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Mineral Resource Assessment of the Pacific Margin Sponge Reef Areas of Interest

J.V. Barrie

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MINERAL RESOURCE ASSESSMENT OF THE PACIFIC MARGIN SPONGE REEF AREAS OF INTEREST

J.V. Barrie

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ABSTRACT

Glass sponge reefs (*Hexactinellida*, *Hexactinosida*) off the Pacific Margin of Canada are both geologically and ecologically unique and represent the only global occurrence. In order to provide protection to these unique living cold-water reefs, the Department of Fisheries and Oceans under the Oceans Act have made the four large reefs within the Pacific North Coast Integrated Management Area (PNCIMA) designates for protection as Marine Protected Areas (MPA). The federal government's process for evaluation of a MPA of Interest requires an assessment of the non-renewable resource potential, including marine minerals.

Based on the limited knowledge of the offshore British Columbia surficial mineral potential, two settings that may contain mineral placers of gold and titanium include drowned beach and reworked shelf deposits at water depths of 150 m to the modern beach. In addition, extensive areas of construction aggregate and calcium carbonate occur on the shelf. The deep water sponge reefs within the Areas of Interest occur in depths below 150 m within glacial sediments and, therefore, outside the potential setting for mineral placers or industrial minerals. Consequently, the enactment of the sponge reef Marine Protected Areas will not include any surficial mineral deposits of economic potential.

INTRODUCTION

The Department of Fisheries and Oceans (DFO) is proposing to establish Marine Protected Areas that enclose the four large sponge reefs within the Pacific North Coast region (Fig. 1). As part of the considerations in proposing such an area, Natural Resources Canada has undertaken a review of the mineral potential of the area. This document reviews the published and unpublished literature that is relevant to an assessment of offshore non-fuel mineral resources within the study area and presents a judgement regarding the likelihood of their exploitation over the next century. In addition, this report outlines the present state of global marine mineral mining and the regulations that govern such operations.

The genesis of mineral resources in regions such as this is controlled by geological history and oceanographic regime. In order to address the potential of any surficial mineral resource in the area of concern, a review of the Quaternary geology and the driving processes that resulted in the present surficial geology is presented. From this a descriptive model of potential mineral occurrences can be proposed and then applied to the sponge reef area of interest to determine if any of the criteria are meet when considering mineral exploitation within the next century.

GEOLOGICAL SETTING

The Queen Charlotte Basin, including Hecate Strait, Queen Charlotte Sound, and Dixon Entrance, is a semi-enclosed continental shelf basin bordered to the east by the British Columbia mainland, to the west by the Haida Gwaii (Queen Charlotte Islands), and to the south by Vancouver Island (Fig. 1). It opens to the Pacific in the south and southwest through Queen Charlotte Sound and to the north through Dixon Entrance. Within the basin, glacial troughs, up to 500 m deep, are separated by banks that reach to within 30 m water depth. A large area of northwestern Hecate Strait is a very shallow (20–40 m) bank extending to Haida Gwaii.

Late Quaternary Geological Processes

Tectonism

Tectonism gave rise to the existence and location of Queen Charlotte Basin. The Pacific plate slides northward and slightly into North America at an average rate of 50 to 60 mm per year along the Queen Charlotte Fault (Fig. 1; Riddihough, 1988; Rohr et al., 2000). At the junction of the two plates, this motion has been accompanied by frequent earthquakes, which vary in intensity along the fault, although the overall pattern has been stable since records have been kept (Bird, 1997). Along with numerous small events, four large earthquakes have occurred this century, with the largest (magnitude 8.1) occurring in 1949 adjacent to the northwestern edge of the continental shelf of northern Haida Gwaii (Fig. 1), and the most recent on February 17, 2001 (magnitude 6.1). During the 8.1 earthquake, approximately 7 m of movement occurred over 490 km (Bostwick, 1984).

Late Wisconsin Glaciation (Fraser Glaciation)

Glaciation has happened many times in Queen Charlotte Basin, although extensive evidence has only been found for the youngest glacial episode, which

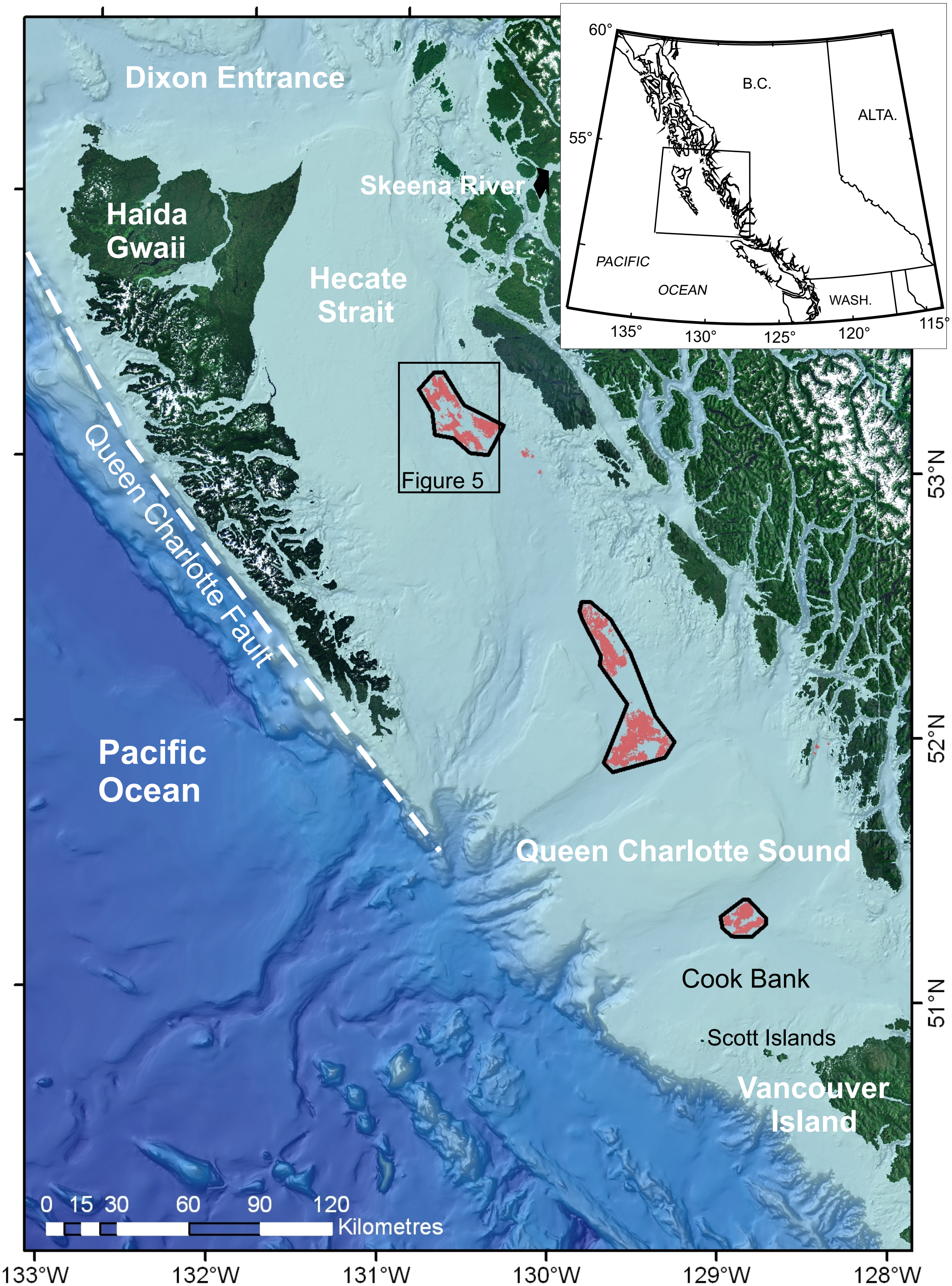

Figure 1. The Pacific north coast region of offshore British Columbia showing the distribution of sponge reefs (red) and the Areas of Interest, as proposed by the Department of Fisheries and Oceans. Location of Figure 5 is shown.

occurred over much of the islands as well as offshore (Clague et al., 1982a). The Fraser Glaciation, as the last main phase of continental glaciation is known in British Columbia, began approximately 25,000 to 30,000 years ago (Clague, 1977, 1981).

Ice from the massive Cordilleran sheet extended westward across northern Hecate Strait and through Dixon Entrance and coalesced with ice from Haida Gwaii, deflecting it westward along Dixon Entrance (Sutherland-Brown, 1968; Hicock and Fuller 1995; Barrie and Conway, 1999). This coalescence was probably short-lived (Clague, 1989). Ice also moved south down the central trough in Hecate Strait (Barrie and Bornhold, 1989) coalescing with ice coming through the troughs of Queen Charlotte Sound to the edge of the shelf (Luternauer and Murray, 1983; Luternauer et al., 1989a; Josenhans et al., 1995).

Glaciation reached its maximum extent sometime after 21,000 ^{14}C yr BP (Blaise et al., 1990). The late Fraser glaciation terminated with rapid climatic amelioration, resulting in rapid retreat and melting of the ice. In Heate Strait and Dixon Entrance glacial retreat began sometime after 15,000 ^{14}C yr BP and ice had largely left the lowlands and offshore of the region by 13,500 to 13,000 ^{14}C yr B.P (Barrie and Conway, 1999; Barrie and Conway, 2002a). Icebergs were calved from the retreating glacial ice front. These icebergs impacted the seafloor and left characteristic plough features or iceberg furrows that are ubiquitous in the troughs of the basin between 110 and 350 m depth (Luternauer and Murray, 1983; Barrie and Bornhold, 1989; Barrie and Conway, 1999). The curvilinear furrows have incision depths of up to 7 m but are mostly less than 3 m deep. They typically display a preferred orientation in the direction of the trough.

Distribution of glacial extent on the continental shelf is inferred from glacial deposits that suggest ice-contact sediments extending to the shelf edge through the large troughs that empty into Queen Charlotte Sound (Josenhans et al., 1995) and also Dixon Entrance (Barrie and Conway, 1999). A minimum ice thickness of 400 m is suggested for the shelf areas, allowing the ice to infill the 300 m deep troughs and maintain a 100 m ice thickness before spilling onto the bank tops (Josenhans et al., 1995; Barrie and Conway, 1999; Barrie and Conway, 2002a). This same geophysical evidence (i.e. lack of ice contact deposits) also suggests that glacial ice was not present on the bank tops in Queen Charlotte Sound (Josenhans et al., 1995).

Sea Level History

A regional lowering of sea level along the northern Pacific margin of Canada began soon after the late Fraser glacial maximum and continued during deglaciation due to isostatic rebound (Barrie and Conway, 1999). The oldest known record of open marine conditions occurs at 14,380 ^{14}C yr BP at the present water depth of 37 m in northern Hecate Strait (Barrie and Conway, 1999). At this time, relative sea level was above 30 m but not higher than present sea level, as there is no record of submergence of the eastern coast of the Haida Gwaii (Clague et al., 1982b). Just 9 kilometres southwest of this site, three cores were collected that contain terrestrial sediments formed in a tundra environment (Barrie et al., 1993) and dated to 13,790 ^{14}C yr BP. This means that sea level dropped significantly in as little as 590 years (using a 600 year reservoir correction to compare marine with terrestrial radiocarbon dates). In central Hecate Strait, sea level fell to a lowstand of 150 m by 13,000 ^{14}C years BP and remained low until approximately 12,400 ^{14}C yr BP (Josenhans et al., 1995; Barrie and Conway 2002b; Hetherington et al., 2004).

The subsequent transgression was rapid (up to 5 cm/yr; Josenhans et al., 1997) and by about 9100 ^{14}C yr BP had formed the present shoreline on the Haida Gwaii (Clague et al., 1982b; Josenhans et al., 1995, 1997; Fedje and Josenhans, 2000). Sea levels reached a maximum of 13 to 16 m above current levels by 8900 ^{14}C yr BP, returning to the present level by 2,000 ^{14}C BP (Clague et al., 1982b; Josenhans et al., 1997; Fedje and Josenhans, 2000).

Queen Charlotte Basin is located at the western margin of the North American lithospheric plate where high heat-flow and a relatively thin crust imply rapid crustal response to changes in surface load and a short wave-length (James et al. 2000). The amount of change varies dramatically from east to west in response to loading and rebound from the Cordilleran ice advance (Clague, 1983; Barrie and Conway, 1999). As the eastern ice load retreated, the crust responded, with the maximum flexure occurring nearest the area of maximum change in the ice load. Relative sea-level change has been influenced by isostatic crustal depression and rebound, the raising and lowering of eustatic sea-level, and local tectonic crustal adjustments (Hetherington and Barrie, 2004; Hetherington et al., 2004).

Late Quaternary Stratigraphy

Distribution of glacial ice on the continental shelf in Queen Charlotte Basin is inferred from seismostratigraphic investigations that suggest ice-contact sediments (tills), up to 50 m in thickness, occurring to the shelf edge within the cross-shelf troughs (Josenhans et al., 1995) and Dixon Entrance (Barrie and Conway, 1999). Though these acoustic characteristics are normally associated with till, it is difficult to acoustically differentiate genetically between massive diamict facies using acoustic data alone (Syvitski et al., 1997).

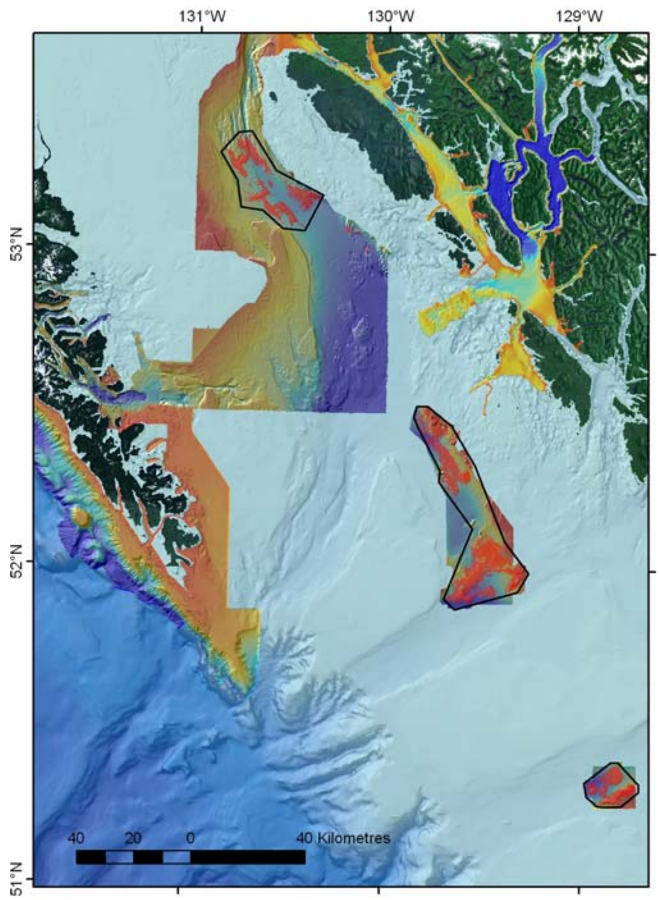

Figure 2. Location of known sponge reefs, the proposed boundaries of the Areas of Interest, and the present mutltibeam swath bathymetry imagery.

Extensive glaciomarine mud (Unit A), up to 20 m thick, overlies thin, ice-proximal sediments ,or more usually a till, over most of the Queen Charlotte Basin in water depths generally greater than 200 m (Luternauer et al., 1989a; Barrie et al., 1991; Barrie and Conway, 1999, 2002a). The mud contains approximately equal proportions of sand, silt, and clay with ice-rafted debris and are bioturbated. The unit is interpreted to have been ice-distal, deposited possibly by iceberg rafting and from floating sea ice, similar to present conditions on the Labrador margin of eastern Canada (Gilbert and Barrie, 1985).

Overlying the glaciomarine mud in the troughs is a sedimentary sequence, designated Unit B, that is up to 20 m thick. The sequence was subdivided by Luternauer et al. (1989a) into two primary subunits based on the radiocarbon age and texture of the sediments. Unit B_1, the lowermost in the package, dates between 13,000 and 12,000 ^{14}C BP. This mud unit is thought to have developed as sea levels were falling on the shelf and, unlike the glaciomarine mud, contains no ice-rafted debris.

Unit B_2 overlies B_1 or, where B_1 sediments are not found, overlies the glaciomarine mud. This sandy mud unit, which is 0.01 to 4 m in thickness, is found within the shelf troughs and represents a lag formed between 12,900 ^{14}C BP and 10,500 to 10,200 ^{14}C BP. It is thought to have been deposited over a period of several hundred years when sea level was lower than at present (Luternauer et al., 1989b; Barrie et al., 1991; Barrie and Conway, 1999).

Postglacial Holocene mud (Unit C), composed of up to 40 m of olive, clay-rich mud, forms a drape of variable thickness, reaching a maximum thickness in the troughs of 50 m. The mud is similar to the matrix of the sponge reefs, but contains less clay, is somewhat finer in texture, and contains less organic matter. On the bank tops, a thin (usually less than 10 m) sand and gravel unit was deposited as the coast migrated during sea-level rise. Marine sediments also occur up to 15 m elevation in coastal areas of the Haida Gwaii (Clague et al., 1982b; Clague, 1989). Present sedimentation in the region is minimal.

OCEANOGRAPHY

In Hecate Strait and Queen Charlotte Sound, strong rectilinear tidal currents, usually in the order of 15 to 25 m/s, are classified as mixed, mainly semi-diurnal, with a 4.5 m tidal range (macrotidal) in the central portion of Hecate Strait (Thomson, 1981). The tidal crest enters Queen Charlotte Sound and spreads northward into Hecate Strait where it encounters the opposing crest that entered eastward through Dixon Entrance (Fig. 1). Normally, tidal currents flow along the orientation of the Strait at nearly uniform speed at all depths, but where abrupt changes in the seafloor bathymetry occur currents are enhanced (Sinclair et al., 2005). In addition to tidal forcing, circulation in Hecate Strait is also affected by winds and river runoff. The influence of these two factors are generally out of phase, with river runoff (Skeena River, Fig. 1) dominating circulation in late spring through early summer and wind forcing having its greatest influence during the fall and winter months. Consequently, winter circulation is both tidal and wind driven with a net northward component resulting from the prevailing southeasterly storm winds (Crawford and Thomson, 1991). Current velocities exceeding 0.80 m/s, measured 15 m above the seabed, occur during winter storms and spring tides (Barrie and Bornhold, 1989).

Wave conditions over the area vary in response to fetch and the sheltering effect of land on oceanic swell. Annual average significant wave height is 1.8 m and the peak period is 10 s with wave heights of less than 3 m being most frequent. The most active season is November through January, with maximum wave heights of 14.3 m in December (Eid et al., 1993). Wave propagation also shows alignment with Hecate Strait, with the main direction from the southeast and less frequently the northwest (Thomson, 1981).

SURFICIAL GEOLOGY OF SPONGE REEF AREAS OF INTEREST

The sponge reef complexes occupy the east-central portions of the three major troughs (Fig. 2) that cross the northwestern Canadian continental shelf. The siliceous sponge reefs (*Hexactinellida*, *Hexactinosida*) are built by framework skeleton sponges that trap clay-rich sediments and colonize relict seafloor surfaces in deep shelf areas. Growth of the reef is by attachment of young sponges to the skeletons of dead individual, much like the frame-building processes that occur at coral reefs (Krautter et al., 2001, 2006). Sponge reefs themselves are composed of a massive matrix of organic-rich, olive slightly sandy, silty clay containing siliceous (glass) sponges found as in situ whole skeletons and as fragmentary subfossils (Conway et al., 2001). The reefs may be up to 20 m in thickness and form diverse shapes, including ridges, mounds, biostromes or layers, and complex forms resulting from coalescence of these reef morphologies. The surface of the reefs is normally undulatory and variably covered with sponges to 1.2 m in height where intact, and is muddy sponge rubble surface with projecting sponge fragments where trawling has occurred or other processes have caused a cessation or hiatus of reef growth. The edges of the reefs may be steep and/or have near-vertical walls, but more commonly display moderate to gentile slopes. The reefs have a sharp transition at the reef edge with the till or distal glaciomarine units (Unit A) that form the reef substrate, or rarely with the recent mud unit (Unit C) that may, in some cases, be found as a thin (<1 m) unit adjacent to the reefs (Conway et al., 2008a,b,c,d).

OCEANOGRAPHY OF SPONGE REEF AREAS OF INTEREST

Shelf waters within British Columbia are noted to have a high ambient relative silica concentration; likely an important control on shallow populations of hexactinellid sponges (Austin, 1998; Whitney et al., 2005). In Queen Charlotte Basin, winter downwelling and the summertime relaxation of downwelling, or weak upwelling, in combination with the focused moderate currents of the semi-diurnal tidal regime are important mechanisms for the development of large sponge reef complexes (Whitney et al., 2005). In the Queen Charlotte Basin, the sponge reefs inhabit areas that are rich in dissolved silicate (>40 μM) and have relatively high fluxes of opaline detritus (~2 mol Si m^{-2} y^{-1}). Bottom currents are moderate (to 35 cm/s), which helps transport both dissolved and particulate materials to sponges and at the same time prevent smothering of living sponges by sedimentation. The trough head location of the sponge reefs provides a means of funnelling enriched bottom waters to the reefs. Detrital material, derived from both onshore coastal sources and the resuspension of offshore particles in a bottom nepheloid layer, are effectively trapped by dense populations of sponges (Whitney et al., 2005). Trapping of these materials results in the observed enrichment of organic carbon, nitrogen, and opal as measured in core, relative to surrounding and underlying sediments (Conway et al., 2001). Near bottom currents are constrained and focused by bathymetry at all sponge reef complexes and reach a maximum velocity of 50 cm/s. The sponges thus exist in relatively enriched zones where several oceanographic processes ensure an optimal delivery of dissolved nutrients and potential food particles. This also keeps fine sediments in suspension, preventing smothering by sediment deposition. Tidal currents repeatedly cycle bottom waters across the reefs. Construction of large mounds is probably favoured due to a positive feedback by increased access to nutrients from sponges living on high points of the reef (Conway et al., 1991). The large obstructing mounds on the seabed appear to deflect tidal currents, creating flow conditions that are more locally complex than outside of the reef areas (Whitney et al., 2005).

OVERVIEW OF MARINE MINING

Marine placer deposits contain a great variety of commodities with economic value (Table 1). In these deposits, heavy minerals (>3.2 g/cm^3) have been mechanically concentrated by selective sorting in rivers and along beaches, and have been subsequently reworked during sea-level changes. Heavy mineral concentrations can also develop through marine processes of wave and current alone (Barrie et al., 1988). Heavy minerals include iron-titanium, zirconium, tin, gold, and diamonds (Table 1). The detrital or light minerals (density of 2.7 g/cm^3), which consist mostly of quartz and feldspar, form the basis for sand and gravel or aggregate mining.

Methods of mining vary depending on the commodity and deposit type. Generally some kind of dredging, either mechanical or hydraulic excavation is employed (James et al., 1999). Mechanical excavation is accomplished with a shovel, grab, or other similar device. Hydraulic excavation involves the use of water under pressure to suspend the material being mined, so it can be brought to the surface vessel as slurry. Some hydraulic dredges use mechanical assistance to help to suspend the material to be excavated. At greater water depths, particularly for precision mining of minerals such as placer diamonds, subsea mining systems mounted on underwater vehicles work independently of the ship (Fig. 3). Mining for aggregates may result

Figure 3. Photograph and artistic operating illustration (inset) of the Nam 1 seabed mining device developed for Namibian Minerals Corporation for deep water diamond mining off Namibia.

in most of the dredged material being retained, while precious metal mining (gold, diamonds, etc.) results in almost all the material being returned to the sea after processing.

The volume of aggregates (sand and gravel) and placer minerals (e.g. gold, diamond, titanium) mined from the sea is increasing rapidly, as on-land sources are depleted or access is denied. In northern Europe, for example, marine aggregate production is extensive with approximately 23 million tonnes per annum mined offshore of the United Kingdom alone (Boyd et al., 2004). Japan is the world's biggest producer of marine aggregates with almost all sand for construction coming from offshore mining. Similarly, over 254 Mm3 of marine sand was extracted in offshore Hong Kong from 1990 to1998 (James et al., 1999). Diamond extraction is the dominant offshore placer mineral presently mined; it has grown into a multi-billion dollar industry for Namibia and South Africa (Garnett, 1999).

INTERNATIONAL REGULATIONS AND ENVIRONMENTAL ASSESSMENT FOR MARINE MINING

Sand and gravel are extracted from the seabed in many European countries, Japan, United States, Australia, Canada, (de Groot, 1986; Wise and Duane, 1988; Barrie and Good, 2007), and Southeast Asia (James et al., 1999), and mineral mining occurs off southern and southwestern Africa, New Zealand, Australia, Indonesia, Thailand, and India. Most of the heavy mineral mining is beach and near shore, while African diamond mining occurs in water depths of up to 200 m. General environmental guidelines for marine mineral extraction, including aggregate dredging, are given in the International Marine Minerals Society (2002) Code for Environmental Management of Marine Mining. This code is intended for the marine mining industry and contains general principles for industry, and more site-specific operating guidelines. Specific guidelines for marine aggregate dredging are provided by the International Council for the Exploration of the Sea (ICES) Guidelines for the Management of Marine Sediment Extraction (ICES, 2003). The ICES 2003 guidelines cover general principles for mineral resource management and the administrative framework for an Environmental Impact Assessment (EIA), topics to be addressed in a pre-extraction EIA, the authorization of extraction, and monitoring of extraction activities.

Member states of the European Union are expected to comply with European Commission Council Directive 97/11/EC regarding Environmental Impact Assessment. Annex II of that directive states that extraction of minerals by marine dredging is an activity that may be subject to an EIA. It is up to the member state to determine whether an assessment is necessary, which may be done on either a case-by-case basis, or by a threshold or other criteria set by that state (Article 4(2) of 97/11/EC (ICES, 2003)). Where the member state decides an assessment is required, the Directive provides general guidelines for such assessments. Overall, it appears the European Union allows each country to decide whether an impact assessment is required or not, but each country is expected to have some process in place for determining the necessity of an assessment.

The United Kingdom has had a coastal aggregate dredging industry for decades, remains a leading producer, and has a Code of Practice for marine aggregate extraction that came into force in 1982 (de Groot, 1986). The code of practice appeared to deal mainly with ensuring that the dredging and fishing industries caused minimal interference or damage to each other (de Groot, 1986), and as stated in section 1.1 of the code itself, it was voluntary (Drinnan and Bliss, 1986). Dredging companies require a licence, both for offshore prospecting and also for extraction, granted by the government's Crown Estate Corporation (CEC). The CEC acts as arbiter between the dredging company, government agencies, and stakeholders such as the fishing industry, and has the final authority for granting licences (Drinnan and Bliss, 1986). In 1989, the requirement for an Environmental Impact Assessment was established (ICES, 1999) and further guidelines for impact assessment have been proposed.

In the Netherlands, seabed sediments currently being extracted are mainly sand that is used for shoreline

Table 1. Offshore placer minerals and aggregate presently mined.

Mineral	Density (g/cm³)	Usage	Countries of Mining
Sand and Gravel	2.7	Construction, Beach Replenishment	Europe, Southeast Asia, Japan, USA, Australia
Calcium Carbonate	2.5 – 2.9	Cement	Iceland, Bahamas
Diamonds	3.5	Jewels, Cutting	South Africa, Namibia
Gold	15.0 – 19.3	Ornament	Alaska, South Africa
Cassiterite (tin)	6.8 – 7.1	Metal Coating	Indonesia, Malaysia, Thailand
Rutile (titanium)	4.2	Metal	Australia
Ilmenite (titanium)	4.5 – 5.0	Pigment	South Africa, India, Sri Lanka, Australia
Zircon	4.2 – 4.9	Refractory	Australia
Garnet	3.5 – 4.2	Abrasive	Australia, India
Monazite	4.9 – 5.3	Catalyst (Oil Refinery)	Australia, India, Sri Lanka, Brazil

replenishment and for building, although shell extraction is also carried out, and licences from the government are required (de Groot, 1986). An Environmental Impact Assessment is required only for “large-scale” operations where the extraction area exceeds 500 hectares, or the extraction volume exceeds 10 million cubic metres (ICES, 2003). Neighbouring Belgium has had seabed sand extraction since 1977, and has required some form of protection for shipping, fishing, and the environment since that time (de Groot, 1986).

France conducted detailed environmental studies of offshore aggregate extraction starting in the mid 1970s; those studies advocated the protection of biologically significant areas and recommended that environmental impact studies should be carried out prior to dredging (de Groot, 1986). France has three coastal areas (Channel, Atlantic, and Mediterranean), with very different local conditions.

Until 1999, Denmark used quantitative regulations, such as a minimum distance from shore, to determine allowable dredging locations (de Groot, 1986; ICES, 1999). In 1999 a new Act came into force that restricted dredging to specified geographic areas; a ten-year transition period, however, allowed for dredging in existing permit areas (ICES, 1999). Dredging more than a total of five million cubic metres from a single project, or one million cubic metres a year in a single area, would automatically require an environmental assessment, and other projects where significant impacts are expected may also require an EIA, in accordance with European Commission regulations (ICES, 2002). Public consultation and government review are required for any dredging in a new area, and greater restrictions appear to apply for water depths of less than 6 metres (ICES, 2003).

German offshore sand and gravel dredging was initially covered by its 1980 mining law, supplemented by a code of practice that restricted dredging by location or season. These precluded dredging of areas exceeding 5 km by 5 km and prohibited the exposure of boulders greater than 0.3 m following dredging (de Groot, 1986). Additional requirements for environmental impact assessments in ecologically sensitive areas were adopted in 1999 (ICES, 1999, 2003).

In Japan dredging for aggregate is regulated by the local (prefectural) governments. Applications for a dredging licence must be accompanied by the submission of a dredging plan and an environmental impact study (James et al., 1999). Dredging is prohibited within 1 to 3 km of the coastline and usually in water depths of less than 30 m. Approval for a dredging licence must also be obtained from the relevant fishery committees that have been established within each prefectural government.

In Southeast Asia, aggregate dredging is very active in Korea, China (Hong Kong), Malaysia, Indonesia, and the Philippines. Several of these countries also had an offshore tin mining industry in past years. At present, offshore production of tin is ongoing in Thailand and Indonesia. Hong Kong requires an EIA to be conducted before any dredging takes place, as well as an active monitoring program during mining (James et al., 1999). Malaysia also requires and EIA, but in other countries in Southeast Asia it is less clear what procedures are to be followed prior to mining. In Indonesia, the removal of living coral reefs for aggregate has lead to the demise of these habitats (James et al., 1999).

In Australia, the federal and local State Governments control the extraction of sand and gravel. A dredging licence may be issued after an Environmental Impact Assessment (EIA) is produced that assesses the environmental impact of the proposal and outlines measures that will be taken to protect the environment during extraction (James et al., 1999). Key components of the EIA are consideration of erosion of adjacent beaches, alteration of wave patterns at the entrance of estuaries, alteration of the seabed causing biological and habitat change, and interference with commercial shipping.

The U.S.A. is experiencing increasing demand for offshore sand and gravel, primarily for beach replenishment (Michel, 2004). At present, the Minerals Management Service (MMS) of the U.S. Department of the Interior is administering a sand and gravel project that is identifying geological and environmental information on offshore aggregate deposits. This project focuses on the Outer Continental Shelf (OCS), which is federally controlled, where areas may be leased for sand and gravel extraction. Within three miles of the coastline, offshore extraction is under State control, although the Federal Coastal Zone Management Act provides general guidelines for environmental management of State-controlled coastal and offshore areas. Overall, there are no specific codes or guidelines that apply to offshore aggregate extraction, however the MMS is planning for the management of offshore sand and gravel resources (Michel, 2004).

As for Canada, no regulations or guidelines regarding marine mineral mining exist, yet on the Pacific coast small-scale marine aggregate mining has occurred for over 45 years (Barrie and Good, 2007). As discussed previously, even in countries where marine aggregate extraction is common, laws specific to marine sediment extraction require years to be enacted. Within Canada, existing laws and regulations appear to require an EIA prior to issuance of a dredging permit, though this has not happened in the past.

When mining of diamonds offshore of southwest Africa was initiated, there were no environmental regulations in place. Subsequently, both Namibia and South Africa now require an EIA prior to any mining (Garnett, 1999). Late in 1998, Namibia drafted legislation known as the Environmental Management Act that specifically addresses offshore and near-shore marine mining. This act requires the identification, prediction, and evaluation of actual and potential biophysical, social, and other relevant effects on the environment prior to project authorization. In particular, the identification of marine protected areas and the interference with fisheries are identified. Like most other published EIA legislation, there is no specific definition of what is required for habitat mapping during any stage of the mining operation.

For offshore mining outside of the EEZ jurisdiction of coastal states, the authority for issuing mining permits and the specific requirements of an EIA come under the International Seabed Authority, which was set up in 1994 under United Nations Convention on the Law of the Sea (UNCLOS) legislation. At present no deep-sea mining is underway, but it is anticipated such activity will increase in the future, particularly for polymetallic sulphides and manganese nodules. For example, Nautilus Minerals Limited has a business plan to mine a massive sulphide copper-zinc deposit off Papua New Guinea and other prospective deep-sea spreading ridge deposits may be considered in the future. The environmental impact of potential manganese nodule mining was considered to be minimal, but recent evidence suggests that there are significant benthic activities in the sub-surface (Jaugari and Pattan, 1999).

BRITISH COLUMBIA OFFSHORE MINERAL POTENTIAL

Overview

The potential for offshore mineral extraction from the near-shore and shelf regions of the Canadian continental margin has been highlighted (Hale and McLaren, 1984; Hale, 1987; Barrie, 1994) but no extraction of offshore minerals other than sand and gravel has been undertaken. This is not, however, a consequence of the lack of potential, but one of uncertain jurisdiction, environmental restrictions, and, until the last decade, the lack of technological development for mineral extraction in the marine environment. On the Pacific margin of Canada this is particularly true, when one reviews the coastal mineral showings and recent sea-level history.

The following is a review of the offshore marine mineral potential of British Columbia. The geological review is a result of the near-shore and coastal mapping program of the Geological Survey of Canada (GSC), Natural Resources Canada (NRCan) and past beach exploration undertaken by industry and the former British Columbia Department of Mines.

There are two environments to be considered for mining of marine placers: the beach (intertidal) and the nearshore or shelf. These can be further subdivided as relict or modern and by their genesis. Placer formation in a marine environment requires a source from which the minerals can be liberated, a transport mechanism to the coast or within the offshore system, and a concentration process. Glaciation has been the dominant mechanism for liberating and transporting minerals to the coastal zone in Canada. Glacial processes tend to disperse minerals rather than concentrate them; therefore glacial environments are generally poor areas for the formation of marine placers (Sutherland, 1985). The exposed beach is one environment in which concentration of transported minerals can take place. The concentration process on beaches is dominated primarily by wave energy, particularly in large arcuate embayments where longshore and/or reinforced tidal currents (Barrie, 1981) can act as a secondary concentrating process. Diamonds are an exception in that they can be found on straight coastlines, such as along the Namibia coast (Sutherland, 1982). Preservation of a coastal deposit is controlled by sea-level changes and regional tectonics. These forces work individually or in combination to either submerge a deposit below the zone of wave destruction or to expose a deposit subaerially.

Figure 4 is a map of potential areas of interest on the Pacific coast of Canada for specific minerals, based on these characteristics and known beach occurrences (e.g. Mandy, 1934; Holland, 1950; Holland and Nasmith, 1958; Samson, 1984). The minerals of interest are primarily gold, titanium, and zircon. Two examples that represent potential marine placer deposits that are typical of the British Columbia coastal margin are described. They are the Au/Ti deposits on and adjacent to the Haida Gwaii, and the offshore Ti deposits in Queen Charlotte Sound, north of Vancouver Island.

Haida Gwaii Mineral Deposits

Placer gold has been mined intermittently from the beaches of northeastern Haida Gwaii and from similar beach deposits around Masset Inlet for more than 100 years. Placer operations on the east coast of Haida Gwaii yielded a reported gold production of 715 troy ounces during the early 1900s (Samson, 1984). The gold was found to be fine grained and to occur in association with black sand (heavy mineral) lenses (Fig. 4). The auriferous black sand deposits were best developed at the base of actively eroding unconsolidated Pleistocene bluffs. In areas of active sedimentation, the black sand lenses are ephemeral, being reworked and redistributed with each storm event. The gold may have been transported to the area by ice from British Columbia or Alaska, or from sources within the Haida Gwaii, and possibly from both.

Extensive drilling of the beach and bluffs sequences along northeastern Haida Gwaii was undertaken in 1957 by Mogul Mining Ltd., who were interested in the sands as a potential source of magnetite (Holland and Nasmith, 1958). The black sands contain hematite and ilmenite, magnetite, garnet, quartz and feldspar, hornblende, epidote, zircon, staurolite, sphene, and rutile (Holland and Nasmith, 1958). The rutile and free ilmenite content of the sands is low and most of the titanium is bound within the ferriferous ilmenite and titanohematite.

Erosion of the coastline has been enhanced in recent years with up to 12 m of retreat per year recorded (Barrie and Conway, 2002b). The mechanism causing this coastal retreat is unclear but the result is an enriched beach deposit with grades reaching 5 g of Au/tonne. These same deposits contain as much as 23% ilmenite and 2% zircon. The present area of heavy mineral concentrations on northeastern Haida Gwaii is continuous over a length of 60 km and varies between 0 and 2 m in thickness (Barrie and Emory-Moore, 1994).

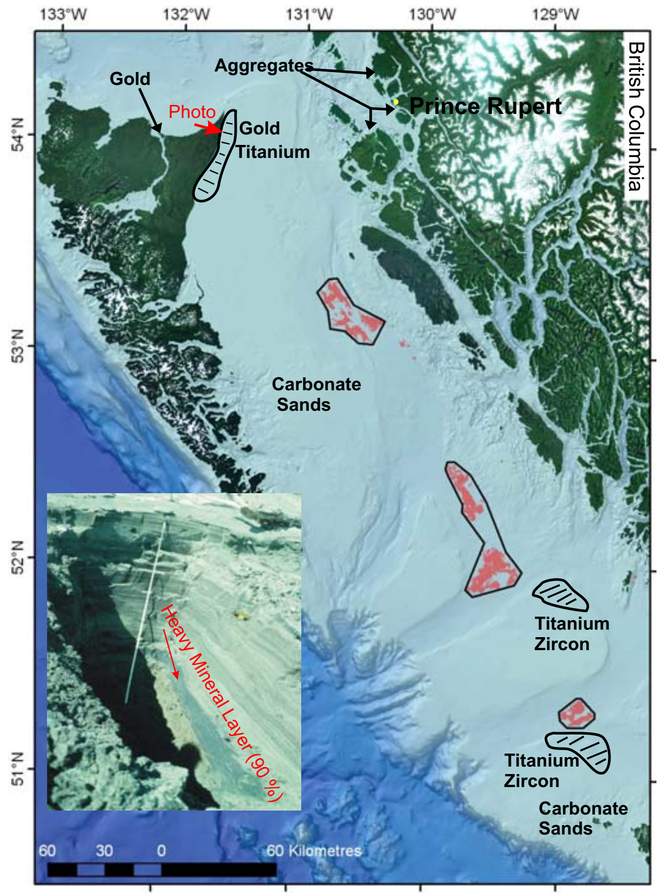

Figure 4. Location of potential mineral deposits off the Pacific north coast in relation to the Areas of Interest. Inset is a photograph of the gold titanium deposit on the beach of northern Haida Gwaii, a site of mineral production in the early 1900s.

Concentration of these mineral sands, as with all other heavy mineral beach deposits, forms by differential entrainment and deposition. Light mineral particles are entrained selectively because they are larger (i.e. particles standing proud of the bed) than hydraulically equivalent heavy mineral grains; they are subject, therefore, to greater lift and drag. This occurs on the backwash of the upper shoreface environment. Wave backwash, having dissipated much of its energy through frictional drag on the shoreface, has a lower entrainment capacity and selectively removes the larger, less dense quartzo-feldspathic minerals, leaving behind a lag or residual deposit of heavy minerals. Not only are heavy mineral lag concentrations formed, but also minerals are separated by density, to develop beach laminations of garnet, epidote and opaques. This type of selective sorting occurs within the intertidal zone but is most pronounced within the supratidal zone where storm deposition predominates. Selective entrainment results in the densest and finest grains being the most difficult to entrain, while the lightest minerals are transported offshore (Komar and Wang, 1984). Consequently, storm deposits can result in 90 to

100% heavy mineral laminations greater than 30 cm in thickness made up primarily of opaques, particularly at the upper end of the intertidal zone. Extensive beach coverage by logs, a result of modern forestry and log transport, has created a secondary concentration mechanism. The logs act as riffles in both wave and aeolian transport.

This particular deposit is limited to the upper end of the intertidal zone and occurs in various areas along eastern coastline of northern Haida Gwaii. Given that this Au and Ti deposit lies on the boundary of a Provincial Park, exploration has focused on the possibility of similar deposits offshore. Given the sea-level history of the region, drowned terrestrial and nearshore deposits may occur. For example, wave-cut terraces mark the shoreline of past lowered sea-level locations. Wave-cut terraces are narrow, gently sloping, constructional coastal benches formed by wave action during lowered sea levels. Multibeam imagery clearly identifies three wave-cut terraces in central Hecate Strait in water depths from 37 m to greater than 160 m (Barrie and Conway, 2011). One extensive north-south curvilinear terrace occurs in water depths of 125 to 164, a second terrace parallels the first terrace in water depths of 95 and 110 m, and a third terrace is located to the west in water depths of 37 to 48 m (Fig. 5). The sub-bottom profiles that cross the terraces show prograding strata to the edge of the terrace, suggesting that the coastline strata were constructional until being eroded. Presently these drowned beaches are eroded and reworked by the action of currents (Barrie and Conway, 2011), further increasing the possibility of heavy mineral concentration.

Fluvial channels crossing northern Hecate Strait were drowned by the quickly transgressing sea (Fig. 5). The numerous braided channels are characteristically 5 to 30 m deep and 200 to 2000 m wide, and are interpreted to be outwash channels (Barrie and Bornhold, 1989; Barrie and Conway, 2011). Both these drowned terrestrial and coastal features could host mineral deposits, particularly gold, as they drain known mineralized terrain and cover extensive areas.

Marine-Formed Placer Deposits

Concentration of heavy minerals to form a placer in a marine environment is normally associated with shoreface processes, predominantly wave shoaling and longshore transport. Marine processes below the shoreface have not generally been considered. Barrie et al. (1988) undertook a simple theoretical study to evaluate mechanisms required to develop such a placer in a shelf environment. As outlined with the beach deposits, continuous differential transport and sorting is necessary for heavy mineral accumulation. In this study, the critical transport thresholds for light minerals (quartz) and heavy minerals (ilmenite) were evaluated to determine the necessary differential entrainment necessary to generate placer enrichment. This allows prediction of the optimum water depth, grain size, grain density, and hydraulic conditions under which a heavy mineral lag deposit will develop. Such deposits form primarily by unidirectional currents, such as tidal currents, at water depths that inhibit yearly storms from subsequently destroying and mixing the deposit.

Using these criteria, Barrie et al. (1988) predicted that a heavy mineral lag of ilmenite would form in well sorted sands between 130 and 160 m water depth on the continental shelf off northern Vancouver Island. The predictions were tested at a site on northeastern Cook Bank, just north of Vancouver Island (Fig. 1), where known heavy mineral occurrences had been observed by Luternauer and Murray (1983). Heavy mineral concentrations of up to 25% containing up to 3.0 to 5.0 weight % ilmenite were found in 120 to 140 m water depth at the northeastern corner of Cook Bank, as predicted by the model (Barrie, 1991). However, the heavy mineral deposit is a thin autochthonous lag resulting from a long period (approximately 9000 years) of continuous reworking of bottom sediments by tidal currents and storm waves, the source being an underlying shoreface deposit formed during the relative sea-level lowering at the initiation of the Holocene (Barrie, 1991).

The shoreface deposit found on Cook Bank (100-140 m water depth) contains on average less than 0.5% Ti but is greater than 20 m in thickness (Barrie, 1991). It was formed during the period of lowered sea levels in an arcuate embayment such as those described for eastern Graham Island. Commercial deposits such as the chromite deposit of coastal Oregon (Peterson et al., 1986), ilmenite sands of Richards Bay, South Africa (Bartlett, 1987), and heavy mineral sands of eastern Australia (Jones and Davies, 1979), occur in similar environments as found here on Cook Bank. This deposit was not economic under 100 m of water when first documented, however, the technological advances in dredging and marine mining off southwestern Africa now make this deposit potentially economic.

Aggregates

The most valuable non-fuel mineral commodity extracted from the seafloor globally is sand and gravel (aggregate) of several types for use as fill material and manufacture of concrete. Offshore extraction of aggregate has been ongoing in British Columbia for many decades, mainly in the vicinity of Prince Rupert (Fig. 4) where nearby onshore resources are essentially nonexistent (Good et al., 2007). A major component of the cost of aggregate is transportation and if extraction can

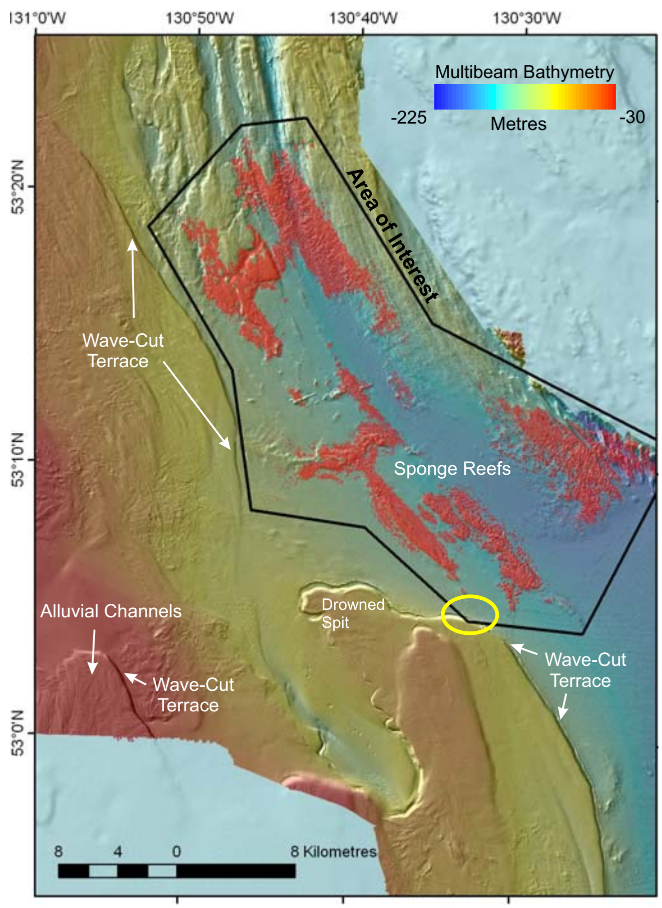

Figure 5. Multibeam imagery of the northern most sponge reef Area of Interest showing the adjacent wave-cut terraces (drowned beaches) and alluvial channels. Note one area where the Area of Interest intersects with the wave-cut terrace (yellow circle).

be undertaken near the location of need, great savings are possible.

For the Queen Charlotte Basin region, expansive areas exist of sand and gravel on the shallow banks between the troughs and over the shallow expanse of northwestern Hecate Strait (Fig. 1). For example, an extensive subaqueous dune field made up of well sorted sand exists in 70 to 100 m water depth in northern Hecate Strait (Barrie et al., 2009). Most of Dixon Entrance has a surficial cover of sands and gravels to depths greater than 400 m (Barrie and Conway, 1999). In addition, many coastal areas within the basin have significant accumulations of sand and gravel.

Calcium Carbonate

On the Cook Bank and elsewhere on the northernmost Vancouver Island shelf, (Fig. 4) there are broad areas with high shell content (Nelson and Bornhold, 1983). Similar deposits are also known in southern Hecate Strait (Carey et al., 1995) and may occur elsewhere in Queen Charlotte Sound and Hecate Strait. These relatively thin deposits form as a result of low modern terrigenous sediment input to the shelf and enhanced biological productivity, the result of periodic upwelling of nutrient-rich waters onto the shelf (Nelson and Bornhold, 1983, 1984). The richest known deposits in the region are centred on the Scott Islands (Fig. 1) and extend over an area of about 2,000 km2; broad areas of more than 75% calcium carbonate with a general increase in percentage from south to north across Cook Bank. The deposits consist mostly of infaunal bivalves, barnacles, bryozoans, and benthic foraminifera. These skeletal carbonates are fragmented, transported, and mixed during storms. Based on radiocarbon dating, the most corroded looking shells have ages of only about 1,000 years (Nelson and Bornhold, 1983).

ECONOMIC POTENTIAL OF THE SPONGE REEFS IN THE AREAS OF INTEREST

Marine Minerals

There are several scenarios where the potential for placer mineral concentrations are excellent for the British Columbia offshore. These include the preservation of drowned terrestrial deposits, such as high energy beaches or alluvial channels, and regions where the combined action of wave and tide are capable of concentrating heavy minerals. In all these cases the requirement is water depths shallower that 150 m, the lowest stand of sea level for the region. In addition, heavy mineral concentrations are normally only found within well sorted sand deposits. The sponge reefs occur in water depths greater than 140 to 150 m and are associated with glacial deposits, and the reefs themselves are made up of a framework of sponge and mud. Sponge reefs are also always found below the maximum wave base, a required condition for reef growth, whereas active mineral sorting to further concentrate heavy minerals often requires a combination of wave and current processes. The reefs are found adjacent to extensive wave-cut terraces that are prospective sites for placer gold and titanium (ilmenite) deposits, however, these fall mostly outside the proposed boundaries. The boundary of the most northern sponge reef includes a small portion of the extensive 150 m wave-cut terrace (Fig. 5). Whether this small area has any mineral potential is not known. In addition, the middle reef area boundary reaches the wave-cut terrace at the most southwesterly corner.

Aggregates

No assessment of aggregate resource has been undertaken for the greater study area, though there are undoubtedly significant quantities of offshore sand and gravel present that would be suitable for a variety of purposes. Within the sponge reef Areas of Interest, good quality sand and gravel does not exist with the exception of some areas of the perimeter outside the reefs themselves, though these are far less suitable than areas outside the Areas of Interest altogether. Overall it is doubtful that sand and gravel deposits will ever be exploited due to 1) the exposure to open ocean wave and swell conditions making dredging operations difficult, 2) the lack of communities within close reach of the Areas of Interest, and 3) there is no regulatory regime in place in Canada for ocean mining, so that any proposed exploitation is the area would result in lengthy discussions between the Federal and Provincial governments regarding jurisdiction and management (Bornhold, 2004).

Carbonates

In some parts of the world where onshore deposits of limestone and dolomite are scarce, such as Iceland, offshore calcareous sediments have been exploited, principally for use in the production of lime. Globally, however, there are generally adequate sources of calcium carbonate on land to meet future demands. There is little likelihood that such deposits will be exploited within the foreseeable future due to 1) the plentiful sources on land for limestone, 2) water depths of the deposits (>50 m), and 3) environmental considerations and conflicts with other users such as fisheries (Bornhold, 2004).

Silica

One other industrial mineral that should not be overlooked is high-quality silica (glass). The glass sponge reefs (*Hexactinellida*, *Hexactinosida*) themselves represent an excellent source of pure silica in vast quantities. Though this goes against the entire rationale of the development of Marine Protected Areas for sponge reefs, a comprehensive evaluation of mineral resources would be incomplete without mention of this resource.

CONCLUSIONS

The offshore region of British Columbia has significant potential for economical mineral production, but has not been significantly explored due to jurisdictional and environment issues. Regardless, known occurrences of placer gold and titanium do occur on the shelf above 150 m water depth. In addition, the area has vast quantities of industrial quality aggregate and calcium carbonate, though mostly far away from any required market. The glass sponge reef Areas of Interest, however, lie outside these areas of mineral potential and the closure of these areas as Marine Protected Areas will not lessen the potential for future surfical mineral exploitation.

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