Fisheries and Oceans Canada
Science

Pêches et Océans Canada
Sciences

C S A S

Canadian Science Advisory Secretariat

S C C S

Secrétariat canadien de consultation scientifique

Research Document 2002/004

Not to be cited without
permission of the authors *

Document de recherche 2002/004

Ne pas citer sans
autorisation des auteurs *

Physical oceanographic and geological setting of a possible offshore oil and gas industry in the Queen Charlotte Basin

Océanographie physique et géologie du bassin de la Reine-Charlotte en vue d'une éventuelle exploitation industrielle du pétrole et du gaz

W. Cretney[1], W. Crawford[1], D. Masson[1] and T. Hamilton[2]

[1] Institute of Ocean Sciences
Fisheries and Oceans Canada
P.O. Box 6000
Sidney, B.C. V8L 4B2

[2] Hamilton Geoscience Service
2180B Calvin Ave.
Sidney, B.C. V8L 4C3

ISSN 1480-4883

Canada

ABSTRACT

Research, mainly by DFO physical oceanographers over the last decade and a half, has deepened our understanding of ocean currents in the Queen Charlotte Assessment Area. In this accomplishment, the Department has followed one of the recommendations of the 1986 West Coast Offshore Environmental Assessment Panel Report on offshore oil and gas issues. Much about the generation of currents and the formation of oceanic eddies has been explained.

Enhanced satellite images of oceanographic features, some with superimposed current vectors, are now available for examination by interested parties. Graphical representations help make understandable the results of complex mathematical equations. In this paper, extensive use of images is made to present some of the known physical oceanography of the region. Still, some phenomena require further explanation.

Our oceanographic knowledge is best for summer and worst for winter. Winter is the time when conditions can be expected to be especially severe for an industry that seeks to operate all year round. Giant waves, as have been observed in the Queen Charlotte Assessment Area, present a dangerous hazard to operations of an offshore oil and gas industry. Research provides some knowledge of the interaction of tide currents and waves to create treacherous conditions. The St. James Island area off the southern tip of Moresby Island has been the focus of studies in the 1990s.

Tsunamis also present the potential for harm by giant waves. The tsunami that 300 years ago devastated the southern B.C. and Washington coasts continues to hold the attention of researchers. Tsunami computer simulations are now available for the Cascadia region. Uncertainties remain in the computations, however. The major uncertainties lie in determining tsunami likelihoods.

Subsea earthquakes of the right types can generate tsunamis. A giant subduction earthquake along most of the length of the area where the Pacific plate moves under the North American plate off Southern B.C and Western U.S.A. is believed to have caused a giant tsunami 300 years ago. Having happened once, this giant subduction event seems likely to happen again, perhaps every few centuries. In the case of the Queen Charlotte Fault, which passes closely by the Queen Charlotte Islands, the question is can it happen at all. Landslides and underwater slumps can generate tsunamis as well. Giant tsunamis with wave heights up to 30 m generated by slides in the Hawaiian Islands likely hit our coast in ancient times.

The seabed of the Queen Charlotte Basin presents a complex topography, as might be expected from the topographical complexity of the bordering lands. Banks and troughs due to past glaciation dominate the seabed structure of the area. The area is replete with evidence of the strong currents that surge along the bottom. Large areas show sand ripples, sand waves and sand ridges. Some of these transitory features achieve heights of 6 m. A number of slopes around banks show evidence of instability. At shallow depth under the seabed are accumulations of biogenic gas and/or thermogenic gas. Throughout much of the area, especially in Hecate Strait, sediments are infused with gas, which renders them more susceptible to liquefaction than gas-free sediments. Although a significant amount is known about the seabed geomorphology, much remains to be learned.

The Queen Charlotte Islands display a large number of liquid petroleum seeps, which provide evidence of a number of source rocks. Submarine seeps of liquid petroleum surely must exist. Evidence of gas seeps appears in acoustic survey profiles. It seems plausible that the coverage of the seabed may mirror that of the land.

RÉSUMÉ

Au cours des quinze dernières années, les recherches effectuées principalement par des spécialistes en océanographie physique du MPO ont permis d’améliorer notre compréhension des courants océaniques dans la Région d’évaluation de la Reine-Charlotte. Le ministère donnait ainsi suite à l’une des recommandations du rapport de 1986 de la Commission d'évaluation environnementale du projet d'exploration au large de la côte ouest sur les problèmes reliés au pétrole et au gaz. Les facteurs d’entraînement des courants et de formation des tourbillons océaniques ont ainsi été en grande partie expliqués.

Des images-satellite accentuées d’entités océanographiques, à certaines desquelles des vecteurs de courant sont superposés, sont maintenant disponibles pour examen par les parties intéressées. Des représentations graphiques illustrent les résultats de la solution d’équations mathématiques complexes. Dans le cadre de cet article nous utilisons abondamment des images pour illustrer certains des éléments connus de l’océanographie physique de la région, mais certains phénomènes doivent encore être mieux expliqués.

Nos connaissances en océanographie sont les meilleures pour la saison estivale et les mois étendues pour l’hiver. L’hiver est la saison pendant laquelle une entreprise cherchant à exploiter à l’année peut s’attendre à des conditions particulièrement rigoureuses. Des vagues géantes, telles qu’observées dans la Région d’évaluation de la Reine-Charlotte, présente un danger pour l’industrie de l’exploitation pétrolière et gazière extracôtière. Les recherches effectuées fournissent une certaine connaissance de l’interaction des courants de marée et des vagues engendrant des conditions dangereuses. Les études effectuées pendant les années 90 ont été centrées sur la région de l’île St. James au large de l’extrémité méridionale de l’île Moresby.

Les tsunamis présentent en outre un risque de dégâts attribuables à des vagues géantes. Le tsunami qui a dévasté il y a 300 ans les littoraux du sud de la C.-B. et de l’État du Washington continue à retenir l’attention des chercheurs. Des simulation de tsunamis sur ordinateur sont maintenant disponibles pour la région de Cascadia, mais les calculs comportent encore des incertitudes, principalement en ce qui a trait à la détermination du degré de vraisemblance des tsunami.

Des séismes sous-marins de types particuliers peuvent engendrer des tsunamis. Un séisme de subduction géant, sur la plus grande partie de la région où la plaque Pacifique s’enfonce sous la plaque de l’Amérique du Nord au large de la C.-B. méridionale et de l’ouest des É.-U., aurait engendré un tsunami géant il y a 300 ans. Un tel épisode de subduction à grande échelle pourrait vraisemblablement se reproduire à des intervalles de quelques siècles. Il faut se demander si le même phénomène peut se produire dans le cas de la faille de la Reine-Charlotte, qui court à proximité des îles de la Reine-Charlotte. Les glissements de terrain et les affaissements sous-marins peuvent également engendrer des tsunamis. Des tsunamis géants soulevant des vagues d’une hauteur atteignant 30 mètres engendrés par des glissements dans l’archipel hawaïen ont vraisemblablement atteint nos rivages à des époques lointaines.

Le fond marin du bassin de la Reine-Charlotte présente une topographie complexe comme le laissait supposer le relief accidenté des étendues émergées limitrophes. Des bancs et des fossés sculptés par les glaciations passées dominent la structure du fond marin dans cette région par ailleurs partout marquée par des indices d’effets de puissants courants sur les fonds. De grandes étendues sont occupées par des rides, des ondes et des crêtes de sable. Certaines de ces entités transitoires peuvent atteindre une hauteur de 6 m. Un certains nombre de talus autour des bancs présentent des signes d’instabilité. Il y a des accumulations de gaz biosynthétique et/ou thermogénétique à de faibles profondeurs sous le fond marin. Sur une bonne partie de la région, et en particulier dans le détroit d’Hécate, les sédiments sont imprégnés de gaz ce qui les rend davantage sensibles à la liquéfaction que les sédiments libres de gaz. Bien que nous disposions de connaissances étendues sur la géomorphologie du plancher océanique, il reste beaucoup à apprendre.

On trouve dans les îles de la Reine-Charlotte de grands nombres de suintements de pétrole liquide témoignant de l’existence d’un certain nombre de roches mères. Il doit assurément exister des suintements sous-marins de pétrole liquide. Les profils établis d’après des relevés acoustiques montrent des indications de dégagements de gaz. Il paraît plausible que les matériaux de couverture du fond marin reflètent ceux des terres émergées.

INTRODUCTION

Moratoria on exploration for offshore oil and gas have been in place for Canada's West Coast for about three decades. Lifting the moratoria was considered in the early 1980s, and deliberations led to the West Coast Offshore Environmental Assessment Panel Report on offshore oil and gas issues that was released in 1986. The moratoria were not lifted in the 1980s for a number of reasons. In recent years the government of British Columbia has expressed a renewed interest in the establishment of an offshore oil and gas industry, principally in the Queen Charlotte Basin. In 1998, the British Columbia Information, Science and Technology Agency tendered a contract to review technological and risk issues of offshore oil and gas exploration and development raised by the environmental assessment panel's report. This review was never officially released. In October 2001, the provincial government released a revised and updated version prepared by Jacques Whitford Environment Ltd. http://www.em.gov.bc.ca/Oil&gas/Offshore/JWLReport/intro.pdf). Subsequent to that report in early 2002, the provincial government released the British Columbia Offshore Hydrocarbon Development: Report of the Scientific Review Panel (http://www.em.gov.bc.ca/Oil&gas/offshore/OffshoreOilGasReport/Default.htm#REPORT%20OF). This panel of academicians led by the former president of the University of Victoria commissioned and reviewed submissions from many experts. While recognising that knowledge gaps exist, these reports looked favourably upon lifting the moratoria.

The present Research Document is based on the first of a group of six Working Papers requested by the Pacific Scientific Advice Review Committee (PSARC) of the Pacific Region of Fisheries and Oceans Canada to further delve into the state of environmental knowledge in the offshore of Western Canada, as it pertains to an offshore oil and gas industry. This Research Document reviews the knowledge and knowledge gaps in the oceanographic and geological setting of the West Coast with focus on the Queen Charlotte oil and gas assessment area. It is within this assessment area that there is the potential of discovering oil as well as gas, and it is within this area that exploration will commence, should the moratoria be lifted.

PHYSICAL OCEANOGRAPHY

History of North Coast Physical Oceanography

The Canadian Hydrographic Service began sea level observations at Prince Rupert in 1912 and has maintained this gauge for 90 years, forming the earliest and longest oceanographic record from the region (Figure 1). Ship-based, physical oceanographic studies began in the 1920s with sampling of temperature and salinity profiles along the outer coast. Daily measurement of these properties at lighthouses began in 1934. The Pacific Oceanographic Group in Nanaimo began more thorough sampling after World War II, with best observations from the mid 1950s to the 1960s.

The observations from this era are presented in thorough reviews by Dodimead (1980) and Tabata (1980). Thomson (1981 – chapter 14) describes the oceanographic regime of the North Coast of B.C., and this book also provides a readable introduction to all aspects of physical oceanography. In addition, a review of oceanographic papers and research for the north coast to 1983 is provided in Petro-Canada (1983 IEE), a document prepared for an Environmental Assessment of the region prior to hydrocarbon exploration.

In 1977, and from 1982 to 1995, the physical oceanographers and hydrographers of Fisheries and Oceans Canada (DFO) at the Institute of Ocean Sciences (IOS) did detailed studies of currents and properties of the oceans surrounding the Queen Charlotte Islands: Hecate Strait, Queen Charlotte Sound, Dixon Entrance, Chatham Sound, West Coast Queen Charlotte Islands, and some nearby channels and inlets. This work too was done in anticipation of hydrocarbon exploration and from 1986 onward complied with recommendations in the "*Report and Recommendations of the West Coast Offshore Exploration Environmental Assessment Panel.*" (1986). The studies were funded jointly by Fisheries and Oceans Canada (DFO) and by the Panel for Energy Research and Development (PERD) project 24110. Crawford (2001) presents data from this program on CD-ROM along with maps of selected drifter tracks, seasonal temperatures and salinities, tidal currents and satellite observations.

The early studies by the Pacific Oceanographic Group revealed most of the basic estuarine features of these waters. The DFO/PERD programs of the 1970s to 1990s examined ocean currents, particularly near-surface currents in summer, and IOS researchers applied numerical hydrodynamic models to the scientific study, through collaborations with fellow scientists at Bedford Institute of Oceanography as well as with several American oceanographers. The DFO/PERD studies relied on the Canadian Weather Buoy Network to provide links between ocean currents and winds. This network began in the late 1980s, funded jointly by Environment Canada and DFO. Satellite imagery has been available since the late 1970s, beginning first with sea surface temperature observations, then with ocean colour imagery, and finally, by late 1980s, with measurements of sea surface heights.

Research vessels provide accurate measurements needed to monitor long term changes in water properties and to evaluate numerical hydrodynamic models. However, cruises are infrequent, and sample at relatively few points. Satellites provide pictures of temperature and ocean colour of the entire region that help to interpret the infrequent and sparse ocean observations taken by research vessels. Satellite observations of sea surface height reveal new features neither previously known nor understood. This section describes the oceanographic features revealed by these combined observations over the past 25 years and updates the summaries by Al Dodimead, Susumu Tabata and Richard Thomson.

Sea Level Changes, past, present and future

The Prince Rupert sea level record of 90 years of nearly continuous measurements provides one of the best climate-related signals in British Columbia. Records from this gauge are processed by the Canadian Hydrographic Service, Pacific Region and archived by the Marine Environmental Data Service of DFO, Ottawa. A summary of the record of annual averages of this gauge, together with records from Tofino and Victoria is presented in the State of the Ocean Report, 2001, at a web site maintained by the Pacific Science Advisory Review Committee (PSARC) [http://www.pac.dfo-mpo.gc.ca/sci/psarc/OSRs/Ocean01.pdf]. These 90 years of observations reveal that Prince Rupert and Victoria sea levels are rising by about 1 mm/year, whereas Tofino sea level is falling by about 1 mm/year. Each of these three sea-level changes is referenced to a benchmark in nearby bedrock, and is therefore a *relative* sea-level change. These three sea-level changes are at the low end of the *absolute* global sea level rise of 1 to 2 mm/year experienced over the past 50 to 100 years.

The anomalous rate at Tofino arises from local ground motion set up by tectonic processes described in companion reports; clearly the ground at Tofino is rising faster than the ocean, a trend expected to continue until the next major Cascadia Zone earthquake. At that time the ground might fall by a metre or so.

Thomson and Crawford (1997) present details of past and expected future sea level changes in British Columbia and the Yukon. Local changes (other than tectonic ones) are not expected to exceed the global rate of sea level rise over the next century. The Intergovernmental Panel for Climate Change (IPCC) issued the following statement in early 2001: “Global mean sea level is projected to rise by 0.09 to 0.88 m between the years 1990 and 2100, for the full range of SRES scenarios, but with significant regional variations. This rise is due primarily to thermal expansion of the oceans and melting of glaciers and ice caps. For the periods 1990 to 2025 and 1990 to 2050, the projected rises are 0.03 to 0.14 m and 0.05 to 0.32 m, respectively.” (SRES is the Special Report on Emissions Scenarios, which anticipates future concentrations of greenhouse gases in the atmosphere.) This statement and additional information are available at the Internet site: [http://www.grida.no/climate/ipcc_tar/syr/009.htm]. Clearly, global sea level rise associated with any climate warming will be a major issue for future generations. Its impacts in British Columbia are minor at present.

Ocean Tides and Tidal Currents

Tides in the Queen Charlotte Assessment region are the largest in British Columbia shelf waters, reaching a range at large tide of almost 8 metres at Prince Rupert and Queen Charlotte City, according to the Canadian Tide and Current Tables, 2002, Vol. 7. Tides throughout the region are classified as mixed, mainly semi-diurnal, a classification that indicates there are almost always two highs and two lows per day, with one high being higher than the other, and one low being lower than the other. Tides move in and out of this basin from the North Pacific. Both semi-diurnal (twice daily) and diurnal (daily) tides propagate anti-clockwise around the northeast Pacific Ocean. The centre of the semi-diurnal system lies between San Diego and Hawaii, and tidal range increases in amplitude with distance from the centre. After the tidal crest enters Queen Charlotte Sound, it spreads southward into Queen Charlotte Strait and northward into Hecate Strait where it encounters the opposing crest that entered eastward through Dixon Entrance. This motion is illustrated in Figure 2, which displays flood tide currents at 1200 PST on 30 March 2002, a time between a Prince Rupert low tide of 0.4 m at 0835 PST and high water of 6.4 m at 1450 PST. Vectors in this figure represent magnitude and direction of tidal currents at mid-point and show the direction of tidal flow as the tidal wave enters coastal waters from the North Pacific Ocean.

Deep-ocean tidal currents seldom exceed a few centimetres per second, but as the wave leaves the 3000-metre-deep ocean and enters the shallower waters of the continental shelf, where depths reach 200 to 300 m, the tidal currents increase, reaching speeds up to several knots. Tidal currents reach their biggest magnitudes in some of the narrow channels, with speeds up to 7 knots in Porcher Narrows and in Stuart Narrows, 6 knots in Otter Passage, and 5.5 knots in Massett Sound. Tidal flow over Nahwitti Bar attains a speed of 5.5 knots. Information for these and other similar channels is found in the *Canadian Tide and Current Tables*, 2002, Vols. 6 and 7. In the more open waters of Dixon Entrance, Hecate Strait and Queen Charlotte Sound the strongest tidal currents are observed at Rose Point and Cape St. James, where speeds may reach up to 4 or 5 knots. Overfalls have been observed in the shallow waters to the northeast of Rose Point, and the intense tidal churning at Cape St. James can bring water from several hundred metres depth to the surface. Both regions need to be treated with respect by mariners.

Additional aspects of these tidal currents are worth noting. Normally, tidal currents flow at nearly uniform speed at all depths, but in some regions, especially where tidal currents flow across abrupt changes in bottom depth, some of the internal density interfaces move up and down and set up internal waves. Such waves exist only if bottom waters are significantly denser than near-surface waters, and the interface between these two is moved up and down by the tide passing over sloping bottom. These waves move the ocean surface up and down by only a few centimetres, but can set up strong tidal currents. One of the largest internal tides is set up at the Hawaiian Ridge (Kang *et al*., 1999) and another by currents flowing through gaps in the Aleutian Ridge (Cummins *et al*., 2001). One of the largest internal tides in British Columbia waters is found in Dixon Entrance, where tidal speeds may reach several knots, and both speed and direction of flow differ between surface and deeper waters (Crawford *et al*., 1998).

In a succession of hydrodynamic models Michael Foreman and colleagues at the Institute of Ocean Sciences have simulated the rise and fall of the tide. Their most recent tidal model (Foreman *et al*., 2000) was able to simulate the full tidal signal in this region to an accuracy of 5 cm or so, a remarkable achievement. This tidal model extended over the entire Gulf of Alaska, and has presently been applied to remove tidal signals from observations of sea surface height by satellites. Output from this model has been made available for other applications.

Ebb and flood motions of the tide have been simulated by Michael Foreman and Patrick Cummins and colleagues of DFO, Institute of Ocean Sciences (Cummins and Oey, 1997; Crawford *et al*., 1998; Ballantyne *et al*., 1996; Foreman *et al*., 1993 and Foreman *et al*. 2000). The image of Figure 2 was generated using tidal constants of the Foreman model. A more thorough description of tidal current models has been provided in a companion Research Document (Crawford *et al*., 2003).

Non-Tidal Currents

Near-surface drifter observations:

A comprehensive program to launch near-surface drifters began in 1982 and continued until 1995. Drifters consisted of a surface float attached to a much larger underwater drogue, usually centred at 5 or 15 m below surface, to track ocean currents at depths not easily sampled by current meters. These drifters established the patterns of near-surface currents. Most drifters determined positions using an inboard Loran-C navigation unit, and transmitted these positions half-hourly to nearby vessels via VHF radio. Surface drifters used System Argos satellites to both compute positions and telemeter data to ground stations. In 1995 about 40 of these satellite-tracked drifters were deployed in Queen Charlotte Sound. These drifters were attached to drogues in the upper 1 metre of the water, and tracks of their motion provided detailed information on surface currents in this sound (Crawford et al., 1999).

Figures 3 and 4 show plots of tracks of almost all drifters deployed between 1990 and 1995 (Crawford, 2001). Plots like these are labelled spaghetti plots, for obvious reasons, and serve mainly to show the region of coverage of drifter tracks.

Several features revealed by these drifter tracks deserve special mention. With data from Loran-C drifters with drogue centre depths at 15 metres below surface, examination of the 1990 summer survey reveals unusual currents near Cape St. James and through southern Hecate Strait. A selection of drifter tracks from this survey are presented in two panels of Figure 5a, from Crawford *et al*. (1995), colour-coded for clarity. Tracks extend in time from less than a day (a40) to several weeks (a35), and reveal the variety of motion found in this relatively small region.

Many drifters passed Cape St. James *en route* from Hecate Strait to the deeper waters of the North Pacific. Outflow currents reached 5 knots and were interrupted only briefly by flood currents. As noted by Crawford *et al*. (1995) most drifters departing Hecate Strait passed within 12 km of Cape St. James through the gap between this cape and Gray Rock. Once out of Hecate Strait, most drifters decelerated and meandered slowly toward the Southeast with the prevailing summer flow. However, one drifter, d36, broke through this flow and continued drifting toward the Southwest. Another, f40, returned into Hecate Strait.

The majority of drifters that remained in Hecate Strait and Queen Charlotte Sound flowed to the Northeast along Moresby Trough or in a clockwise direction around North Bank. Some remained in mid-sound for more than a week and before being picked up by the research vessel displayed little intention of departing either Hecate Strait or Queen Charlotte Sound. None of the drifters deployed later in the summer to the north departed from Hecate Strait. Therefore, the only drifters departing coastal waters passed close by Cape St. James, part of the Gwaii Haanas Marine Conservation Area and a sensitive ecological region. The intense tidal mixing at this Cape has so far defied successful simulation by numerical models, with the result that the simulations of surface current drift, presented in companion Research Document (Crawford *et al*., 2003), fail to represent proper surface drift near this cape. In other regions the models achieve better success, as described in the companion Research Document (Crawford *et al*., 2003).

The 1991 summer survey examined features of northern Hecate Strait and Dixon Entrance, as displayed by selected drifter tracks in Figure 5b. The Rose Spit Eddy dominated the circulation of eastern Dixon Entrance, as revealed by these drifter tracks. Flow periods around this eddy varied from several days in mid-eddy to several weeks around the outer edge. Many drifters completed one circuit of this eddy; few stayed in the eddy for more than one circuit. First described by Crean (1967), the eddy has been examined in more detail by Crawford and Greisman (1987) and Bowman *et al*. (1992).

Another feature revealed by drifter tracks is the quirky behaviour of ocean currents. In Figure 5a drifters c33 and c32 that were deployed at the same point in Hecate Strait at different times are seen to move in completely different directions, a common experience in such experiments, due to variable winds and the turbulent nature of winds and ocean currents. One must understand the inherent inaccuracies of predictions due to these influences. Ensemble average observations are often used to determine common trends of motion within this turbulent behaviour. However, multiple drifter tracks, when plotted together, create the spaghetti plots of Figures 3 and 4 and obscure the general trends of ocean currents within the turbulence. Figure 6 attempts to avoid this confusion by presenting daily average current vectors within individual grids of this region, based on drifter tracks, as well as ellipses to represent standard deviations of these currents, again computed from several tracks through each grid. Details of these average and variable currents are described below.

Satellite observations of surface features, summer:

Figures 7 and 8 present several images of sea surface temperature that were taken from satellite on rare cloud-free days in this region. Figure 7a reveals summer ocean conditions during moderate winds from the Northwest. Features are labelled 1 through 10, as described below:

1. Chatham Sound and Skeena River plume in northern Dixon Entrance.

Fresh water from the Skeena River mixes with salt water in Chatham Sound and flows out of Chatham Sound in a surface layer of brackish water. Sediments in this water absorb light, which warms this layer as it flows northward out of the sound and then westward across northern Dixon Entrance. Much of this flow enters Alaskan waters before turning southward and eventually departs Dixon Entrance to the West. Any brackish water that flows out of Chatham Sound toward the Southwest passes through narrow channels with strong tidal currents that mix deep cold water up to the surface and cool this layer.

2. Western Dixon Entrance and the southern Alaskan Panhandle.

Summer winds generally blow from the Northwest in this region, pushing the surface waters downwind. The effect of the rotation of the earth is to turn these currents to the right, away from Alaskan shores. Waters borne by these currents are replaced at shore by colder deep water that upwells to the surface, a process labelled Ekman divergence and upwelling by oceanographers. The upwelled water can be blown into Dixon Entrance when the Northwest winds are especially strong. This inflow motion tends to stay close to the south side of Dixon Entrance, whereas surface outflow waters from the Skeena tend to stay to the North. Often a branch of Skeena outflow will turn south midway along Dixon Entrance, and re-circulate in the cyclonic Rose Spit Eddy, centred in Eastern Dixon Entrance (Bowman *et al*. 1992) or turn westward to flow out of Dixon Entrance close by Langara Island. Current vectors of drifters in this region in July-August 2001, presented in Figure 6b, reveal strong persistent currents across northern Dixon Entrance, weaker persistent currents across southwestern Dixon Entrance, and more variable currents elsewhere.

3. West Coast Queen Charlotte Islands.

Winds from the Northwest push currents to the Southeast along the west coast of the Queen Charlotte Islands. The Earth's rotation turns these currents to the right, away from the coast. These waters are replaced at the ocean surface by deeper, colder water all along the west coast of Graham Island and much of Moresby Island, again part of the process of Ekman divergence and upwelling.

4. Dogfish Banks.

Waters on Dogfish Banks are generally 10 to 20 metres deep, much shallower than in other areas. There is no deep cool water here for wind and tidal mixing to bring to the surface, allowing the sun to warm these waters more than neighbouring deeper regions.

5. Eastern Hecate Strait.

Summer winds generally blow from the Northwest in this region, pushing the surface waters downwind. Ekman divergence carries surface water away from the mainland side of Hecate Strait. Tidal mixing may also carry cooler water to the surface. Waters that move away from the coast are replaced at the ocean surface by deeper, colder water all along the coast, as far south as the southern end of Aristazabel Island. The cool waters drift southward away from Aristazabal Island, eventually turn toward the Southwest, and enclose the eastern arc of a circulating flow around North Bank, labelled "A" in Figure 7. It is not known if this plume departs Queen Charlotte Sound into the Pacific Ocean, or re-circulates around North Bank once it sinks below surface.

6. Cape St. James, south end of Moresby Island.

Strong tidal currents are found at the southern tip of Moresby Island, within a few kilometres of Cape St. James, where speeds as high as 5 knots are found. In summer the winds from the Northwest push the warm surface waters of Hecate Strait southward past Cape St. James and into the open Pacific Ocean. Tidal currents at this cape bring deep cold water to the surface where they partially mix with warmer surface water. All these water masses flow about 100 kilometres southwestward into the Pacific Ocean, forming a distinctive plume in this image.

To the east of the cape lies Moresby Trough. Surface currents flow to the Northwest along this trough and form the western arc of the circulating flow around North Bank. Current vectors of drifters in this region in July-August 2001 are presented in Figure 6a.

7. Eastern Queen Charlotte Sound.

On this day the fresh water from Rivers Inlet was in a shallow layer along the eastern shores of Queen Charlotte Sound, and was heated by the sun as it gradually drifted into Queen Charlotte Sound.

8. Cape Scott and Cook Bank at north end of Vancouver Island.

Strong tidal currents on Cook Bank and near Cape Scott mix cold deep waters into warm surface flows. The winds from the Northwest push these waters up against the shore and then westward into the Pacific Ocean as well as to the Southeast along the west coast of Vancouver Island. When these winds reverse, the westward flow over Cook bank diminishes or even reverses (Crawford *et al.*, 1985).

9. Clouds West of Graham Island.

Clouds to the west and jet contrails to the northwest of Graham Island are shown in black.

10. Rose Spit

Rose Spit extends far to the Northeast from Rose Point, and strong tidal mixing cools the surface waters in this region. There is little average northward or southward flow through the north end of Hecate Strait in summer; instead there is a variable flow forced by local winds. Current vectors in Figure 6a reveal the variability of this flow.

Satellite observations of surface features, winter:

Figure 8, processed in a similar manner to Figure 7, presents an image of sea surface temperatures on a relatively cloud-free day in the winter and reveals the ocean features expected during sunny conditions in winter, between storms. Features are labelled 1 through 7, as described below:

1. Haida Eddy.

This feature may be the start of a large anti-cyclonic (clockwise rotation) Haida Eddy (Crawford and Whitney, 1999) that forms from outflow currents of Hecate Strait and Queen Charlotte Sound. These eddies form every winter, always rotate anti-cyclonically, drift westward into the Gulf of Alaska, and can persist for several years. They carry much of the volume of water in Queen Charlotte Sound and Hecate Strait into the Pacific Ocean, as well and heat and fresh water (Crawford, 2002). These eddies may carry biota from Hecate Strait throughout the Gulf of Alaska (Mackas and Galbraith, 2002). Their behaviour in the Pacific Ocean has been well studied in recent years, but more research on their formation and interaction with coastal currents is needed.

2. Northern Hecate Strait.

A warm-water current flows northward through Hecate Strait along its deepest channel into Dixon Entrance, pushed by local winds and also by oceanic pressure gradients set up by remote winds. Intense tidal mixing near Rose Point erodes the warm waters on the west side of this current. This pressure gradient also creates an upwind, southward flow along the west side of Hecate Strait that extends all the way to Cape St. James (Hannah and Crawford, 1996).

3. Cape St. James.

A southwestward current carries Hecate Strait water into the Pacific past Cape St. James and contributes to formation of the Haida Eddy. Additional research is required to determine relative and outflow and re-circulation back into Hecate Strait.

4. Eastern Hecate Strait and Queen Charlotte Sound.

Cooler, fresher waters overflow oceanic seawater along the east coast of Hecate Strait and Queen Charlotte Sound, especially during the type of high air pressure conditions that create cloud-free days such as this. During storms this water may be pushed into the coast, and even up into inlets and channels. Understanding this process requires better measurements.

5. The Haida Current

First described by Thomson and Emery (1986), this winter current flows to the Northwest after separating from the coast farther south. Here it appears to meander, and may eventually form an eddy.

6. Dixon Entrance outflow

Cooler water flows out of Dixon Entrance alongside the Haida Current. This particular plume may have been caused by the weather that also created clear skies on this day, and should not be considered a typical feature.

7. Dogfish Banks

The cool regions over Dogfish Banks along the Northeast Coast of Graham Island are created by tidal and wind mixing in shallow waters. Apparently, there is little heat exchange with warmer and deeper water masses to the east.

Moored current meter observations:

Much of the DFO/PERD field program between 1977 and 1995 was devoted to current measurements with moored, internally recording current meters. These current meters were moored throughout the Queen Charlotte Basin (Figure 9), normally for at least the summer and sometimes for a complete year, at nominal depths of 50, 100, and 150 m below nautical chart datum, as well as 15 m above ocean bottom. (Nautical chart datum is the elevation of the ocean at lowest normal tides, about 3 to 4 metres below mean sea level in these waters.) In some cases current meters were set 15 or 25 m below nautical chart datum in summer only.

Crawford (2001) has provided on CD-ROM details of all observations, as well as the complete data set. Each mooring was anchored to bottom by concrete block or railway wheels and held upright by a steel line connected to a sub-surface float. Current meters were connected along the mooring line, and recorded current observations at intervals of 15, 30 or 60 minutes on magnetic tape. All meters recorded temperature observations at the same time intervals, most recorded salinity observations. The time interval between observations was determined by the expected time to recovery of the mooring by the next research cruise. A 15-minute interval was selected for moorings of a few months duration; and a 60 minute interval, for over-winter moorings.

The large surface waves of winter have been shown to move the sub-surface floats back and forth, and create spurious current speeds on many of the current meters used in this program. To avoid this motion the winter sub-surface floats were set near 50 m below surface, with the nearest current meter at 50 m below surface. In summer additional nearby moorings were set with floatation near 15 or 20 m below surface, and the closest meters right at these depths. These current meters were a type that minimises the effect of mooring motion on speed sensors. During the 1977 summer mooring program the floatation on many moorings was set closer to surface, and some current meter records appear to show signs of speed contamination, and were not included in the following figures and discussion.

Figures 10 and 11 display vectors of seasonal average currents, for summer and winter, respectively, separated into three panels by depth of current meter. Near-surface currents in summer are strongest near Cape Scott at the northern tip of Vancouver Island and at Cape St. James at the southern tip of the Queen Charlotte Islands. In both these regions the strong flows are due to constriction of outflow currents by these capes. Their southward flow is forced by prevailing winds from the north. Near-surface vectors in eastern Dixon Entrance reveal the features of the Rose Spit Eddy in both summer and winter. Mid-depth vectors show this feature in summer only. Average near-surface currents in Hecate Strait in summer are generally weak, a flow feature supported by drifter observations described previously. Within Queen Charlotte Sound the near-surface currents appear random in direction, but, as noted by Crawford *et al.* (1995), they actually flow clockwise around Goose Island Bank in mid-sound and more parallel to the coast at regions close to shore.

A few other features, noted in the pattern of drifter motion, also appear in these views of average current vectors. The northeastern portion of the clockwise gyre around North Bank is visible in the near-surface summer currents. The northern portion of a counterclockwise flow around this bank is visible in near-surface and mid-depth currents in winter. Flow around this bank reverses from summer to winter in response to the prevailing winds. The behaviour of flow around the southern portion of this bank in winter is poorly known, and may be a critical factor in retention of cod larvae in Hecate Strait and Queen Charlotte Sound in winter (Crawford *et al*., 1990).

Flow features at Cape St. James are particularly interesting. Average currents close by this cape in both summer and winter flow toward the south. This feature is investigated in detail by (Crawford *et al*, 1995). The southward flows near the cape are set up by local winds in summer and by along-strait sub-surface pressure gradients in winter. In addition, within a few kilometres of the cape, a process called rectification of tidal currents sets up prevailing southward flows, first noted by Thomson and Wilson (1987).

Near-bottom currents in summer generally flow into Dixon Entrance, as one would expect for an estuarine-type flow. Near-bottom currents in summer flow into Queen Charlotte Sound near Cape Scott, out of the sound near Cape St. James, and offer a confusing pattern elsewhere. Within Hecate Strait the summer near-bottom currents are generally weak and yet flow in opposing directions near the northern end of this channel. Winter near-bottom currents are stronger than the summer flows in Dixon Entrance. Again the prevailing direction is into the basin. Elsewhere the strongest near-bottom currents generally flow northward, in the downwind direction, suggesting that even at the bottom the currents respond to the northward wind stress along the West Coast of British Columbia.

Crawford and Thomson (1991) provide a more thorough discussion of near-bottom currents and their impact on these three basins.

NATURAL HAZARDS

Earthquakes

Slip fault earthquakes: The known seismic hazard from earthquakes in the Queen Charlotte Assessment Area has arisen mainly from strike-slip and thrust events with infrequent extensional events, reflecting a transpressional environment (Rohr et al., 2000; Rohr, 2001). In 1949 Canada' s largest historical earthquake (M=8.1) occurred a few kilometres off the west coast of Graham Island on the Queen Charlotte Fault (Fig. 10). Sizeable as it was, this earthquake was on a vertical fault (Rogers, 1983) and was not a giant megathrust earthquake resulting from underthrusting of the Pacific plate beneath the North American plate (see below). In 1990 an M=5.3 event occurred under the north end of Hecate Strait. This quake was within one of several zones of microearthquakes located in the area. Because compressive deformation apparently has progressed from south to north over the last few million years, seismic activity should remain concentrated in the north (Rohr et al., 2000; Rohr, 2001).

Megathrust earthquakes: Underthrusting of the ocean crust beneath the west coast of the Queen Charlotte Islands was proposed by Yorath and Hyndman (1983) and Hyndman and Hamilton (1993). Smith (1999) discussed the possibility that such underthrust faulting could produce great subduction thrust earthquakes of at least M=8. However, Rohr *et al.* (2000) recently have presented evidence that the convergence of the Pacific and North American plates has resulted in crumpling of the plates at the boundary and uplifting of the Queen Charlotte Islands. They argued that "a 'megathrust' event between underthrust oceanic and overriding continental plates … is highly unlikely."

Roy Hyndman, NRCAN, still favours underthrusting of the oceanic plate, a position that he notes is supported by new GPS data (personal commun.). He thinks "there is the possibility that great earthquakes occur on the Q.C. Islands margin," but notes that there is no direct evidence of past events (personal commun.). In contrast, much evidence exists that a giant megathrust (M=9) earthquake took place off the B C. coast to the south on January 26, 1700, at about 9 P.M. (Hyndman, 1995). Japanese researchers provide a precise date of the earthquake and its occurrence along the North American coast from the written record of a tsunami that washed ashore in Japan (Hyndman, 1995; www.pgc.nrcan.gc.ca/seismo/hist/1700.htm). Roy Hyndman notes that a Queen Charlotte Fault "thrust event could produce West Coast tsunamis" (personal commun.).

Potential impacts on industrial installations: The possibility of great earthquakes along the Queen Charlotte Fault cannot be dismissed. Those responsible for producing building codes for offshore structures must be cognisant of this possibility. The Geological Survey of Canada (GSC) of Natural Resources Canada (NRCan) is charged with the responsibility for monitoring earthquakes and producing national seismic hazard maps. Standard methodology is used to quantify seismic hazards. The GSC uses such methodology to produce national seismic hazard maps for the National Building Code of Canada (Fig. 11). The Canadian Standard Association (CSA S471-M1989) publishes seismic design standards for offshore structures. Design standards for oilrigs in the Queen Charlotte Basin should take into consideration site-specific characteristics such as sea-bottom stability.

Tsunamis

The perception of tsunami hazards on the Canadian West Coast rose abruptly in the 1960s, first with the Chilean 1960 earthquake whose tsunami created maximum rise or fall of the sea surface of 1.3 m at Tofino, 1 m in Barkley Sound, and less than 0.5 m in northern British Columbia (Fred Stephenson, personal commun.). Few tide gauges existed in northern BC then, so there might have been larger undetected waves. The Alaskan 1964 earthquake set up even higher waves, with maximum rise or fall of 3 m at Tofino and more than 5 m at Port Alberni. Amplitude at Prince Rupert was about 1 m (Fred Stephenson, personal commun.). (Some sources use the trough-to-crest range as the tsunami height. Here it is the height or trough magnitude that is reported.) Prior to the 1980s these two regions were considered the most dangerous tsunami generating regions to British Columbia.

On October 12, 2001, a magnitude 6.3 earthquake located south of the entrance to Tasu Sound on Moresby Island generated a little tsunami whose amplitudes were recorded by tide gauges on Vancouver Island (Rogers *et al*., 2002). Thrust faulting with possible outcropping on the sea floor (Rogers *et al*., 2002) appeared to have caused the earthquake and resultant tsunami. The earthquake seemed to have been located on a subsidiary fault east of the Queen Charlotte Fault, which runs roughly parallel to the islands about 20 km offshore. A megathrust earthquake along the Queen Charlotte Fault could cause a tsunami, as noted above, with far greater amplitude than the about 20-cm maximum (Rogers *et al*., 2002) recorded on tide gauges for the October 12 event.

Geophysicists who began to re-examine theories of earthquakes along the Cascadia Subduction Zone in the 1980s now believe the zone may be subject to a megathrust earthquake of magnitude up to 9 and is capable of setting up severe tsunamis between northern California and British Columbia (Hyndman, 1995). Details of these earthquakes are presented in the previous section of this paper.

A series of tsunami simulations for the Cascadia region have been prepared since the 1980s: Hebbenstreit and Murty (1989), Murty and Hebbenstreit (1989), Ng *et al*. (1990a,b), Myers and Baptista (1991), Whitmore (1993), and Myers *et al*. (1999). Most studies have focused mainly on impacts on the coastline to the south of the Queen Charlotte Assessment Region, and American simulations have been used to prepare tsunami inundation maps of coastal communities in the Unites States, and evacuation routes. Tsunami evacuation signs have been posted in many American communities. With diminishing tsunami heights north of Brooks Peninsula, the west coast of Vancouver Island has been proposed as the main Cascadia tsunami impact region of Canada . Nevertheless, Ng *et al*. (1990a,b) have simulated heights of order 4 m at Quatsino on the west coast of Vancouver Island, and 1 m at Cape St. James and Queen Charlotte City.

Dunbar *et al*. (1991) examined tsunamis originating from Chile, the Aleutian Islands and Kanchatka. They examined impacts in many inlets of the Queen Charlotte Assessment Region, as well as open waters of this region. They determined the following:

> "On the north coast of British Columbia, the Alaskan tsunami generated the largest amplitudes. In all other regions of the West Coast, the largest amplitudes were generated by the Shumagin Gap simulation [Aleutians]. Wave amplitudes in excess of 9 m were predicted at several locations along the coast, and current speeds of 3 to 4 m/s were produced. The most vulnerable regions are the outer coast of Vancouver Island, the west coast of Graham Island, and the central coast of the mainland."

Most uncertainty in tsunami simulations arises from uncertainty of vertical ground motion under the sea during the earthquake. Recent studies, for example by Priest *et al*. (2000), attempt to revise the sea deformations used in simulations, based on the type of tsunamis set up, simplified geological models, and evidence of past tsunamis in the sediment record. These new deformation rates may revise, and narrow some of the ranges of tsunami predictions arising from numerical models.

Warnings of tsunamis are now provided by the Alaskan Tsunami Warning Center and the International Tsunami Warning System (González, 1999), Hubbard and Duncan, 2002). The Alaskan Tsunami Warning Centre is the primary warning system for British Columbia and provides rapid warnings over the Internet and phone lines. The Provincial Emergency Program (PEP) is responsible for spreading these warnings within British Columbia. The Canadian Hydrographic Service provides regional information, such as local tides and arrival times, during these events. Any hydrocarbon-exploration and development operators must be plugged into this system. These international and Alaskan warning systems now rely on coastal sea-level gauges in U.S. waters, as well as real-time information from American deep-sea gauges. Canadian tsunami gauges at Tofino, Winter Harbour and Langara Island will be on this system soon, for instant access during tsunami events (Fred Stephenson, personal commun.). At present these and all other Canadian tsunami and sea level gauges may be accessed by staff of the Canadian Hydrographic Service in real time during tsunamis, to download high-sample-rate data and provide this information to either of the warning agencies.

A modest research effort is now underway at the Institute of Ocean Sciences, conducted by Fred Stephenson and Josef Cherniawsky, to evaluate the harbour currents due to future Cascadia Subduction Zone tsunamis. It is funded by the Canadian Coast Guard New Initiatives Program, in order to provide advice to fleet operators, search and rescue staff, and volunteers on how to respond to a Cascadia earthquake. This project applies recently developed numerical simulations together with high-spatial-resolution bathymetric data. Tsunamis from Cascadia earthquakes may hit southern British Columbia in much less than an hour, and the earthquake itself will be the warning. Vessel operators need to know if currents in their harbour will be unsafe for navigation during a tsunami, and whether they should ride out the tsunami on land, or in their vessel in the harbour. This study can be extended to Northern British Columbia.

Tsunamis set up by underwater landslides, or landslides that enter the ocean, are another source of concern. A tsunami created by such an event in Skagway in 1994 (Kulikov *et al*., 1996, Rabonovich *et al*., 1999, Nottingham, 2002) is known to have killed one person. The Papua New Guinea tsunami of 1998 is now thought to have been generated by an underwater landslide triggered by an earthquake. There is potential for a Cascadia Subduction Zone earthquake to create these slides in British Columbia, but it is difficult to determine the risks of such an event. Some recent assessments of such events are provided by Kulikov *et al*. (1998), Fine *et al*. (2002), Rabinovich *et al*. (2002), and Mosher and Thompson (2002). At the extreme end of the scale, Satake (2001) computes tsunami heights of 10-40 m in Washington State waters from an underwater-landslide-generated tsunami in the Nuuanu region north of the Hawaiian Island of Oahu, and even higher tsunamis can be caused by impacts of meteorites in the ocean. These events would inflict major damage and loss of life throughout the Pacific.

The Ng *et al*. (1990a,b) and Dunbar *et al*. (1991) simulations can now be updated for the Queen Charlotte Assessment region, using better simulations of bottom deformation. In addition, newer numerical simulations of tsunamis, faster computers, and better-digitised bathymetry are now available to improve on earlier simulations in the Queen Charlotte Assessment Region.

Impacts of tsunamis on hydrocarbon exploration and production may be considerable. Tsunami damage is normally most severe in ports, where waves are highest and vessels can be thrown together or into wharves. However at sea, the combination of tsunami height and current may impact drill rigs. Tsunami waves extend all the way to ocean bottom, and the height of a 1-m tsunami may not upset operations, but the large, uniform surface-to-bottom current of the wave may exceed tolerances for operations.

Extreme weather, giant waves

The coastal waters of northern British Columbia are subjected to frequent and intense storms. Consequently, local wave conditions can be considered relatively severe, especially during the winter months when the Aleutian Low predominates and produces strong south-to-southeasterly winds. In addition, it is believed that strong surface currents can interact with the surface wave field to create treacherous conditions.

Off the southeast coast of South Africa, wave-current interaction has been proposed as a possible mechanism for the formation of giant waves known to occur in areas of strong coastal currents. On the B.C. coast, local navigators have long respected the waters around Cape St-James for their vigorous tidal flow and associated dangerously heavy seas. For example, in October 1968, during an intense North Pacific storm, an oil-drilling rig anchored in the vicinity of the cape was hit by an enormous wave of 29-m height, propagating against a strong local ebb current (James, 1969).

In August 1991, with joint funding from DFO and the Panel for Energy Research and Development (PERD), Masson (IOS) carried out a field program in the vicinity of Cape St-James to investigate the effect of the strong tidal currents on the local wave climate (Masson, 1996). Maps of surface current were obtained from a CODAR-type HF radar (Seasonde), Loran-C drifters were deployed to validate the radar measurements, and wave information was acquired with three wave buoys. Masson found that the strong tidal currents significantly modulate the wave properties in the vicinity of the Cape. Such strong interactions undoubtedly have contributed to the severity of the local wave climate.

Knowledge of local extreme wave conditions is a critical requirement for offshore engineering design and operation applications. This information is usually presented in terms of some long-term statistics of the random wave field such as the 50- or 100-year return period wave. This wave has an uncharacteristically large height that might be expected with a certain small probability during the period of operation considered. Because of the relatively short time period over which wave measurements have been available, such long term wave statistics are usually obtained from a combination of historical wave data analyses and numerical modelling of previous storm events (hindcasting).

In 1992 such a study was completed for the West Coast of Canada (MacLaren Plansearch (1991) Limited and Oceanweather Inc., 1992), in which a wave-hindcast and extreme-analysis study was performed for the period 1957 to 1989. The study determined a 100-year significant wave height, Hs, which is a statistical parameter approximating the average height of the highest one-third of the waves. For the offshore coastal area of northern BC, Hs was estimated to be about 13 m, and the associated maximum wave height, Hmax, about 25 m. The models used in this study included neither shallow-water effects, nor wave-current interactions. More up-to-date wave models, which do include these effects, as well as new wind fields of historical storm events could be used to update the 1992 estimates.

First activated in 1987, an array of weather buoys continues to collect wind and wave information from along the Canadian West Coast. The buoy network presently comprises 16 buoys, with 8 of them in the northern BC coastal waters. The data collected are used for weather monitoring and to establish wave climatology. On several occasions during the last decade these buoys appear to have registered wave heights reaching extreme values approaching 30m (Gower and Jones, 1994), significantly above the estimated 100-year return wave height. However, it is important to realise the limitations of such measurements. A fixed accelerometer measures the acceleration along the main axis of the buoy. An algorithm then converts the measured acceleration to a wave height. In heavy seas, the instrument may be tilted, thus confusing horizontal and vertical acceleration. In order to improve the wave measurement accuracy, plans exist to use gimballed accelerometers. This action would also allow measurements of wave directionality, in addition to wave frequency that is presently measured. There are plans to install such a directional wave sensor, a TRIAXYS wave sensor, on one of the meteorological buoys this year.

Concern has been expressed that global warming may be increasing the frequency and intensity of severe storms and extreme waves. Using NCEP-NCAR reanalysis and *in situ* data, Graham and Diaz (2001) identified an increase in frequency and intensity of winter cyclones in the North Pacific Ocean over the period 1948-1998. In addition, from wave measurements and model hindcast results they inferred related significant increases in Hs of about 30% along the California Coast. However, their results indicated that, for the BC coast, the change would be smaller, with an increase in Hs of only 5% (their Fig. 11d). A similar study that was conducted for the Northeast Atlantic (WASA, 1998) found that the storm and wave climate had roughened in recent decades, but that the present intensity of storm and wave climate seemed comparable with that at the beginning of the 20th century. Such long-term variability could have important implications for future oil and gas industry activities and should be addressed carefully in terms of the local climate.

Bottom topography and potential hazards to industrial installations and activities

Description of bottom topography: Bornhold and Harper (2002) present an excellent overview of the seabed hazards to the offshore oil and gas industry in the Queen Charlotte Basin. Much of the material summarised here is drawn from that overview, and readers are referred to it for a more in depth discussion. As in that overview, this summary focuses separately on three major parts of the basin: Queen Charlotte Sound, Hecate Strait and Dixon Entrance.

Queen Charlotte Sound: Bedrock outcroppings occur mainly along the land margins of the sound near the Scott Islands north of Vancouver Island and adjacent to the mainland. Some exposed bedrock occurs in the central part of the sound. Bolder beds exist at the margin with Hecate Strait along the eastern edge of Moresby Trough. Sediments laced with cobble and gravel are found frequently on North, Goose Island and Cook Banks. These banks, which are exposed to waves and currents of the open Pacific Ocean, provide such evidence of water-borne sediment mobility as megaripples, linguoid ripples, sand ribbons and sand waves to a water depth of 200 m. Oscillation ripples occur to depths of 90 m. Topographically enhanced tidal currents erode sediments in troughs that cross the sound between banks. These troughs, which originate from glacial scouring, present some very steep slopes. Moresby Trough has slopes exceeding 15^o and shows evidence of slope failure.

Hecate Strait: Bedrock outcroppings occur mainly along the strait's eastern margins and western margin with Moresby Island. Bedrock exposures also occur at the south end of Moresby Trough. Boulder beds occur on some of the shallow banks, such as Laskeek Bank off Moresby Island. Dogfish Bank along Graham Island likely has boulder beds as well. Sand waves commonly occur around the perimeters of Laskeek and Dogfish Banks. In addition, sand waves and lingoid bedforms, with amplitudes over 3 m in places, occur in narrow channels southwest of Laskeek Bank. Megaripples, sand waves and sand ridges are common bottom features occurring alongside the central terrace in Hecate Strait and extending northward into Dixon Entrance (Barrie and Bornhold, 1989). Some sand waves and sand ridges exceed 6 m in amplitude. Evidence of slope failures exists for various sites, notably for those between Laskeek Bank and Moresby Island. The shoreline with Graham Island is erosionally unstable. Currents sweep shoreline sediments northward towards Rose Spit. Although erosion occurs at a rate of about 1 m/y, winter storms appear to account for much of it (Conway and Barrie, 1994). Different storms affect different sections of the coastline. Episodic storm events noticeably change the shoreline at affected sites (Conway and Barrie, 1994).

Dixon Entrance: Bedrock outcroppings occur on Celestial Reef and Learmonth Bank located centrally at the west and east ends of the entrance. Bedrock reefs extend offshore from the Alaskan border Islands on the north side of the entrance, and outcroppings occur near the south shore west of Masset Inlet and in the eroded seabed of McIntyre Bay. Steep slopes tend to be associated with these features. Boulder beds commonly occur in near-shore areas, on major banks and to water depths of 250-350 m along the centre of Dixon Entrance. Megaripples, oscillation bedforms and sand waves occur on the shelf west of Masset Inlet to 100-m depths and north of Rose Spit on the flanks of a small topographical high. To the north of Masset Inlet lies a wave-cut terrace and scarp having steep slopes. At places the scarp is over 20 m high.

Hazards of seabed features: Bedrock outcroppings, boulder beds and steep slopes present difficulties for drilling activities, but they present particularly serious problems for pipeline burial, which is a large expense for oil companies. Without burial, pipelines are susceptible to damage from trawling and anchors. Without burial, pipelines present a significant hazard to trawling that continues after oil field depletion and abandonment. Exclusion zones to protect pipelines may seriously affect the livelihood of fishers. Unburied pipelines spanning topographical features are subject to stresses from strong seabed currents that over time can lead to premature mechanical failure. Pipelines in areas of high sediment mobility may be subject to underscouring. As noted by Patin (1999), "pipelines are among the main factors of environmental risk during offshore oil developments, along with tanker transportation and drilling operations." Slope failure is a hazard to all seabed activities of the oil and gas industry.

Bathymetric charts for the Queen Charlotte Basin are available from the Canadian Hydrographic Service (CHS), but all are based on pre-1970’s survey data. Some recent localised charts and uncharted data are available through the CHS (contact, T. Curran, IOS). A national initiative called the Seabed Resource Mapping Program (SEAMAP) is proposed for mapping Canada’s offshore. The Queen Charlotte Basin is a West Coast regional priority. (For more information contact Richard Pickrill, NRCAN (PickrillDickNRCAN@dfo-mpo.gc.ca)).

Sub-bottom formations and potential hazards to industrial activities

Queen Charlotte Sound: Faults are found in Tertiary strata, but none seem to have offset Quaternary strata or broken through the seafloor. Nevertheless, faulting attributable to Quaternary post-glacial loading and isostatic rebound is recorded for some of the glacial troughs. At water depths of 300-400 m in Moresby Trough are located shallow, biogenic-gas accumulations. Although seabed features indicating gas escapement occur at depth in the eastern sound area, the acoustic evidence excludes the presence of gas accumulations.

Hecate Strait: Many Tertiary faults exist under the strait. No seismic activity in Tertiary strata resulting in seafloor displacement is documented. As in the sound, Quaternary faulting is related to past glaciation. The deeper parts of Moresby Trough's extension into the strait have shallow gas accumulations. The bases of underwater terraces show evidence of gaseous sediments. Gaseous sediments occur in many areas throughout the strait.

Dixon Entrance: Although faults appear to cut the seafloor east of Learmonth Bank and next to exposed bedrock in the centre of the entrance, historical seismicity seems not to be associated with them. Biogenic gas accumulations lie in Holocene muds to the south and southeast of Celestial Reef and farther afield within the trough leading into Hecate Strait.

Seismicity on the faults has the potential to cause liquefaction of sediments and slope failure. Gaseous sediments have lower strengths than gas-free sediments and present a greater hazard. Gas pockets present a hazard to drilling, but one that should be easily avoidable.

ORGANIC GEOCHEMISTRY OF CANADIAN WEST-COAST HYDROCARBON-BEARING BASINS

Background

Three major sedimentary basins lie off the West Coast of British Columbia: the Georgia Basin, the Tofino Basin, and the Queen Charlotte Basin. The geological setting, tectonic evolution, stratigraphy and structure of the basins are described in Hannigan *et al*. (2001). The Georgia Basin encompasses 14000 km^2 of southwestern B.C. and northwestern Washington State. The Tofino Basin underlies 15000 km^2 of the continental shelf west of Vancouver Island. The Queen Charlotte Basin covers an area of 40000 km^2 and includes Queen Charlotte Sound, Hecate Strait, eastern Graham Island and portions of Dixon Entrance.

A succinct geochemical overview is provided here as background information for oil and gas in the B.C. marine environment. Whiticar (2002) provides an excellent, and somewhat complementary, overview of the geology and geochemistry of the Queen Charlotte Basin. The best, most complete, and most recent study of the petroleum resource potential is by Hannigan *et al* (2001). Most of the relevant data is cited therein or in previous GSC/NRCan studies dating from the Frontier Geoscience Project on Queen Charlotte Basin post 1987. These studies include those of Cameron and Hamilton (1988) and Hamilton and Cameron (1989) for geological background and seep descriptions, as well as those of Snowdon *et al* (1988a,b) and Fowler *et al*. (1988), subsequently, for hydrocarbon typing and characterisations. The work of Hyndman and Hamilton (1993), Hamilton and Dostal (1993, 2001), Rohr and Deitrich (1992), Rohr and Furlong (1995), Rohr and Currie (1997), and Rohr *et al*. (2000) define the tectonics and geological setting with the most modern data and analysis. Older work by Shouldice (1971) dates from the time of the “fish” and “bird” wells in the late 60's. The whole of the West Coast off shore is a frontier area, because there is no developed production. There is considerable indication for naturally occurring hydrocarbons in reservoirs and seeps that reach the shallow sediment horizons and the water column. These hydrocarbons may be impacting biological communities. Some information on oil seeps is available in the literature and some from anecdotal experience of researchers involved in prior studies; some may be accessible through reviews of existing or archival data. The main purpose of this overview is to identify important natural variables, diverse environments, data sets and data gaps to constructively and efficiently focus and direct future studies.

Wherever there are sediments and sedimentary rocks that have organic contents, there is a background level of natural hydrocarbons. Where these sedimentary packages are thick enough, natural heat flow has caused some organic maturation and migration to generate gas and oil. Canada’s West Coast has two groups of sedimentary basins that are geographically and geologically separate and distinct with regards to hydrocarbon generation and the types of natural seeps that they contribute to the marine environment. The southern basins around Vancouver Island and the lower mainland all contain thin strata, have low heat flow, and are generally only gas prone. The northern basins from northern Vancouver Island through the Queen Charlotte Islands and adjacent regions have greater thickness, larger geological variability, more hydrocarbon sources, and higher heat flow than the other coastal basins, and they are prone to both oil and gas.

Gas prone southern basins - Low Heat Flow Areas over the Cascadia Subduction Zone

The southerly basins: Juan de Fuca, Tofino and Georgia are all in a low heat flow area over the modern subduction zone. The heat flow is regionally depressed at about 35 mW/m^2. When this geophysical feature is considered in light of the thin accumulation of Tertiary and Quaternary sediments (total < 2 km) and Cretaceous sedimentary rocks (total < 1.6 km), most of the region is undermature and only prone to generate gas. A number of gas seeps are known or mapped in these basins (Hart and Hamilton, 1993). The most abundant and widely distributed seeps include shallow biogenic gas from bacterial degradation of organic detritus in buried modern or Recent unconsolidated sediments. Of secondary abundance are thermogenic gas seeps from underlying sedimentary rock formations chiefly of Tertiary age, though there are also some Cretaceous sources. Most of the exploration and shallow production in the Bellingham and Whatcom Basins of Washington State yields small reservoirs of thermogenic methane with little hydrocarbon component above C6 and virtually no condensate. These hydrocarbons are thought to arise from the underlying Tertiary strata.

Rare occurrences of degraded heavy tars and bitumens are found from the west coast of the Olympic Peninsula to Beaver Point on Saltspring Island and Ladysmith, indicating some minor environmental load of liquid petroleum hydrocarbons. There are both terrestrial woody kerogen and marine phytoplankton sources for all of the strata in these southern basins from the Cretaceous and younger strata. Hydrocarbon maturation and leakage of gas and oil is a continuous phenomenon here for at least 45 Ma, with the pronounced structural deformation of the Cretaceous Nanaimo Group Rocks of Eastern Vancouver Island (England, 1989; England and Hiscott, 1992, Muller and Jeletsky, 1970), the Gulf Islands, and Georgia Basin. The overlying Tertiary strata are also considered prospective traps and secondary sources for hydrocarbons, whose setting is described by Johnson (1984).

In the offshore on the exposed west coast in Tofino Basin, the leakage of thermogenic gas from the Tertiary strata below the continental shelf and slope generates gas hydrates, which continually contribute a light hydrocarbon flux to the shallowest sediments and to the sea. This flux greatly affects the geochemistry, infauna and benthic communities around these seeps.

In terms of sampling and characterising the natural background hydrocarbons, it is important to recognise the diversity of geological sub-basins within this southerly area. Sampling sites and strategies should be devised that take into account the different shallow substrate types and bedrock geology. For instance, portions of Juan de Fuca Strait that are underlain by relatively impermeable Quaternary diamicts and have Metchosin/Crescent Formation Basalts would be expected to have very low hydrocarbon levels. Areas like the Gulf Islands, where all the faulted and folded Cretaceous reservoirs come near to the surface with large areas of relatively coarser and more permeable unconsolidated sediment, will have high levels of natural hydrocarbons. These areas are inherently far more polluted and less pristine than others are, when considered from a perspective of potential spills from exploration drilling, production, or transport. Georgia Basin has the greatest hydrocarbon potential with the greatest thickness of sedimentary formations. Nonetheless, areas like the Fraser Delta and southern Strait of Georgia would be expected to have mainly shallow, biogenic methane gas leaks coming from the thick modern sediment wedge regardless of the Tertiary and Cretaceous bedrock underneath. The shallower strata would occlude or swamp the signal from below.

In terms of devising a sampling scheme for this area, there is sufficient background information of near-surface and bedrock geology to divide the region into basins and sub basins. A review of existing publications or archival seismic data would aid the selection of areas likely to contain seep versus those with impermeable seals or lacking in bedrock formations capable of generating hydrocarbons.

Queen Charlotte basin

Geologically, the Queen Charlotte Basin is a Tertiary Basin that includes several sub-basins stretching from northern Vancouver Island though Queen Charlotte Sound, Hecate Strait and Dixon Entrance, the Queen Charlotte Islands themselves, and shallow near-shore portions of the west coast of the Mainland. A major transform fault is adjacent to this entire region, which at times over the past 45 Ma has involved tectonic rift zones. This activity accounts for a thin crust, a shallow warm upper mantle, active faults, and a complex array of small geological regions of 3-10 km in extent.

The regions have different substrates, different geological histories, different organic sources, variable high heat flows (>70 mW/m^2), different maturation histories, and a variety of reservoir strata and traps. With only a limited number of exploration boreholes of shallow penetration, most geological knowledge for the region comes from the upturned basin edge exposed in the Queen Charlotte Islands. From the geology of this region various source beds and reservoir rocks can be delineated. Hydrocarbon sources range from Lower Jurassic Marine strata (Kunga and Maude Groups), through various mid-Cretaceous marine and marginal continental strata (Queen Charlotte Group), and through marine and terrestrial Tertiary strata - all lumped as the Skonun Formation. Locally, though, this formation can reach 7 km thick.

Diverse kerogen types are present, as confirmed by collection and analysis, with published data serving to typify several different Type II and Type III sources from H/C/O character and biomarker composition (Fowler *et al*., 1988). Clastic reservoir facies are recognised chiefly in the Haida and Honna Formations of the Cretaceous Queen Charlotte Group, and Tertiary Skonun Formation. Published studies from land surveys delineate widespread natural oil seeps (Hamilton and Cameron, 1989; Fowler *et al*., 1988). These seeps confirm both the widespread nature of hydrocarbon generation and leakage to the environment and demonstrate diverse sources and oil types from the entire sedimentary column. Although the Queen Charlotte Islands, as a continental margin, have experienced intense tectonic and magmatic episodes, the chief time of hydrocarbon maturation and migration dates from 45-10 Ma in conjunction with the formation of Queen Charlotte Basin.

To a first approximation, the areal extent of the oil seeps encountered on land can be used to predict a similar distribution in the offshore areas. On land, most oil seeps are water-washed and biodegraded tars and pyrobitumens. They range from thin sticky aromatic oils on fresh exposures to stiff tars with choncoidal fracture. Biomarker fingerprints demonstrate marine Jurassic sources as well as oils derived from terrestrial woody higher plants in both the Cretaceous (tricyclic terpenoids) and Tertiary (18α-bisnorhopane). In all likelihood there are submarine seeps like those known on land, especially at faulted locations of Tertiary strata as occurs in Tian Bay, along the inner coast of South Moresby, Lyell and Tar Islands and along Juan Perez Sound. Environments like these are far from pristine and likely to contain considerable natural hydrocarbon input. Other sub-regions, such as NE Hecate Strait, have thinner sediments, igneous and metamorphic bedrock like the adjacent Coast Mountains and relatively impermeable shallow glacial tills (diamicts) that contain little evidence for natural petroleum hydrocarbons or gas seeps.

During the seep sampling described above, a number of degraded oil blobs and balls were found on the shoreline beaches. Some of these residues were analysed and found to be degraded oil spills from the abundant shipping and fishery traffic. These findings have formed part of a background characterisation that implies that biota exist that are capable of degrading spilled oil.

Considering the likely distribution of seeps and the variety in marine benthic communities, one can speculate that some communities are based in part on hydrocarbon flux from below. One of the objectives of background characterisation should be to identify and study the benthos in areas of likely or known natural seeps.

There is a large database in NRCan of both deep and shallow high-resolution seismic lines that can be reviewed with the intent of defining a few different characteristic domains from a perspective of hydrocarbon sources and seeps. A number of gas plumes, fields of pockmarked seafloor, and underlying strata with acoustic evidence of hydrocarbon migration (as gas bright spots or gas masks) are evident in the archival survey data, which were acquired for this region in the late 1980's and early 1990's during regional mapping. By describing and selecting a few typical locations for each set of geological conditions (e.g., hydrocarbon prone bedrock type, reservoir beds, shallow unconsolidated formations, faulting, seabed activity etc.), it would be possible to design “smart” comparative sampling projects to typify sediments and biological benthic communities containing natural hydrocarbon inputs, as well and defining background levels for uncontaminated seafloor containing various substrate types.

Much of the shallow seafloor is quite mobile and active with both geological erosion and transport (Conway and Barrie, 1994 and references therein). This property has twofold significance to any substrate sampling. Both substrate lithology and activity in terms of source and location need to be considered in any sediment-sampling program. Obviously, much transport and mixing is likely where active sediment processes occur over reservoir or seep areas. There is also likely a different environmental load on an unsedimented bank versus an active sedimenting channel fill. This difference would impact the interpretation and reporting of fluxes, loads and concentrations of hydrocarbon analytes in the sediments.

Geo-environmentally analogous basins

Some analogous basins are worth consideration in studying and comparing the physical/geological aspects of the environment, such as natural hydrocarbon fluxes, and the marine environment's capacity to absorb, utilise or disperse hydrocarbon compounds. For the Queen Charlotte Basin, the two basins that are the most comparable are Cook Inlet, Alaska, and the offshore basins of coastal California. Of the more southerly group of basins in B. C., the regions of Oregon and Washington are most relevant.

Cook Inlet has comparable older bedrock strata to the Wrangellia tectonostratigraphic terrane of the Queen Charlottes, in addition to the complexity of Tertiary sedimentary formations and active tectonics. That region contains natural seeps as well as petroleum potential and production. It also has a similar cold, active well-mixed marine environment and similar biota.

The offshore basins of coastal California are dominated by Tertiary formations in sedimentary environments controlled by strike slip faulting. Their source and reservoir beds are restricted to the Tertiary and are dominated by marine diatomaceous kerogen sources. Whereas some California oils have relatively high API gravities, they are not as variable in source or properties as those are that come from hydrocarbon shows in the Queen Charlottes. Although Cook Inlet provides the best analogue for comparative literature and background studies, some of the California work should still be relevant.

Estimates of oil and gas potential

No oil and gas reserves have been proven for any of Western Canada's three major marine basins. All estimates of oil and gas are potential quantities only. Play analysis is a method used to generate estimates, where a "play" consists of a set of discovered or undiscovered oil and gas accumulations in a geological and geographical zone having very similar characteristics. The assessment technique used by the GSC for the West Coast basins is *conceptual play analysis* (Hannigan *et al*., 2001). As the name implies, the analysis is not based on any discoveries or established reserves. It is based on the analysis of geochemical and geophysical characteristics that are known from a body of work to co-occur in oil and gas producing areas.

Conceptual play analysis is a probabilistic method. The recently published GSC Bulletin by Hannigan *et al*. (2001) gives the total median estimates of in-place hydrocarbon volumes for all the West Coast basins. The volumes are 1.56 x 10^9 m^3 (9.8x 10^9 bbl) of oil and 1.22 x 10^{12} m^3 (43.4 TCF) of gas. All the potential oil is in the Queen Charlotte Basin. About 60% of the gas volume is considered to be present in that basin's plays as well. Hence, for the Canadian West Coast, interest in offshore & oil and gas focuses on the Queen Charlotte Basin.

Some further caveats should be placed on the estimates. At the 90 % probability level (high confidence), the total oil potential for the Queen Charlotte Basin is 0.66 x 10^9 m^3 (4.1x 10^9 bbl) (Hannigan *et al*., 2001). Only about a quarter of the estimated oil volume is likely to be recoverable. As well, Hannigan *et al* (2001) state: "The exploration risks estimated in the assessment suggest success rates for exploratory drilling in the region should average one in nine." The success rate for the Queen Charlotte Assessment Region, which includes the adjacent Hecate Basin, is zero for 18 for the period before 1971 when the last drilling was done. However, the drill depths and sites chosen are considered suboptimal now, based on present-day knowledge.

An encouraging aspect of the estimates of oil and gas volumes on the West Coast has been their increase over the last couple of decades, as more geophysical and geochemical knowledge has become available. In 1983, the potential estimates of recoverable oil and gas on the West Coast were 0.05 x 10^9 m^3 (0.315 x 10^9 bbl) and 0.27 x 10^{12} m^3 (9.5 TCF), respectively (Proctor *et al*, 1983, as cited in Hannigan *et al*. 2001). Recoverable oil today has been estimated as 0.41 10^9 m^3 (2.6 x 10^9 bbl), an increase of over 8-fold since 1983. The potential recoverable-oil volume, as noted above, has been attributed entirely to the Queen Charlotte Assessment Region. Because about 80 % of the potential gas volume is considered recoverable, the estimate of the potential recoverable gas volume for the West Coast has also increased about 3.5-fold to 0.94 x 10^{12} m^3 (33.4 TCF).

The Geological Survey of Canada (GSC) published a volume of 31 reports and papers in 1991 entitled *Evolution and Hydrocarbon Potential of the Queen Charlotte Basin, British Columbia*, edited by G.J. Woodsworth. The basin project was initiated under the Frontier Geoscience Program (FGP) to provide a current assessment of the evolution and hydrocarbon potential of the Basin. A series of geological maps accompanied the volume. The FGP also recognised that there were natural hazards that could affect exploration and/or development. These hazards included sea-floor stability and physical forces that might disrupt establishment of an oil industry The FGP recognised environmental concerns that oil exploration techniques, such as seismic surveys employing large airgun arrays, might have a negative impact on sea life. Also included was an annotated bibliography of geoscience studies of the Queen Charlotte Islands and Queen Charlotte Basin. One chapter described the design and accessibility of a database of all Triassic fossil collections from the Kunga Group on the Queen Charlotte Islands.

SUMMARY OF KNOWLEDGE AND KNOWLEDGE GAPS

Major advances have been made in the physical oceanography of the Queen Charlotte Assessment Area over the last two decades. In these accomplishments, the Department of Fisheries and Oceans has followed the recommendation of the West Coast Offshore Environmental Assessment Panel to "…develop and implement a program to improve general knowledge of current movements in the region…."

Current movement are known with enough detail to describe the formation of eddies and the influence of wind driving on currents. Especially known and understood are surface currents in summer. Although an impression may be given that all oceanographic features are well understood, several aspects remain to be resolved, especially the motion and impact of mid-depth and bottom currents on biota and the nature of late autumn and winter currents at all depths. Although DFO/PERD projects examined some details of currents and water properties along the eastern portion of Hecate Strait, through lack of time detailed studies of the Inside Passage waters and adjacent channels remain undone. Water from heavy rains of late autumn and winter quickly washes off the land and into these channels on the ocean surface, and then flows into Hecate Strait. If this were the only oceanic process to move surface currents, then few surface contaminants would enter these narrow channels from Hecate Strait. However, storm winds that bring these rains also push surface waters of Hecate Strait into these channels, through the process of Ekman convergence and downwelling, the reverse of upwelling in this region in summer.

As storms pass through, the sea-surface boundary between fresh outflow and saltier oceanic waters will form, erode, and move seaward and landward. Although none of these processes have been examined well, floating contaminants released into this environment will concentrate along this boundary. The impact of these contaminants on the environment will depend on the physics of these processes.

Although much has been learned in the last two decades about earthquakes in the Queen Charlotte Basin, a nagging uncertainty still lingers about the possibility of a megathrust earthquake along the Queen Charlotte Fault. The prospects of resolving the issue seem good, through continuing research, particularly by NRCan scientists. Apart from the issue of megathrust earthquakes, further knowledge of the location and seismicity of faults in the Queen Charlotte Basin should make drilling activities safer.

Tsunami models pertinent to the Canadian West Coast are available that simulate tsunami generation from undersea thrust earthquakes as well as subaerial and submarine landslides. A future offshore hydrocarbon industry must consider the possible impact of tsunamis, through both wave height and associated current speeds. New tsunami simulations for the Queen Charlotte Assessment region are required, to apply new technology and information and to refine estimates of wave heights, duration and arrival time. All marine operators, not just those involved in the industry, must have on-line access to the Alaskan Tsunami Warning System.

Extreme weather and giant waves present a hazard to all marine activities, including those of any future oil and gas industry. Some knowledge of the interaction of strong tidal currents and the local wave field around Cape St. James is available to explain dangerously heavy seas that are found in the area. Although giant waves have been recorded in the Queen Charlotte Basin, the buoys currently in use do not have the capacity to distinguish between vertical and horizontal motion. The giant waves measured may be artefacts of the bobbing about of the buoys in heavy seas. Installation of directional wave sensors, as appears to be beginning, will solve the problem of measurement. Then, a true measure of giant waves can be made. True measures of heights of very large waves will provide better estimates of the size of the 'hundred-year wave' that can be employed in setting design criteria for drilling rigs and platforms.

A good knowledge of the surface morphology is available through past research in Queen Charlotte Sound, Hecate Strait and Dixon Entrance. This knowledge lacks resolution and evenness of coverage. The SEAMAP program offers to provide digitised high-resolution mapping of the area. Along with mining the present database, the newly generated database from SEAMAP would permit researchers to identify and locate likely sites of oil and gas seeps as well as unstable seabed features.

The geochemistry of the seabed sediments in the Queen Charlotte Assessment area is almost unknown. Characterisation of the sediments for hydrocarbon biomarkers is essential to provide a benchmark against which oil lost from an industry can be compared, to establish responsibility and liability. Because oil and gas seeps are almost certain to occur offshore, their location and characterisation are necessary in establishing a useful benchmark. As noted above, the SEAMAP program would likely identify probable seep areas, and so permit a focused geochemical sampling design.

RECOMMENDATIONS

- Physical oceanography programs should continue to provide details of the current regime in all seasons, with special emphasis on bottom currents and freshwater runoff
- Physical oceanography projects should continue to elucidate the interaction of strong currents and waves to create giant waves in the Basin area. We recommend the fitting of new sensors to the existing buoy array to accurately measure giant waves and the two-dimensional wave spectra.
- NRCan should be encouraged in its continuing studies of earthquakes in the Queen Charlotte Basin.
- Tsunami modelling studies should be encouraged for assessing the affect of megathrust event on the Queen Charlotte Fault. Simulations of tsunamis originating from regions within the Queen Charlotte Basin could also be encouraged
- Efforts should be intensified to get SEAMAP going for the Queen Charlotte Assessment Area
- Studies of the geochemistry of the seabed in the Queen Charlotte Assessment Area should begin, perhaps in concert with SEAMAP and other studies of the geomorphology of the area.

ACKNOWLEDGEMENTS

We thank Fred Stephenson, CHS/DFO, Dave Mackas, OSAP/DFO, and Roy Hyndman and Garry Rogers, PGC, NRCan for advice and information. We thank an anonymous reviewer for insightful comments and suggestions, and Brenda Burd and Cynthia Wright of Ecostat Research Ltd. for editorial and other assistance.

REFERENCES

Ballantyne, V.A., Foreman, M.G.G., Crawford, W.R., and Jacques, R. 1996. Three-dimensional model simulations for the north coast of British Columbia. Continental Shelf Research 16: 1655-1682.

Barrie, J.V., and Bornhold, B.D. 1989. Surficial geology of Hecate Strait, British Columbia continental shelf. Canadian Journal of Earth Sciences 26: 1241-1254.

Bornhold, B., and Harper, J. 2002. Appendix 11: Overview of geological hazards to offshore petroleum development - British Columbia continental shelf. *In* British Columbia Offshore Hydrocarbon Development: appendices to the Report of the Scientific Review Panel. *Edited by* D. Strong, P. Gallagher and D. Muggeridge. Ministry of Energy and Mines, Government of British Columbia, Victoria, B.C., pp. 60-70.

Bowman, M.J., Vissar, A., and Crawford, W.R. 1992. The Rose Spit Eddy in Dixon Entrance: Evidence for its existence and underlying dynamics. Atmosphere-Ocean 30: 70-93.

Cameron, B.E.B., and Hamilton, T.S. 1988. Contributions to the stratigraphy and tectonics of the Queen Charlotte Basin, British Columbia. Current Research Part E(88-1E): 221-227.

Conway, K.W., and Barrie, J.V. 1994. Coastal erosion on the east coast of Graham Island, Queen Charlotte Islands, British Columbia Current Research 1994-E, Geological Survey of Canada, pp. 53-58.

Crawford, W., Cretney, W., Cherniawsky, J., and Hannah, C. 2003. Modelling Oceanic Fates of Oil, Drilling Muds and Produced Water from the Offshore Oil and Gas Industry, with Application to the Queen Charlotte Basin. Pacific Science Advice Review Committee Report 2002/120 (http://www.pac.dfo-mpo.gc.ca/sci/psarc/ ResDocs/habitat_02_e.htm).

Crawford, W.R. 2001. Oceans of the Queen Charlottes Islands. Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C. Canadian Technical Report of Fisheries and Aquatic Sciences: 2383, 1 CDROM p.

Crawford, W.R., Cherniawsky, J.Y., and Cummins, P. 1999. Surface currents in British Columbia coastal waters: Comparison of observations and model predictions. Atmosphere-Ocean 37: 255-280.

Crawford, W.R., Cherniawsky, J.Y., Cummins, P.F., and Foreman, M.G. 1998a. Variability of tidal currents in a wide strait: A comparison between drifter observation and numerical simulations. Journal of Geophysical Research 103: 12,743-12,759.

Crawford, W.R., Cherniawsky, J.Y., Foreman, M.G.G. and Gower, J.R.R. 2002. Formation of the Haida-1998 oceanic Eddy. Journal of Geophysical Research 107(C7): 10,1029/2001JC000876.

Crawford, W.R., and Greisman, P. 1987a. Investigation of permanent eddies in Dixon Entrance, British Columbia. Continental Shelf Research 7: 851-870.

Crawford, W.R., Huggett, W.S., Woodward, M.J., and Daniel, P. 1985. Summer circulation of the waters of Queen Charlotte Sound. Atmosphere-Ocean 23: 393-413.

Crawford, W.R., and Thomson, R.E. 1991. Physical oceanography of the western Canadian continental shelf. Continental Shelf Research 11: 669-683.

Crawford, W.R., Tyler, A.V., and Thomson, R.E. 1990. A possible eddy retention mechanism for icthyoplankton in Hecate Strait. Canadian Journal of Fisheries and Aquatic Sciences 47: 1356-1363.

Crawford, W.R., and Whitney, F. 1999. Mesoscale eddies aswirl with data in Gulf of Alaska Ocean. EOS, Transactions of the American Geophysical Union 80(33): 365-370.

Crawford, W.R., Woodward, M.J., Foreman, M.G.G., and Thomson, R.E. 1995. Oceanographic features of Queen Charlotte Sound and Hecate Strait in summer. Atmosphere-Ocean 33(4): 639-681.

Crawford, W.R., Woodward, M.J., Foreman, M.G.G., and Thomson, R.E. 1995. Oceanographic features of Queen Charlotte Sound and Hecate Strait in summer. Atmosphere-Ocean 33(4): 639-681.

Crean, P.B. 1967. Physical oceanography of Dixon Entrance, British Columbia. Fisheries Research Board of Canada Bulletin 156: 67.

Cummins, P.F., and Oey, L-Y. 1997. Simulation of barotropic and baroclinic tides of Northern British Columbia. Journal of Physical Oceanography 27: 762-781.

Cummins, P.F., Cherniawsky, J.Y., and Foreman, M.G.G. 2001. North Pacific internal tides from the Aleutian Ridge. Journal of Marine Research. 59(2): 167-191.

Dodimead, A.J. 1980. A general review of the oceanography of the Queen Charlotte-Hecate Strait-Dixon Entrance region. Canadian Manuscript Report of Fisheries and Aquatic Sciences 1574: 248.

Dunbar, D., LeBlond, P., and Murty, T.S. 1991. Evaluation of tsunami amplitudes for the Pacific Coast of Canada. Progress in Oceanography 26: 115-177.

England, T.D.J. 1989. Late Cretaceous to Paleogene Evolution of the Georgia Basin, Southwestern British Columbia. Ph. D. Thesis, Memorial University, St. John's, Newfoundland, 482 p.

England, T.D.J., and Hiscott, R.N. 1992. Lithostratigraphy and deep water setting of the upper Nanaimo group (Upper Cretaceous), outer Gulf Islands of southwestern British Columbia. Canadian Journal of Earth Sciences 29(3): 573-595.

Fine, I.V., Rabinovich, A.B., Thomson, R.E., and Kulikov, E.A. 2002. Numerical Modeling of Tsunami Generation by Submarine and Subaerial Landslides. *In* NATO Science Series, Underwater Ground Failures On Tsunami Generation, Modeling, Risk and Mitigation. Proceedings of the 2001 Istanbul NATO Tsunami Workshop. Istanbul, Turkey, Kluwer Publishing., pp. (in press).

Foreman, M.G.G., Crawford, W.R., Cherniawsky, J.Y., Henry , R.F., and Tarbotton, M. 2000. A high-resolution assimilating tidal model for the Northeast Pacific Ocean. Journal of Geophysical Research 105: 28,629-28,652.

Foreman, M.G.G., Henry, R.F., Walters, R.A., and Ballantyne, V.A. 1993. A finite element model for tides and resonance along the north coast of British Columbia. Journal of Geophysical Research 98(C2): 2,509-2,531.

Fowler, M.G., Snowdon, L.R., Brooks, P.W., and Hamilton, T.S. 1988. Biomarker characterisation and hydrous pyrolysis of bitumens from Tertiary volcanics, Queen Charlotte Islands, British Columbia, Canada. Organic Geochemistry 13: 715-725.

González, F.I. 1999. Tsunami! Scientific American 280(5): 56-65.

Gower, J., and Jones, D.M. 1994. Canadian west coast giant waves. Mariners Weather Log (Spring): 4-8.

Graham, N.E., and Diaz, H.F. 2001. Evidence for Intensification of North Pacific Winter Cyclones since 1948. Bulletin of the American Meteorological Society 82(9): 1869-1893.

Hamilton, T.S., and Cameron, B.E.B. 1989. Hydrocarbon occurrences on the western margin of the Queen Charlotte basin. Bulletin of Canadian Petroleum Geology 37(4): 443-466.

Hamilton, T.S., and Dostal, J. 1993. Geology, geochemistry, and petrogenesis of middle Tertiary volcanic rocks of the Queen Charlotte Islands, British Columbia (Canada). Journal of Volcanology and Geothermal Research 59: 77-99.

Hamilton, T.S., and Dostal, J. 2001. Melting of heterogeneous mantle in a slab window environment: examples from the middle Tertiary Masset basalts, Queen Charlotte Islands, British Columbia. Canadian Journal of Earth Sciences 38: 825-838.

Hannah, C.G., and Crawford, W.R. 1996. Winter transport and sea level fluctuations in Hecate Strait, British Columbia. Journal of Geophysical Research 101(C12): 28,356-28,376.

Hannigan, P.K., Dietrich, J.R., Lee, P.J., and Osadetz, K.G. 2001. Petroleum Resource Potential of the Sedimentary Basins on the Pacific Margin of Canada, Geological Survey of Canada, pp. 72 p.

Hart, B.S., and Hamilton, T.S. 1993. High resolution acoustic mapping of shallow gas in unconsolidated sediments beneath the Strait of Georgia, British Columbia. Geomarine Letters 13: 49-55.

Hebenstreit, G.T., and Murty, T.S. 1989. Tsunami amplitudes from local earthquakes in the Pacific Northwest region of North America. Part 1: The outer coast. Marine Geodesy 13(2): 101-147.

Hubbard, J.R., and Duncan, S.A. 2002. Tsunami hazard mitigation and the NOAA national water level observation network. Science of Tsunami Hazards 20(1): 19-25.

Hyndman, R.D. 1995. Giant Earthquakes of the Pacific Northwest. Scientific American 273: 68-75.

Hyndman, R.D., and Hamilton, T.S. 1993. Queen Charlotte area Cenozoic tectonics and volcanism and their association with relative plate motions along the Northeastern Pacific margin. Journal of Geophysical Research 98: 14,257-14,277.

James, R.W. 1969. Abnormal changes in wave height. Mariners Weather Log 13: 252-255.

Johnson, S.Y. 1984. Stratigraphy, age and paleogeography of the Eocene Chuckaanut Formation, northwest Washington. Canadian Journal of Earth Sciences 21: 92-106.

Kang, S-K., Foreman, M.G.G., Crawford, W.R., and Cherniawsky, J.Y. 1999. Numerical modeling of internal tide generation along the Hawaiian Ridge. Journal of Physical Oceanography 30: 1083-1098.

Kulikov, E.A., Rabinovich, A.B., Fain, I.V., Bornhold, B.B., and Thomson, R.E. 1998. Tsunami generation by landslides at the Pacific coast of North America and the role of tides. Oceanology 38: 323-328.

Kulikov, E.A., Rabinovich, A.B., Thomson, R.E., and Bornhold, B.B. 1996. The landslide tsunami of November 3, 1994, Skagway Harbor, Alaska. Journal of Geophysical Research 101: 6609-6615.

Mackas, D.M., and Galbraith, M.D. 2002. Zooplankton distribution and dynamics in a North Pacific eddy of coastal origin: I. Transport and loss of continental margin species. Journal of Oceanography 58(5): 725-738.

MacLaren Plansearch (1991) Limited and Oceanweather Inc. 1992. Wind / Wave Hindcast Extremes for the West Coast of Canada. Canadian Climate Centre. excluding appendices, 143 p.

Masson, D. 1996. A case study of wave-current interaction in a strong tidal current. Journal of Physical Oceanography 26: 359-372.

Mosher, D.C., and Thomson, R.E. 2002. The Foreslope Hills: deep water sedimentary bedforms in the Strait of Georgia, British Columbia. *In* Special Issue on Recognition and interpretation of deep-water sediment waves: Implication for palaeoceanography, hydrocarbon exploration, and flow processes interpretation. *Edited by* R.B. Wynn and D.A.V. Stow. Marine Geology.

Muller, J.E., and Jeletzky, J.A. 1970. Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia. Geological Survey of Canada. Paper 69-25, 77 p.

Murty, T.S., and Hebenstreit, G.T. 1989. Tsunami amplitudes from local earthquakes in the Pacific Northwest region of North America. Part 2: Strait of Georgia, Juan de Fuca Strait and Puget Sound. Marine Geodesy 13(3): 189-209.

Myers, E.P., Baptista, A.M., and Priest, G.R. 1999. Finite element modeling of potential Cascadia Subduction Zone tsunamis. Science of Tsunami Hazards 17(1): 3-18.

Myers, E.P., and Baptista, A.M. 1991. Finite element modeling of potential Cascadia Subduction Zone tsunamis. Science of Tsunami Hazards 17(1): 3-18.

Ng, M., LeBlond, P.H., and Murty, T. 1990a. Simulation of tsunamis from great earthquakes on the Cascadia Subduction Zone. Science 250: 1248-1251.

Ng, M., LeBlond, P.H., and Murty, T. 1990b. Numerical simulation of tsunami amplitudes on the coast of British Columbia due to local earthquakes. Science of Tsunami Hazards 8(2): 97-127.

Nottingham, D. 2002. Review of the 1994 Skagway, Alaska tsunami and future plans. Science of Tsunami Hazards 20(1): 42-49.

Patin, S. 1999. Environmental impact of the offshore oil and gas industry. Eco-Monitor Publishing, East Newport, NY, 425 p.

Petro-Canada. 1983. Offshore Queen Charlotte Islands: Initial Environmental Evaluation. Prepared for: Environment Canada and Ministry of Environment, Lands and Parks Canada. 3 volumes p.

Priest, G.R. *et al*. 2000. Source simulation for tsunamis: Lessons learned from fault rupture modeling of the Cascadia Subduction Zone, North America. Science of Tsunami Hazards 18(2): 77-107.

Rabinovich, A.B., Kulikov, E.A., Fine, I.V., Thomson, R.E., and Bornhold, B.D. 1999. The landslide-generated tsunami of November 3, 1994 in Skagway Harbor, Alaska: A case study. Geophysical Research Letters 26: 3009-3012.

Rabinovich, A.B., Thomson, R.E., Bornhold, B.B., Fine, I.V., and Kulikov, E.A. 2002. Numerical modelling of tsunamis generated by hypothetical landslides in the Strait of Georgia, British Columbia. PAGEOPH Pure and Applied Geophys: (in press, October 2001).

Rogers, G., Ristau, J., Bird, A., Rabinovich, A., and Thomson, R. 2002. The October 12, 2001, Queen Charlotte Islands earthquake and tsunami *Presented at* Annual Meeting, Seismological Society of America, April 17-19, 2002, Victoria, British Columbia.

Rogers, G.C. 1983. Seismotectonics of British Columbia. Ph.D. Thesis, University of British Columbia, Vancouver, B.C.

Rohr, K.M.M. 2002. Appendix 8: Faulting and seismicity in Queen Charlotte Basin. *In* British Columbia Offshore Hydrocarbon Development: appendices to the Report of the Scientific Review Panel. *Edited by* D. Strong, P. Gallagher and D. Muggeridge. Ministry of Energy and Mines, Government of British Columbia, Victoria, B.C., pp. 47-49.

Rohr, K.M.M., and Currie, L. 1997. Queen Charlotte Basin and Coast Mountains: Paired belts of subsidence and uplift caused by a low -angle normal fault. Geology 25: 819-822.

Rohr, K.M.M., and Dietrich, J.R. 1992. Strike-slip tectonics and development of the Tertiary Queen Charlotte Basin, offshore western Canada: Evidence from seismic reflection data. Basin Res. 4: 1-19.

Rohr, K.M.M., and Furlong, K.P. 1995. Ephemeral plate tectonics at the Queen Charlotte triple junction. Geology 23: 1035-1038.

Rohr, K.M.M., Scheidhauer, M., and Trehu, A.M. 2000. Transpression between two warm plates: the Queen Charlotte Fault revisited. Journal of Geophysical Research 105 (B4): 8147-8172.

Satake, S. 2001. Tsunami modeling from submarine landslides. *In* Proceedings, International Tsunami Symposium. pp. 665-674.

Shouldice, J.G. 1971. Geology of the western Canadian Continental shelf. Bulletin of Canadian Petroleum Geology 19(2): 405-436.

Smith, A. 1999. Structure, deformation, and thermal regime of the Queen Charlotte Transform Margin. M.Sc. Thesis, University of Victoria, Victoria, B.C., 179 p.

Snowdon, L.R., Fowler, M.G. and Hamilton, T.S. 1988b. Sources and Seeps: Organic Geochemistry Results of the Queen Charlotte Islands. *In* CSPG Field Guide "Some Aspects of the Petroleum Geology of the Queen Charlotte Islands, September 1988 Field Trip". *Edited by* R. Higgs. CSPG, pp. 37-43.

Snowdon, L.R., Fowler, M.G., and Hamilton, T.S. 1988a. Progress Report on Organic Geochemistry, Queen Charlotte Islands, British Columbia. Geological Survey of Canada. 88-1E.

Tabata, S. 1980. An Inventory of Physical Oceanographic Information for the Waters of Queen Charlotte Sound, Hecate Strait and Dixon Entrance and their Vicinity. Fisheries and Ocean Canada, Institute of Ocean Sciences, Sidney, British Columbia. 80-7, 47 p.

Thomson, R.E. 1981. Oceanography of the British Columbia Coast. Canadian Special Publication of Fisheries and Aquatic Sciences 56: 235-258.

Thomson, R.E., and Emery, W.J. 1986. The Haida current. Journal of Geophysical Research 91: 845-861.

Thomson, R.E., and Crawford, W.R. 1997. Processes affecting sea level change along the coasts of British Columbia and the Yukon. *In* Responding to Global Climate Change in British Columbia and the Yukon, Volume I of the Canada Country Study: Climate Impacts and Adaptation, Proceedings of workshop. Simon Fraser University, Burnaby, B.C., February 27-28, 1997. Environment Canada and British Columbia Ministry of Environment, Lands and Parks, pp. 1-19 in Chapter 4.

Thomson, R.E., and Wilson, R.E. 1987. Coastal countercurrent and mesoscale eddy formation by tidal rectification near an oceanic cape. Journal of Physical Oceanography 17: 2096-2126.

WASA Group. 1998. Changing waves and storms in the Northeast Atlantic. Bulletin of the American Meteorological Society 79: 741-761.

West Coast Offshore exploration Environmental Assessment Panel. 1986. Offshore Hydrocarbon Exploration: Report and Recommendations. B.C. Ministry of Environment, Lands and Parks.

Whiticar, M.J. 2002. Appendix 6: Geological situation and hydrocarbon potential of the Queen Charlotte Basin. *In* British Columbia Offshore Hydrocarbon Development: appendices to the Report of the Scientific Review Panel. *Edited by* D. Strong, P. Gallagher and D. Muggeridge. Ministry of Energy and Mines, Government of British Columbia, Victoria, B.C., pp. 26-36.

Whitmore, P.M. 1993. Expected tsunami amplitudes and currents along the North American coast for Cascadia Subduction Zone Earthquakes. Natural Hazards 8: 59-73.

Yorath, C.J., and Hyndman, R.D. 1983. Subsidence and thermal history of the Queen Charlotte Basin. Canadian Journal of Earth Sciences 20: 135-159.

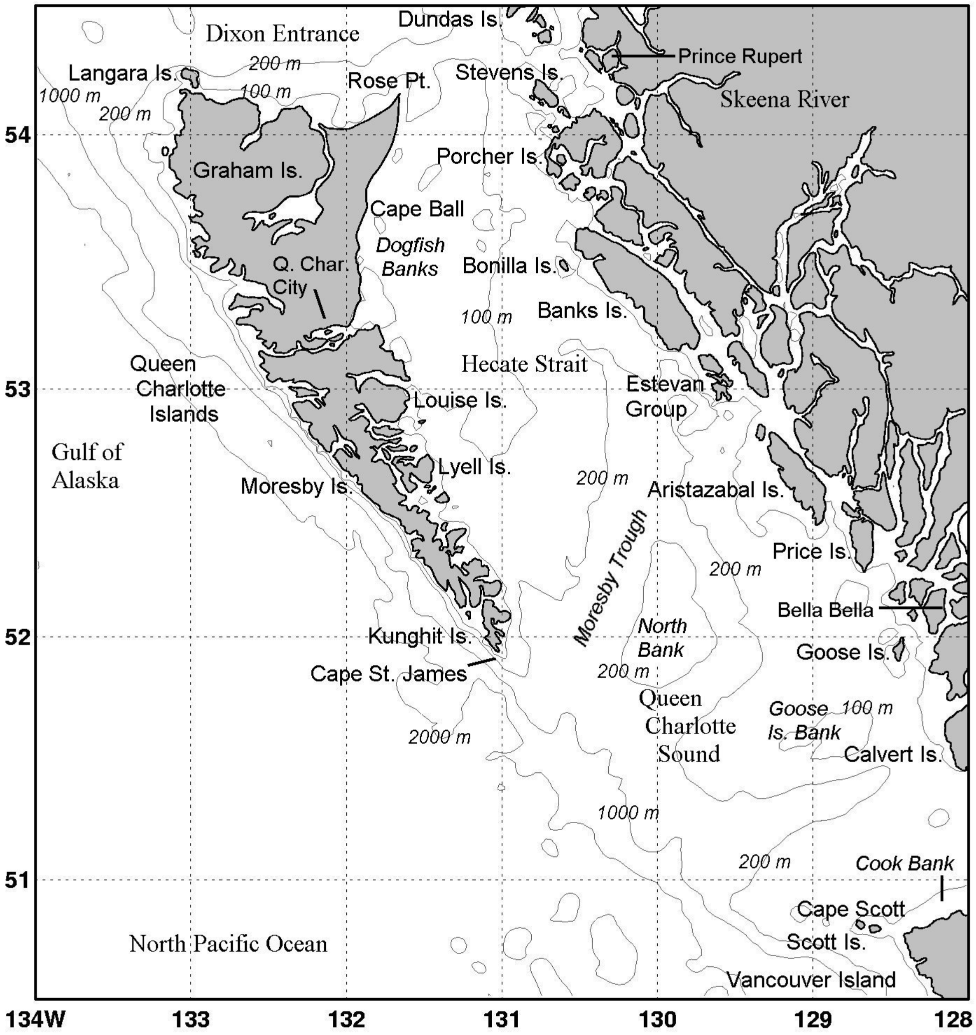

Figure 1: Geographical region.

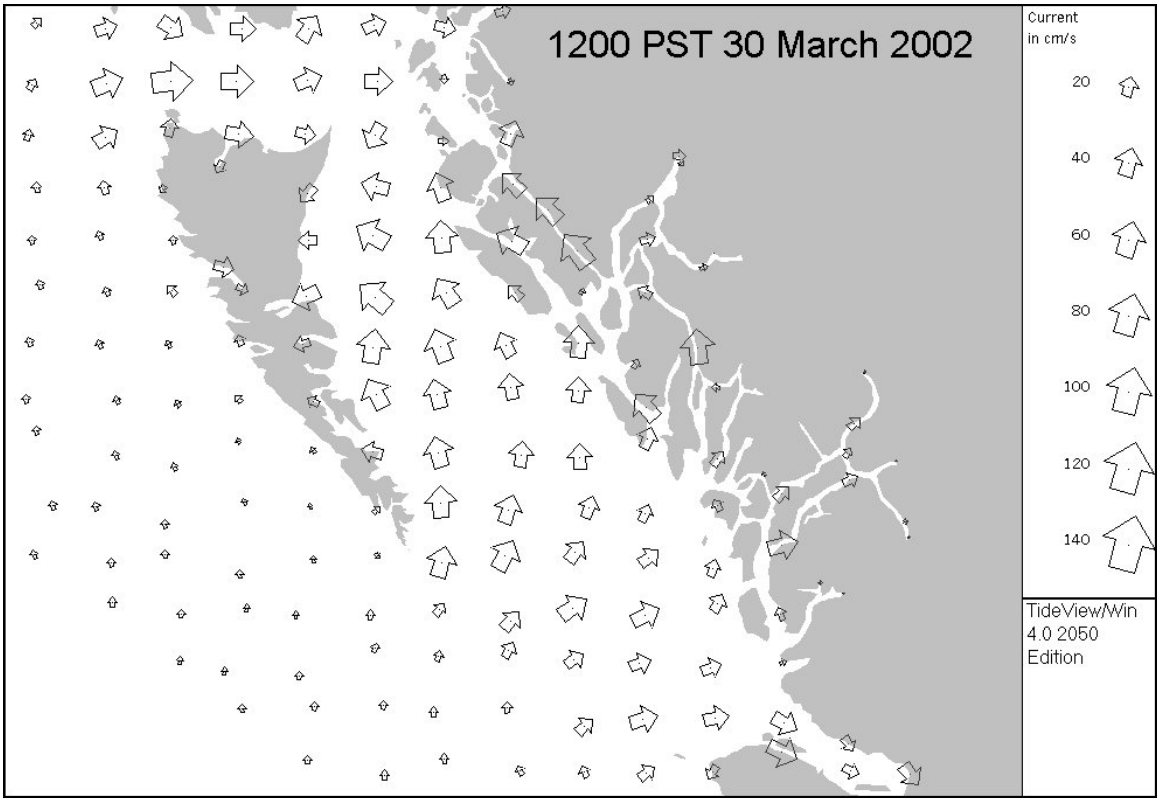

Figure 2: Tidal current vectors provided by the software program Tideview (North Coast Module) for 12:00 p.m., 30 March 2002 (a computer screen capture of this program). Arrows denote magnitude and direction of tidal currents at this time, with arrows at right providing speed scale.

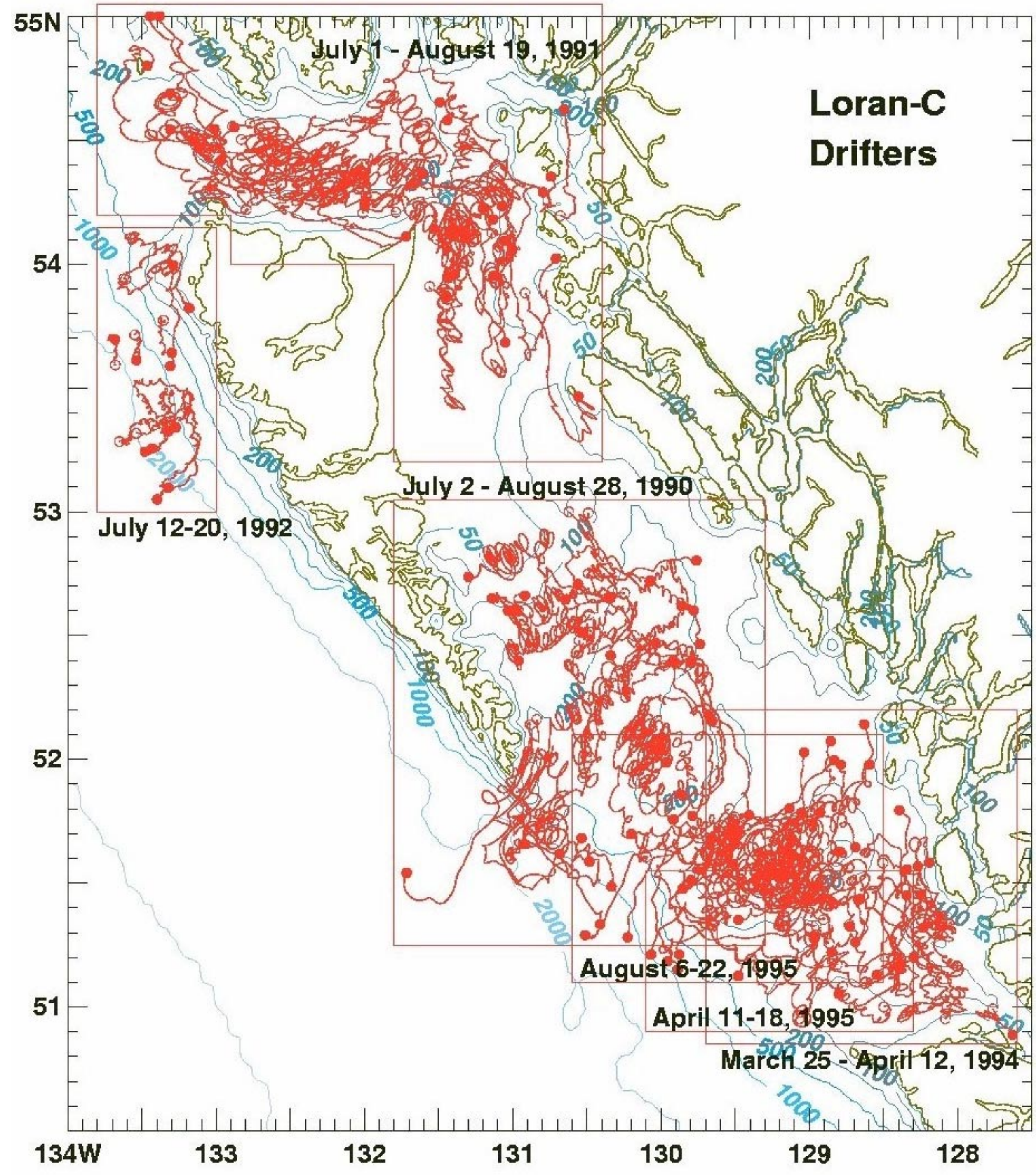

Figure 3: Tracks of near-surface drifters drogued at 15 m or 5 m below surface and tracked using Loran-C navigation. Open circles denote drifter deployment sites, solid dots denote drifter recovery positions (from Crawford, 2001).

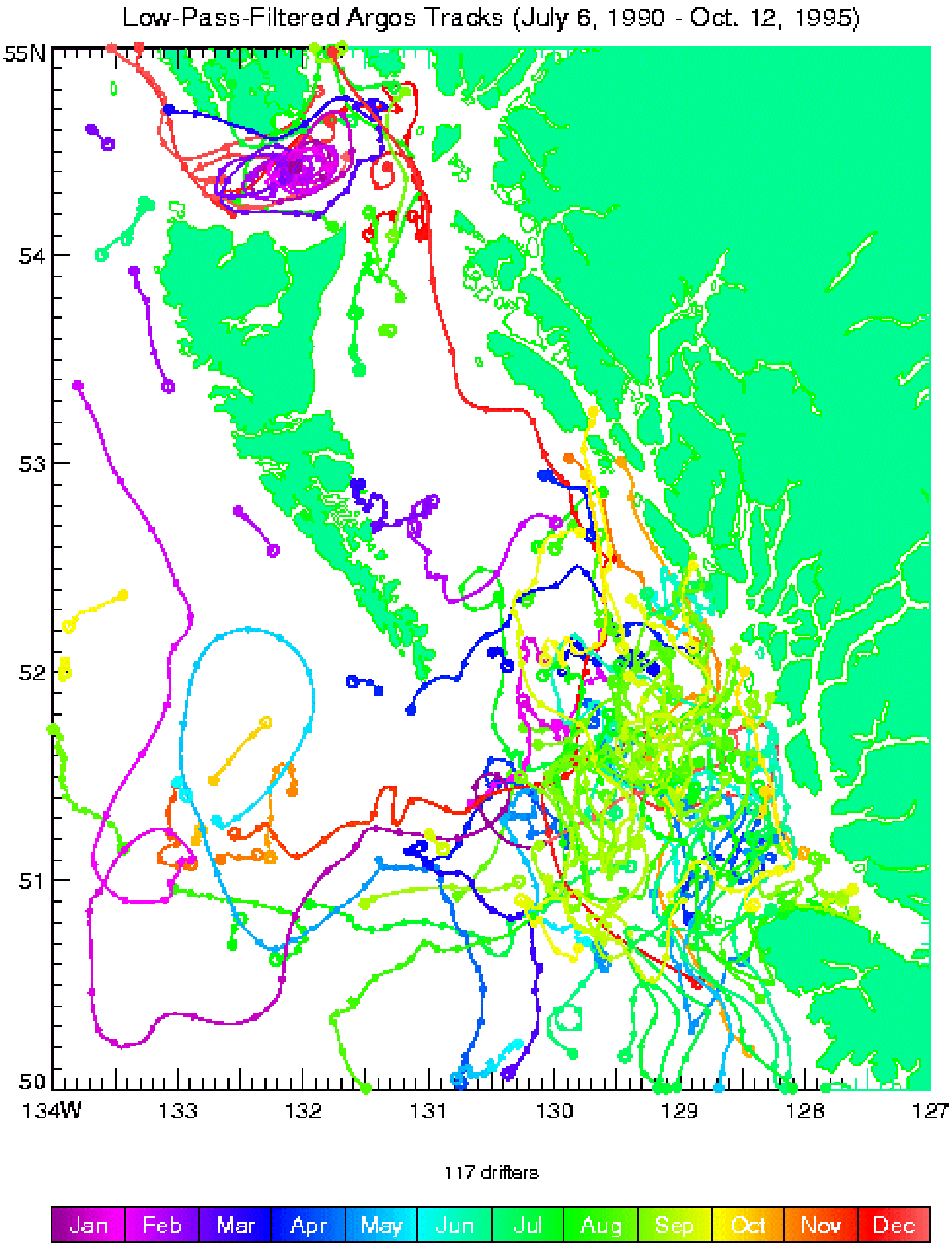

Figure 4: Tracks of Argos surface drifters drogued in the upper 1 metre of the ocean. Open circles denote drifter deployment sites, solid dots denote drifter recovery positions. Colour of track denotes month of year (from Crawford, 2001).

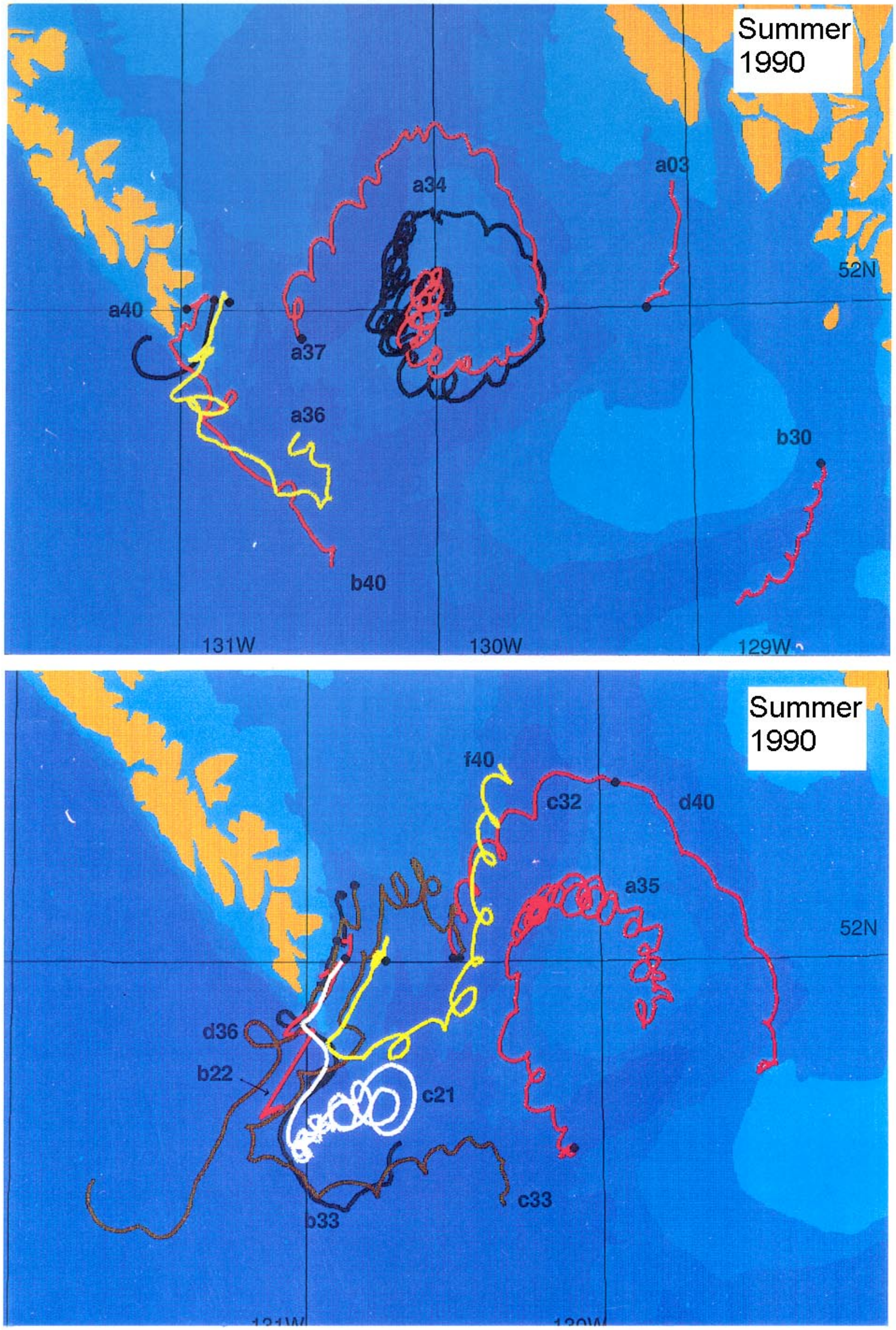

Figure 5a: Tracks of near-surface drifters launched in (a) southern Hecate Strait and Queen Charlotte Sound in July-August 1990 (from Crawford *et al*., 1995),

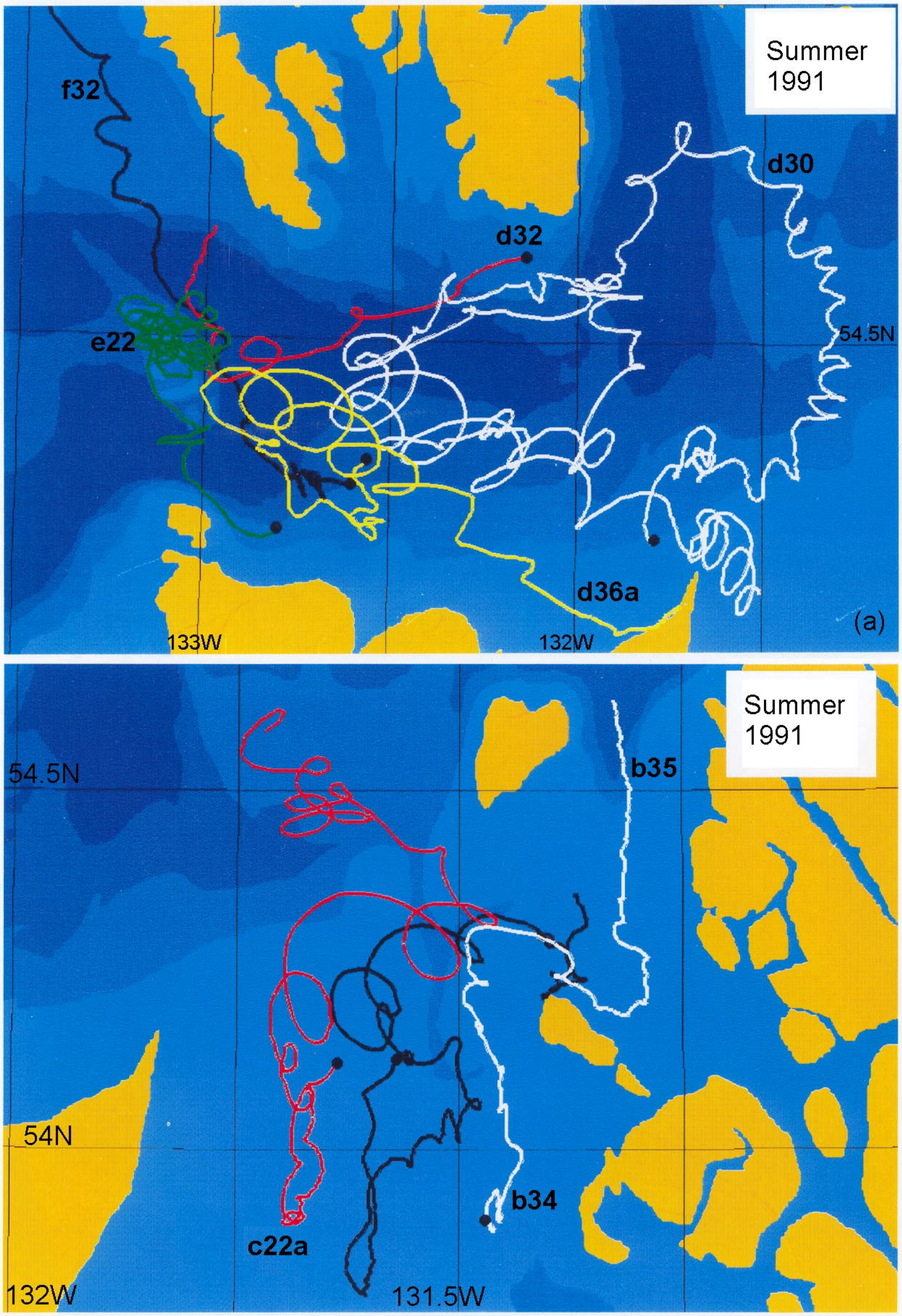

Figure 5b: Tracks of near-surface drifters launched in (b) northern Hecate Strait and Dixon Entrance in July-August 1991. Shadings of blue denote 100-, 200- and 300-m depths. Each track begins at a black dot, and is labelled by an unique alphanumeric symbol of the type “a35”.

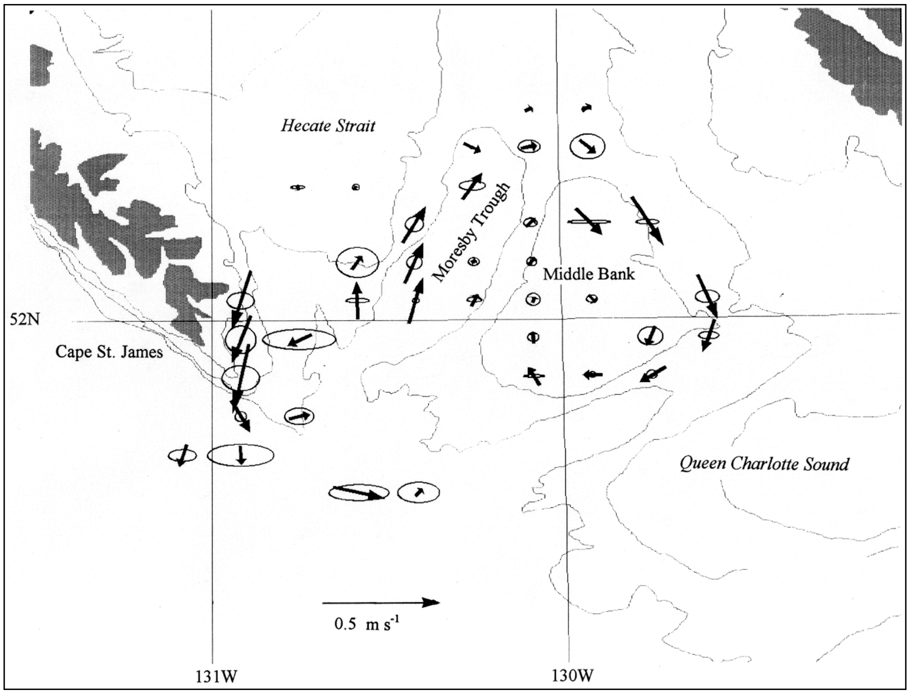

Figure 6a

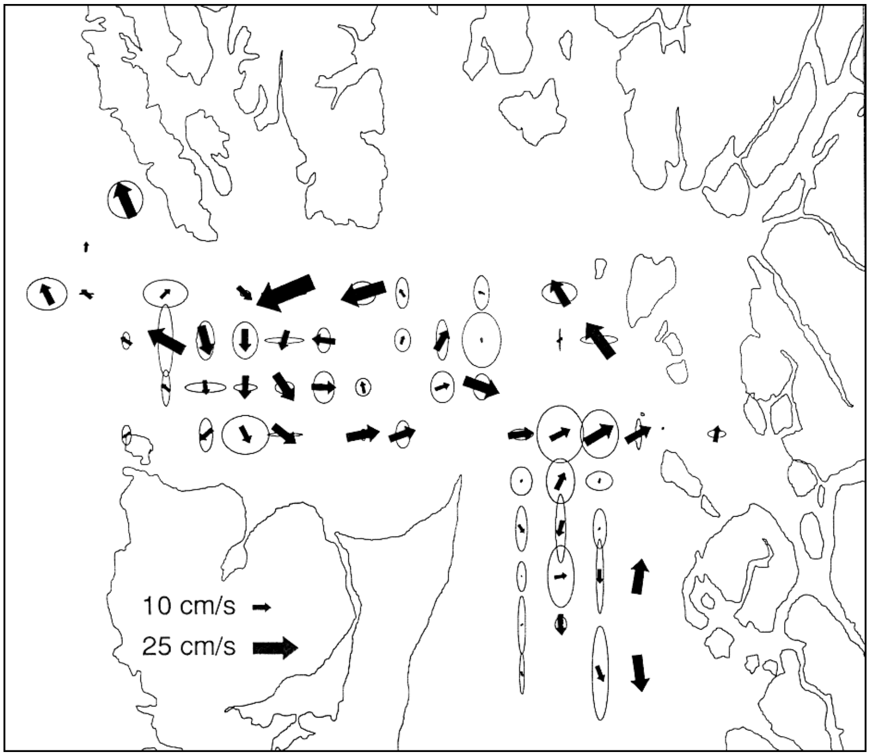

Figure 6b

Figure 6: Average currents as calculated from near-surface drifter tracks. Estimated standard deviations are shown as ellipses around each vector. Lack of an ellipse indicates only one observation was available. (a) southern Hecate Strait and Queen Charlotte Sound in July-August 1990 (from Crawford *et al*., 1995), and (b) northern Hecate Strait and Dixon Entrance in July-August 1991 (from Ballantyne *et al*., 1996).

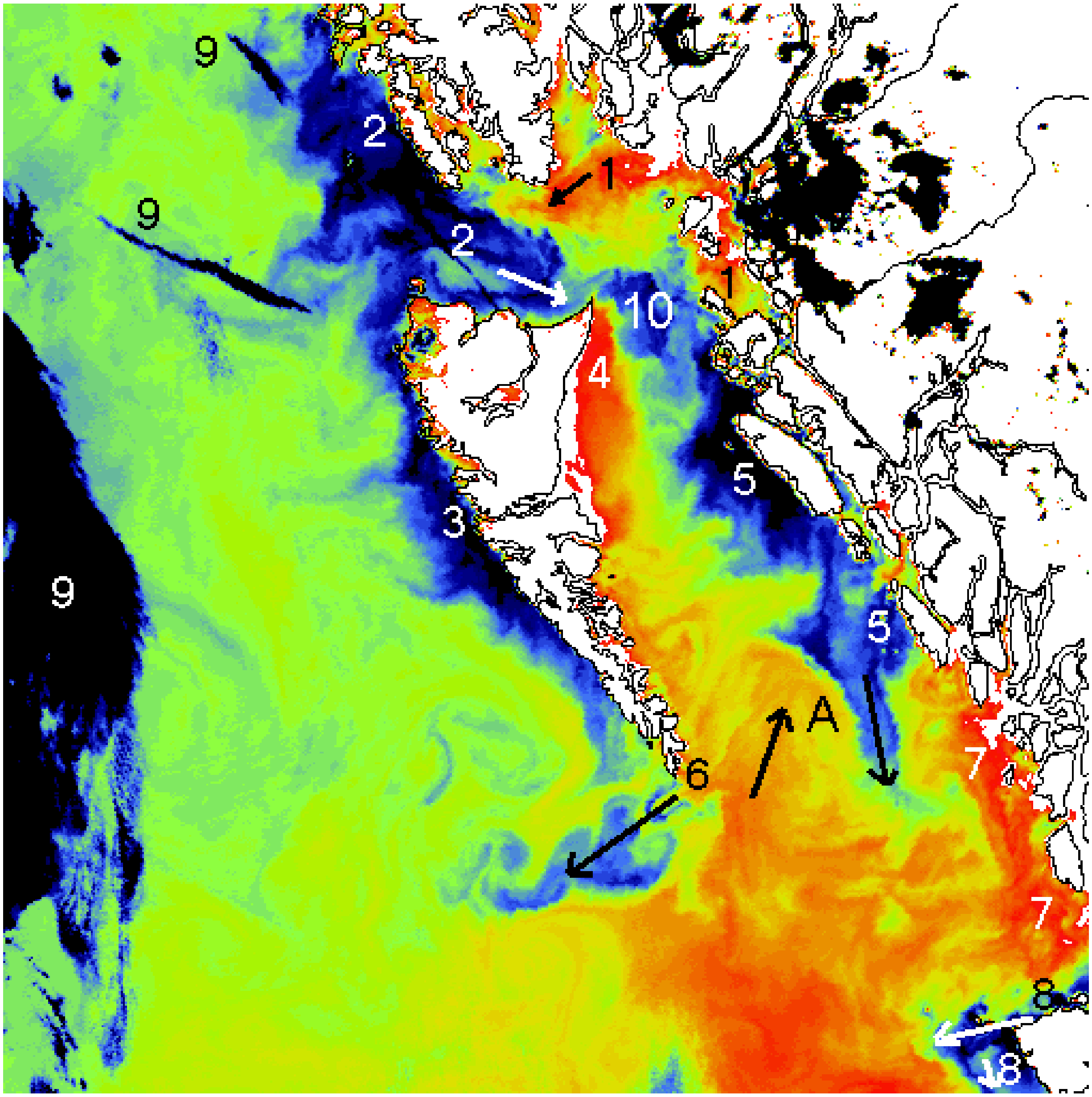

Figure 7: Satellite images of summer sea surface temperature, based in measurements of infrared light by NOAA satellite on 24 July, 1994, and processed by Jim Gower and John Wallace of DFO, Institute of Ocean Sciences. Dark blue regions are about 10 °C; bright red regions are about 16 °C, and temperatures increase through colours from blue to green to yellow to orange to red. Black regions are clouds or jet contrails. White denotes land. Arrows denote direction of surface currents implied by this image. Letter A denotes centre of persistent clockwise eddy in summer, identified by drifter tracks. Numbered features are described in text.

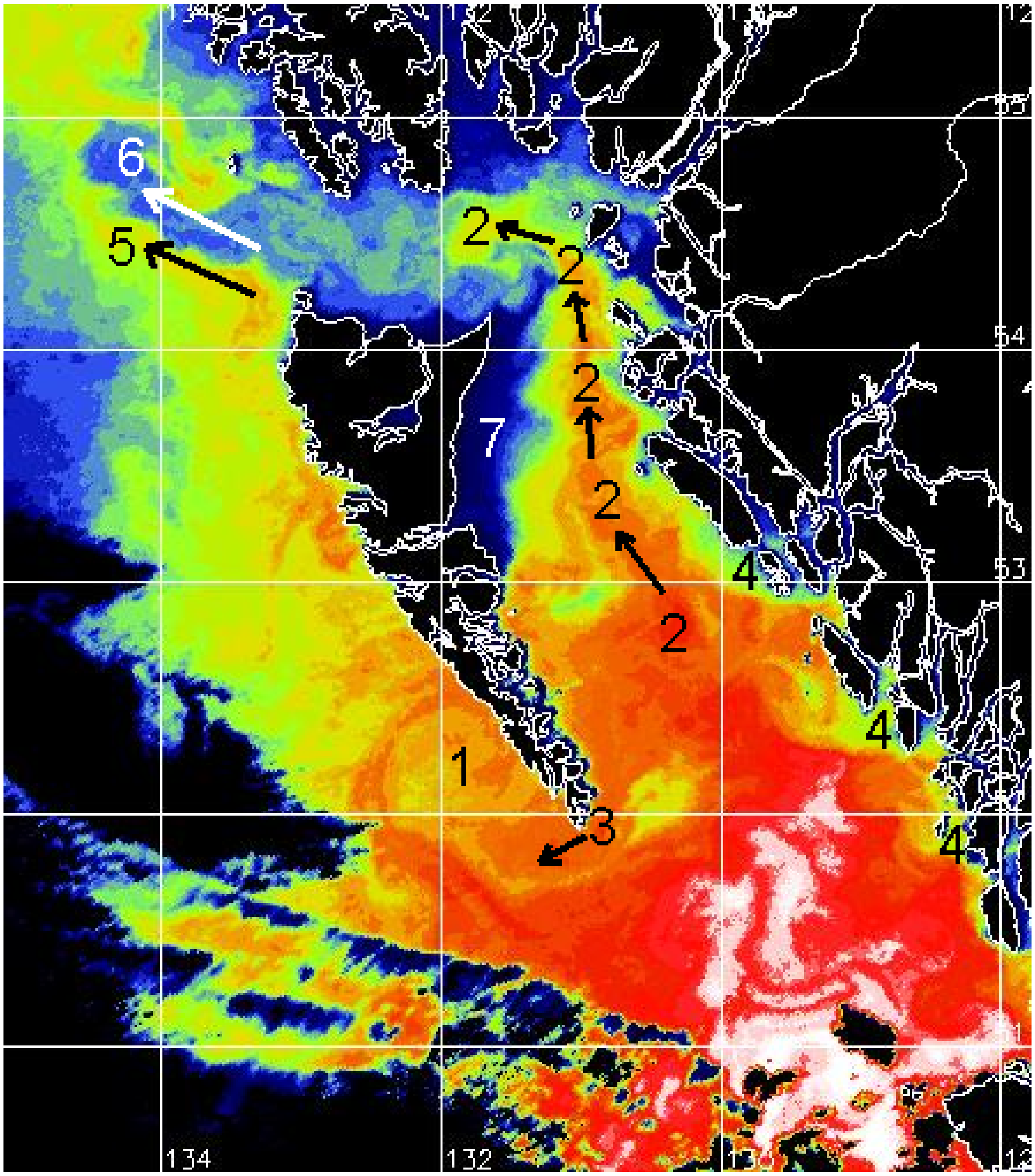

Figure 8: Satellite images of winter sea surface temperature, based in measurements of infrared light by NOAA satellite on 25 December, 1996, and processed by Jim Gower and John Wallace of DFO, Institute of Ocean Sciences. Dark blue regions are about 4 °C; white regions are about 8 °C, and temperatures increase through colours from blue to green to yellow to orange to red to white. Black regions are clouds or land. Arrows denote direction of surface currents implied by this image. Numbered features are described in text.

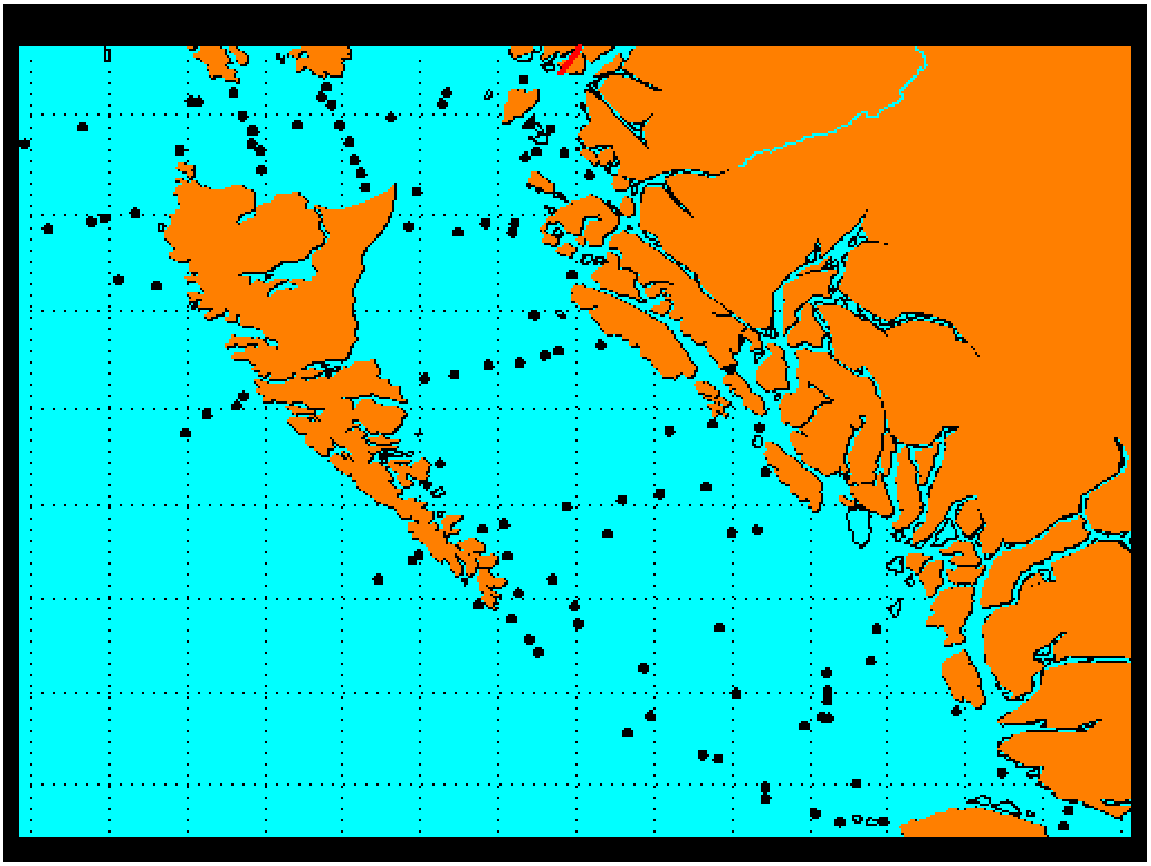

Figure 9: Locations of current meter moorings established by scientists and hydrographers of DFO at the Institute of Ocean Sciences, 1977, and 1982 to 1995.

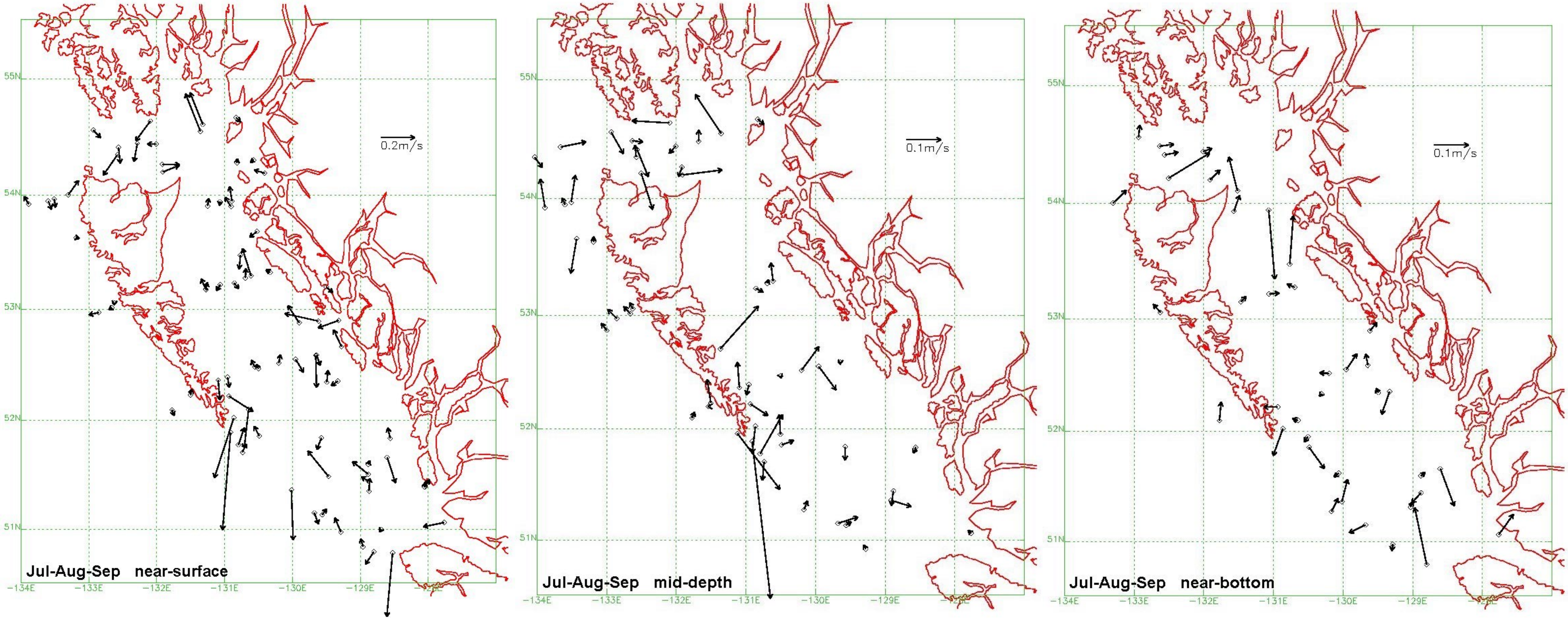

Figure 10: Average currents in summer. The speed scale of surface currents differs from scale of mid-depth and near-bottom currents. All vectors are based on measurements by continuously recording current meters, suspended between bottom anchors and near-surface or surface floats. Meters with less than one-month of data did not contribute to this figure. Base of current vectors denotes mooring site. Moorings were deployed between 1977 and 1995 by Fisheries and Oceans Canada. Some 1977 measurements were discarded due to high speeds resulting from rotor pumping by sub-surface float. (Measurements were made by Fisheries and Oceans Canada staff at Institute of Ocean Sciences, funded jointly by DFO and Panel for Energy Research and Development.)

near-surface:	within 50 metres of surface.
bottom:	within 20 metres of bottom
mid-depth	between near-surface and near-bottom

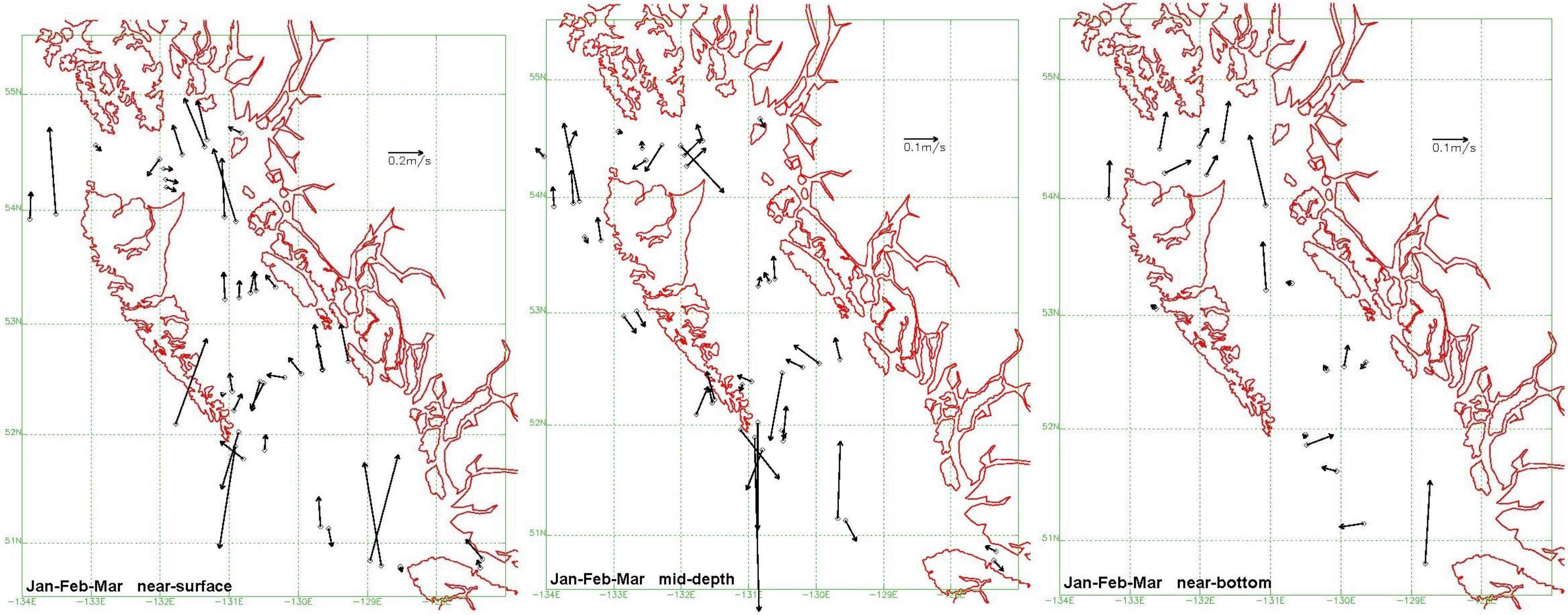

Figure 11.: Average currents in winter. The speed scale of surface currents differs from scale of mid-depth and near-bottom currents. All vectors are based on measurements by continuously recording current meters, suspended between bottom anchors and near-surface or surface floats. Meters with less than one-month of data did not contribute to this figure. Base of current vectors denotes mooring site. Moorings were deployed between 1977 and 1995 by Fisheries and Oceans Canada. Some 1977 measurements were discarded due to high speeds resulting from rotor pumping by sub-surface float. (Measurements were made by Fisheries and Oceans Canada staff at Institute of Ocean Sciences, funded jointly by DFO and Panel for Energy Research and Development.)

near-surface:	within 50 metres of surface.
bottom:	within 20 metres of bottom
mid-depth	between near-surface and near-bottom

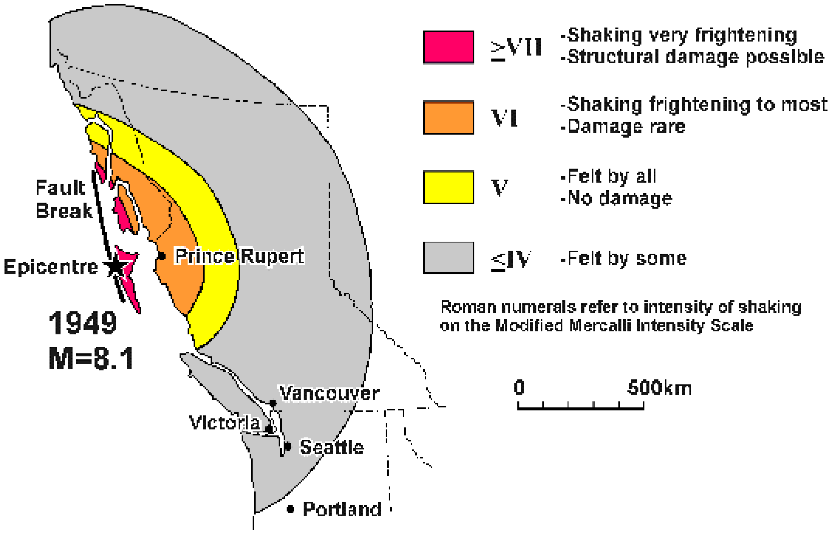

Figure 12.: Map showing the epicentre of the magnitude 8.1 earthquake that occurred on August 22, 1949 on the Queen Charlotte Fault (copyright National Resources Canada, from www.pgc.nrcan.gc.ca/seismo/hist/1949.htm)

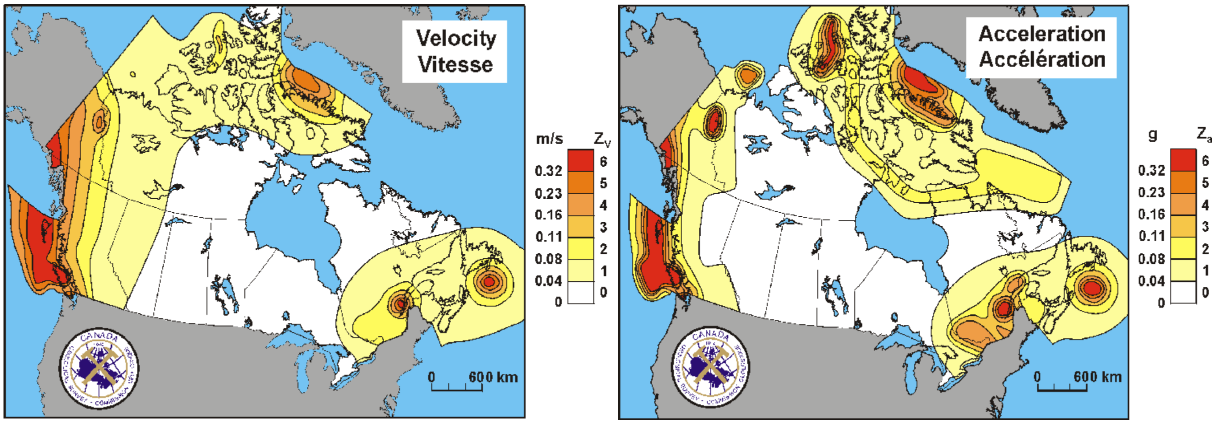

Figure 13: Seismic hazard maps of Canada showing the maximum velocity of shaking at 1 cycle/second and the maximum acceleration in gravitational units at 5 cycles /second. The maps are probabilistic maps. An earthquake exceeding the velocity or accelerations shown for a given zone will only occur about once in every 500 years. (copyright Natural Resources Canada, from www.pgc.nrcan.gc.ca/seismo/eqhaz/seishaz.htm).