propulsion and prevention of in-transit breakup in warm seas. Proposed means of moving a sufficiently large ice mass over such long distances have ranged from conventional towing to use of a nuclear submarine to wind power. None has proven feasible.

Destruction of Icebergs

Attempts at destroying icebergs have been numerous and varied. Perhaps the most-studied technique has involved the use of explosives, which have been extensively tested on glacial ice in the form of glaciers and ice islands. Both crater blasting and bench blasting have been attempted. The results of this testing suggest that ice is as difficult to blast as typical hard rock, and that therefore the use of explosives for its destruction is impractical.

Other methods tested include spreading carbon black on the berg's surface to accelerate melting, and introducing various gases into the ice to create holes or cavities that can then be filled with explosives of choice. Attempts have also been made to cut through the ice using various means. There is little evidence that any great success was achieved with any of these methods.

The only report of a successful attempt to break up an iceberg involved the use of thermit, a welding compound that reacts at very high temperatures ($\sim 3000°C$). The explanation was that the very high heat produced by the thermit caused massive thermal shock within the mass of ice that ultimately resulted in its disintegration, much as glass can be fragmented by extreme temperature changes.

Conclusions

There is a great deal of uncertainty surrounding iceberg properties, behavior, drift, and other aspects relating to individual icebergs as opposed to laboratory samples or intact glaciers. This is mostly because of the high cost of expeditions to the remote areas where icebergs are most numerous, and the inherent dangers of hands-on measurement and sampling.

Glossary

Calving The breaking away of an iceberg from its parent glacier or ice shelf. Also the subsequent loss of ice from the iceberg itself.

Equilibrium line On a glacier, the line above which there is a net gain due to snow accumulation and below which there is a net loss due to melt.

Firn Permeable, partially consolidated snow with density between 400 kg m^{-3} and 830 kg m^{-3}.

Growler A small fragment of glacial ice extending less than a meter above the sea surface and having a horizontal area of about 20 m^2.

Keel The underwater portion of an iceberg.

Ram Lobe of the underwater portion of an iceberg that extends outward, horizontally, beyond the sail.

Sail The above-water portion of an iceberg.

See also

Antarctic Circumpolar Current. Arctic Basin Circulation. Current Systems in the Southern Ocean. Florida Current, Gulf Stream and Labrador Current. Ice-induced Gouging of the Seafloor. Sea Ice: Overview; Variations in Extent and Thickness. Sonar Systems. Sub Ice-shelf Circulation and Processes. Weddell Sea Circulation. Wind Driven Circulation.

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ICE-INDUCED GOUGING OF THE SEAFLOOR

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doi:10.1006/rwos.2001.0009

Introduction

Inuit hunters have long known that both sea ice and icebergs could interact with the underlying sea floor, in that sea floor sediments could occasionally be seen attached to these icy objects. As early as 1855, no less a scientific luminary than Charles Darwin speculated that gouging icebergs could traverse isobaths, concluding that an iceberg could be driven over great inequalities of [a seafloor] surface easier than could a glacier. Only in 1924 did similar inferences of the possibility of sea ice and icebergs affecting the seafloor again begin to reappear in the scientific literature. However, direct observations of the nature of these interactions were lacking until the early 1970s. The reason for the increased interest in this rather exotic phenomena was initially the discovery of the supergiant oil field on the edge of the Beaufort Sea at Prudhoe Bay, Alaska. Because the initial successful well was located on the coast, there was immediate interest in the possibility of developing offshore fields to the north of Alaska and Canada. It was also apparent that if major oil resources occurred to the north of Alaska and Canada, similar resources might be found on the world's largest continental shelf located to the north of the Russian mainland. Offshore wells are typically tied together by subsea pipelines which take the oil from the individual wells either to a central collection point where tanker pickup is possible or to the coast where the oil can be fed into a pipeline transportation system. If sea ice processes could result in major distrubances of the seafloor, this would clearly become a major consideration in pipeline design. Some time after the Prudhoe Bay find, another large offshore oil discovery was made to the east of Newfoundland. Here the ice-induced gouging problem was caused not by sea ice but by icebergs. In both cases the initial step in treating these perceived problems was to investigate the nature of these ice–seafloor interactions. One needs to know the frequency of gouging events in time and space as well as the widths and depths of the gouges, the water depth range in which this phenomenon occurs, and the effective lifetime of a gouge after its initial formation. Also of importance are the type of subsea soil and the nature and extent of the soil movements below the gouges, as this information is essential in calculating safe burial depths for subsea structures. The following attempts to summarize our current knowledge of this type of naturally occurring phenomenon.

As extensive studies of ice-induced disruptions of the seafloor have been undertaken only during the last 30 years, there is as yet no commonly agreed upon terminology for this phenomenon. In the literature the process has been described as scouring, scoring, plowing and gouging. Here gouging is used because at least in the case of sea ice, it is felt that it more accurately describes the process than do the other terms.

Observational Techniques

A variety of techniques have been used to study the gouging phenomenon. Typically, a fathometer is used to resolve the seafloor relief directly beneath the ship with a precision of better than 10 cm (**Figure 1**)

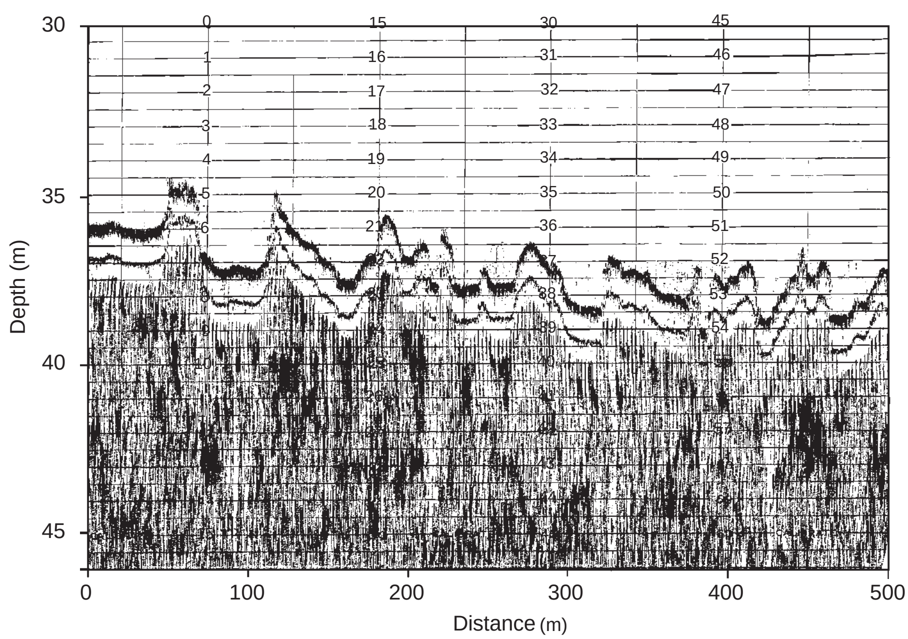

Figure 1 Fathogram of an ice-gouged seafloor. Water depth is 36 m. Record taken 25 km NE of Cape Halkett, Beaufort Sea, offshore Alaska. The multiple reflections from the upper layer of the seafloor are the result of the presence of a thawed active layer in the subsea permafrost. (From Weeks *et al.*, 1983.)

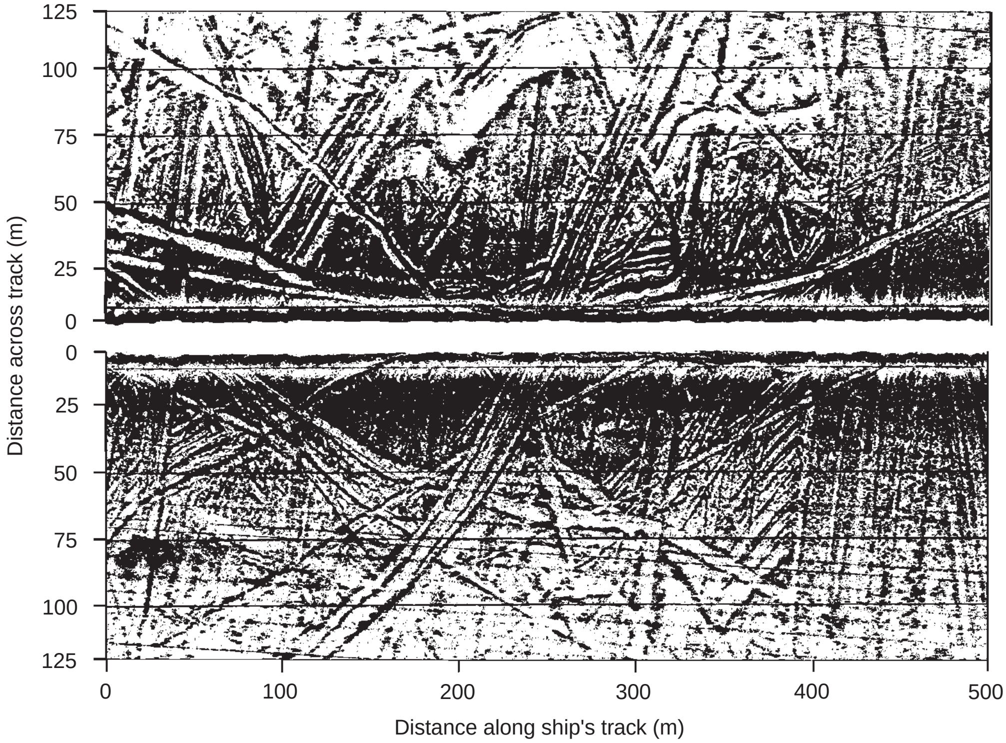

Figure 2 Sonograph of an ice-gouged seafloor. Water depth is 20 m. Record taken 20 km NE of Cape Halkett, Beaufort Sea, offshore Alaska. (From Weeks *et al*., 1983.)

while, at the same time, a sidescan sonar system provides a sonar map of the seafloor on either side of the ship (**Figure 2**). Total sonar swath widths have been typically 200 to 250 m not including a narrow area directly beneath the ship that was not imaged. The simultaneous use of these two different types of records allows one to both measure the depth and width of the gouge (fathometer) at the point where it is crossed by the ship track and also to observe the general orientation and geometry of the gouge track (sonar). Along the Alaskan coast the ships used have been small, allowing them to operate in shallow water. In some cases divers have been used to examine the gouges and, at a few deeper water sites off the Canadian east coast, manned submersibles have been used to gather direct observations of the gouging process.

Results

Arctic Shelves

The most common features gouging the shelves of the Arctic Ocean are the keels of pressure ridges that are made of deformed sea ice. As the ice pack moves under the forces exerted on it by the wind and currents, pressure ridges typically form at floe boundaries as the result of differential movements between the floes. These features can be very large. Pressure ridge keels with drafts up to 50 m have been observed in the upward-looking sonar records collected by submarines passing beneath the ice. The distribution of keel depths of these deformed features is approximately a negative exponential, in that there are many shallow ridge keels while deep keels are rare. Deformation can be particularly intense in near-shore regions where the moving ice pack contacts an immovable coast with the formation of large shear ridges that can extend for many kilometers. Such ridges are frequently anchored at shoal areas where large accumulations of highly deformed sea ice can build up. Such grounded ice features, which are referred to using the Russian term stamuki, can have freeboards of as much as 10 m and lateral extents of 10–15 km. As the offshore ice field moves against and along the coast, it exerts force on the sides of any such grounded features, causing them to scrape and plough their way along the seafloor. Considering that surficial sediments along many areas of the Beaufort Sea Coast of Canada and Alaska are fine-grained silts, it is hardly surprising that over a period of time such a process can cause extensive gouging of the seafloor sediments. **Figure 3** is a photograph showing active gouging. The relatively undeformed first-year sea ice in the foreground is moving away from the

Figure 3 Photograph of active ice gouging occurring along the coast of the Beaufort Sea. The grounded multiyear ice floe that is being pushed by the first-year ice has a freeboard of ~ 2 m. The thickness of the first-year ice is ~ 0.3 m. (Photograph by GFN Cox.)

viewer and pushing against a piece of grounded multiyear sea ice (indicated by its rounded upper surface formed during the previous summer's melt period), pushing it along the coast. The interaction between the first-year and the multiyear ice has resulted in a pileup of broken first-year ice, which when the photograph was taken was higher than the upper surface of the multiyear ice. Also evident is the track cut in the first-year ice as it moves past the multiyear ice. The fact that both the multiyear ice and the pileup of first year ice are interacting with the seafloor is indicated by the presence of bottom sediment in the deformed first-year ice and on the far side of the multiyear ice.

The maximum water depth in which contemporary sea ice gouging is believed to occur is roughly 50–60 m, corresponding approximately to the draft of the largest pressure ridges. Although gouges occur in water up to 80 m deep, it is generally believed that these deep-water gouges are relicts that formed during periods when sea level was lower than at present.

Not surprisingly the depths of gouges in the seafloor mirrors the keel depth distributions observed in pressure ridge keels in that they are also well approximated by a negative exponential with the character of the falloff as well as the number of gouges varying with water depth. As with ridge keels, shallow gouges are common and deep gouges are rare. As might be expected, there are fewer deep gouges in shallow water as the large ice masses required to produce them have already grounded farther out to sea. For instance, along the Beaufort Coast in water 5 m deep, a 1 m gouge has an exceedance probability of approximately 10^{-4}; that is, 1 gouge in 10 000 will on the average be expected to have a depth equal to or greater than 1 m. In water 30 m deep, a 3.4 m gouge has the same probability of occurrence. Gouges in excess of 3 m deep are not rare and 8 m gouges have been reported in the vicinity of the Mackenzie Delta.

As might be expected, the nature of gouging varies with changes in seafloor sediment types. Along the Beaufort coast where there are two distinct soil types, the gouges in stiff, sandy, clayey silts are typically more frequent and slightly deeper than those found in more sandy sediments. Presumably the gouges in the more sandy material are more easily obliterated by wave and current action. It is also reasonable to assume that the slightly deeper gouges in the silts provide a better picture of the original incision depths. An extreme example of the effect of bottom sediment type on gouging can be found between Sakhalin Island and the eastern Russian mainland. Here the seafloor is very sandy and the currents are very strong. As a result, even though winter observations have conclusively shown that seafloor gouging is common, summer observations reveal that the gouges have been completely erased by infilling.

Gouge tracks in the Beaufort Sea north of the Alaskan and western Canadian coast generally run roughly parallel to the coast, with some regions having an excess of 200 gouges per kilometer. Histograms of the frequency of occurrence of distances between gouges are also well described by a negative exponential, a result suggesting that the spatial occurrence of gouges may be described as a Poisson process. Gouge occurrence is hardly uniform, however, with significantly higher concentrations of gouges occurring on the seaward sides of shoal areas and barrier islands and fewer gouges on their more protected lee sides. This is clearly shown in **Figure 4** in that the degree of exposure to the moving pack ice decreases in the sequence Jones Islands–Lonely–Harrison Bay–Lagoons. **Figure 5** is a sketch based on divers' observations showing gouging along the Alaskan coast of the Beaufort Sea.

The second features producing gouges on the surface of the outer continental shelf of the Arctic Ocean are ice islands. These features are, in fact, an unusual type of tabular iceberg formed by the gradual breakup of the ice shelves located along the north coast of Ellesmere Island, the northernmost of the Canadian Arctic Islands. Once formed, an ice island can circulate in the Arctic Ocean for many years. For instance, the ice island T-3 drifted in the Arctic Ocean between 1952 and 1979, ultimately completing three circuits of the Beaufort Gyre (the large clockwise oceanic circulation centered in the offshore Beaufort Sea) before exiting the Arctic

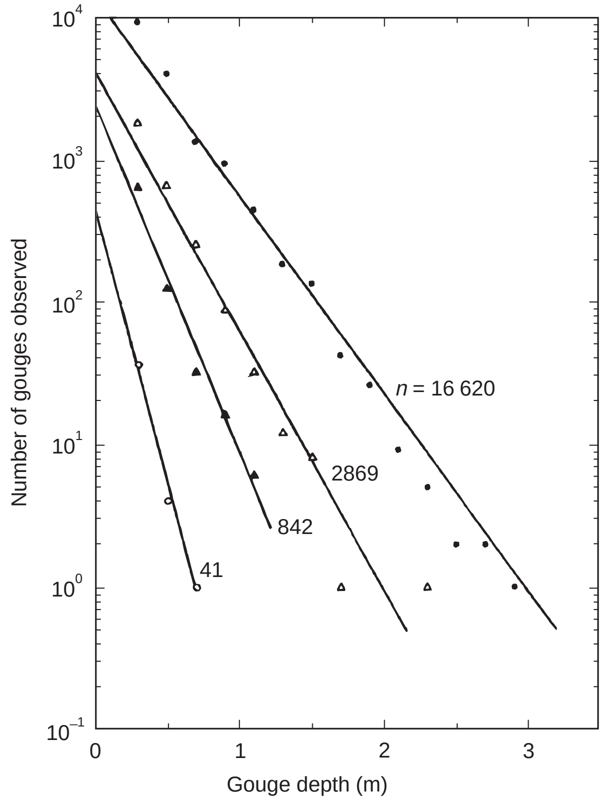

Figure 4 Semilogarithmic plot of the number of gouges observed versus gouge depth for four regions along the Alaskan coast of the Beaufort Sea. ●, Jones Island and east; △, Lonely; ▲, Harrison Bay; ○, Lagoons. (From Weeks *et al.*, 1983.)

Ocean through Fram Strait between Greenland and Svalbard (Spitzbergen). The lateral dimensions of ice islands can vary considerably from a few tens of meters to over ten kilometers. Thicknesses, although variable, are typically in the 40–50 m range; ice islands possess freeboards in the same range as

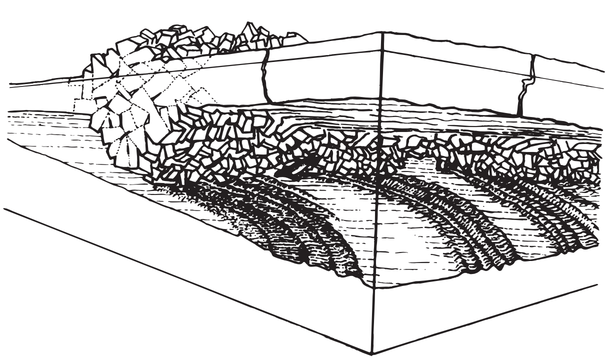

Figure 5 Diver's sketch of active gouging occurring off the coast of the Alaskan Beaufort Sea. Some sense of the scale of this drawing can be gained from the observation that commonly the thickness of the ice blocks in such ridges ranges between 0.3 and 1.0 m. (Drawing by TR Alpha, US Geological Survey.)

exhibited by larger sea ice pressure ridges. In the study of fathometer and sonar data on gouge distributions and patterns, no attempt is usually made to separate gouges made by pressure ridges from gouges made by ice islands, as the ice features that made the gouges are commonly no longer present. However, it is reasonable to assume that many of the very wide, uniform gouges are the result of ice islands interacting with the seafloor.

It is relatively easy to characterize the state of the gouging existing on the seafloor at any given time. It is another matter to answer the question of how deep one must bury a pipeline, a cable, or some other type of fixed structure beneath the seafloor to reduce the chances of it being impacted by moving ice to some acceptable level. To answer this question one needs to know the rates of occurrence of new gouges; these values are in many locations still poorly known, as they require replicate measurements over a period of many years so that new gouges can be counted and the rate of infilling of existing gouges can be estimated. The best available data on gouging occurrence along the Beaufort Coast has been collected by the Canadian and US Geological Surveys and indicates that gouging occurs in rather large scale regional events related to severe storms that drive the pack ice inshore – about once every 4–5 years. Because there is no absolute technique for dating the age of existing gouges, there is no current method for determining whether a particular gouge that one observes on the seafloor formed during the last year or sometime during the last 6000 years (after the Alaskan shelf was submerged as the result of rising sea levels at the end of the Pleistocene). It is currently believed that gouges in shallow water formed quite recently. For instance, during the late summer of 1977 when the Beaufort Coast was comparatively ice free, strong wave action during late summer storms obliterated gouges in water less than 13 m deep and caused pronounced infilling of gouges in somewhat deeper water. It is generally estimated that such storms have an average recurrence interval of approximately 25 years. On the other hand, gouges in water deeper than ~ 60 m are believed to be relatively old in that they are presumed to be below the depth of currently active gouging. The lengths of time represented by the gouges observed in water depths between 20 and 50 m are less well known. Unfortunately, this is the water depth range in which the largest gouges are found. Stochastic models of gouging occurrence, which incorporate approximate simulations of subsea sediment transport, suggest that if seafloor currents are sufficiently strong to exceed the threshhold for sediment movement, gouge infilling will occur comparatively rapidly (within a few years).

To date, two different procedures have been used to estimate the depth of gouges with specified recurrence intervals. In the first case, the available rates and geometric characteristics of new gouges at a particular site are used. If a multiyear high-quality dataset of new gouge data is available for the region of interest, this would clearly appear to be the favored approach. In the other case, information on the draft distribution of pressure ridge keels and pack ice drift rates are combined to calculate the rates of gouging. The problem with using pack ice drift rates and pressure ridge keel depths is that drift rates in the near shore where grounding is occurring are undoubtedly less than in the offshore where the ice can move relatively unimpeded. In addition, it is doubtful that offshore keel depths observed in water sufficiently deep to allow submarine operations provide accurate estimates of keel depths in the near-shore.

One might suggest that offshore engineers should simply bury pipelines and cables at depths below those of known gouges and forget about all these statistical considerations. Although this sounds attractive, it is not a realistic resolution of the problem. In the first place, for a pipeline to avoid deformation, buckling, and failure it must, depending on the nature of the seafloor sediments, be buried at depths up to two times that of the design gouging event. Considering that gouges in excess of 3 m are not rare at many locations along the Beaufort Coast of Alaska and Canada, this means burial depths > 5 m. Burial at such depths is extremely costly and time consuming considering the very short operating season in the offshore Arctic. It is also near the edge of existing subsea trenching technology. Another factor to be considered here is that the deeper the pipeline is buried, the more likely it is that its presence will result in the thawing of subsea permafrost that is known to exist in many areas of the Beaufort and Chukchi Shelves. Such thawing could result in settlement in the vicinity of the pipe, which could threaten the integrity of the pipeline. There are engineering remedies to this problem but, as one might expect, they are expensive.

Canadian East Coast

The primary problem to the east of Newfoundland and off the coast of Labrador is not sea ice but icebergs. Although the majority of these originate from the Greenland Ice Sheet calving to the west into Baffin Bay, some icebergs do originate from the East Greenland coast and from the Canadian Arctic (*see* **Icebergs**). Considering their great size and deep draft, icebergs are formidable adversaries. Iceberg gouges with lengths > 60 km are known and many have lengths > 20 km. Gouge depths can exceed 10 m and recent gouging is known to occur at depths of at least 230 m along the Baffin and Labrador Shelves. Icebergs also appear to be able to traverse vertical ranges of bathymetry up to at least 45 m. As with the sea-ice-induced gouges of the Arctic shelves, iceberg gouge depths are exponentially distributed, with small gouges being common and deep gouges being rare. Iceberg gouges can be straight or curved. Pits are also common, which occur when the iceberg draft is suddenly increased through splitting and rolling. The iceberg can then remain fixed to the seafloor while it rocks and twists as a result of the wave and current forces that impinge upon it. At such times pits can be produced that are deeper than the maximum gouge depth otherwise associated with the iceberg.

Although considerable information is available on the statistics of iceberg gouge occurrences, in studies of iceberg groundings more attention has been paid to the energetics of the ice–sediment interactions than to the statistics. Also, more emphasis has been placed on iceberg 'management' in order either to reduce or to remove the threat to a specific offshore operation. For instance, as icebergs are discrete objects as compared to pressure ridges, which are giant piles of ice blocks that are frequently poorly cemented together, icebergs can be deflected away from a production site via the use of tugboats in combination with trajectory modeling. Such schemes can also utilize aerial, satellite, and ship reconnaissance techniques to provide operators with an adequate warning of a potential threat. Surface-based over-the-horizon radar technology has also been developed as an iceberg reconnaissance tool, but at the time of writing it has not been used operationally.

Other Locations

Although the discussion here has primarily focused on the Beaufort Coast of the Arctic Ocean and the offshore regions of Newfoundland and Labrador, this is only because the interest in offshore oil and gas reserves at these locations has resulted in the collection of observational information on the local nature of the ice-induced gouging phenomenon. However, regions where ice-induced gouging is presently active are very large and include the complete continental shelf of the Arctic Ocean, the continental shelves of Greenland, of eastern Canada, and of Svalbard, as well as the continental shelf of the Antarctic continent where typical shelf icebergs are known to have drafts of ~200 m with lateral dimensions as large as 100 km. In addition, relict iceberg gouges exist and as a result affect seafloor topography in regions where icebergs are no longer common or no longer occur, such as the Norwegian Shelf and even the northern slope of Little Bahama Bank and the Straits of Florida. Finally, although 230 m is a reasonable estimate for the maximum depth of active iceberg gouging, relict gouges presumed to have occurred during the Pleistocene have been discovered at depths from 450 m to at least 850 m on the Yermak Plateau located to the northwest of Svalbard in the Arctic Ocean proper.

Conclusions

There is clearly much more that we need to know concerning processes acting on the poorly explored continental shelves of the polar and subpolar regions. The ice-induced gouging phenomenon is clearly one of the more important of these, in that an understanding of this process is essential to both the engineering and the scientific communities. At first glance, icebergs and stamuki zones might appear to be exotic entities that are out of sight somewhere way to the north or south and that can be safely put out of mind. However, as oil production moves to ever more difficult frontier areas such as the offshore Arctic, a quantitative understanding of processes such as ice gouging becomes essential for safe development. Lack of such understanding leads to poor, inefficient designs and the increased possibility of failures. The last thing that either the environmental community or the petroleum industry needs is an offshore oil spill in the high Arctic.

See also

Icebergs. Rigs and Offshore Structures. Sea Ice: Overview; Variations in Extent and Thickness. Sub Ice-shelf Circulation and Processes. Sub-sea Permafrost.

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