similar set of maps in 1996 for the 1997 NEHRP.

For eastern Canada the GSC applied the Cornell McGuire method to two new seismic source models, one historical and one geological. The larger of the two results were selected to produce a "robust" map. In the eastern U.S. the USGS employs spatially smoothed representations of historic seismicity to directly calculate probabilistic hazard without the use of subjective source zones.

Despite the different methodologies and the application of different strong ground motion relations, preliminary results generally indicate good agreement at the border. Of course not all the hazard captured by the GSC's "geological" model is represented in the USGS results (eg. where large earthquakes may happen in areas of low historical seismicity). The reasons behind the differences will be explained where they are evident. For illustration purposes, a smoothed map (created by employing a simple ramp function) will be featured for use in public education.

Sensitivity Analysis in the Probablistic Seismic Hazard in Korean Peninsula

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Lessons learned from the IPEEE(Individual Plant Examination ofthe External Event) of the Yonggwang Nuclear Power Plant Unit 3 & 4, located in the southwestern part of Korean Peninsula, have shown that the high degree of dependence on the experts' opinions is supposed to be generic cause of uncertainty of annual exceedance probablity in the probablistic seismic hazard analysis. The report has also suggested that the large difference in input data of seismicity and variety of strong ground motion attenuation model for the same seismotectonic regions, among the experts, is one of the principal causes of uncertainty. Several panelists in strong ground motion attenuation model have suggested attenuation models from the Eastern North America and North China.

This study investigated the sensitivity of one of the seismicity parameters, focal depth, which is one of the most uncertain seismicity parameters in Korean Peninsula. In the analysis of the probablistic seismic hazard, the influence on the uncertaintirs of probablistic of exceedance per year for the whole ranges of seismic hazard levels from 0.1g to 0.99g was investigated for the given combination of the seismic input parameters. The computer code from the USGS open file was mainly used for evaluating probablistic seismic hazard and resultant uncertainties of annual exceedance probablities for the interested ranges of seismic hazard levels.

Using cumulative probability density function, annual exceedance probablistic corresponding to 10%, 50%, and 90% were compared to the mean values at each seismic hazard level. The resultant values of annual exceedance probabilities, which conside focal depth, corresponding to 10 seismic hazard levels are much less than those without considering focal depth. The decrease in the values of annual exceedance probabilities is up to 1/10,000. For 5 different density functions, which are the results from aggregating the combinations for 5 different experts individually, the shapes of the probability density function, which considered the focal depth parameter, were much more symmetrical compared to those without considering focal depth parameter. The shapes of the probability density functions of 5 experts for each seismicity group may be good measure to investigate degree of consistency of each expert, to parameter seismically the same historical and instrumental documents on earthquake phenomena in Korean Peninsula.

Two results may imply that it is necessary to derive focal depth parameter more effectively from the historical and instrumental documents on earthquake phenomena in Korean Peninsula for the future study of PSHA. The results from this study could be used for steering the future direction of geological and seismological research in Korea, which may reduce the uncertainty in seismic hazard analysis and, finally, that in core damage frequency.

Microtremor Measurements to Obtain Resonant Frequencies and Ground Shaking Amplification for Soil Sites in Boston, MA

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An understanding of ground motion amplification due to sedimentary deposits neat the Earth's surface and its relationship to structural design can be used to improve stability of buildings should an earthquake occur that generates strong ground motion. The measurement of microtremors to constrain soil resonance and ground shaking amplification has proven successful in previous studies. The two popular methods utilize spectral ratio techniques. In the first method, ground motion is measured at both soil and bedrock sites, and the spectral ratio of the soil site to the bedrock site is analyzed for spectral peaks. The spectrum gives information about resonance and relative amplification for each site. The second method uses the spectral ratio of the horizontal to vertical components of ground motion at one soil site to determine resonant frequency.

Boston is a prime candidate for this type of analysis due to the presence of extensive fill and soil cover overlying the bedrock in many areas, the high population density which contributes to a high risk of life loss during an earthquake, and the age of many buildings in the city (pre-dating the earthquake building code). During the summer of 1997, 15 sites in the Boston area were analyzed using both spectral ratio techniques. Comparison of results from both methods shows good correlation between resonant peaks at each site. Resonant frequencies calculated for Boston lie between 1 and 5 Hz, depending on soil composition and depth to a high impedance boundary, and in general, amplification is relatively high for fill areas than for hard rock sites. Repeat experiments at the sites show similar results with each trial. Models of the response of soils have been computed to form a comparison between theoretical and experimental results.

Guidelines for Post¡earthquake Communications by Eastern Canadian Seismologists.

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In Eastern North America, widely felt earthquakes can have a lasting social impact, partly due to the lack of preparedness of the population. Due to their knowledge of earthquakes, seismologists become major sources of information for the media, the emergency organizations, and the public. The basic information given by seismologists can dissipate some apprehension in the public. Thus, seismologists can be very helpful in a post¡earthquake period: by answering questions from the general public, they relieve the emergency organizations of this task, who will in turn, focus their efforts on more urgent situations.

To be efficient, however, seismologists must have a communications strategy. In the plan developed for Eastern Canada, seismologists use small earthquakes to become known by the media, especially the ones located in high risk areas. When a moderate to large earthquake occurs, a high priority is given to the population in shock (generally the population near the epicentre). The message conveyed deals with basic information on earthquake phenomena and on individual preparedness. In the field, communications that may have a social impact are developed with local organizations. Seismologists should be ready to take part in public meetings if needed. With this strategy, seismologists can help alleviate some post¡earthquake public fear and promote positive response.

Offshore Faults of the Charlevoix Seismic Zone, as Interpreted from Seismics, Magnetics and Gravity.

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In the Charlevoix Seismic Zone (CSZ), most earthquakes occur in the Precambrian basement under the St. Lawrence River. There, the potentially seismogenic faults are masked by a thick sequence of Appalachian rocks and by a series of valleys filled with Quaternary sediments up to 600 m thick. To define the position and extent of the basement faults better, proprietary seismic, magnetic and recently¡acquired offshore gravity data were interpreted. Contrasts in acoustic impedance (seismics), in magnetic susceptibility (magnetics) and in density (gravity) are used to map the Precambrian¡Appalachian interface at depth. In addition, the solutions from the Euler deconvolution of the magnetic field are used to estimate the depth to the magnetic basement. A series of river¡parallel normal faults (possibly related to the St. Lawrence paleo¡rift system) are interpretated from the gravity and magnetic fields. Another series of normal faults at high angle with the river axis also exists. As most seismic profiles, acquired in the early 70's, do not clearly image the deeper structures, one of these seismic lines was reprocessed using modern techniques. The new migrated section, relieved of the strong water¡bottom multiples, shows reflectors, some as deep as 15 to 18 km. On this profile, a few normal faults are suggested by the discontinuous reflectors near the Appalachian front. The fault system that emerges from these geophysical indicators is one of regional normal faults parallel to the river axis crossed by local complexities, possibly introduced by the Charlevoix impact structure. Although one of these regional normal fault appears seismogenic; most regional faults are inactive or at best, constrain the seismic activity. One highly¡faulted area in the impact crater is also highly seismically active.

Local Magnitude Scale and Seismicity Rate for Tanzania, East Africa

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A local magnitude scale is developed for Tanzania, East Africa, using data collected by the 1994/1995 Tanzania Broadband Seismic Experiment. The waveform data from 1189 local and regional earthquakes located within East Africa were corrected for instrument response and convolved with the nominal Wood-Anderson Torsion seismograph response appropriate for the original definition of local magnitude. 24710 maximum S wave amplitudes were incorporated into an iterative regression for individual event local magnitudes, 38 horizontal component station factors, and 2 linear distance-dependent factors in the log Ao term of the equation for ML. The resulting distance correction, log Ao, is given by:

$$-\log Ao = 0.776 \log(r/17) + 0.000902(r - 17) + 2.0$$

where r is hypocentral distance in km. This distance correction yields much less ground motion attenuation than observed for Southern California and is similar to that observed for local S waves and regional Lg waves propagating in Eastern North America. Normalizing the distance correction using the standard constraint of 1 mm ground motion at 100 km for a magnitude 3.0 earthquake results in a bias of nearly a half of a magnitude unit between mb and ML, with ML being larger. Normalizing using the constraint of 10 mm of motion at 17 km for ML 3.0 removes the bias in magnitude measures and indicates that structure within Tanzania is relatively high Q. The seismicity rate of Tanzania for 1994/1995 was examined using the Gutenberg-Richter seismicity distribution and is seen to follow the relation:

$$\log N = 4.60 - 0.83\ ML$$

where N is the number of earthquakes per year of local magnitude ML or greater. The catalog of events used in this study is seen to be complete to magnitude 2 to 2.5.

Dynamic Behaviour and Monitoring of the Confederation Bridge

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The 12.9 km long Confederation Bridge is the world's longest prestressed concrete box girder bridge built over salt water. With 45 main spans of 250 m each and a 100 year design life, the design criteria of the Confederation Bridge are not covered by any code or standard in the world. A comprehensive monitoring and research program is being carried out to monitor and study the behavior and performance of the bridge under ice forces, short- and long-term deformations, thermal stresses, traffic load and load combinations, dynamic response due to wind and earthquake, and corrosion. The monitoring and research project represents a partnership between universities, private industry and various government agencies. It is joinly funded by the Natural Sciences and Engineering Research Council of Canada, Public Works and Government Services Canada, and Strait Crossing Development Inc, the private developer of the bridge.

Because of its location and long span length, the bridge is subjected to significant dynamic loads due to wind, sea current, ice floe impact, heavy vehicles and earthquakes. This paper describes a long-term dynamic monitoring program of the Confederation Bridge. The objectives and scope of the monitoring program, and the design and layout of the instrumentation, are presented. The network of monitoring instruments includes over 100 channels of accelerometers, dynamic tiltmeters, displacement transducers, strain gauges and wind anemometers, to obtain information about the vibrational behaviour of the various components of the bridge. The spatial variation of the ground motions at the base of four bridge piers are measured. Direct measurement of the near-field spatial variation of seismic wave propagation and its effect on large structures is rare. The Confederation Bridge offers an unique opportunity to obtain information and to conduct research in this area.

Some ambient vibration data collected as part of the calibration and testing of the monitoring instruments are presented. The field measured data agree well with the predicted results computed using three-dimensional finite element models of the bridge, thus confirming the proper installation and operation of the monitoring equipment. The monitoring project will not only establish a large comprehensive database on the dynamic behaviour and performance of such a unique concrete structure, but will also provide information for effective maintenance of the facility.

Seismic Risk of Seoul, Korea

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Seoul is the capital of the Republic of Korea and has a population over ten millions. Seoul is the center of the political, economical, and social affairs of Korea and many tall buildings have been built with rapid economic growth of the country in recent years. However, the seismic risk of the city has not been studied as yet. Historical documents of Korea indicate that about three hundred earthquakes occurred in Seoul and its metropolitan area of about 1 degree latitude by 1 degree longitude. Among them the earthquake occurred in 87 caused large scale ground failures, destroyed a number of houses and brought about many deaths. It appears about more than four destructive earthquakes of MMI equal to or greater than VIII occurred in the Seoul metropolitan area over the last two thousand years. Instrumentally recorded earthquakes in the 20th century amount to about forty. The seismic risk of the Seoul metropolitan area is estimated with earthquakes having attenuated MMI equal to greater than V in the area. The study area is divided into a grid system of 0.1 degree latitude by 0.1 degree longitude. Extreme value method is applied to attenuated intensity data at each grid point to obtain horizontal acceleration with 90% possibility of being exceeded in 100, 200, 500, and 1000 years.Since earthquake data over the last 600 years is rather complete compared to the previous data, risk estimations are made with the whole data as well as with the rather complete part of data. It turns out the risk level with the whole data is lower than that with the data over the last 600 years. In the central part of the Seoul metropolitan area, the extreme horizontal acceleration with 90% of being exceeded is greater than 0.2g in 500 years.

Alternatives in Evaluating Soil- and Rock-Site Seismic Hazard

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Seismic design requirements for critical facilities normally require the development and application of a uniform hazard spectrum having a specified return period. For a soil site, hazard results are often evaluated for bedrock level and soil surface. In many instances, use of soil hazard results can be problematic for a generic site response result because un-conservative generic soil amplification functions may have been used in the ground motion attenuation model or a site specific result may be required. For sites with dated site specific uniform hazard results, the site-specific soil model used in the ground motion attenuation model may be out-of-date with more recently collected data. In these cases, the available options, short of an expensive redo of the soil uniform hazard evaluation, are to use the bedrock outcrop hazard results and adjust or correct for the effects of site response. This paper presents a methodology to evaluate soil hazard by using relatively easily derived soil amplification functions and bedrock hazard results.

For a typical deep soil site in the southeastern U.S., magnitude and distance dependent de-aggregated rock hazard results are used to estimate the probability of occurrence of events within specified ranges of earthquake magnitude and distance and structural frequency. Tables of magnitude and frequency dependent soil (non-linear) amplification functions are compiled for a suite of bedrock control motions. A suite of desired soil ground motion levels are specified. For each bedrock level of motion (derived in the hazard evaluation), the probability of exceedance of each of the suite of soil motions are computed using the source description contained in the rock hazard de-aggregation and the distribution of soil amplification. Products of the event probabilities and soil probabilities of exceedence are summed over the available hazard range to produce soil hazard curves. Example soil hazard curves are shown using EPRI rock hazard results. Comparisons are made using uniform hazard spectum computed at the soil surface with that computed using a rock outcrop hazard spectrum and mean soil factors.

Seismic Safety of Concrete Dams in Eastern North America: Research in Progress and Research Needs

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The consequences associated with the release of a reservoir due to the seismic failure of large concrete dams are catastrophic. Many of these aging structures were initially designed with minimal considerations concerning their earthquake resistance. Cracking and structural damage are acceptable under the selected maximum design earthquake (MDE) as long as the reservoir is contained. The scope for research, development and validation of accurate, efficient, and reliable numerical techniques to study the seismic response of concrete dams is virtually unlimited (material constitutive models and testing, hydrodynamic and dam-foundation interaction mechanisms, experimental validation on small dam models, in-situ field testing, analysis and design of defensive measures).

The following research projects, are currently in progress or have been recently completed by École Polytechnique's research group working on seismic response of concrete dams: (1) development of dynamic smeared crack concrete constitutive models for mass concrete and construction joints, (2) definition of spectrum-compatible accelerograms to perform fracture analysis (synthetic records or historical records with modified Fourier spectra), (3) 2D numerical analyses to characterize the dynamic stability of cracked dams, (4) 3D linear seismic response analyses of spillways, non-straight gravity dams and dams with openings, (5) experimental static and dynamic sliding shear tests on 0.25m x 0.50m concrete lift joint specimens with different surface preparations (monolithic, water blasted, untreated and flat independent), (6) shake table dynamic fracture and sliding tests of 3.4m concrete dam models with and without lift joints, (7) study of seismic strengthening by post-tensioning and earth buttressing.

Concrete dams are short period structures with fundamental periods of the order of 0.05s for a 10m high gravity dam to 0.35s for a 100m high dam. Rigorous seismic analyses require the definition of suitable time history of input ground motions. The cracking response is sensitive to the presence of long acceleration pulses and residual sliding displacements are strongly affected by the earthquake durations. The seismological prediction of the ground motion characteristics is generally the most critical step and has also the greatest source of uncertainty in the seismic safety evaluation procedure. In an intraplate tectonic environment, as Eastern North America, it is difficult to define the MDE from a deterministic basis, ie. magnitude-distance scenarios from identified active faults. The MDE is usually selected for different Annual Exceedance Probability (AEP) (eg. 1 in 2000 yrs for Hydro-Quebec'dams). Thus, there is a need to define target design spectra (2 horizontal and 1 vertical) at different AEP (main shock and after shocks). Related 3D time histories of ground motions suitable for seismic analysis of short period structures are needed. A database of site-specific 3D input accelerograms set could be prepared for different AEP at typical dam sites. Particular attention should be given to the following items (1) the shape of the response spectra in the very short period range below 0.04s, (2) the characteristics of the vertical excitations and cross-correlations of 3D components, and (3) the duration of strong shaking. A standard methodology should also be developed for base line correction of strong motion accelerograms suitable for analysis of short period structures.

High Resolution Seismic as a Tool to Determine the Recent Seismic Activity on the Charlevoix Seismic Zone

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The Charlevoix Seismic Zone (CSZ) is the most seismically active area of eastern Canada. The absence of a documented surface rupture in this highly seismic zone is enigmatic. If the moderate to large earthquake activity has been continuous for the last thousands of years, some surface expressions of this activity must exist. This paper reviews our search for a rupture under the St. Lawrence river as implied by the moderate to large earthquake occurrences in the CSZ. It describes the methodology used and illustrates the evidences and lack of evidences of these ruptures. Two sources of information are used: seismic profiles acquired in the early 70's under the leadership of SOQUIP and a series of shallow seismic profiles acquired to map the thick sequences of Quaternary deposits. The latter work was carried out jointly by INRS-Océanologie and UQAM. Thick sequences of unconsolidated Quaternary deposits lie over the top of the bedrock. Under the middle St. Lawrence estuary, these sequences represent several glacial and non glacial periods during at least the last 250,000 yrs. They are up to 450 m thick and may be up to 600 m (SOQUIP lines) in river- parallel buried trenches. The upper sismostratigraphic units are correlated with the units of the 150 m Ile aux Coudres continuous drill core sequence. This sequence comprises a lower glacial complex, the Baie-Saint-Paul glacial Complex, which is related to the Illinoian Glacial, a marine-prodelta-delta continuous unit, named the Ile aux Coudres Formation, and which is overlain by recent fluvial sediments. On most SOQUIP seismic sections, continuous sub-horizontal reflectors were evident in the Quaternary sequences, in the basement and in the apparent interface between the two . No major unambiguous rupture was found, but some minor features are observed close to the threshold resolution level . The area which we considered the prime target for a rupture, the NE end of the CSZ, did not show any major evidence of a rupture. Disruptions were visible on Lines 13, 35 and 37, including in the thick Quaternary sequence near the north shore. These features are close to the limit of the resolution and their origin has to be confirmed by shallow seismics.. The analysis of some 200 km of deep seismic reflection lines and some 200 km of shallow seismic reflection lines in the CSZ could not yield clear evidence of a major surface rupture under the St. Lawrence estuary. We dont have yeat evidence of ruptures in the sector near Petite-Rivière-Saint-François and Ile aux Coudres. The coverage of the most active zone is not complete. In any case, the 11 m bathymetry line should not be used as an argument for a sub-surface fault. No fault ruptured the sediments where this isocontour lies. Hence, the 6 fathom line is only a surficial feature.

The Canadian National Seismological Data Centre

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The Canadian National Seismological Data Centre (CNSDC) is a computer facility that supports the National Earthquake Hazards and Comprehensive Test Ban Treaty (CTBT) Verification Programs of the GSC. Almost a gigabyte of continuous, compressed seismic ground motion data from 136 CNSN components are acquired, quality controlled, processed, and archived within the CNSDC on a daily basis. Event detection, automatic location, and issuing e-mail alerts are accomplished within minutes of local and regional events. Automatic processing of Yellowknife Array (YKA) data allows global events to be detected, locations refined, and e-mail alerts issued to national and international subscribers within three minutes of p-wave arrival. The National Earthquake Database (NEDB) is the national repository/index for all raw data, phase measurements, and derived parameters.

The CNSDC supports the development of the CTBT International Monitoring System (IMS) in part by forwarding continuous data in near real-time from YKA and 4 other stations to the prototype International Data Centre (IDC) in Arlington, VA. The IDC regularly requests additional data from 6 secondary stations via AutoDRM. Continuous data from 10 broad band sites designated "Federation" (FDSN) stations are supplied to the IRIS DMC for archive.

Event-related digital waveforms since 1975 are available from regional networks in Eastern and Western Canada, as are continuous CNSN data since 1992. AutoDRM provides convenient access to on-line waveform data less than 40 days old plus selected data from the NEDB. Our Web server has been active since April 1995.

Planned developments include an expanded Web presence via a new server, further enhancements to the acquisition systems, providing continuous data from West Coast stations to the Pacific Tsunami Warning System (CREST initiative), and closer cooperation/data exchange with the U.S. CNSS. Support for the final CTBT IMS will require implementing the new GSE V2.1 format in AutoDRM, authenticating station data, and developing an infra-sound site.

The Effect of the Distribution and Orientation of Small Random Crustal Reflectors on the Nature of the Wide-Angle Reflection Field

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Two methods of randomizing the earth's crust are investigated. Both methods employ a two-dimensional low pass filter with an associated correlation distance to add 2 D structure of various scales to random variables as follows:

(1) Smoothed randomally oriented small scale seismic reflectors are "embedded" in in a uniform seismic velocity gradient field. The effect of the velocity gradient is to make the reflective field for downgoing waves much greater than for upgoing waves. The off/on switching characteristics as a function of angle of incidence of the reflection coefficients of weak intracrustal reflectors plays a major role in generating the Pg coda in seismic wide-angle reflection experiments. Numerical experiments show that complexity of the coda or the presence or absence of the PmP branch is related to the distribution and random orientations of the small scale reflectors. The shingling effect of Pg first arrivals is predicted by these experiments.

(2) Smoothed random small scale velocity fluctuations are added to a uniform seismic velocity gradient field. The numerical experiments show that the addition of the velocity fluctuations will tend to break up a smooth travel-time curve into segments giving one the illusion that the earth is layered with significant intracrustal boundaries.

Data from recent Lithoprobe seismic coincident near vertical and wide angle reflection experiments conducted across the Canadian Shield are presented to show how one may separate the indeterministic components of the data from the deterministic components. A method of measuring signal complexity is proposed to characterize differences in the nature of the crust from one area to another.

GEOLOGIC, ECONOMIC AND SOCIAL CONSEQUENCES OF THE AKZO-NOBEL RETSOF SALT MINE COLLAPSE (MARCH 94-APRIL 96)

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The initial USGS identification of the "seismic" event of March 12, 1994 (05:43 EST) in western New York State was as a normal tectonic earthquake (m~3.6). When a day later it was discovered that a large underground collapse had taken place at the Akzo-Nobel Company salt mine just east of Cuylerville, NY, it was suggested by the Company that the nearby "earthquake" caused the collapse. However, the "event" showed several unmistakable signs of being very shallow, with seismic energy mainly in low frequencies and intense but small "felt" area, more typical of a collapse than of a tectonic earthquake. In addition, when a later improved seismic relocation of the "event" placed it within a few kilometers of the collapse area (42.7768°N, 77.8603°W), it became clear that the mine collapse was not caused by an earthquake but was the "earthquake". The initial mine collapse at 350m depth, and the subtle ground deformation at the surface directly above, later led to additional smaller collapses at depth and much more intense deformation of the ground at the surface, including two deep 200 m diameter sinkholes. A change in the mining technique in that part of the mine could be the cause for the initial collapse there but additional or other causes cannot be ruled out. After March 25 the "seismic aftershock" activity was monitored by a four-station seismic network operated by the New York State Geological Survey in cooperation with the Akzo-Nobel Company. The smoked-paper portable seismic recorders were provided by the NYS Geological Survey (3) and the Cornell University (1). During the total period of monitoring (March 94-April 96) about 1000 "events" were detected. Most of them were tiny (m<0), and all were confined near the initial collapse area. In most cases the detected seismic activity at the surface could be associated only in general terms with the complex deformation and collapse of the region below. In spite of a major, costly effort by the Akzo-Nobel Company to plug the "leak," the whole extensive mine, in operation for over 100 years, was lost to flooding by the end of September 1995. The mine was located under the Genesee River flood plain and the collapse occurred directly under Beards Creek, a small tributary. The loss of the mine amounts to a loss of a 12 million dollar payroll and over 325 jobs and represents a severe economic and social blow for the Livingston County.

New Seismic Hazard Maps for the United States: Deaggregation, Uniform-Hazard Spectra, and Uncertainty

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We have completed new probabalistic seismic hazard maps for the conterminous United States, which are available in electronic or printed form at our website at http://geohazards.cr.usgs.gov. The maps show peak ground acceleration and 0.2-, 0.3-, and 1.0-second response spectral values for 10%, 5%, and 2% probabilities of exceedance in 50 years. Design maps derived from the hazard maps will be included in the 1997 edition of the NEHRP Recommended Provisions for Seismic Regulations for New Buildings, a resource document for building codes published by the Building Seismic Safety Council. We used three models to compute the hazard: 1) smoothed historical seismicity, 2) faults with recurrence times derived from geologic slip rates - most of them in the western U.S., and 3) broad background zones for areas with low historic activity. Logic trees were used to account for alternative models of seismicity, fault recurrence, and ground-motion attenuation. Hazard curves were calculated for more than 100,000 sites. We have deaggregated the hazard into magnitude and distance contributions for 100 cities. In the central and eastern U.S. large, distant earthquakes (New Madrid and Charleston) generally dominate the low-frequency (1 Hz) hazard, while close, moderate-size earthquakes tend to dominate the high-frequency (> 3 Hz) hazard. We will compare uniform-hazard spectra for several cities, and discuss how uncertainties in seismicity parameters, maximum magnitudes, and attenuation relations contribute to uncertainty in the estimated hazard.

Lake Sediments and Holocene Seismic Hazard Assessment Within the St-Lawrence Valley, Québec

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Seismoacoustic profiling of 34 lacustrine basins within the St.Lawrence Valley in southern Québec shows the presence of faulting, convolution, diapirs, and gravitational slumping beneath, within, and at the surface of the Holocene deep-water-sediment zone. In small, deep lakes in the highlands of the Charlevoix-Tadoussac region, a thin (2-6m) Holocene organic sedimentary unit, which directly overlies over a seismo-opaque substratum, exhibits considerable deformation. These subaquatic sediment disruptions are exclusively restricted to lakes located within a radius of about 100 km of the well-known Charlevoix seismic zone.

According to the present seismicity of the region and the spatial distribution of the slump frequency, the minimal-triggering threshold for earthquakes was found to be as low as 0.17 g. These results indicate that the Charlevoix seismic zone has occupied the same area throughout at least the Holocene, and it appears that no major seismic shock has occured over the past several thousand years outside of the zone.

The Relationship Between Hypocenters and Crustal Velocities in the New Madrid and Eastern Tennessee Seismic Zones

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Seismic velocity studies in the New Madrid Seismic Zone (NMSZ) prior to the installation of the closely spaced, three-component PANDA stations, have indicated a positive correlation between anomalously low velocity and earthquake occurrence. The positive correlation has been attributed to the presence of fluid-saturated cracks and microcracks; increased pore pressure reduces effective stress and facilitates fault movement. A recent joint hypocenter-velocity inversion for the Eastern Tennessee Seismic Zone (ETSZ) indicates a different relationship between hypocenters and velocity anomalies. Although the magnitude of the low velocity anomalies found for the ETSZ are comparable to those found for the NMSZ, hypocenters do not concentrate in regions of lowest velocity. Earthquakes tend to occur in regions of average velocity located either between large magnitude velocity anomalies of the same sign or between velocity anomalies of opposite sign. Earthquakes in the ETSZ probably occur on ancient faults and fractures, some of which separate rocks of different composition. Reactivation of fault segments may be controlled by variations in fluid pressure.

The relationship between hypocenters and velocity anomalies has important implications for the mechanism generating earthquakes, particularly in intraplate seismic zones. The differences in the relationship noted above for the NMSZ and the ETSZ prompted us to conduct a new joint hypocenter-velocity inversion for the NMSZ incorporating data obtained by PANDA stations. The inversion involves an initial data set of 925 earthquakes providing 8,661 P-wave and 8,887 S-wave arrival times recorded during the period 1989–1992. Preliminary results indicate that earthquakes do not concentrate in regions of lowest velocity. The implications of this result for earthquake generation mechanisms will be discussed.

NEW SEISMOTECTONIC MAPS OF THE LOWER WABASH VALLEY AREA

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A folio of six 1:250,000-scale, colored maps of southwestern Indiana, southeastern Illinois, and western Kentucky spans 36.5°-39°N and 87°-89°W. The maps resulted from a collaboration between the USGS and the Illinois Basin Consortium (IBC – the Illinois State (ISGS), Indiana, and Kentucky Geological Surveys). The first two maps of the folio show seismicity and intensities (USGS maps I-2583-A and -B, 1996). The second two present locations of selected wells, geophysical data sources, and structures, and are exhibited here. The last two show the engineered infrastructure and thicknesses and lithologies of surficial materials, and will be published by the IBC as ISGS on-demand open files. The digital database of the maps will be published separately.

The map area includes the Wabash seismic zone, epicenters of 16 damaging historical earthquakes, epicentral areas of four large prehistoric shocks, most of the sparsely seismically active Rough Creek Graben, and the northeastern end of the coeval, seismically active Reelfoot Rift. The structure map shows exposed and near-surface faults, and fault traces on the buried Cambrian-Precambrian unconformity. Structure contours on the unconformity indicate that it reaches depths exceeding 6.7 km in the Reelfoot Rift and 9.1 km in the Rough Creek Graben. Thus, the structure map allows estimation of shapes and locations of a few large faults at hypocentral depths. The structure map also locates known and suspected neotectonic features; 202 known and aeromagnetically inferred, Early Permian, alkalic, ultramafic dikes and sills; and three large lineaments inferred from potential-field analyses. The lineaments – the Commerce Geophysical, South-Central Magnetic, and Paducah Gravity Lineaments -- show various spatial relations to epicenters.

Did the Opening of the Central Atlantic Ocean Reactivate Faults in the Saguenay-Charlevoix Area?

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The triangular Jacques-Cartier horst (JCH) appears to have seismogenic boundaries at least along its southeastern (the Charlevoix-Kamouraskaseismic source zone) and northern (the 1988 Saguenay earthquake) sides. It has an isostatic behavior different from that of the surrounding areas. The question is whether or not there is also a distinct tectonic environment. We propose that three features in the Saguenay-Charlevoix area (the northeast corner of the JCH) , that are characterized by downfaulted Ordovician sediments and well defined fault scarps, have reached their final form during the Jurassic opening of the Central Atlantic Ocean (190-170 ma): 1- Some fault segments of the Iapetan rift margin (ca 600 ma) along the north shore of the St-Lawrence river were reactivated during the late middle Ordovician Taconian Orogeny (450 ma) and were reactivated again in post middle Ordovician times. The reactivated rift margin forms the southeast side of the JCH. 2- The north side of the JCH is bound by the the Saguenay graben , the present-day features of which (offset walls and twisted floor) are best interpreted as a post middle Ordovician trans-tensional basin. 3- The Devonian Charlevoix astrobleme (360 ma) is transected near its center by a composite fault scarp along the north shore of the St-Lawrence river, and only the NW third of its outline exhibits a conspicuous scarp. Two N-S relay fault zones link it to the Saguenay graben across the northeast tip of the JCH. The N-S St-Maurice lineament, which is aligned with the Hudson River - Lake Champlain lineament to the south, forms the third side of the JCH. The mafic dykes of Jurassic age found along the St-Lawrence river near Kingston (Ont.) and at Anticosti Island (Qué.) indicate the extent of continental stretching related to the break-up of Pangea. The preservation of Ordovician limestones within the early Mesozoic (214 ma) Manicouagan astrobleme is consistent with the delay till the Jurassic of the final uplift of the Canadian Shield to the north of the St-Lawrence River in eastern Québec. Thus, the JCH appears to be a partly uncoupled tectonic block along the southeast side of the Canadian Shield hinging about the St-Maurice lineament.

A Case Study of Historians', Geologists' and Geophysicists' Contribution to Emergency Preparedness Planning in St. Lawrence, Newfoundland

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A tsunami struck the Burin Peninsula of Newfoundland in the early evening of November 18, 1929 after the 1702 NST magnitude 7.2 earthquake occurred in the Laurentian Slope Seismic Zone. The tsunami swept into the coast of Newfoundland two-and-a-half hours after the seismic event near the top of a high spring tide. Water levels first fell below normal, then rose two to seven metres. At the heads of several long narrow bays on the Burin Peninsula the momentum of the tsunami carried water as high as 27 m. St. Lawrence at the head of Great St. Lawrence harbour was one of the communities inundated, fortunately with no loss of life, but with substantial property damage. The collective community memory of St. Lawrence has been sampled through oral history interviews with senior community members aged 72 to 96 years, through first-hand reports of residents published in late-1929 newspaper accounts, and through various other published and unpublished accounts available. These recollections have been transcribed onto a 1: 2500 contoured topographic map of the community to map the 1929 tsunami runup zone. The map indicates a 1929 tsunami height of about 4 m, a runup height of about 13 m and a runup distance of at least 760 m at the head of the harbour. A tsunami-laid sand layer in the dark peat between the Bank of Nova Scotia and the high school provides graphic evidence of the 1929 tsunami's path.

St. Lawrence has grown since 1929 and has encroached steadily into the 1929 tsunami runup zone. Some 30 residents, all the fishing activity, almost all the St. Lawrence commercial activity, its two gasoline stations, the fire station, the RCMP office, the pharmacy, the bank, the high school, the recreation centre and soccer fields, the town hall and garage, a water treatment facility, the senior citizens' manor and three important bridges and their related roads could be severely affected. St. Lawrence presently has no planning policies to address further growth in a potential tsunami runup zone and does not have provision for a tsunami alert in its *Emergency/ Disaster Plan*. The study suggests that emergency measures personnel develop a plan that institutes a tsunami alert the moment a strong felt earthquake is experienced in southern Newfoundland. It is suggested that such people be reacquainted with the plan every two years to allow for new or rotating personnel.

Behaviour and Design of Seismic Resistant Concrete Structures

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Seismic resistant structures are designed for strength and ductility. These two design quantities are closely linked, while being inversely proportional. Often, the required strength for elastic response during an earthquake can not be justified, and hence the design force level is lowered as the ductility requirement becomes more stringent. In Eastern Canada, where the level of seismic activity is low in comparison to the Pacific coast, ductility requirements are easily attainable, but should not be ignored. Improving ductility of a structure built from a brittle material like concrete often posses challenges to structural engineers. This is done through proper detailing of reinforcement used in concrete. The level of detailing required is closely related to the expected level of ductility and associated seismic activity of the region. Therefore, a close and an important link exists between the activities of structural engineers and seismologists.

Strength and ductility demands of a structure during seismic excitations can only be established if the structure at hand is analysed using a reliable analysis tool, equipped with well verified analytical models. Even then, the analysis can not provide meaningful results if the ground motion record employed is not representative of the seismic region and the soil conditions involved. Therefore, previously recorded strong motion accelerograms and artificial design earthquakes are employed with care and apprehension. Because of inherent uncertainties associated with representative earthquake motions and associated seismic demands, structural engineers often concentrate on improving the capacity rather than to improve the accuracy of demand. Strength and ductility capacities of structural components are improved to satisfy certain conservative criteria established through past experience. This involves laboratory testing of large structural components under simulated seismic action in the form of slowly applied static load reversals. The results of such experimental research are used to establish the design methods included in building codes. It is the objective of this paper to illustrate the analysis and design approaches followed by structural engineers in designing earthquake resistant concrete structures, while also illustrating the need for a closer relationship between structural engineers and seismologists.

The Dillsburg, Pennsylvania, Earthquake of 16 June 1997

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An earthquake with duration magnitude 2.4 occurred about 0543:17 UT, 16 June 1997,near the town of Dillsburg in northern York County, Pennsylvania. An intensity survey located the center of the zone of maximum intensity (MM IV) at 40.445 N., 77.002 W. An initial conjecture that this event might have been caused by collapse of one of the abandoned magnetite mines in the vicinity was rejected because no mines are located within the zone of maximum intensity.The maximum intensity zone has a marked elongation along azimuth 340 degrees, which is roughly perpendicular to the northwestern margin of the Gettysburg Basin, a Mesozoic rift associated with past seismicity in southeastern Pennsylvania. The inferred epicenter is located within the basin, on the clastic Gettysburg Formation, about 7.5 km. southeast of the basin margin. This is the first well-documented earthquake to have occurred near the basin margin west of the Susquehanna River. Although no faults have been mapped previously in the immediate vicinity of the epicenter, evidence for a nearly north-striking fault just west of the zone of maximum intensity has been found in field work following the event.

Intensitites were enhanced, especially at the MM III level, on thick diabase sills north and east of the epicenter. This enhancement did not occur, however, on a small erosional remnant of a sill located west of the epicenter. A relatively strong aftershock (duration magnitude 1.6) was felt about 0204 UT, 17 June, and local residents report continued seismicity as recently as 3 August 1997.

The Geologic Stability of the Coastal Plain of South Carolina

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The marine terraces and estuaries of the Coastal Plain of South Carolina contain topographic features that mark high-stands of the sea. These prehistoric sea level markers constrain tectonic deformation over the past 1.6 million years in a 30,000 square kilometer region surrounding the epicenter of the Charleston, South Carolina, earthquake of 1886. By deciphering the chronological development of the marine terraces, single terraces could be statistically analyzed to determine the vertical distortion of features marking high-stands of the sea. The current elevation and distortion of ancient sea level references suggests that regional deformation, tilt parallel to the current shoreline is sub-meter across 500 kilometers over the past 1.6 million years. The sub-meter deformation is on the order of and compatible with glacio-isostatic response, but is not consistent with repeated vertical movement of faults that would suggest long term seismic activity. Distinct submeter vertical displacements covering less than 100 km are only identified within marine terraces which are less than one million years old, those within 50 km of the current shoreline. They were found in regions near Savannah, Charleston, and Myrtle Beach, and are coincident with regions containing paleoliquefaction and historic liquefaction features. Based on the findings of this study the Coastal Plain within 250 kilometers of Charleston, South Carolina, and inland to the Orangeburg Escarpment has been deformed locally by less than a meter over the last 1.6 million years. The upward displacement of the area coincident with the aftershock zone of the 1886 Charleston earthquake appears to be between 0.5 and 1 meter.

Characterizing Microseismicity Associated with Water Injection in an Oil Field

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We analyze the microseismicity associated with a fluid injection operation performed at Imperial Oil Ltd's Cold Lake oil field in Alberta. The experiment consisted of several water injection tests with the injection rate increasing from 2 m3/hr to 40 m3/hr, for a total injected volume of 1100 m3. The seismic activity was monitored using a 32-channel data acquisition system in the frequency range from 10 Hz to 2 kHz. The test site included a primary well used for water injection into the shales at a depth of about 220 m, and four observation wells located around the injection well at distances of 60m to 100m. Two three-component geophone assemblies with downhole amplification were lowered at 200m and 250m of depth and cemented in place in one observation well. Strings of 5 hydrophones (depth range: 180m-260m) were lowered in each of the three other observation wells. Primacord shots in the well bores before and after the experiment were used to orient the 3-component geophones, to quantify P- and S-wave velocities and to calibrate the data acquisition system.

The several hundred events recorded during these tests can be classified into three categories. 'Noise events' consisted of low-frequency signals related to the injection process and water circulation within the formation. 'Local events' showed high-frequency signals detected by sensors at one borehole only. 'Microseismic events', on the other hand, had clear P- and S-wave arrivals and were generally detected by sensors in more than one borehole. The frequency content of the signals of different types of events varies in the range from several tens of Hertz to several hundreds of Hertz. A collection of 12 microseismic events was selected for an in-depth analysis of the origin of microseismicity. The ratio of Peak Particle Velocity (PPV) of S-waves to that of P-waves varies in the range 0.7- 1.4. Also, the ratio of S-wave energy to P-wave energy varies in the range 1-10 with one exception. There is definite evidence that the latter ratio for natural earthquakes ranges between 10 and 30 (e.g. Boatwright and Fletcher, 1984). The above observations indicate that the present events are not caused by pure shear failure. Spectral analysis was performed using an interactive graphics package. Corner frequencies of P- and S-waves are in the range 15-100 Hz; a higher value was found for P-wave signals in the majority of cases. Applying the Brune's model to the present data would result in source radii of the order of 2-15 m and unusually low values for stress drop. The moment magnitude of the present events ranges between -1.5 and -3.

S-Wave Attenuation Measurements in a Deep Hard-Rock Mine

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We study the attenuation of S waves generated by mine-induced seismic events in a hard-rock mine in Ontario, Canada. Creighton mine is themost seismically active mine in the Sudbury mining district in northern Ontario. Mine-induced activity in the magnitude range ($0 < mN < 3$) was recorded by a macroseismic data acquisition system installed by CANMET at this mine. Seismic signals in the frequency range 1 - 1500 Hz are detected by five triaxial sensors installed in the depth range 1.5 - 2.0 km. The system has been fully calibrated and the FFT (Fast Fourier Transform) spectra are corrected for the response of the system.

A collection of 150 events was analyzed in the present study. Source-sensor distances for these events are less than 1 km and mainly in the 0.2 - 0.6 km range. The spectral decay technique was used for attenuation measurements. This method consists of measuring the slope of the high-frequency descending trend of displacement spectra of recorded signals using a least-squares technique and estimating the quality factor of S-waves (Qs) based on the difference between the measured slope and the most often observed value of –2. The measured Qs factors vary in the range 20–500, the maximum concentration being in the range 50–150. The results indicate the need for attenuation correction prior to measuring seismic source parameters, specially for events recorded at large distances. Lower values (Qs < 50) seem to be related to the presence of zones of highly fractured rock and can be used as an indication of the presence of such zones.

On the Nature of Reservoir-induced Seismicity

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In most cases of reservoir induced seismicity, seismicity follows the impoundment, large lake level changes, or filling at a later time above the highest water level achieved till then. We classify this as initial seismicity. This "initial seismicity" is ascribable to the coupled poroelastic response of the reservoir to initial filling or water level changes. It is characterized by an increase in seismicity above preimpoundment levels, large event(s), general stabilization and (usually) a lack of seismicity beneath the deepest part of the reservoir, widespread seismicity on the periphery, migrating outwards in one or more directions. With time, there is a decrease in both the number and magnitudes of earthquakes, with the seismicity returning to preimpoundment levels.

However, after several years some reservoirs continue to be active; whereas, there is no seismicity at others. Preliminary results of two dimensional (similar to those by Roeloffs, 1988) calculations suggest that, this "protracted seismicity" depends on the frequency and amplitude of lake level changes, reservoir dimensions and hydromechanical properties of the substratum. Strength changes show delays with respect to lake level changes. Longer period water level changes (~1 year) are more likely to cause deeper and larger earthquakes than short period water level changes. Earthquakes occur at reservoirs where the lake level changes are comparable or a large fraction of the least depth of water. The seismicity is likely to be more widespread and deeper for a larger reservoir than for a smaller one. The induced seismicity is observed both beneath the deepest part of the reservoir and in the surrounding areas. The location of the seismicity is governed by the nature of faulting below and near the reservoir.

Soil Profiles in Areas of Paleoliquefaction in the Coastal Plain of South Carolina

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During the last decade, over 100 paleoliquefaction features (sand blows) have been discovered in the Coastal Plain of South Carolina. Using Standard Penetration Testing we obtained blow-counts and split-spoon samples at four sites. Data were collected on the banks of drainage ditches at Gapway and Sampit in Georgetown County and at two sites near the Charleston Air Force Base (CAFB). SPT data and split-spoon samples were obtained in four borings at Gapway, two of which were adjacent to sand blows. At Sampit data were obtained in six borings, three of which were adjacent to sand blows. The borings ranged in depth from 20-30 ft. At all locations a clay layer was found, with almost zero blow counts. Its thickness varied between 5 and 10 ft, and its top was at a depth of 6-8 ft at Gapway, 21-24 ft at Sampit. A layer of clean sand overlying this clay layer was found to be the source bed of the sand blows. It was found to be 2-4 ft thick, and was overlaid by varying thickness of sands and clays. The occurrence of sand blows was found to depend on the relative thickness of the source sands, the overlying mixed (sand/clay) and underlying clay layers. A similar soil profile was obtained at CAFB (near Ten Mile Hill) the location of extensive sand blows associated with the 1886 Charleston earthquake.

Characterization of Rock Mass Behaviour Using Induced Microseismicity

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Several case studies are presented on the use of seismic techniques to map active structures, evaluate changes in stress levels, and identify the conditions leading to large magnitude seismic events and the generation of rockbursts in Canadian mines. The results suggest that microseismicity can be used to identify the orientation of active fractures; define regions of relatively high and low stress, and those most likely to host a rockburst; determine the role of local stress on observed shear failures; and identify the path of stress transfer associated with the remote triggering of rockbursts. Additionally, the conditions leading to rockbursts can be characterized by a significant increase in the clustering of microseismic events along the fault plane orientation of an impending event, and an increase in the effective stress levels. It is concluded that the analysis of microseismicity provides the means for remotely monitoring rock mass behaviour as a result of mining.

A Natural Hazards Electronic Map and Assessment Tools Information System (NHEMATIS)

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The Natural Hazards Electronic Map and Assessment Tools Information System (NHEMATIS) is a centralized, automated facility for the collection, representation, and analysis of natural hazard information. It is intended that NHEMATIS will be combined with characterizations of population and infrastructure to allow diverse risk and vulnerability analyses, with subsequent impact on both policy-making and readiness. In supporting risk assessment, NHEMATIS will, in the long term, include complex analysis and modelling capabilities to address the Canadian situation, including neighbourhood analysis, network analysis, topological analysis, and visibility analysis. It is expected that custom development will be required to address a substantial portion of these requirements. The envisioned risk assessment application is intended to provide a number of significant benefits, including shared knowledge between hazard experts and national, provincial, and local organizations who have a vested interest in supporting emergency preparedness for various geographic locations in Canada. It is intended also that NHEMATIS be a means of integrating the knowledge base of professionals from complementary disciplines, to provide a valuable source of data for research purposes.

It is envisioned that the NHEMATIS System will be built over a four year period. At the present time it is in its third year of development, with the NHEMATIS prototype v0.2 successfully completed March 31, 1997. NHEMATIS is being developed by a consortium of companies led by ESSA Software Ltd. of Vancouver. ESSA has extensive experience in the application of systems methodologies, simulation modelling, and software development in the areas of natural resource management and environmental and social analysis. LaMorte and Associates, another company in the consortium, is responsible for working with other hazard management experts to develop the hazard assessment methodology for NHEMATIS. LaMorte and Associates have experience in the areas of hazard assessment, emergency response, and natural hazard issues. Geomatics International, a third company, is responsible for collecting, assessing and converting the spatial data that will be utilized in NHEMATIS. Geomatics International is a well respected company in the provision of Geographic Information Systems database construction. Within the federal government, scientific expertise and data is being provided by Environment Canada, Natural Resources Canada, and Public Works and Government Services Canada.

The NHEMATIS System employs an application shell that integrates an expert system driven rulebase, Geographic Information System (GIS) functionality (using ESRI's ArcView product), relational database(s) and quantitative models. The system will demonstrate the ability to integrate information on all natural hazard types, capture location specific information, provide drill-down capabilities and provide hazard impact assessment modelling capabilities on selected areas of interest and hazard types.

The first version of NHEMATIS (prototype v0.1) demonstrated the feasibility of the overall concept including basic analytical and forecasting functionality and showed it's applicability as an emergency planning tool. It was based on ArcView 2.1 for it's GIS capabilities. Phase 2 (prototype v0.2) integrates the new enhanced ArcView 3.0 functionality which gives more advanced analytical capabilities to provide greater quantitative abilities to NHEMATIS. Some of the features incorporated into Phase 2 of the NHEMATIS system include:

- Advanced models and algorithms used to predict earthquake damage from shaking, liquefaction, landslides, and fire.
- Development of a general algorithmic approach to the estimation of building damage from earthquakes and other hazards.
- Development of basic algorithms for floods and landslides as separate hazards.
- Incorporation of polygon clipping into the inferencing process to give more accurate and realistic damage predictions for all hazards but particularly for tornadoes.
- Enhancement of the system to produce useful map output based on the impacts of the hazards on combinations of different components.
- Compilation of extensive geographic databases for five main study areas (Vancouver, Regional Municipality of Ottawa-Carleton, Edmonton, Montreal and Fredericton) and, in addition, development of a British Columbia regional study area to demonstrate the use of NHEMATIS at this scale.
- Enhancement of the user interface through the production of wizards for selecting and managing study areas, specifying hazards, and creating map outputs.
- Incorporation of new features of ArcView 3.0 including polygon operators to allow polygon clipping and raster map operators for enhanced map production.

The third phase of development of NHEMATIS will focus more intensively on working with potential end users and further refining both the system and the understanding of how it can best be packaged and used. This phase of development will bring NHEMATIS to a stage to begin operationalizing the system in the fourth year of the project. During Phase 3, ESSA Software Ltd. will continue to work with domain experts from Environment Canada, Natural Resources Canada, Public Works and Government Services Canada, as well as U.S. agencies, to refine, review, and further develop hazards knowledge.

Influence of Excavations and Geologic Structures on Seismic Strain Rates and Trajectories

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This study attempts to use pressure and tension axes calculated from microseismic events ($M < 0$) to evaluate spatial variations in seismic strain rate associated with successive stages of a sill pillar excavation between April and June, 1993, at about 900 m depth in Campbell mine, Canada. Microseismic monitoring was carried out using an underground 64 channel microseismic network. A total 559 fault plane solutions were obtained based on at least 13 polarity readings for events with moment magnitudes ranging from -2.8 to 0. Generally, the strain trajectories were similar in orientation to the regional stress field, however, in close proximity to excavations, they were highly variable (interchange of intermediate and minimum strain axes) as a result of local perturbations in the stress field. Increased strain rates adjacent to excavations were considered to define the extent of excavation influence, whereas similar increases away from openings showed strong correlations with the presence of geologic contacts and dykes. Further investigations will onsider the relationship of seismic strain rates to measured (underground) and 3-D numerical modelling derived strain parameters.

Does the Seismogenic St. Lawrence Fault Zone Extend Into the Western Lake Ontario Area?

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The populous and industrial western Lake Ontario area is the center of ongoing debates regarding earthquake potential. Because seismicity results from movement along faults, the characteristics of the major faults and seismicity there must be known in trying to resolve the differences which are relevant to earthquake risk.

It has been postulated that the seismically active St. Lawrence fault zone (SLFZ) extends along the St. Lawrence valley and Lake Ontario toward the center of the U.S. Conversely it has been suggested that, rather than reaching Lake Ontario, it stops in the area of Cornwall (Ontario)-Massena (New York).

The Rochester Basin, an ENE-trending linear trough in the southeastern corner of Lake Ontario, lies along the proposed extension of the southern part of the SLFZ. Submarine dives in May, 1997 revealed inclined layers of glaciolacustrine clay along two different scarps within the basin. The strata strike parallel to the long dimension of the basin, and dip about 20% to the NNW suggesting that they are the result of rigid body rotation consequent upon recent faulting. If the Rochester Basin lies along the SLFZ, which remains to be proved, those findings bear on the seismic hazard around western Lake Ontario.

ULF—The Unlocated Local Seismic Event Filter

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The Geological Survey of Canada (GSC) uses a conventional STA/LTA algorithm to detect seismic events in the data stream of the Canadian National Seismograph Network (CNSN). The CNSN detector is implemented in the frequency domain in four spectral bands simultaneously (typically 1-3 hz, 3-6 hz, 6-12 hz and 12-15 hz) and applied to vertical-component signals from all stations. Local earthquakes and blasts are (almost) always detected, but the problem is that the detector also produces many noise detections which make it difficult and labour intensive for seismologists to verify the real events. Approximately 6000 detections are recorded each day for the 40 CNSN stations east of the Rocky Mountains, of which only 2-3% represent the signals from local seismic events. The CNSN detector output is fed into the automatic real-time location system which groups and associates detections from different stations and produces provisional locationand magnitude for the larger local seismic events, but many of the smaller events still go unlocated and unrecognised.

In order to improve the detection capability for small magnitude local seismic events, the GSC have developed additional criteria to identify and classify local seismic events from the single station data streams, i.e. an Unlocated local seismic event Filter (ULF). The ULF criteria provide,

1 an almost two-order-of-magnitude improvement in the signal-to-noise ratio in the detection of local seismic events over the conventional STA/LTA detector,
2 efficient identification of short-duration complex noise spikes, including signals from ice cracks, and
3 single-station preliminary local magnitudes for unlocated events

ULF criteria have been used routinely in the processing of local seismicity from the CNSN stations in eastern and northern Canada for more than six months. The presentation will give some examples of the process and its outputs.

Seismic Images of the Grenville and Superior Provinces of the Southeastern Canadian Shield From Recent Lithoprobe Seismic Refraction/Wide-Angle and Near-Vertical Reflection Surveys

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Over the past few years, a series of long range Lithoprobe seismic refraction/wide-angle reflection and near vertical reflection experiments were conducted across the southeastern part of the Canadian Shield. The Central Metasedimentary belt, the Grenville Front, the Sudbury basin and the Abitibi-Greenstone belt were some of the key targets of these studies.A tomographic analysis of the 1992 seismic refraction data was performed in two stages. In the first stage a delay-time method was adapted to obtain information on the near surface velocity structure. In the second stage the deeper portions of the models were parameterized for lateral and vertical heterogeneity using triangular blocks. Velocity anomaly images were also produced by subtracting the regional crustal gradients from the conventional velocity solutions. Our refraction results were also compared to images derived from near vertical experiments where available. The latter images were produced using a pattern recognition method for stacking the seismic traces.

The results of our analysis show that the Central Metasedimentary belt and Grenville Front tectonic zones are made up of a southeast dipping region of anomalous velocity gradients and shear zones. The velocities under the Grenville Province were in general much larger than under the Superior province. The Sudbury basin is well imaged as a basinal structure of low velocity underlain by a moderately dipping velocity gradient. The Moho was in general not visible in the near vertical data. The wide-angle data showed great variability in thickness and depth in the transition zone from one terrane to another. The sharpest Moho occurred south of the Grenville Front in a region where the crust thickens.

The New Madrid and Southern Appalachian Cooperative Seismic Networks

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The Center of Earthquake Research and Information (CERI) at the University of Memphis operates two regional seismic networks in collaboration with four other eastern academic institutions. The Cooperative New Madrid Seismic Network (CNMSN) is operated jointly with Saint Louis University (SLU) and is designed to monitor seismic activity in the New Madrid Seismic Zone (NMSZ) covering portions of Missouri, Illinois, Kentucky, Tennessee, Mississippi, and Arkansas. Historical and geologic records reveal that the NMSZ is capable of repeatedly producing very large earthquakes. Prior to 1900 several magnitude 6+ events occurred, including the 1811-1812 New Madrid sequence of three M~8 events. Currently over a dozen earthquakes are felt in the region each year. The Southern Appalachian Cooperative Seismic Network(SACSN) is operated in collaboration with Virginia Polytechnic Institute, and the University of North Carolina at Chapel Hill and is designed to monitor seismic activity in the Southern Appalachian Seismic Zone (SASZ) which covers portions of Kentucky, West Virginia, Virginia, North Carolina, South Carolina, Georgia, Alabama, and Tennessee. The SASZ has produced the second highest release of seismic strain energy in the U.S. east of the Rockies during the last decade, using seismic moment release per unit crustal volume as a basis of comparison; only the NMSZ is more seismogenic. Unlike the NMSZ, the SASZ has not experienced a large, destructive earthquake in historical time (the largest known event is the Feb. 21, 1916 magnitude>5 western North Carolina earthquake). The spatial dimensions of the SASZ and its association with prominent potential field anomalies, however, suggest that the potential for larger, more damaging earthquakes is greater than the historical record suggests. Over the past few years we have focused our efforts in upgrading the field hardware to 3-component short period and broadband stations. The CNMSN design consists of 76 short-period and 28 broadband stations; the SACSN includes 44 short-period and 5 broadband stations. Each collaborating institution operates independently and thus datalogging and telemetry systems vary. Due to unavoidable telemetry requirements, some data are FM transmitted to remote nodes where they are digitized, and where the datalogging system "eqacquire" records triggered data segments. For nodes without direct internet access, postscript images of the triggered data streams are transferred daily to CERI via ISDN telephone for routine event classification. Appropriate data files are subsequently transferred for location and/or archiving. We expect to have the short-period upgrades completed by 1997 and the broadband upgrades completed by 1998. Additionally we have recently focused considerable resources on streamlining and automating the routine and rapid response processing as well as providing end user products such as timely bulletins, CNSS and CSS3.0 parametric archives, and SEED waveform archives. This research is supported by the U.S. Geological Survey (USGS), Departmentof the Interior, under USGS award numbers 1434-95-A-10296 and 1434-95-A-10297.

An Automatic Real-Time Earthquake Location System for the Canadian Landmass

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Automatic location of regional earthquakes in an area the size of Canada presents challenges because of uneven distribution of seismic stations and large areas with sparse coverage, a variety of types of seismic noise sources, and the necessity of identifying and utilizing regional phases.

The initial FFT-based detector is run on the continuous data from each station, averaging about 100-150 detections per day on each of 50 stations. From these, autoloc selects groups of detections which are close in time and space and which have good SNR and signal duration; waveforms associated with these are extracted for further processing. Three-component processing provides azimuthal estimates for P-type phases (P, Pn and Pg) and verticality and coherence information which is useful for classifying phases as P-type or S-type. Angle of emergence also provides a very rough distance estimate.

A grid search is conducted, with an initial grid over Canada and coarser grid over most of the rest of the globe; then two stages of finer grids near the suspected epicentre. The effect on location of false detections on noise is largely eliminated by the use of a non-least-squares norm which assigns an unvarying zero weight to phases with large time residuals. Azimuth estimates and other information are incorporated into the solution process in a natural and straightforward way.The weight for each phase is the product of functions of the time residual and azimuth residual, distance and phase type estimates, if any. The weight for a phase is adjusted downwards if the station is much more distant from the epicentre than the nearest station to the epicentre which did not detect the event; this helps eliminate unlikely solutions. For each epicentre, each arrival is tried as a P, S or Lg phase, and associated as the phase type with the highest weight. The epicentre with the highest norm (sum of weights for all phases) is chosen as the location. The location program attempts to find further events using the leftover unassociated detections; thus events in different parts of the country close in time can be found.

Email messages with the automatically-determined locations of the seismic events are sent out to seismologists in real time (usually within 6 to 8 minutes of the events).

Seismic Hazards in Southern Ontario—Analysis of Uncertainty

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In this paper we present the analysis of the probabilistic seismic hazard model developed in the companion paper by K.J. Coppersmith, T.A. Crampton, and R.R. Youngs. The seismic hazard model included both regional source zones and local feature-specific seismic sources. The uncertainties in defining specific sources and characterizing the frequency, spatial distribution, and size distribution of future earthquakes was modeled by a logic tree formulation with 19 levels of uncertainty. Extensive sensitivity analyses were conducted to examine the effect of alternative interpretations of seismic sources and source parameters on the seismic hazard at sites in southern Ontario. The logic tree formulation was used to disaggregate the overall uncertainty in the seismic hazard into the contributions from each of the 19 levels of uncertainty in the seismic hazard model. Major contributors to the uncertainty in the hazard include: uncertainty in attenuation models and attenuation model parameters, evaluation of whether or not the local features represent seismic sources, characterization of the local sources as zones or true faults, and uncertainty in estimates the Gutenberg-Richter b-value in areas of low seismicity. Reduction of the uncertainties in many of these assessments is expected to occur with the gradual advancement of scientific understanding of the earthquake process in the region. The study was sponsored by the Atomic Energy Control Board of Canada.

Seismic Wave Propagation and Source Parameters from Mine Tremors in Southern Africa

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Crustal and upper mantle structure of southern Africa and source parameters are being investigated by regional waveform modeling using data from South African mine tremors, and by teleseismic receiver functions. A moderate seismic event (mb 5.6, Ms 4.7) occurred in South Africa on October 30, 1994 at the President Brand mine, likely caused by mining activities. Several other events have also occurred near or at this mine. The source processes of these events are important because 1) they may have special source properties different from that of natural earthquakes; 2) source properties of seismicity induced by mining can provide information for industrial operators to monitor and control such seismicity; and 3) source properties of mining seismicity are important for seismic discrimination problems. The source depths and source mechanisms of these events are investigated using both teleseismic and regional waveform data. The results for the 1994 October 30 event indicate that this event occurred at a very shallow depth (1 km), and the moment tensor inversion results contain a large non-double-couple component. The regional waveforms contain a large vertical SV phase which can not be easily explained by double-couple mechanisms, a non-double-couple component in the source's moment tensor is required to model this phase. Regional wave propagation is understood by modeling the body and surface waveforms. Teleseismic receiver function data are used to investigate the thickness of the crust and the average seismic velocities. Preliminary results indicate a simple one layer crust in which seismic velocities gradually increase with depth. A very thin top layer is required to model the regional surface waves.