CRUSTAL MOTION AND DEFORMATION MONITORING OF THE CANADIAN LANDMASS

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The science of geodesy and the corresponding reference systems it develops have increasingly been applied to measuring motions and slow deformations of the Earth's crust driven by plate tectonics. Improvements to geodetic methodologies have therefore enabled better understanding of the Earth's systems, including improved modelling and forecasting of changes that may affect society. These geophysical processes also systematically affect the reference frames used as standards for geodetic surveys. Reference frames therefore must not only define the system of coordinate axes (including orientation, origin, and scale), but also characterize the time-evolution of spatial coordinates on the Earth's surface. When evaluating the effect on reference standards within a given area, it is also important to realize that geodynamic processes operate on various spatial scales. In this paper we summarize some of NRCan's efforts to monitor contemporary crustal dynamics across Canada. Progressing from continental to smaller regional scales, we outline the rationale, techniques, and results. The observational data and interpretations presented are fundamentally dependent on the Canadian Spatial Reference System yet in turn also contribute to the incremental improvement of its definition and maintenance.

La science de la géodésie et les systèmes de référence correspondants ont été de plus en plus utilisés pour mesurer les mouvements et les lentes déformations de la croûte terrestre causés par les plaques tectoniques. L'amélioration des méthodes géodésiques nous a donc permis de mieux comprendre les systèmes de la Terre en nous permettant, entres autres, de mieux modéliser et prévoir les changements qui risquent de nous toucher. Ces processus géophysiques modifient aussi systématiquement les cadres de référence qui servent de normes aux levés géodésiques. Les cadres de référence doivent alors non seulement définir le système des axes des coordonnées (incluant l'orientation, l'origine et l'échelle), mais doivent aussi définir l'évolution temporelle des coordonnées spatiales sur la surface terrestre. Lorsqu'on évalue leur effet sur les normes de référence dans une zone donnée, il est aussi important de réaliser que les processus géodynamiques se produisent à plusieurs échelles spatiales. Dans cet article, nous résumerons certains des efforts de surveillance de la dynamique contemporaine de la croûte terrestre canadienne par Ressources naturelles Canada. De l'échelle continentale à l'échelle régionale, nous présenterons un survol du besoin, des techniques et des résultats. Les données et les interprétations observationnelles présentées dépendent fondamentalement du Système canadien de référence spatiale tout en contribuant à l'amélioration de sa définition et à sa maintenance.

1. Introduction

> *Today the Earth Sciences Sector (ESS) continues to respond to the Order in Council that created the Geodetic Survey of Canada in 1909 tasking the then Minister of Interior "to determine… the positions of points throughout the country… which may form the basis of surveys for all purposes, topographical, engineering or cadastral, and thereby assist in the survey work carried on by other departments of the Dominion Government, by Provincial Governments, and by municipalities, private persons or corporations."*

[passage from Canadian Spatial Reference System (CSRS) service logic model].

Geodynamic monitoring is demanding in terms of observational accuracy and stability over a wide range of spatial- and temporal-scales. An appropriate reference frame is a requisite tool that enables better understanding of geodynamic systems that in turn provides better constraints to predicted impacts on society. However, the effects of geodynamic and geophysical crustal deformation processes can systematically bias the reference frames used for geodetic surveys. Kinematic processes affecting the Earth's surface can systematically affect geodetic measurements and ultimately lead to inconsistencies between observations at different epochs. As measurement and processing accuracies and requirements have increased, the Canadian Spatial Reference System (CSRS) is now in an era in which the time-variability of its outputs must be evaluated.

For Canada the largest observed deformation rates are at the level of 1-2 cm/yr. Millimetre-per-year resolution, and better, is required to investigate many processes of the dynamic Earth and consequently to better quantify their potential impacts on society (*e.g.* natural hazard and climate change effects). Measuring these rates requires very high-precision geodetic techniques coupled with suitably long observation windows. The frequency of observations is largely dependent on the magnitude of the deformation process and the precision of the measurement technique. Survey design and data processing must also consider any quasi-periodic signals (*e.g.* the annual signals resolved by GPS) that could bias estimates of geodynamic motions.

Within ESS of Natural Resources Canada (NRCan), regions of geophysical interest (particularly hazards) have warranted densified geodetic infrastructure. For ESS, long-term topics of interest for geodetic investigations include studies of post-glacial isostatic adjustment across the Canadian landmass, the Saint Lawrence seismic zone in eastern Canada, the active plate boundary above the Cascadia subduction zone along Canada's west coast, and the active fault margin of the Queen Charlotte Islands. Additionally, investigations of the vulnerability of Canada's coasts to climate change processes have increasingly relied on precise geodetic observations.

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Targeted regional studies within ESS augment the CSRS and thus contribute to aiding and strengthening international services to the geophysical and geomatics communities. The international- and national-scale geodynamic monitoring efforts, in turn, support regional deformation studies. Within a specific region there are often different kinematic processes operating on various spatial scales. At the largest scale, rigid tectonic plate motions may need to be considered. Then, measuring long-wavelength signals at a broader (*e.g.* national) scale provides the regional deformation "background signal" which is useful when assessing more localized deformation signals during regionally-targeted kinematic studies.

This paper outlines a number of efforts within ESS that contribute to monitoring crustal motion and deformation at differing scales across the Canadian landmass. It is not a complete review, but rather intends to provide a well-rounded cross-section of Sector studies. Progressing from larger to smaller spatial scales, the rationale, methodology, and results (for established studies) are summarized for the geodynamic investigations. Although this article emphasizes the work of ESS, a considerable amount of data, analyses, and interpretations have been dependent on the work and productive collaborations of numerous other groups and agencies. Further information and details may be found in the publications referenced in each section.

2. Global-Scale Plate Kinematics and the ITRF

With the wide-spread use of space-based techniques for positioning in the scientific and engineering communities, a unified and consistent global spatial reference system has long been necessary. The International Terrestrial Reference System (ITRS) was proposed and implemented over two decades ago. Its physical realization, the International Terrestrial Reference Frame (ITRF), provides a high accuracy and easily accessible global coordinate system for the study of Earth dynamics at all scales [*Altamimi et al.* 2001]. Several updates of the ITRF have been made available with each one improving on its predecessor. Although originally developed for and by the scientific community, this system eventually became the most widely used reference system for positioning. For example, some countries have adopted versions of the ITRF as the national standard and even WGS84, the native reference system for GPS, is now based on ITRF. Additionally these frames provide velocity information and use kinematic constraints in their realizations.

Any ITRF is composed of a set of station coordinates at a given epoch and their velocities in three dimensions with appropriate covariance information. The frame is currently defined via four techniques: (1) Very Long Baseline Interferometry (VLBI), (2) Satellite Laser Ranging (SLR), (3) Global Positioning System (GPS), and (4) Détermination d'Orbite et Radiopositionement Intégré par Satellite (DORIS) [*Boucher et al.* 2004]. A combination of the techniques is necessary because none alone is sensitive to all the parameters necessary to define a reference frame. The combination takes advantage of the strength of each technique; *e.g.* the SLR contribution is essential for the determination of the origin while VLBI and SLR contribute to determine the scale. The combination of the networks from each technique also requires that they be connected at as many collocated sites as possible. Repeated local surveys are required to precisely measure the three-dimensional offsets between the markers for each collocated technique and detect any potential change. All of the techniques contribute to the velocity field, which is used to solve for the time evolution and the no-net rotation condition of the system. For the general user community, it is the GPS products (coordinates and satellite orbits) that enable easy access to the ITRF.

Earth scientists rely on ITRF products for many investigations related to large-scale mass redistribution, including characterization of the Earth's interior and climate change studies. In particular, space-geodetic techniques have revolutionized the study of plate tectonics. At one time, plate motion models were primarily constrained by seafloor magnetic anomalies and other geological information with rates averaged over millions of years. With GPS it is possible to directly measure contemporary tectonic plate movement on a time scale of years. The motion of any rigid body on the surface of a sphere can then be represented by a rate of rotation about an axis (*i.e.* Euler pole) and expressed as a rotation vector. The North American Plate, for example, undergoes a counter-clockwise rigid body rotation around an Euler pole located near equatorial, northwestern South America (*refer to* Figure 1). The associated tectonic plate motions for Canadian sites are on the order of 2 cm/yr.

When accurately defining the rotation vector of a plate, it is important to ignore stations biased by local site effects and those in known deforming zones unless reliable models of such deformations are available. Ideally, only the sites that best represent the rigid parts of the tectonic plate should be used. High-precision GPS has allowed scientists to discriminate subtle differences in velocities within what had been considered individual tectonic units, and in the process identify new plates or sub-plates and quantify their individual rotation vectors. The improved resolution of plate rotation vectors is also very useful for investigations that utilize kinematic information (*e.g.* fault and other crustal deformation studies). However, the comparison of precise GPS-determined results is often complicated by investigators using different techniques to produce a plate-fixed reference frame in which to express their results. For North America the SNARF initiative (discussed in the next section) will provide a consistent reference system in which scientific and geomatics results (*e.g.* positions in tectonically active areas) can be produced and inter-compared.

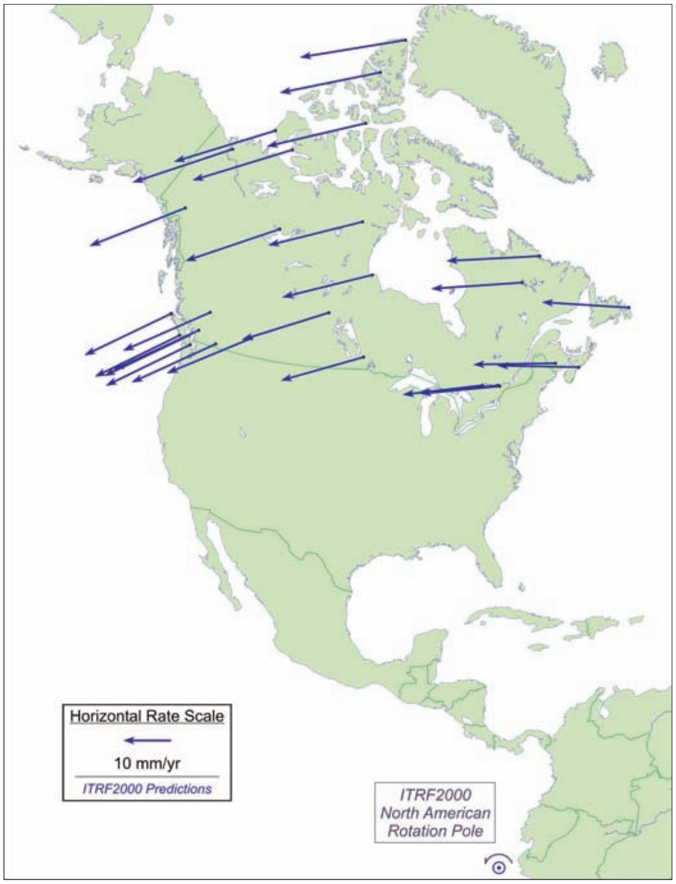

Figure 1: North American plate rotation pole and predicted velocities. The blue vectors represent the motion for those sites predicted from North American rotation about its pole. The arrow lengths are proportional to the rates at their origin point and are given for Canadian continuous GPS sites present in the IGS cumulative solution (GPS week 1345). The North American rotation pole is from ITRF2000 [*Altamimi et al.* 2002].

3. Continental & National Scale Monitoring Efforts

3.1 NAREF Densification of ITRF in North America

Since the beginning of 2000, ESS has been playing a leading role in the North American Reference Frame (NAREF) Working Group of the IAG Sub-Commission 1.3c (Regional Reference Frames for North America) [*Craymer and Piraszewski* 2001]. One of the primary objectives of this working group is the densification of the ITRF in North America using continuously operating GPS (CGPS) stations. Following the distributed processing approach advocated by the International GNSS Service (IGS) [*Blewitt* 1997], the NAREF working group members have been independently computing weekly regional coordinate solutions for CGPS sites throughout North America.

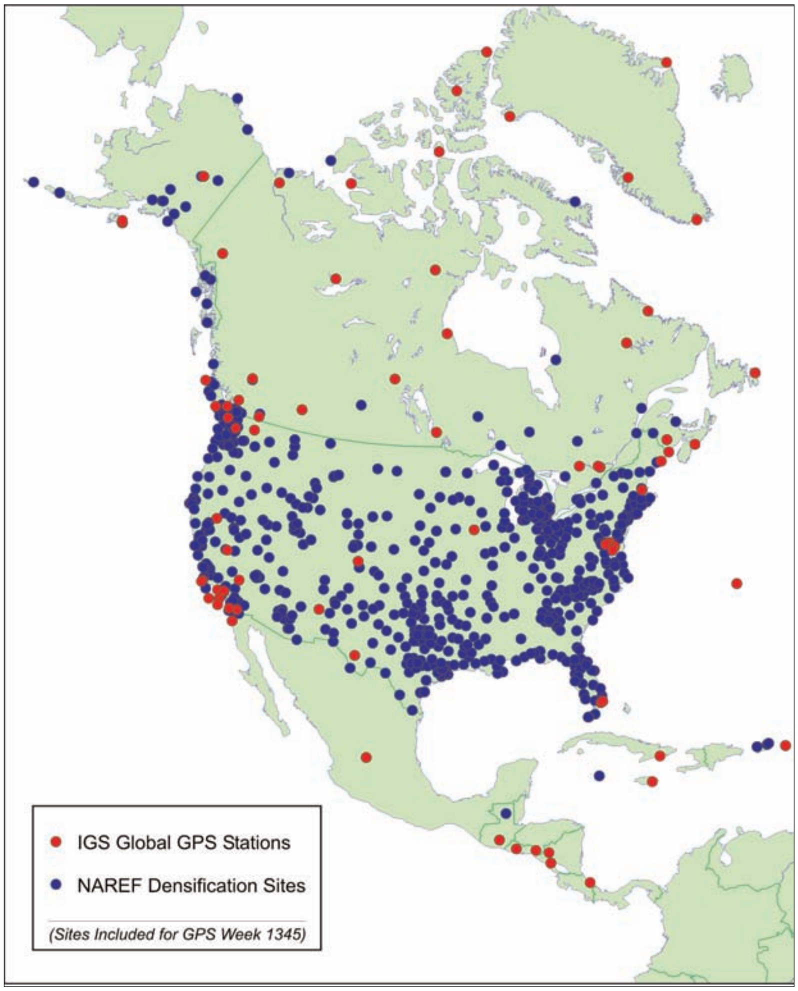

Figure 2: NAREF network of continuous operating GPS receivers. The red circles represent stations in the IGS global network while the blue circles represent densification stations.

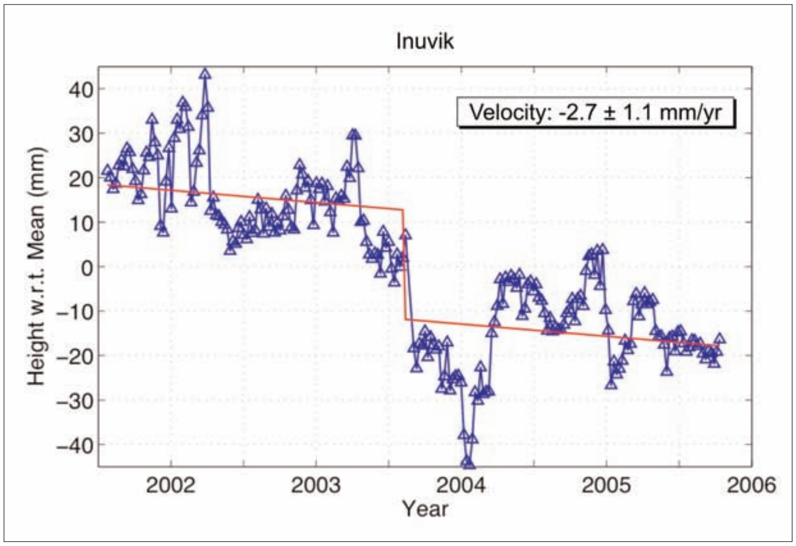

Figure 3: Time series for station INVK in Inuvik, NWT illustrating relatively large seasonal fluctuations primarily due the effects of snow on the antenna phase centre. Note also the step (discontinuity) in the time series just after 2003.5 due to the addition of an antenna dome.

NRCan has been producing three such weekly regional solutions for Canada. Two are being generated by NRCan's Geodetic Survey Division (GSD) on a regular basis for redundancy and quality control. One of these solutions incorporates additional stations just outside Canadian borders for further redundancy and continuity with American solutions. In addition, NRCan's Geological Survey of Canada—Pacific Division has also been contributing weekly solutions for their Western Canada Deformation Array (see later section) on the west coast. Other solutions include a preliminary version of the Plate Boundary Observatory from the Scripps Institution of Oceanography, and the entire US CORS (Continuously Operating Reference Stations) network from the US National Geodetic Survey that includes nearly 700 stations. More recently, efforts are underway to include stations from provincial GPS networks, including those of British Columbia, Quebec and, soon, New Brunswick.

Following internationally accepted densification methodologies [*Ferland et al.* 2003], these different regional solutions are being combined into a single NAREF weekly solution. NAREF combination solutions beginning the first week of 2001 have been submitted to the IGS data archives and are usually available with about a four-week latency. There are presently over 800 stations in the combined NAREF network (*refer to* Figure 2). Many stations are included in more than one solution to provide redundancy checks and to allow for the correct weighting of the different solutions relative to each other and to the global solutions. The goal is to have all stations included in at least two different solutions. All regional solutions agree with each other and with the global ITRF and IGS solutions at the level of a few millimetres.

The weekly NAREF solutions have recently been combined into a single so-called cumulative (multi-epoch) solution to provide estimates of both station coordinates and their velocities with respect to a consistent reference frame throughout North America. Velocity estimates with accuracies of less than 1 mm/yr are expected to be achievable in the near future with the accumulation of several years of data. This relatively long time series is required in order to estimate and remove systematic annual and semi-annual signals due to seasonal effects and discontinuities caused by changes in equipment or software (*refer to* Figure 3). Nevertheless, even today, these solutions can be used to support geodynamics studies of both large and small scale crustal motions, including the direct measurement of the motion of the North American tectonic plate and intra-plate deformations such as post-glacial rebound as discussed later in this paper. A preliminary version of this NAREF velocity solution has also been used to help define a North American plate-fixed reference frame for studies of intra-plate crustal motions (see next section).

3.2 A Stable North American Reference Frame (SNARF)

As discussed earlier, regional reference frames fixed to the stable part of a tectonic plate are often required to facilitate geophysical interpretation and inter-comparison of geodetic solutions of crustal motions. In 2003, the Stable North American Reference Frame (SNARF) Working Group was established under the auspices of UNAVCO, Inc. and IAG Regional Sub-Commission 1.3c for North America especially to address needs for the US-led EarthScope project. The goal is to define a regional reference frame that is consistent and stable at the sub-mm/yr level throughout North America.

The SNARF Working Group identified and addressed several issues that must be dealt with to properly define such regional frames, including (1) the selection of "frame sites" based on geologic and engineering criteria for stability, (2) the selection of a subset of "datum sites" which represent the stable part of the plate and will be used to define a no-net rotation condition, (3) the modelling of any significant intra-plate motions using a relatively dense GPS velocity field, and (4) the generation and distribution of reference and deformation products for general use [*Blewitt et al.* 2005]. The SNARF vertical datum is consistent with ITRF2000 in that the centre of mass of the whole Earth system is taken to be the origin while the horizontal datum differs by a rotation rate that brings the rotation of the stable part of North America to rest.

The first release of SNARF provides a rotation rate vector that transforms ITRF2000 velocities into the SNARF frame, and an initial reference frame is defined via a list of selected sites, epoch coordinates and velocities in a Cartesian system. This rotation effectively defines the SNARF reference frame in relation to the ITRF. It was computed using only stable sites from a combination of velocity solutions from GSD for the NAREF network and the Canadian Base Network (see next section), and a velocity solution from Purdue University for a selection of US CORS stations. Horizontal intra-plate velocities in the SNARF frame exhibit a pattern that is more consistent with expected deformations from post-glacial rebound than velocities obtained from other estimates; *e.g.*, ITRF2000 (*refer to* Figures 4a & 4b). In addition, these velocity solutions were also used to determine a semi-empirical model of post-glacial rebound based upon a novel assimilation technique that combines GPS velocities with a geophysical model [*Blewitt et al.* 2005] (*see* Figure 5). Over the next few years SNARF will be incrementally improved through further research and as more accurate velocity solutions become available.

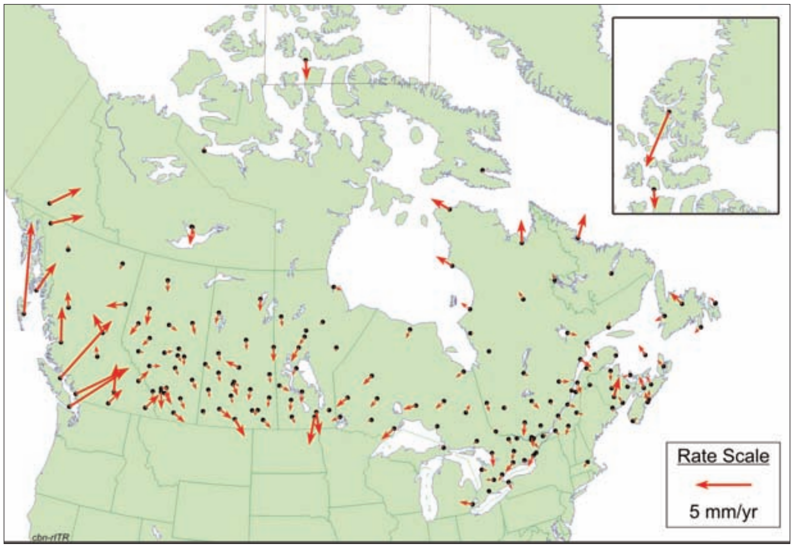

Figure 4a: Residual horizontal intra-plate velocities of CBN network using North American plate motion estimates (rotations) from ITRF2000. The plate motion estimate absorbs much of the horizontal motion from post-glacial rebound that is expected to radiate outward from the areas of maximum uplift. Little outward horizontal motion is seen in the intra-plate velocities.

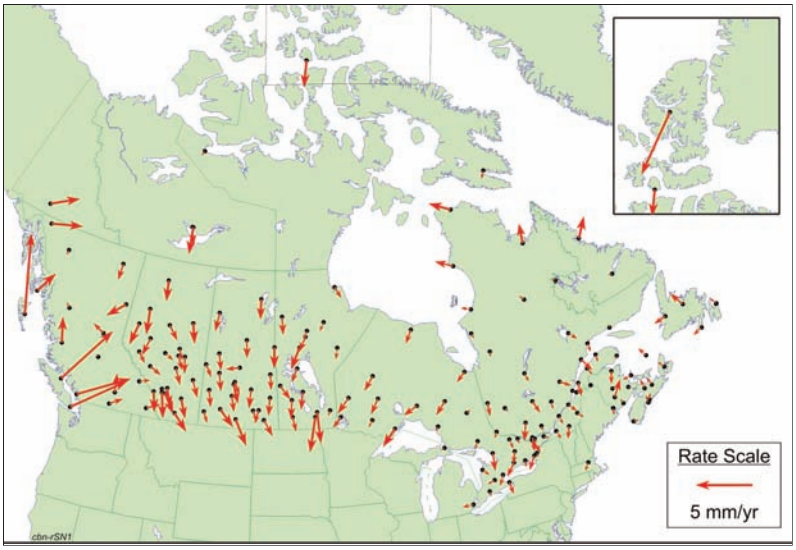

Figure 4b: Residual horizontal intra-plate velocities of CBN network using North American plate motion estimates (rotations) from SNARF 1.0. In this reference frame defined by the SNARF plate motion estimate, the outward pattern of intra-plate velocities is more clearly visible. The SNARF plate motion estimate is affected less by post-glacial rebound.

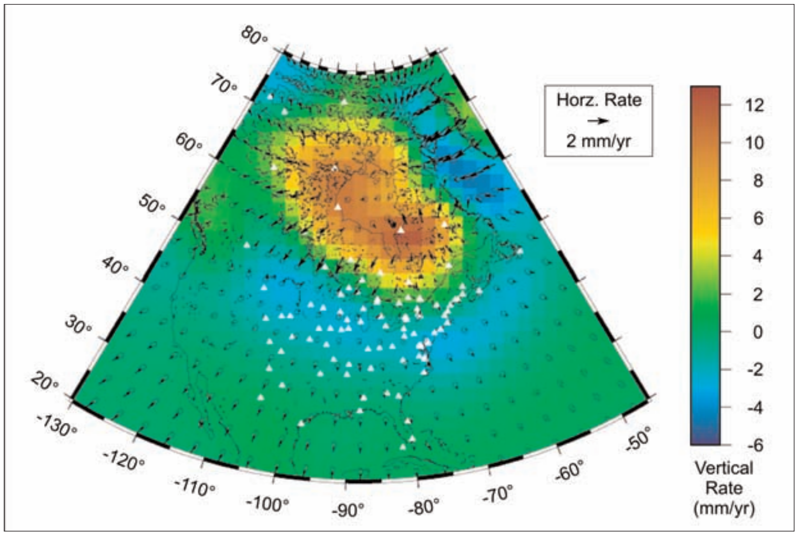

Figure 5: Post-glacial rebound rates from the SNARF model (courtesy of Jim Davis, Harvard-Smithsonian Center for Astrophysics [after *Blewitt et al.* 2005]). This empirical model of post-glacial rebound employs a novel technique that combines observed GPS velocities with a geophysical model.

3.3 Geodynamic Observations from the CBN

Initiated in 1994, the Canadian Base Network (CBN) is a national network of high-stability pillar monuments with forced-centering mounts for Global Positioning System (GPS) receiver antennas. The initial role of the CBN was to complement the Active Control System (ACS) of the CSRS by providing easily accessible 3D reference coordinate sites, with a reasonable distribution across Canada. In order to maintain the accuracy of the CSRS reference frame realization, CBN sites have been reoccupied to confirm initial positions and to detect crustal movements. By combining nearly 10 years of repeated multi-epoch (episodic) GPS measurements, GSD has begun to estimate velocities at the CBN sites in order to provide an increased spatial sampling of crustal deformation throughout Canada. To determine individual station velocities, regional CBN solutions for each measurement epoch are systematically combined into a single Canada-wide, multi-epoch cumulative solution (*i.e.* similar to the previous discussions for NAREF and SNARF). In order to generate time series of consistent, high-accuracy coordinates for velocity estimation, it is necessary to ensure consistency of the integration into the reference frame. This is accomplished by aligning each of the individual CBN solutions to a subset of stations from a recent cumulative solution for the IGS global network in ITRF. Fortunately, there are many IGS stations in Canada and most were included in each regional CBN solution to strengthen the connection to reference frame and ensure consistency between epochs. Consistent and realistic weighting of the individual CBN solutions is improved through the estimation of separate variance components relative to the IGS global solution. After the individual CBN solutions are aligned and weighted, they are combined together in a simultaneous cumulative solution to produce velocities at each site [*Henton et al.* 2004].

On the national scale, glacial isostatic adjustment is the most significant geodynamic process driving vertical deformation [*e.g., Tushingham and Peltier* 1991; *Peltier* 1994]. Preliminary results from the combination of CBN regional solutions in Canada exhibit a spatially coherent pattern of uplift consistent with the expected post-glacial rebound (PGR) signal (*refer to* Figure 6). Regions of highest uplift rates are generally consistent with areas of greatest ice accumulation during the last period of continental glaciation [*e.g., Dyke* 2004; *Peltier* 1994]. Horizontal velocities associated with PGR are also spatially coherent (typically directed radially outward from regions of highest uplift) but have smaller rates. These modest horizontal velocities can provide an important additional constraint to PGR models. However, the horizontal vectors may be significantly biased by differing reference system rotation-rate vectors (*e.g.*, Figures 4a & 4b). The definition of SNARF should minimize this issue. Eventually the deformation maps, coupled with PGR model predictions, may allow NRCan to interpolate or estimate coordinates at different epochs for regions that display spatial coherence in the velocity field.

3.4 Using Absolute Gravity to Monitor Uplift at CBN Sites

The integration of geodetic techniques is desirable when monitoring geodynamic processes (and simplifies any connections between corresponding reference standards). Absolute gravimetry (AG), which is independent of GPS, has demonstrated that it plays a complimentary role to GPS especially while measuring vertical crustal motions [*e.g., Lambert et al.* 2001]. In addition, repeated GPS and AG observations at common sites provide insight into the geophysical processes that drive the observed deformation since AG is sensitive to internal mass changes and not just deformation alone. Therefore, issues such as mass redistribution or changes in density contrasts within the Earth may be addressed by monitoring positional changes (*i.e.*, primarily height changes) and integrating these observations with gravitational variations. However, the observed rates of gravity change resulting from

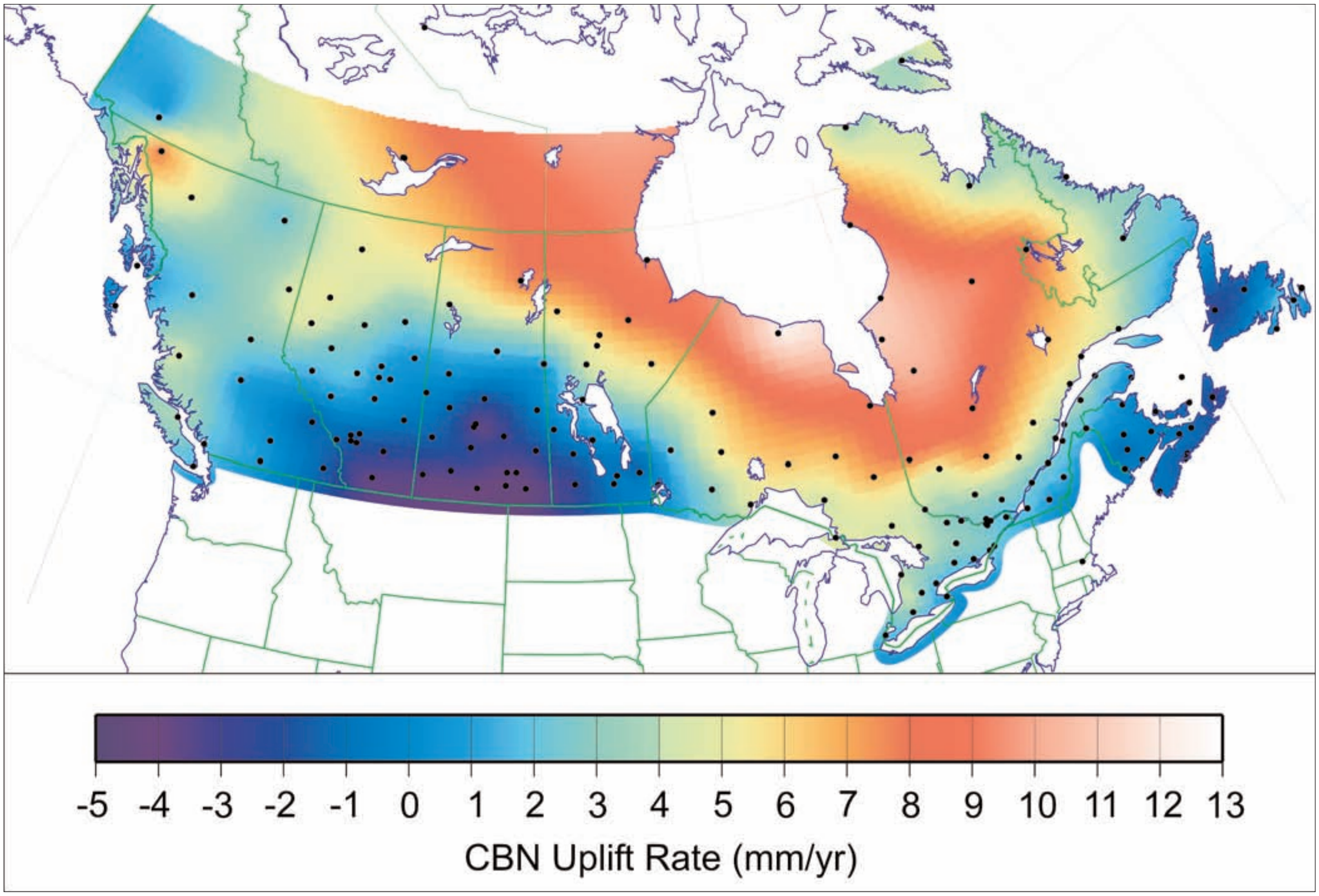

Figure 6: Contour map of observed CBN vertical rates. Preliminary results from the combination of CBN regional solutions in Canada exhibit a spatially coherent pattern of uplift consistent with the expected post-glacial rebound (PGR) signal. Black dots represent the locations of CBN sites.

post-glacial rebound in Canada are no greater than approximately -2 µGal/yr (one µGal is approximately one part-per-billion of the Earth's surface gravity). Observing such a small signal requires a suitable combination of high-precision and observation length. The principle of most modern absolute gravimeters is to observe (using laser interferometry) the acceleration of a free-falling test mass in a vacuum. This technique therefore requires very precise measurements of length and time over repeated "drops." Despite the simple fundamental principles, high-accuracy absolute gravimeters involve a great deal of instrumental and electronic sophistication. Properly operated and after careful processing, AG can provide the value of the Earth's gravity at a point with an accuracy of one part-per-billion, and the instruments can be maintained nearly drift-free. Also the AG instruments of the CSRS are tied to international standards through comparisons at the Bureau International des Poids et Mesures (BIPM). Continued improvements in absolute gravimetry have made these instruments more compact, robust, and efficient.

In order to monitor the temporal variations in gravity resulting from regional glacial isostatic adjustment, a set of absolute gravity measurement sites has been established in northern Quebec, collocated near pillars of the CBN. The Nouveau Quebec-Labrador region of eastern Canada was the site of one of the major ice domes of the Laurentide Ice Sheet [*e.g., Dyke* 2004; *Peltier* 1994] and is currently experiencing post-glacial rebound. For eastern Canada the highest uplift rates are in the vicinity of James Bay through to southwestern Labrador. Rates decrease to the south and become negative towards the coastal Atlantic margins. For post glacial rebound, surface gravity measurements sense the effect of increasing distance from the centre of mass of the earth (*i.e.* gravity decreases) coupled with the redistribution of mass due to viscous flow at great depth (increases gravity). The resulting regional gravity decrease associated with uplift due to post-glacial uplift is approximately -0.15 µGal/mm [*Lambert et al.* 2001]. Preliminary absolute-gravity trends for this region show decreasing gravity with time. Values range from about -2 μGal/yr (*i.e.* ~13 mm/yr for regional PGR) near Kuujjuarapik and Radisson and decrease southward to approximately -0.5 μGal/yr (~3 mm/yr) near Val d'Or. These preliminary results exhibit general agreement between the rates for GPS uplift velocities and gravity trends. Additionally, the observed (GPS & AG) rates are generally consistent with predictions of vertical crustal motion from post-glacial rebound models. To better contribute to the definition of the vertical component of a highly accurate, multi-purpose, active and integrated CSRS, efforts are now underway to create a sparse array of absolute gravity observation sites collocated with geometric reference (*i.e.* VLBI, continuous and episodic GPS) stations across Canada.

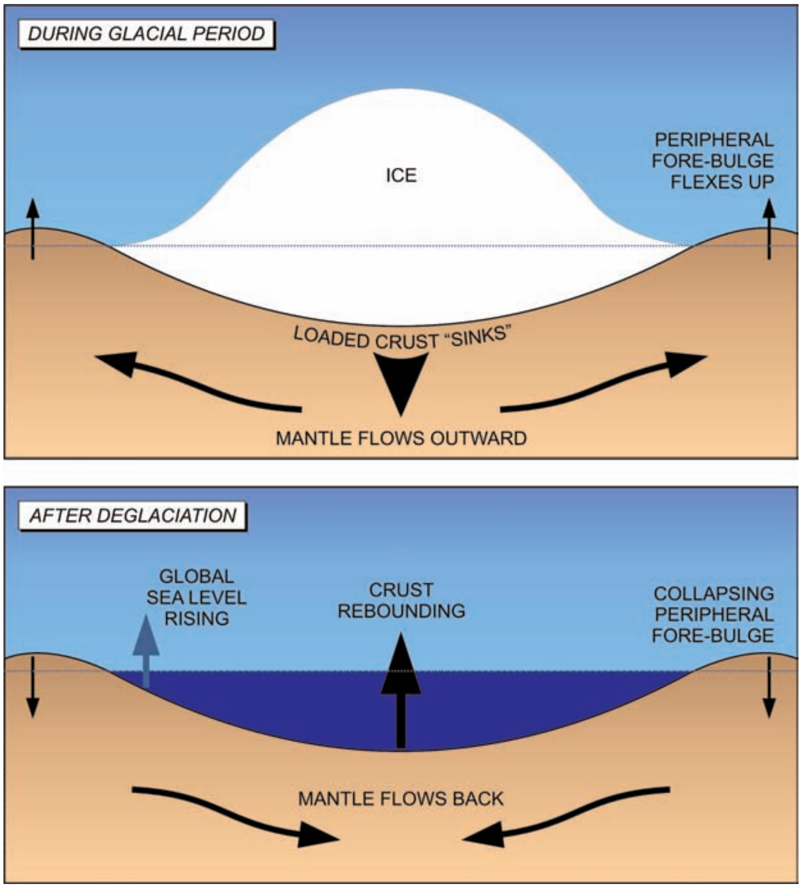

Figure 7: Generalized process of post-glacial rebound. The mantle acts like an extremely viscous fluid; it continues to flow back to regions where heavy ice sheets had forced out portions of the mantle 18,000 years ago. These regions, like northern Quebec, experience "post-glacial rebound." Around the edges of the ice sheet the crust flexes upward creating a peripheral fore-bulge. After deglaciation, the fore-bulge slowly collapses resulting in subsidence for regions such as the Maritimes.

4. Monitoring Relative Sea Level for Coastal Impact Studies

4.1 Introduction

As potential impacts of climate change and sea-level rise on coastlines depend in large measure on the localized rates of relative sea-level height change, it is important to quantify vertical deformation velocities in vulnerable coastal regions. The magnitude of the rate of relative sea-level change can be used to better understand future impacts (*e.g.* flooding, storm-surge levels). Sea level heights have traditionally been determined by tide gauges which measure the relative sea level height with respect to land. The long-term changes in relative sea level observed at tide gauges reflect both the vertical component of regional crustal kinematics and the change in the regional (and/or global) sea level surface. Through this linkage with relative sea level observations, understanding the kinematics of post-glacial rebound in vulnerable coastal areas is an important adjunct to relative sea level studies.

4.2 Eastern Canada

While most of the Canadian landmass is currently experiencing uplift associated with post-glacial isostatic adjustment, the Maritimes are experiencing subsidence. This is primarily due to collapse of the peripheral bulge following the deglaciation of the Laurentide Ice Sheet (*refer to* Figure 7), in addition to the effects of rising post-glacial sea level loading the continental shelf. The subsidence rates are not particularly large, typically on the order of -1 to -2 mm/yr. However they are of the opposite sign to sea level height change (on the order of +2 mm/yr) and consequently relative sea-level rise (with respect to land) is regionally more rapid. Sea-level rise can produce significant impacts in the coastal zone, particularly for low-lying parts of the Maritime Provinces [*e.g., Forbes et al.* 2004b]. These include storm impacts on the coast (waves, surges, and flooding), sediment movement and erosion hazards, impacts on ecological systems (*e.g.* coastal wetlands and fisheries), and damage to private or commercial property and public infrastructure [*e.g., O'Reilly et al.* 2005]. Work is underway within ESS to better quantify these hazards through the installation of additional geodetic infrastructure (*e.g.* new continuous GPS sites at select regional tide gauges).

4.3 Great Lakes

The Great Lakes is an important economic corridor where lower water levels can have significant impacts such as the need for expensive dredging of ports and harbours, and reduction in hydro-electric power generation. Additionally, elevated erosion rates have been evident in regions of the Great Lakes during previous higher water levels. These potential impacts ultimately depend in large measure on the rate of change of relative water-level heights with respect to land. Again, although the rate of crustal tilting driven by PGR is not particularly large, it steadily accumulates over time and can be clearly observed in water-level gauge records [*e.g., Mainville and Craymer* 2005]. This regional vertical deformation must be considered when evaluating long-term impacts on datums, water management, infrastructure, and basin ecology.

The regions north of the Great Lakes are rising faster than the regions to the south. In fact, much of the southern areas are part of the collapsing glacial "forebulge" and are experiencing subsidence. This on-going process of crustal "tilting" (*see* Figure 8) results in a pattern of slowly declining lake levels on northern shores with a commensurate rise in lake levels on southern shores. These relative changes of water level for a single lake can be resolved quite precisely from a long history of water gauge observations [*e.g., Mainville and Craymer* 2005]. However, it is difficult to accurately relate levels on one lake with those of another.

GPS stations have recently been established at Great Lakes water gauge sites in Canada by GSD in collaboration with the Ohio State University, and in the US by the US National Geodetic Survey. Combining these with other GPS measurements (*e.g.* the CBN) is enabling the determination of an accurate and spatially coherent pattern of absolute crustal velocities that is consistent with the expected rates of glacial isostatic adjustment. These results will enable lakes to be linked to each other as well as to sea level in support of bathymetry, hydraulic operations, and hydrological studies in the Great Lakes Basin.

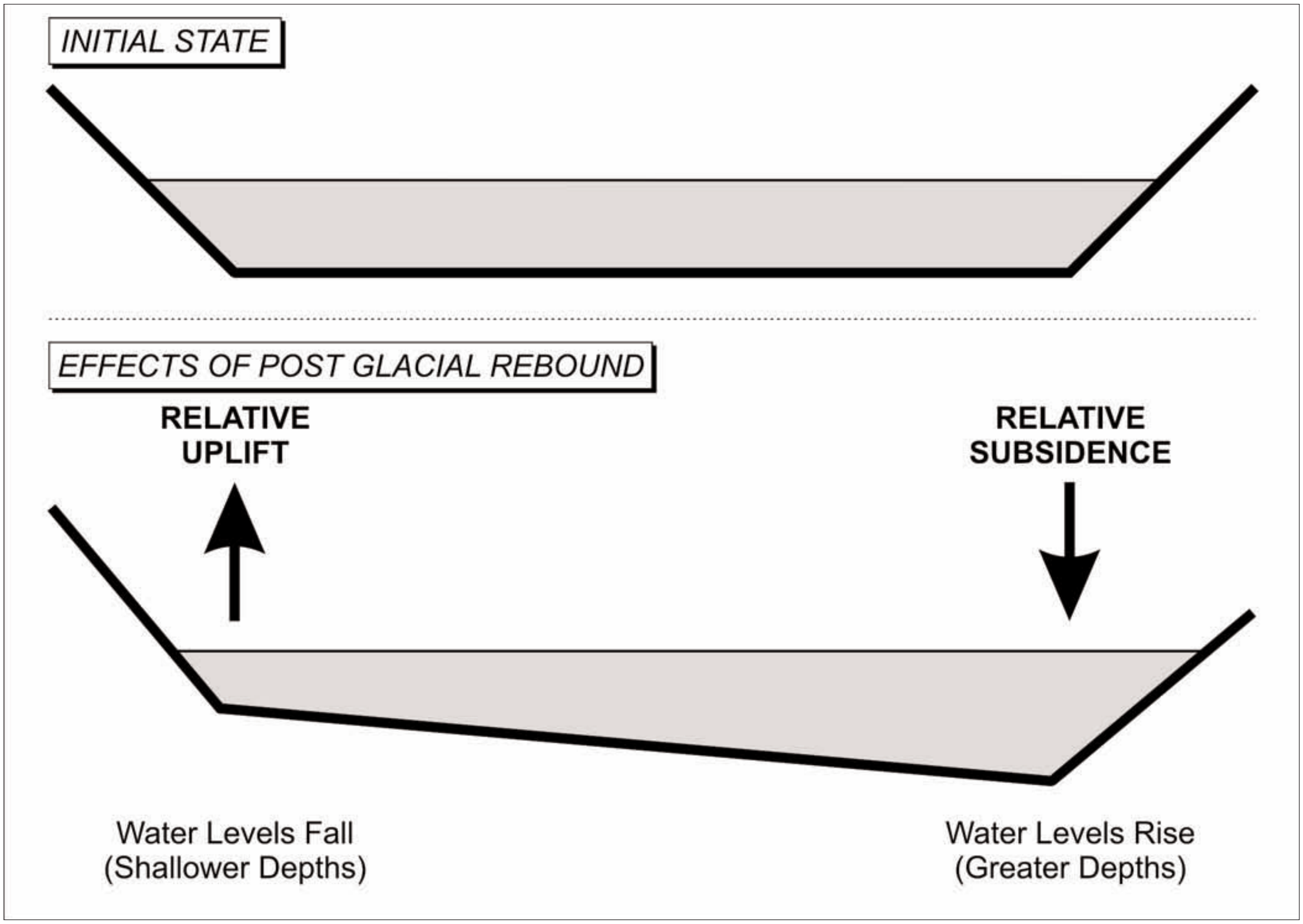

Figure 8: Glacial isostatic effects along lake shorelines. In addition to the effect of "tilting" generalized in this illustration, on-going changes in average water level may also contribute to the impact on vulnerable coastal regions.

4.4 Arctic Canada

Observed climate warming in the Arctic may lead to increases in Arctic Ocean sea level [*Proshutinsky et al.* 2001]. Sea-level rise increases the flooding risk and is a clear concern for coastal communities such as Tuktoyaktuk [*Manson et al.* 2005]. Furthermore the coastal area subject to rising relative sea level is expected to expand [*Forbes et al.*, 2004a]. With recent infrastructure development associated with hydrocarbon production in the Mackenzie River delta region, this work has become more timely. As the impacts on coastlines ultimately depend in large measure on the localized rate of relative sea level height change, it is important to better quantify crustal deformation velocities throughout coastal northern Canada. Inherent to this study is the need to better map the observed pattern of PGR throughout northern Canada in order to more tightly constrain post-glacial isostatic adjustment models.

To provide a framework in which to monitor these changes, a consistent velocity field will be determined from GPS observations throughout North America, including the Canadian Arctic Archipelago and the Mackenzie Delta region. To determine the contribution of vertical motion to sea-level rise under climate warming in the Canadian Arctic, ESS in collaboration with the Canadian Hydrographic Service has established collocated tide gauges and continuous GPS at a number of sites across the Canadian Arctic, from Alert and Qikiktarjuaq in the east to Ulukhaktok (Holman) and Tuktoyaktuk in the west. The continuous GPS sites have been augmented with multi-epoch (episodic) sites in places such as Kugluktuk (Coppermine) and Mercy Bay (northern Banks Island). This expanded network will further enhance regional geophysical studies including the discrimination of crustal motion, other components of coastal subsidence, and sea-level rise.

5. Campaign GPS Constraints on Regional Tectonics and Seismicity

5.1 Introduction

GPS and other geodetic measurements of crustal deformation provide an important new tool for estimating earthquake hazard. In addition to the standard method of earthquake hazard based on past earthquake statistics, it is now possible to relate current deformation rates to the frequency of large earthquakes. Both continuous and campaign GPS stations have been established for earthquake hazard in four areas, the western Canada subduction zone, the Queen Charlotte transform fault zone, the Yukon crustal deformation region, and the eastern Canada region of high seismicity.

As a complement to a network of continuous GPS stations, campaign GPS surveys provide an economical way to obtain a denser map of crustal deformation. Major limitations associated with campaign GPS measurements are: (1) lack of resolution of short-term (less than one year) deformation episodes, and (2) less accurate estimates of long-term velocities. Relative velocities across tectonically active regions are typically of the order of 5 - 50 mm/yr, which can generally be resolved with campaign GPS data acquired every year over a three to five year period. In the following sub-sections, two examples of campaign surveys in western Canada (Queen Charlotte Margin and Northwestern Canada, investigated in collaboration with University of Victoria) are described, where the relative motions are associated with plate boundary interactions and strain transfer within the Canadian Cordillera.

In contrast, relative velocities across intraplate (tectonically stable) regions are typically less than 1 mm/yr. Such relative motions are at the current limit of resolution of GPS measurements. An example of a GPS survey (in collaboration with Université Laval) of intraplate deformation at the eastern edge of the Canadian Shield along the lower Saint Lawrence Valley is presented. In all of the examples within this section, typical surveys consisted of measurements of two to three full days at each site. The data, along with data from nearby continuous stations, were processed at the Pacific Geoscience Centre (Geological Survey of Canada—Pacific Division, Sidney, BC) with the Bernese GPS Software package. Processing details can be found in the publications referenced in each section.

5.2 The Queen Charlotte Margin

Since mid Eocene (*ca.* 42 Ma), the Queen Charlotte (Q.C.) margin has been primarily under a strike-slip tectonic regime associated with the Pacific-North America relative motion [*Hyndman and Hamilton* 1993]. At about 5 Ma, a small change in the Pacific-America relative motion resulted in the current oblique convergence along Q.C. margin. A wide range of geophysical data indicates a component of convergence and possibly under-thrusting along the southern Q.C. margin (*e.g.* high offshore heat flow, seismic structure studies) [*Smith et al.* 2003]. The seismicity shows primarily strike-slip faulting (*e.g*. the great M=8.1 earthquake of 1949), although there are some thrust mechanisms near the southern end of the islands.

In 1998, NRCan established a small local network of five campaign GPS sites in the central and northeastern Q.C. Islands. These sites were re-surveyed in 1998 and 2001 [*Mazzotti et al.* 2003a]. In 2002, three new sites along the west coast of the islands and one on the mainland at Prince Rupert were then added [*Bustin et al.* 2004]. The full network (nine sites) has been surveyed every year from 2002 to 2005. These campaign GPS network sites were augmented by the continuous station at Williams Lake, to provide a stable tie to the North America plate, and campaign measurements from the Canadian Base Network sites in northern British Columbia, to provide some constraints for the kinematics of the central Cordillera. The GPS velocity field, with respect to North America, indicates oblique convergence along the Q.C. margin, with relative motion of 5 - 10 mm/yr directed mostly northward (*refer to* Figure 9). The landward gradient in left lateral shear (*i.e.* decrease in margin-parallel motion) shows that the Q.C. fault is currently locked and is building up strain until the next large earthquake rupture [*Mazzotti et al.* 2003a]. The results also show that a small component of the Pacific-North America oblique convergence (~10 per cent) is probably accommodated by distributed shear across the Q.C. margin and possibly in mainland [*Mazzotti et al.*, 2003b]. A possible interpretation is that this oblique convergence is accommodated mainly by partitioning into strike-slip earthquakes on the Q.C. fault and infrequent large under-thrusting earthquakes beneath the margin [*Bustin et al.*, 2004]. Thus, the earthquake hazard along the Q.C. margin may be higher than current estimates based solely on an active transcurrent Q.C. fault.

5.3 The Yukon & Northwestern Canada

Northwestern Canada is known for the intense tectonism during the Mesozoic (*ca.* 250 to 65 Ma) associated with the accretion and deformation of the different terranes that form the Canadian Cordillera. No sign of significant tectonic activity has been recorded along the major faults and deformation zones in most of northwestern Canada for the last ~50 Myr. In contrast, the southwestern Yukon Territory and adjacent Alaska Panhandle region is the locus of intense deformation due to the collision of the Yakutat block, a composite oceanic-continental terrane that is currently being accreted in the corner of the Gulf of Alaska. This collision produces the highest mountain ranges in Canada (*e.g.* St. Elias range and Mount Logan). Earthquake activity is very high in this collision zone including several M~8 events, but surprisingly substantial seismicity also occurs in the far-field Mackenzie and Richardson Mountains, around 800 kilometres northeast of the collision zone [*Mazzotti and Hyndman* 2002; *Hyndman et al.* 2005]. The Mackenzie Mountains appear to be undergoing NE-SW shortening, while N-S right-lateral strike-slip deformation is occurring in the Richardson Mountains.

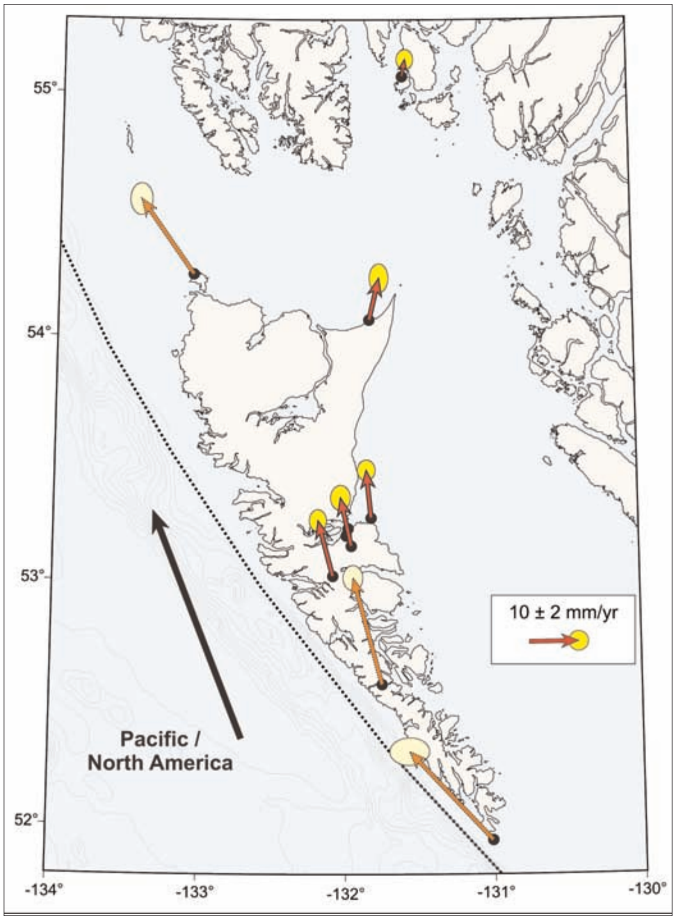

Figure 9: GPS velocities along the Queen Charlotte margin. Red and orange vectors show velocities with respect to stable North America for campaign sites with five years of data or more and three years of data, respectively. Uncertainty ellipses show the 95 per cent confidence region. The large black vector shows the motion (from the rotation vector of *DeMets and Dixon* [1999]) of the Pacific plate relative to North America.

In order to understand the details of the whole northwestern Canada tectonics and seismicity, NRCan started a campaign GPS survey in 1999 across the Yukon and Northwest Territories. The current network comprises 20 campaign GPS sites, supplemented by a larger network of 28 continuous GPS stations from British Columbia to Alaska [*Leonard et al.* 2005]. The campaign sites were surveyed at four or five epochs since 1999. The interpretation of these results have been complicated by the occurrence of the very large (magnitude M~8) Denali earthquake in December 2002. Coseismic and postseismic displacements related to this earthquake at our GPS sites reach a few centimetres and create an offset that needs to be removed in order to estimate the long-term velocities of our sites. Overall, the continuous and campaign GPS velocities are consistent with the transfer of compressive strain (~5 mm/yr) across the northern Canadian Cordillera to the foreland fold-and-thrust belt with little intervening deformation [*Mazzotti and Hyndman* 2002; *Leonard et al.* 2005] (*see* Figure 10). These results indicate that the whole northern Cordillera is currently part of the large-scale Pacific-North America plate boundary zone and accommodates about 10 per cent of the full relative plate motion.

5.4 The Lower Saint Lawrence Valley

The Saint Lawrence Valley, Quebec, presents one of the largest concentrations of earthquakes in eastern North America. Background seismicity extends over 900 kilometres from the Gulf of Saint Lawrence to Montreal following the Paleozoic Iapetan Rift system [*e.g., Adams and Basham* 1991; *Lamontage et al.* 2003]. Two main seismic zones occur along this trend: Charlevoix, the most active in eastern Canada and the locus of at least five M6+ earthquakes in the last 350 years; and lower Saint Lawrence, where the largest known earthquakes are about M5. Integration of earthquake moment statistics in both zones indicates that the equivalent seismic deformation rates are 1.0 ± 0.5 mm/yr and 0.2 ± 0.3 mm/yr, respectively [*Mazzotti and Adams* 2005; *Mazzotti et al.* 2005].

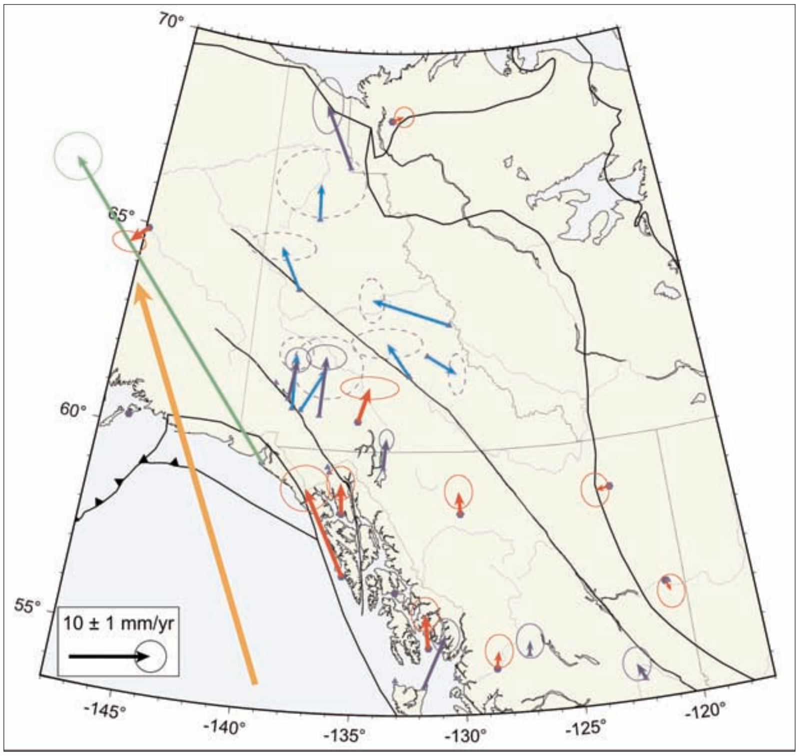

Figure 10: GPS velocities in northwestern Canada. Red and blue vectors show velocities with respect to stable North America for continuous and campaign GPS sites, respectively. The green vector shows the Yakutat site GPS velocity. Uncertainty ellipses show the 95 per cent confidence region. The large orange vector shows the Pacific/North America relative motion from *DeMets and Dixon* [1999].

Unlike plate margins where the seismic activity is directly correlated with plate interactions, eastern Canada earthquakes lie in the “stable” interior of the North American Plate. The driving mechanisms behind of these earthquakes are thus more difficult to determine. Additionally, the hazard posed by potentially devastating earthquakes for this region is not well constrained due to limitations with the probabilistic seismic hazard estimation method (*e.g.* the inexact nature of extrapolating the rate of occurrence of frequent small events to the occurrence of infrequent larger events, relatively short instrumental and historical records, and limited paleoseismic evidence for past large events).

In 2003, NRCan started a new program to study the geodynamic aspects of earthquake hazard in eastern Canada. The study [*Mazzotti et al.* 2005] used the existing network and data for the Canadian Base Network and added an additional survey to a network of 16 stations surrounding the Saint Lawrence Valley. These high-precision campaign data provide relative velocities and strain rates across both the Charlevoix and lower Saint Lawrence seismic zones based on three to four campaigns over the last seven to nine years. On a regional scale, horizontal strain rates are 0.5-2 nanostrain per year of roughly NNW-SSE shortening (*refer to* Figure 11). This strain pattern agrees well with earthquake focal mechanisms. Horizontal velocity vectors on both sides of the Saint Lawrence River suggest that this shortening corresponds to a maximum convergence of 0.5 ± 0.5 mm/yr between the north and south shores, in general agreement with the rate from earthquake statistics. Assuming that seismicity in Charlevoix follows typical Gutenberg-Richter statistics, the GPS results constrain the return of a potentially very damaging magnitude M~7 earthquake to ~170 years.

6. Monitoring Crustal Motions at an Active Plate Boundary with Continuous GPS

6.1 Introduction

The coastal region of southwestern British Columbia comprises the northern portion of the

Cascadia Subduction Zone (CSZ) that forms the convergent plate boundary between the Juan de Fuca and North America plates. This boundary is marked by extensive earthquake activity as well as a belt of active arc volcanoes stretching from northern California to southwest British Columbia. Special aspects of this subduction zone are the relative youth of the subducting oceanic crust, which ranges from six to 10 Ma at the oceanic trench, and a modest convergence rate of under 40 mm/yr. Seismic, thermal, and geodetic studies have determined that the shallower interface of the CSZ is locked, and that stress is accumulating for the next great subduction thrust earthquake. From paleoseismic evidence, such great events occur every 500 to 600 years, the last having occurred in 1700.

The monitoring of crustal motions along the coastal margin of southwestern BC using continuous GPS stations was initiated on Vancouver Island in 1992 with sites established in Victoria (ALBH) and Holberg (HOLB) [*Dragert and Hyndman* 1995]. These sites, along with a reference site near Penticton (DRAO), form the basis of the Western Canada Deformation Array (WCDA) which now consists of 16 stations in southwestern BC. Using low-multipath antennas mounted on stable geodetic monuments, the relative position of these stations hundreds of kilometres apart can be monitored on a daily basis to an accuracy of a few millimetres. This level of accuracy allows the resolution of long-term crustal movement associated with major plate motions as well as the relative squeezing and buckling of the plate margins. More recently, GPS data from a number of WCDA stations have also revealed transient crustal motions that are related to repeated slow slip on the deeper subducting plate interface.

6.2 Long-term Deformation

Analyses of GPS data from WCDA sites have confirmed that long-term elastic deformation occurs along the northern Cascadia Margin due to the locking of converging plates across a portion of the subduction interface between the Juan de Fuca (JDF) plate and the overlying North America (NA) plate [*cf. Flueck et al.* 1997; *Mazzotti et al.* 2003c]. The motion vectors shown in Figure 12, the largest exceeding 1 cm/yr, are based on the linear trends in the time series of changes in horizontal positions of GPS sites with respect to the reference site DRAO, located south of Penticton, British Columbia, and assumed fixed on the NA plate. The pattern of the regional crustal velocity field is a key constraint in determining the location and extent of the locked fault zone - *i.e.* that portion of the fault that will ultimately rupture in a great subduction-thrust earthquake [*cf. Wang et al.* 2003]. For the northern Cascadia margin, the fully locked portion of the subducting plate interface lies offshore beneath the continental slope and the "transition zone," marked by a transition from fully-locked to free-slipping plates, terminates directly beneath the coastline of Vancouver Island and the western edge of the Olympic Peninsula. The landward extent of the incipient rupture zone for the next megathrust earthquake is a key parameter for estimating strong motions that can be expected in the densely populated areas of Vancouver and Seattle from such an earthquake.

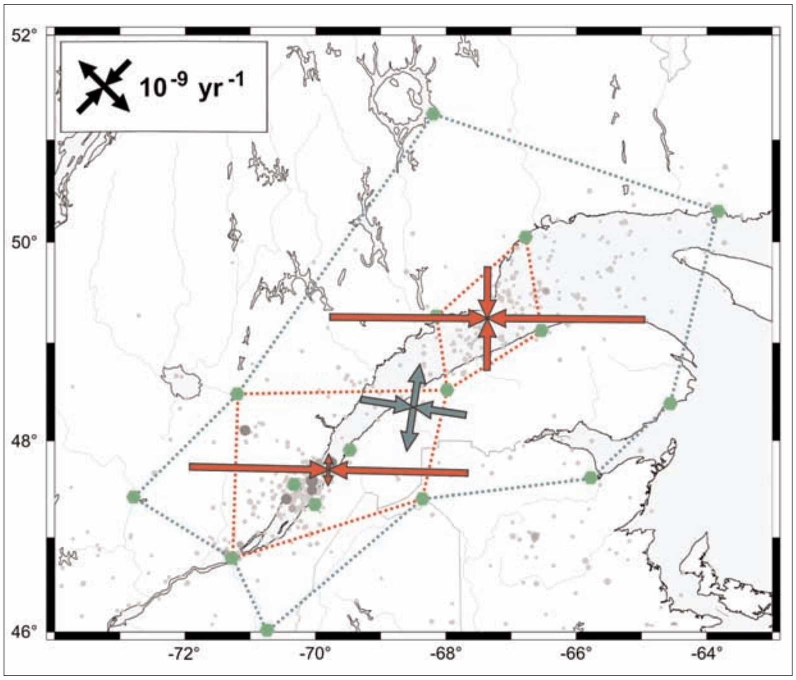

Figure 11: GPS horizontal strain-rates for the Saint Lawrence seismic zones. Dark cyan arrows show the average horizontal principal strain rates for the network (spatial extent given by dotted grey polygon). Red arrows show the horizontal principal strain rates for sub-networks around the Charlevoix and lower Saint Lawrence seismic zones (spatial extent given by dotted red polygons). Light grey circles indicate the pattern of regional seismicity [after *Mazzotti et al.* 2005].

6.3 Episodic Tremor and Slip

Improvements in the accuracy of IGS precise orbits and the regional densification of continuous GPS coverage were two key factors leading to the discovery of a "silent" slip event that occurred along the Cascadia Subduction Zone in August 1999 [*Dragert et al.* 2001]. Analysis of GPS data from 1994 to 2005 has revealed that the motions of continuous GPS sites in northern Washington State and southern Vancouver Island are marked by numerous, brief, episodic reversals. This is best illustrated by the east-component time series at the

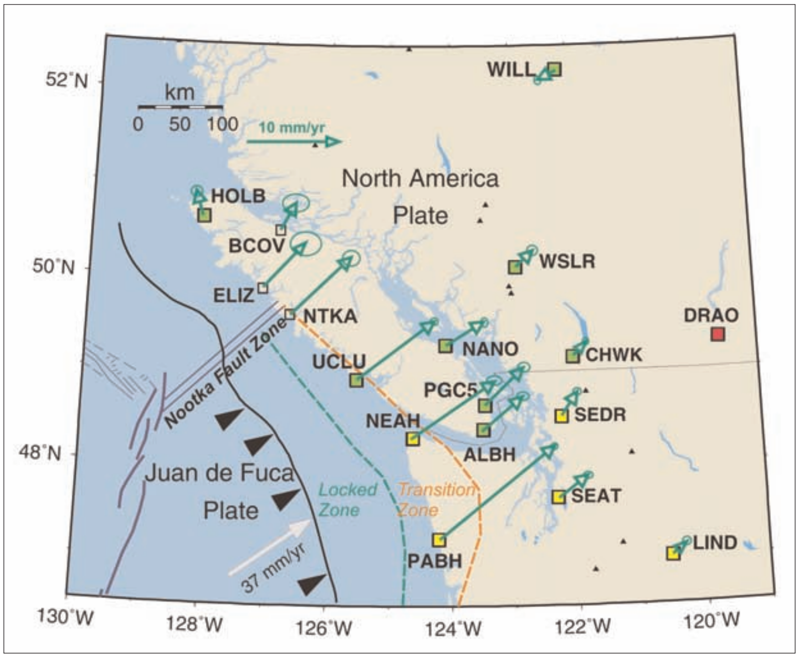

Figure 12: Long-term velocities of regional continuous GPS sites. Three to 10-year linear trends in the horizontal position with respect to Penticton (DRAO) for some of the sites of the Western Canada Deformation Array (WCDA: green squares) and the Pacific Northwest Geodetic Array (PANGA: yellow squares) are plotted by green arrows with 95 per cent error ellipses. The position of the strongly coupled zone determined from slip-dislocation models is indicated by the locked and transition zones. The convergence vector of the Juan de Fuca plate is with respect to the North America (NA) plate, and the GPS reference station DRAO is assumed fixed on the NA plate [from *Dragert et al.* 2004].

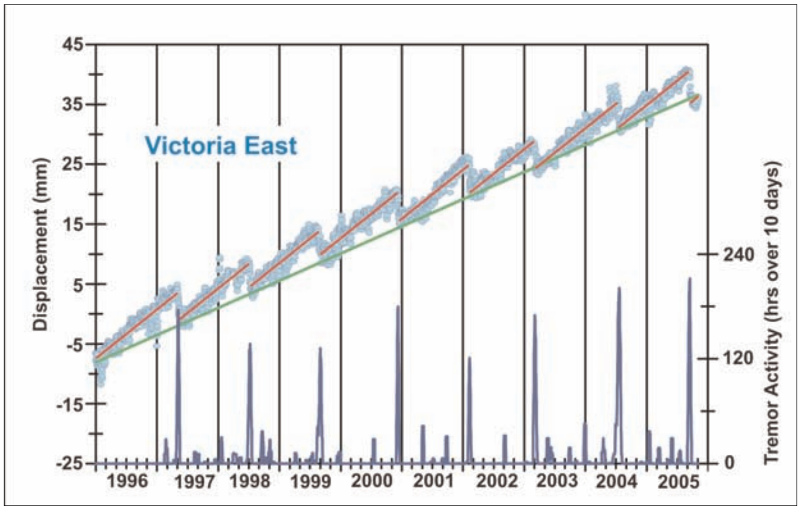

Figure 13: Record of slip and tremor activity observed for the Victoria area. Blue circles show day-by-day change in the east component of the GPS site ALBH (Victoria) with respect to DRAO (Penticton) which is assumed fixed on the North America plate. Continuous green line shows the long-term (interseismic) eastward motion of the site. Red line segments show the mean elevated eastward trends between the slip events which are marked by the reversals of motion every 13 to 16 months. Bottom graph shows the total number of hours of tremor activity observed for southern Vancouver Island within a sliding 10-day period. Ten days corresponds to the nominal duration of a slip event. Pronounced tremor activity coincides precisely with slip events.

Victoria GPS site (ALBH) where the motion relative to DRAO is clearly characterized by a sloped saw-tooth function: For periods of 13 to 16 months, there is eastward motion that is more rapid than the long-term rate, followed by a one to three week period of reversed motion (*refer to* Figure 13). These transient reversals of motion are surprisingly regular events, having a recurrence interval of 445 ± 35 days. The cumulative displacements over the two-week periods of these transient events is generally less than six millimetres, in a direction opposite to the longer-term deformation motion. For the longer-lasting events, station displacements were not simultaneous at all coastal margin sites but appear to migrate along strike of the subduction zone at speeds ranging from 5 to 15 km/day. These transient events are accompanied by distinct, low-frequency tremors [*e.g., Rogers and Dragert* 2003], similar to those reported in the forearc region of southern Japan [*Obara*, 2002]. The one-to-one correspondence of slip events with pronounced tremor activity prompted the naming of this phenomenon as "Episodic Tremor and Slip" (ETS) [*Rogers and Dragert* 2003].

The transient surface displacements can be replicated by simple slip-dislocation models if one adopts the subduction interface geometry from *Flueck et al.* [1997] and assumes that slip occurs at the plate interface and consists of updip motion of the overlying crustal block. Figure 14 shows modelling results for four of these events. The good agreement between observed and modeled displacements shows that the transient motions can be represented by simple slip on the subducting plate interface between depths of 25 and 45 km, with the slip region parallel to the strike of the subducting plate. The downdip boundary appears to be sharper whereas the updip boundary is more diffuse, requiring a gradual tapering of the slip amplitude. Although the maximum slip is only a few centimetres per event, the large area of slip generates an equivalent moment magnitude for these "slow earthquakes" ranging from 6.5 to 6.8.

Although the physical processes involved are not well understood, Figure 15 outlines the conceptual kinematic model for ETS on the northern CSZ. Both offshore and at greater depths (>50 km), the two plates converge steadily at ~4 cm/yr, the geological average rate. Across the shallower interface, the plates are locked for centuries, moving catastrophically past each other only at times of great thrust earthquakes. At depths of 25 to 45 km, plates resist motion temporarily for ~14 months accumulating some stress, and then slip the equivalent of a few centimetres over periods of one to two weeks releasing that small stress accumulation. This release is accompanied by unique seismic tremors on and above the region of slip. In the context of seismic hazard, the recognition of this ETS slip zone has two significant implications. First, since the repeated slip events define a region where little or no shear stress accumulates over longer periods of time, the updip edge of the slip zone can serve as a proxy for the maximum downdip (*i.e.* landward) extent for subduction thrust rupture. This can be used to improve estimates of strong motion in the densely populated regions of southwest BC. Secondly, it can be shown that the occurrence of slip on this deeper part of the plate interface adds stress to the shallower portion of the locked plate interface, driving it closer to rupture in discrete increments. Consequently, during the time of slip, the weekly cumulative probability of a megathrust earthquake is significantly greater than at times between slip events [*Mazzotti and Adams* 2004]. This provides, for the first time, a potential basis for time-dependent seismic hazard estimates.

7. Summary

Geophysical processes systematically affect the spatial reference frames used for geodetic surveys. Geodynamic rates in most of Canada (*i.e.* away from active plate margins) are generally rather modest (typically 1-2 cm/yr). However, when highest accuracy is required, the measurable effects of geodynamic processes must be considered. When evaluating the effect on reference frames within a given

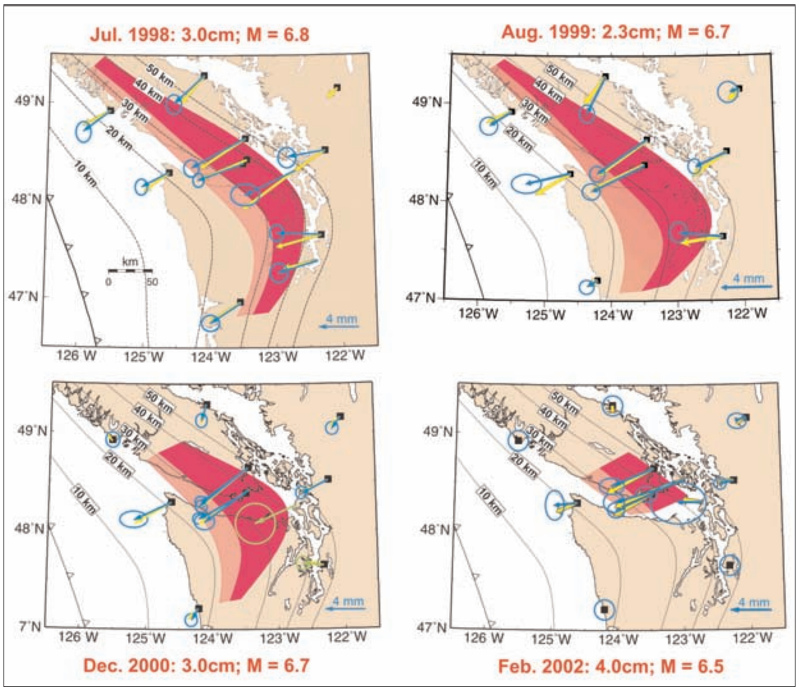

Figure 14: Models for slow slip events. The geometry of the subducting plate interface established from structural studies [*Flueck et al.*, 1997] is adopted, and simple linear slip distribution directed up-dip is assumed. The four panels illustrate the results of elastic dislocation modelling [*Okada*, 1985] of four recent slip events. Blue arrows show observed horizontal surface displacements with 95 per cent error ellipses that were used to constrain the models; green arrows show surface displacements obtained from separate analyses and not used in model constraint; yellow vectors show model displacements. Dark shading indicates fault areas with full slip whose magnitudes are shown in panel headers; light shading indicates fault areas where slip is tapered linearly from full to zero at the up-dip end. Also shown are equivalent moment-magnitudes assuming a rigidity of 40 Gpa [from *Dragert et al.* 2004].

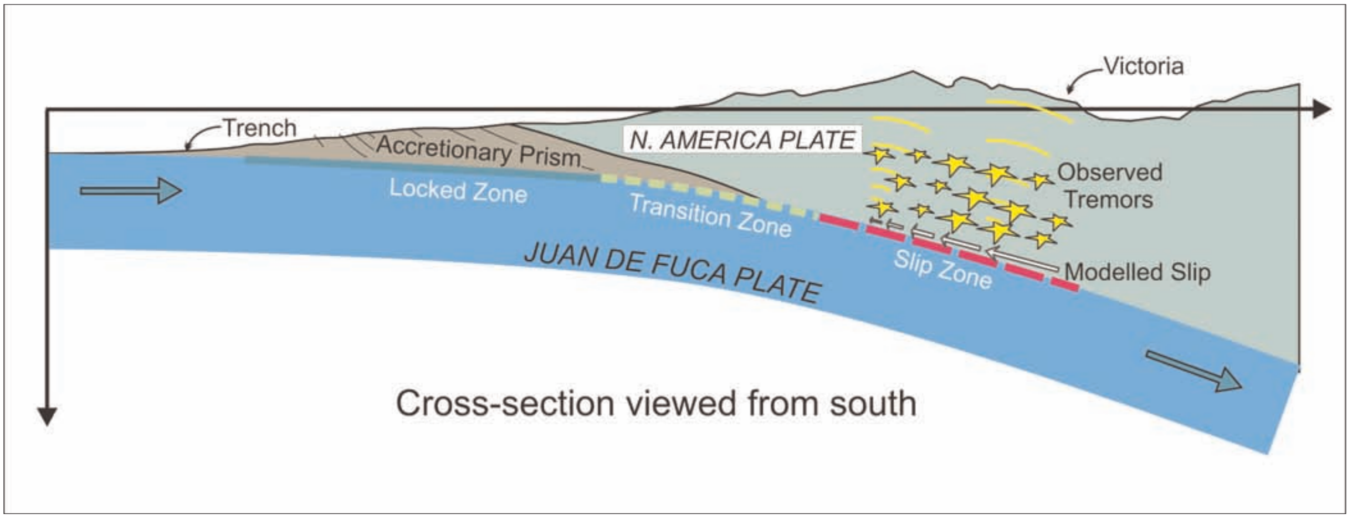

Figure 15: Cross-section of a conceptual model for CSZ plate-interface kinematics. The blue region represents the subducting Juan de Fuca plate and the green and brown regions, the overlying margin of the North America plate. Seaward of the trench (to the left of the diagram) and landward of Victoria (to the right), the plates converge continuously. Beneath the continental slope, mostly comprised of the accretionary prism, the plates are fully locked thereby causing an accumulation of stress that will be released in the next megathrust earthquake. At depths of 25 to 45 km, plates resist motion temporarily for ~14 months and then slip a few centimetres over periods of one to two weeks, accompanied by distinct seismic tremors (yellow stars). The transition zone marks the region on the plate interface where a transition from “locked” to “stick-slip” behaviour occurs.

area it is important to note how kinematic processes operate on various spatial scales.

Within regions of particular interest (*e.g.* earthquake hazards), NRCan has complemented the CSRS and installed additional geodetic infrastructure to monitor specific geodynamic processes. An observation strategy for geodynamics based mainly on GPS should optimize both the accuracy of results and the use of complementary data sets from independent techniques where tenable (*e.g.* absolute gravity, tide gauges). All geodynamic investigations require a long-term commitment to systematic monitoring in order to determine the relatively small kinematic rates and to subsequently develop useful quantitative models. Many years of observations are therefore invaluable and often required to better understand the particular regional geodynamic processes. Furthermore, the data and results can be used to improve the realization and maintenance of national NAD83(CSRS) reference frame for the general georeferencing community.

For much of the Canadian landmass the most significant crustal movement is vertical motion, as demonstrated by current models and analyses of post-glacial rebound. Post-glacial isostatic adjustment, whose maximum uplift rates occur generally near Hudson Bay, is a process that is evident throughout much of Canada. Crustal tilt associated with post-glacial rebound can, albeit slowly, affect water resources and alter risks associated with flooding. Of specific practical importance are changes in relative sea level for coastal areas including regions that may be particularly vulnerable to climate change such as arctic regions. It is therefore highly useful to monitor and confirm coastal height variations at geodetic reference stations over time.

Seismic activity in intraplate zones tends to be related to the regional stress fields, with earthquakes concentrated in regions of crustal weakness. Horizontal strain rates can be directly related to the frequency of large earthquakes. Vertical motions may provide additional insight into the regional seismic process. Thus the occurrence of large earthquakes in active seismic regions of eastern Canada (e.g. lower Saint Lawrence Valley, Charlevoix, and Ottawa Valley) can be better characterized through long-term precise geodetic monitoring.

Detailed regional surveys continue to map the crustal deformation field associated with the geophysical processes in Canada noted above. For regions with active seismicity and/or faults, measurements of crustal deformation supply direct information on crustal-strain accumulation which is essential for studies of tectonic and seismogenic processes and is increasingly used in seismic hazard assessments. Particularly exciting was discovery of the "silent-slip" phenomenon along the Cascadia subduction-zone interface. This was first observed within the time-series of precise, continuous GPS measurements on Canada's west coast and its implications continue to be explored.

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