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Deepwater drilling in the Arctic Ocean's permanent sea ice[1]

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Chapter contents

Abstract

A fundamentally new multiple-vessel approach was developed under the auspices of the Ocean Drilling Program and the Integrated Ocean Drilling Program (IODP) to drill and recover deeply buried sediments in the Arctic Ocean. This approach overcame the difficulty of maintaining position over a drill site and recovering sediments in waters that are covered in moving ice floes. In August 2004, a convoy of three icebreakers met at the ice edge, northwest of Franz Josef Land, and headed north to begin the Arctic Coring Expedition, IODP Expedition 302. This expedition successfully recovered core at depths >400 meters below seafloor in 9/10 ice-covered water depths ranging from 1100 to 1300 m. Expedition 302 involved >200 people, including scientists, technical staff, icebreaker experts, ice management experts, ships' crew, and educators. At the drill site, temperatures hovered near 0°C and occasionally dropped to –12°C. Ice floes 1–3 m thick blanketed 90% (i.e., >9/10 ice cover) of the ocean surface, and ice ridges, several meters high, were encountered where floes converged. The ice drifted at speeds of up to 0.3 kt and changed direction over short time periods, sometimes within 1 h. A Swedish diesel-electric icebreaker, the *Vidar Viking* was converted to a drill ship for this expedition by adding a moonpool and a geotechnical drilling system capable of suspending >2000 m of drill pipe through the water column and into the underlying sediments. Two other icebreakers, a Russian nuclear vessel, the *Sovetskiy Soyuz,* and a Swedish diesel-electric vessel, the *Oden* protected the *Vidar Viking* by circling "upstream" in the flowing sea ice, breaking the floes into smaller pieces that wouldn't dislodge the drilling vessel >75 m from a fixed position. Despite thick and pervasive ice cover, the fleet and ice management teams successfully enabled the drilling team to recover cores from three sites. Ice conditions became unmanageable only twice, forcing the fleet to retrieve the pipe and move away until conditions improved. The scientific results from this drilling will significantly advance our understanding of Arctic and global climate.

Background

The Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP), which operated from 1968 to 2003, were the first scientific efforts to sample the deep subsurface of much of the global

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ocean. DSDP operated the drillship *GLOMAR Challenger,* the first ship to drill in ultra-deep water (>3000 m). ODP began operating a larger and more capable drillship, the *JOIDES Resolution,* in 1985. These two programs made fundamental discoveries and advanced our understanding of the evolution and structure of Earth. DSDP and ODP occupied roughly 1000 sites and drilled and recovered thousands of kilometers of ocean sediment and crust from every major ocean basin—except the Arctic.

The Arctic was excluded from drilling during both DSDP and ODP owing to technical and logistic challenges of operating in ice-covered waters. Furthermore, the lack of geophysical site surveys in the Arctic Ocean and even basic maps of bathymetry and ocean crustal composition severely limited proponents in terms of selecting and proposing drill sites.

Even with icebreaker support, most existing drillships (National Research Council, 1991) were insufficiently ice strengthened to safely work within the main polar ice pack. In addition, most of the important scientific Arctic ocean drilling targets are in water depths >1 km and are influenced by moving pack ice where holding station for days against the drift of the ice would be required. Regional ice movements follow two major circulation patterns: a clockwise flow, the Beaufort Gyre, in the Amerasian Basin and a cross-basin flow, the Transpolar Drift, in the Eurasian Basin (Fig. **F1**). Methods to stay on location against moving ice had been developed for shallow areas on the Arctic continental shelves for hydrocarbon exploration but were nonexistent for deepwater areas of the basin (National Research Council, 1991; Clark et al., 1997).

In an effort to advance scientific exploration of the Arctic and the technology required to do so, single- and multiple-ship icebreaker expeditions to the central Arctic Ocean conducted stationkeeping exercises. One of the first exercises, during the Arctic '91 Expedition (Fütterer, 1992), was conducted by the icebreaker *Oden* (Nansen Arctic Drilling, 1997) in single-ship mode. During heavy ice-breaking operations, the *Oden* was able to stay within 50 m of a fixed position for several hours, suggesting that stationkeeping could be achieved. Later, during a single-ship expedition in 1996, the *Oden* conducted carefully planned stationkeeping tests (Kristoffersen, 1997). Under moderate ice conditions (8–9/10 ice cover), the *Oden* was able to stay on location for more than a day.

The moderate success of these tests prompted an initially small group of scientists (J. Backman, L. Mayer, K. Moran, Y. Kristoffersen, and M. Jakobsson) to develop the first scientific ocean drilling proposal for a deepwater site in the central Arctic Ocean on the Lomonosov Ridge (ODP/Integrated Ocean Drilling Program [IODP] Proposal 533), based on site survey data acquired in 1991 (Jokat et al., 1992; see also Thiede et al., 1992) This submission to ODP was the first to propose the concept of multiple ships, including an ice-strengthened drillship. This idea was spawned from experience that team members had acquired in scientific ocean drilling and in the Canadian Beaufort Sea, where ice-strengthened drillships had successfully cored in shallow-water settings. Although details of this concept required considerable development, the robustness of the approach was repeatedly reinforced by groups of experts, primarily ice management and icebreaker specialists. The proponent team, with support from Joint Oceanographic Institutions (JOI), Inc., continued to develop the details of the concept with the help of these experts because the scientific drilling community, including management groups, showed significant skepticism about the possibility for success.

A pivotal meeting occurred when a group of icebreaker captains met with the proponents in Helsinki in 2001. At that meeting, Admiral Anatoly Gorshkovsky, Head of the Russian Ministry of Transport's Northern Sea Route Administration, suggested an option to ensure success with three nuclear icebreakers as support icebreakers and a drilling ship, "to break a 100 m wide lead upstream of the drill ship." This meeting marked the beginning of detailed planning for Expedition 302 and confirmed one key element of the concept—that whatever number of vessels were finally selected, at least one had to be a nuclear icebreaker.

Although the drilling proposal was submitted to ODP and was ranked first among all other proposals, the program did not schedule the project, primarily because of the effort required a change to existing ODP contracts. Instead, ODP, through its advisory structure, Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES), initiated an Arctic Detailed Planning Group (ADPG) whose mandate was to develop a detailed plan to execute a Lomonosov Ridge drilling project.

ODP ended in September 2003 and was succeeded by the IODP. IODP includes riserless drillship operations provided by the United States that are identical to those in ODP, new riser drilling provided by Japan, and an innovative option to use mission-specific platforms (MSPs) to conduct operations that could not be achieved with either the U.S. or the Japanese vessels. With the incorporation of MSPs into the scientific ocean drilling capabilities, the proponents directed their efforts to making Expedition 302 the first MSP expedition for IODP. IODP selected the proposal, scheduled it for August–September 2004 as the first MSP operation, and formally designated it as IODP Expedition 302.

Technical planning

In 2001, the JOIDES ADPG developed the first formal plan for drilling on the Lomonosov Ridge (Backman, 2001). A subset of the proponent group (J. Backman and K. Moran) were members of the ADPG and presented the multiple-ship concept to the ADPG, which was composed of scientists, naval architects, drilling and coring experts, and managers, most with Arctic or high-latitude experience. Given the scope of the mandate, the ADPG also engaged additional outside experts by writing work statements for specific planning tasks that were contracted and managed by JOI. The results of these contracts were incorporated into the ADPG report.

The ADPG was tasked with 15 different aspects of planning for the Lomonosov Ridge expedition. The most important were recommendations on vessels and vessel configurations, drilling systems and drilling preparations, ice forecasting, and management.

The group recommended several ship options but ranked a three-ship operation the highest. This option included an ice-strengthened drillship with two supporting icebreakers, a 75,000 hp Russian nuclear icebreaker and one diesel-electric Arctic-class icebreaker (~25,000 hp).

Several different drill rigs and equipment were evaluated, with Seacore's C200 the recommended choice. The recommendation was made because the Seacore system met requirements that included the ability to be mobilized on the selected ship and the ability to recover continuous core using ODP-type coring tools. The group recommended that the drilling system be tested on the selected vessel in advance of the expedition to provide ample time for testing and to allow time between the test and the expedition for any required modifications to be made.

Ice forecasting was determined by the ADPG to be important for selecting general transit routes but essential for

- Maintaining the drillship in dynamic positioning (DP) mode during drilling over extended periods of time,
- Making decisions on the relative positions of the vessels ahead of the drilling platform,
- Deciding on optimal icebreaking modes, and
- Providing long-term forecasting of the predominant heading of ice movement.

Because of the significant role of ice forecasting, the ADPG also recommended that an "ice management system" be incorporated into the drilling project. Based on Beaufort Sea drilling experience, these systems are a combination of ice monitoring techniques and icebreaking methods (break or deflect) and include techniques for surveying both regional and local ice conditions that include satellite imagery (Radarsat), airborne Synthetic Aperture Radar, helicopter reconnaissance, visual observations (local ice conditions), and weather forecasting. Ice management systems use this ice monitoring information to develop icebreaking and management operations on a daily basis. The ice management system for Expedition 302 was further developed by the Swedish Polar Research Secretariat (SPRS), under contract to JOI. SPRS engaged experts from Russia, Canada, Finland, and Sweden to assist them in developing the plan.

An overall project manager was recommended to oversee the planning of the program (beginning 2 y prior to the scheduled project). The ADPG further recommended that it was essential for this person to have Arctic experience and a good knowledge of drilling management. The group recommended that the expedition be led by an ice/vessel expert who would have Arctic operational management and multivessel drilling expertise.

To increase the potential for success of drilling in moving sea ice, the proponent team requested and was granted approval to position drill sites along seismic lines rather than at single points on a line. This increased the flexibility for siting holes where one location along a line could have severe ice conditions whereas another line location could have more favorable conditions.

Concept

Overall, the approach developed by the ADPG and refined by SPRS was relatively simple. In the three-ship operation (Fig. F2), the nuclear icebreaker would first manage the oncoming ice by breaking the large floes into smaller floes. If the nuclear icebreaker was not able to "manage" a floe, drilling would have to be suspended and the drill pipe tripped to the seafloor until the floe passed.

The nuclear icebreaker would have to operate at a distance far enough (~500 m–1 km) upstream so that there would be enough time to trip the drill pipe and move the drillship away from any "unbreakable" oncoming floes. At the same time, a second, more maneuverable icebreaker would work between the nuclear icebreaker and the path to the drillship, reducing the size of the ice floes and keeping the drillship relatively free of ice so that it could maintain station in DP mode.

The ice management plan included Radarsat images to provide an overview of conditions, helicopter reconnaissance to map the local ice field near the drill sites, an onboard weather observation team, and real-time monitoring of ice speed and direction using ice-based monitoring equipment. With this suite of tools, the ice management team would be able to forecast ice conditions in a 24–48 h window.

SPRS recognized the critical importance of ice and fleet management and defined a critical position for the expedition, the Fleet Manager, responsible for leading the overall operations.

SPRS, in planning the fleet and ice management, made conservative estimates on the length of time that the drillship would be able to maintain station. Their estimate was ~48 h. They viewed this estimate as workable based on time estimates for coring and logging calculated by Seacore, who had updated estimates made by the proponents in Proposal 533. The British Geological Survey (BGS) coring operation estimates were as follows:

- Pipe trips: 5–6 h in 1200 m of water,
- Piston coring: 4.5 m of core recovery every 50 min, and
- Extended/Rotary coring: 4.5 m core recovery every 70 min.

These estimates equate to a total of 9.2 days for tripping pipe, double-coring the upper 400 m, logging one hole, and temperature measurements in one hole. Seacore further estimated that if a third hole were required to core 100 m into basement (and assuming a pipe trip was needed to change the bottom-hole assembly [BHA]), the added time would be 57 h. This estimate was based on being able to wash ahead at a rate of 20 m/h.

SPRS's ice management protocols incorporated *T*-time estimates. *T*-time was the time required to trip or recover the pipe from the hole so that the ship would be free from the seabed and could move under heavy ice forces. If ice management could not achieve a good ice condition window longer than the *T*-time, drilling operations would be suspended by tripping pipe out of the hole.

Expedition 302 experiment

As the MSP science operator for IODP, the European Science Operator, led by BGS, conducted Expedition 302. BGS contracted SPRS to provide the two support icebreakers, the *Oden* and the *Sovetskiy Soyuz,* fleet and ice management programs, logistics associated with these two vessels, and helicopter services and information technology (IT) for the entire fleet. BGS directly managed contracts associated with provision of the drillship *Vidar Viking* and drilling services provided by Seacore Ltd. Coring tools were supplied and operated by BGS. SPRS subcontracted ice management to AKAC Inc. because of this company's ice experience in the Beaufort Sea and the Sakhalin region. The ice management strategy was to collect ice and weather data and combine into a single ice and risk analysis routine. Weather, ice drift predictions (from wind forecasts and ice drift "buoys"), ice maps prepared by hand from each of the ships and helicopter reconnaissance, and Radarsat images were compiled and analyzed by the ice manager. This analysis resulted in an ice alert report to the Fleet Manager that showed ice status with respect to *T*-time.

The *Vidar Viking* is a supply/anchor handling icebreaker, classed ICE-10, built in 2000 primarily to enable work in the Baltic Sea. Under Swedish flag, the ship is co-owned by B&N Viking Icebreaking and Offshore AS (Kristiansand, Norway). The *Vidar Viking's* size (84 m × 18 m; 3.382 gross tonnage) and in particular its large deck space (603 m^2 with a large 40.2 m × 15.0 m fantail) made it particularly suitable as the drillship. A moonpool was installed to provide a pass through for the drill pipe midships during drilling operations, and a helicopter deck was installed at the stern. An ice-protective steel "skirt" was lowered in the moonpool while on site to protect the drill string from pieces of ice under the hull of the ship.

The *Oden,* owned by Svenskt Isbrytarkonsortium KB, is one of seven icebreakers operated by the Swedish Maritime Administration. The *Oden,* built in 1988, was designed for escort ice-breaking and for Arctic research operations. One of the most capable diesel electric icebreakers in the world (classed as DNV 1A1 and Icebreaker POLAR–20), the *Oden* has conducted many single-ship expeditions to the Arctic Ocean. The ship's size (107.8 m × 31 m at its widest beam), scientific laboratory capabilities, and fuel capacity made it ideal for serving multiple capacities in the Expedition 302 fleet. In addition to the primary function, to protect the *Vidar Viking* during drilling operations, the *Oden* also served as the communication center for the fleet, was home to the fleet and ice management teams, served as the science center, carried the helicopter fleet, and supplied fuel to the *Vidar Viking.*

The nuclear-powered icebreaker selected for Expedition 302 was the *Sovetskiy Soyuz,* which is Polar ice–classed and can break ice 2–3 m thick continuously at 3 kt. The ship is large (148 m × 30 m) and can carry more than 200 people. Built in 1989, the *Sovetskiy Soyuz* is owned by the Russian government and operated by the Murmansk Shipping Co. The *Sovetskiy Soyuz* had two primary functions: break ice for the fleet to transit quickly to the drill site area and provide the first protection against ice during drilling operations. To enable efficient communications among the icebreaker masters, two members of the ice management team were onboard the *Sovetskiy Soyuz* during operations.

Prior to meeting the *Oden* in the port of Tromsø, the *Vidar Viking* mobilized in Aberdeen (to install the drilling system) and Landskrona (to install the helicopter deck). The *Oden* conducted much of its mobilization in Göteborg before sailing north to the port of Tromsø. On 7 August 2004, the *Oden* sailed north from Tromsø, followed by the *Vidar Viking* on 8 August. The *Oden* and the *Vidar Viking* met the *Sovetskiy Soyuz* at the edge of the polar ice pack on 10 August at 81°30′N. Upon entering the ice pack, the three ships formed a convoy with the *Sovetskiy Soyuz* leading, followed by the *Oden,* and then the *Vidar Viking* (Fig. **F3**).

The fleet made faster time than expected, transiting to the primary drill site at an average speed of 5 kt. This speed was achieved because of the ice-breaking capability of the *Sovetskiy Soyuz,* Radarsat ice reconnaissance information, and by following another nuclear icebreaker (*Yamal*) track part of the way.

Upon arrival on 14 August (2350 h Universal Time Coordinated) at the primary drill site (87°34′N, 138° 8.4′E), the ice management team began their first stationkeeping test. The site was covered in >9/10 ice, and the test began after the *Oden's* captain gave the order to begin breaking ice. Although the concept for maintaining station had been discussed well in advance, the icebreaker masters were not able to develop the practices in advance. They relied on their experience in icebreaking to develop details first-hand, and after 1.5 days of experimenting with icebreaking directions and patterns, they were able to maintain the *Vidar Viking* within a watch circle of 50–75 m for drilling to proceed.

During this test it became clear that the drillship had to use manual positioning because the icebreaking could not achieve a clear pool of open water around the *Vidar Viking* for DP to operate properly. However, because the ice generally moved in one constant direction, the manual positioning primarily required that the officers on watch (two officers were always on watch at any one time) steered the bow so that the ship's heading stayed in the upstream direction of the ice drift.

Once the stationkeeping test was successfully completed, the Fleet Manager gave the go-ahead for the drillship to begin operations. On 15 August 2004 at 1130 h, drilling operations began (Fig. **F4**). During the expedition, the time taken by various activities was logged and assigned to the following categories: drilling operations, waiting on ice, transit, and breakdown (Table **T1**).

Drilling operations, however, did not start with positive results. At the first site (Site M0001), the BHA was lost. The loss was first attributed to excessive vibration but was later linked to an error in applying the appropriate torque to a drill collar. After the loss of the BHA, the piston corer, which was needed to sample the upper ~100 meters below seafloor (mbsf), failed to recover core, and a high-pressure valve on the drill rig's top drive cracked. After partially overcoming these problems, relatively routine core recovery began on 19 August at Site M0002.

Coring continued in a single hole (Hole M0002A) until 23 August with the drill pipe at a depth of 272 mbsf when the Fleet Manager suspended operations because of excessive ice pressure. After waiting for better ice conditions and rig floor repairs, coring continued on 25 August but was suspended again the next day because the piston core became stuck in the BHA and could not be recovered.

During the break-in drilling operations, the ice management team analyzed the long-term ice forecast using new reconnaissance data and recommended a move to a new site. Drilling operations continued on 28 August after relocating to the new site ~15 nmi away and conducting repairs on the rig floor.

Over the next 9 days, the fleet and ice management teams were able to maintain the position of the drillship over the final site (Site M0004), a record achievement. Drilling operations continued during this time period and were interrupted by drilling problems (some due to freezing equipment) and short periods of time waiting on ice as precautionary measures. Drilling operations officially ended on 5 September 2004. Target depths were achieved with an average 68% core recovery.

Discussion

The fleet and ice management program far exceeded expectations by maintaining the drillship on location continuously over many days. The duration of the "possible" drilling operational window had been estimated to last up to 48 consecutive hours.

Prior to the expedition, SPRS thought that as much as 50% of time on site would be lost to weather, ice, and environmental circumstances. This achievement was even more remarkable given that the operations were carried out in >90% ice coverage with 7–8/10 of this composed of rugged multiyear ice.

Exceeding predicted stationkeeping capabilities proved to be critical to the success of Expedition 302 because the coring times did not meet predicted expectations. Pipe trips took twice as long, 10–12 h, core recovery averaged 1.4 m/h (a factor of ~3 slower than estimated), and the best washing ahead rate was 12 m/h.

Overall, the *Vidar Viking* performed better than anticipated and was able to stay on location in very heavy ice. However, the *Vidar Viking's* DP system was not functional under these ice conditions, and a manual method had to be developed. The method that worked best was to provide the *Vidar Viking* with the near–real time ice drift predictions (speed and direction). The *Vidar Viking* would then set a course exactly counter to this direction. As large pieces of ice impacted the ship, the *Vidar Viking* "leaned" toward the broken ice by driving ~20 m upstream of the drill site location and then slowly drifting with the ice to ~20 m downstream from the drill site location before repeating the same process again. Thus, accurate ice drift direction was critical for positioning. When the prediction was wrong, the *Vidar Viking* would not drift back exactly over the drill hole. Once the vessel was off-track, it was difficult to move sideways back to the optimal track path again because of the heavy ice to port and starboard. When ice became too difficult, the *Oden* broke ice close to the *Vidar Viking* so that the ship could maneuver sideways. These tight maneuvers were successful because of the experienced and capable captains who trusted each other.

Because of the critical nature of the ice drift direction, predicting direction became a high priority for the ice management team. A new approach for measuring ice speed and direction was developed by SPRS and used successfully during Expedition 302. By helicopter, radar reflectors were placed on selected ice floes and their positions were tracked upstream of the drill site location.

The biggest problem in predicting ice drift was when the wind speed dropped and wind measurements became unreliable. On these occasions, the whole ice sheet "stalled" and began to rotate because of Coriolis forces. This caused significant problems for the *Vidar Viking* because a regular heading could not be maintained and maneuvering became almost impossible. During some of these times, drilling was temporarily suspended (keeping the drill pipe in the hole) until ice began to move again in one direction. Stationkeeping was best achieved during conditions of steady, predictable ice drift. However, even during these severe events, the watch circle limit (100 m) was never exceeded (Fig. F5) The largest deviations from the center point occurred during conditions of no ice drift and when the ice sheet revolved 360°. The ice management team gained experience during the expedition and succeeded in making accurate predictions even during times of low wind speed, which improved the difficult situation for the drillship.

The ice alert system used during Expedition 302, based on experience from the offshore industry in Sakhalin, served very well as a tool for documenting the operations but was of limited value during critical times when rapid decision-making was required. During these situations, the Fleet Manager relied most heavily on the ice drift and meteorological predictions.

The Expedition 302 communication system, provided under subcontract by Per Frejvall, long-time consultant to SPRS in matters of IT and communication, was also important to the success of the operation. Full cellular coverage, provided by Eriksson Response, was installed on the *Oden* with links to the *Vidar Viking* and the *Sovetskiy Soyuz*. In addition, the ships were linked 24 hours per day, 7 days per week by Internet. These systems, in addition to ships' radios, made communication almost seamless. Fleet management provided frequent and regular updates to the fleet bridges on the current ice situation specific to each vessel. This system also enhanced communication among the ships' captains. After the first week, the captains became more familiar with each other and learned quickly what each vessel and crew could achieve. This level of familiarity and trust played a large factor in the fleet's ability to keep station for ~9 consecutive days at the last site. Also, as operations continued, maneuvering and vessel coordination were fine-tuned, and this significantly reduced the amount of power required for icebreaking.

Conclusions

By successfully keeping a drillship on location in heavy multiyear sea ice for a number of days, Expedition 302 broke one of the last remaining barriers to scientific investigations in the Arctic. The multiple-ship concept, framed by the proponents in 1998, was the first of several keys to success. Success was also achieved through the efforts of first-rate fleet and ice management teams (made up of individuals with extensive Arctic icebreaking, ice prediction, and weather forecasting experience) and a team of hard-working, experienced, and innovative drilling experts. The captains of each of the three vessels individually and as a team developed the ice-breaking techniques on location that maintained the drillship within a fixed position with only two major drive-offs and for as long as 9 consecutive days. SPRS developed and applied a new ice drift measurement system using ice-deployed radars that immediately became integral to the operation. The communication system provided the means for developing the much-needed relationships among the captains, fleet managers, ice managers, and drillers.

Although an overall success, there were some failures and improvements that should be made for future operations. The most important of these is the drilling system. As originally recommended by the ADPG, future drilling systems, including all major components and coring tools, should be tested and proven before being deployed to the Arctic. Drilling operations were not supposed to be the challenge during Expedition 302. Because of a lack of resources and time dedicated to equipment acquisition and testing they turned out to be. Critical equipment failures during Expedition 302 included

1. A high-pressure valve that was located in a vulnerable location on the drill floor,
2. A refurbished iron roughneck that cracked,
3. Equipment that froze in relatively mild Arctic temperatures (–12°C), and most importantly,
4. Coring tools that did not function as anticipated.

Ice conditions during Expedition 302 were severe with >9/10 ice cover, much of it composed of hard, multiyear ice. Therefore, by using a similar fleet with a similar if not identical Arctic-experienced professional team, the success of Expedition 302 can be achieved in virtually any other area of the Arctic Ocean.

Acknowledgments

We thank the following for their professionalism, hard work, and dedication to Expedition 302: Fleet Managers Captains Anders Backman and Anders Vikström; Ship Masters Captains Tomas Årnell, Jørgen E. Haave, and Stanislav Smith and their crews; SPRS Director Anders Karlqvist; Logistics Officer Ulf Hedman; Operations Manager Alister Skinner and the ESO team; Seacore Drilling Supervisor Tony Halliday and his team; Ice Manager Arno Keinonen and his team; Meteorologists Bertil Larsen and Sandy Olsson; Helicopter Pilot Sven Stenvall and his team; IT and Communications Manager Per Frejvall; and Eriksson Response's Ingemar Pomlin. Thanks also to Dave Huey for his real-time advice and support, Harry Hoggeboom and Marius Lengkeek, who provided technical advice and moral support in the early planning stages, and Bruce Colbourne, Larry Mayer, and G. Leon Holloway for their constructive reviews.

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Figure F1. Schematic diagram showing positions of sea ice and ocean circulation patterns in the Arctic Ocean and marginal seas. The Lomonosov Ridge is generally located below the Transpolar Drift.

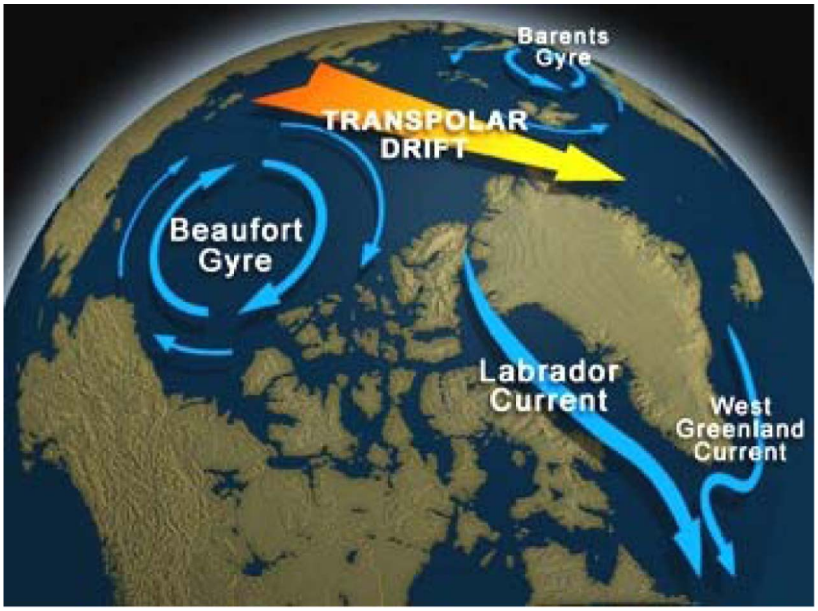

Figure F2. Configuration of the Expedition 302 fleet. The nuclear icebreaker breaks large floes and the diesel-electric breaks these into small “bergy bits” to protect the drillship.

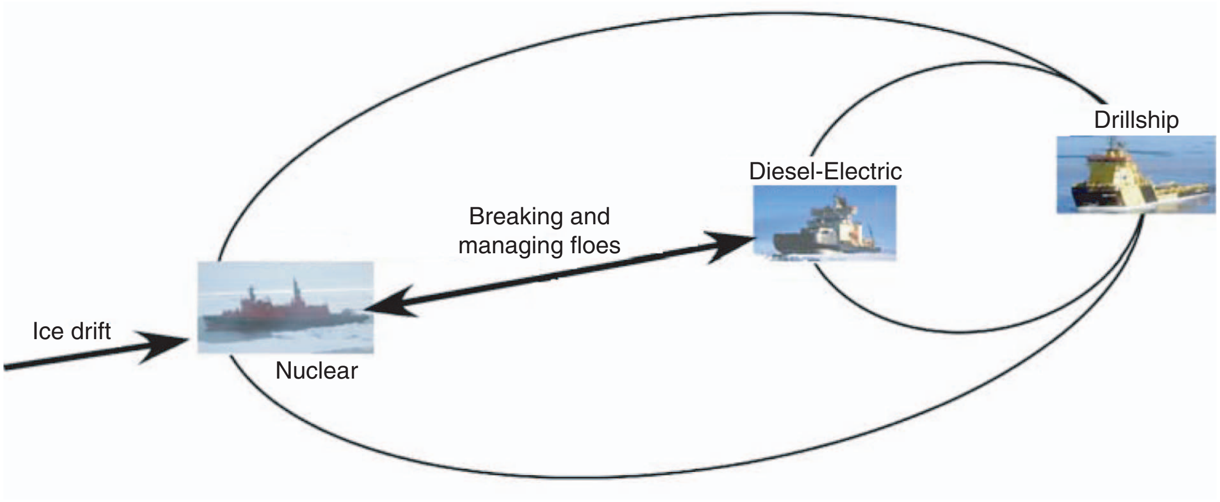

Figure F3. The Expedition 302 fleet during the transit north, the *Sovetskiy Soyuz* leading, the *Oden* following, and the drillship *Vidar Viking* in the rear (photo taken by Sven Stenvall).

Figure F4. The Expedition 302 fleet during drilling operations. Ice drift direction is top to bottom. The *Sovetskiy Soyuz* (circled at the top of the image) is breaking a large floe. The *Oden* (middle circle) is breaking the broken floe into smaller and smaller pieces. The *Vidar Viking* is holding position (bottom circle) (photo taken by Per Frejvall).

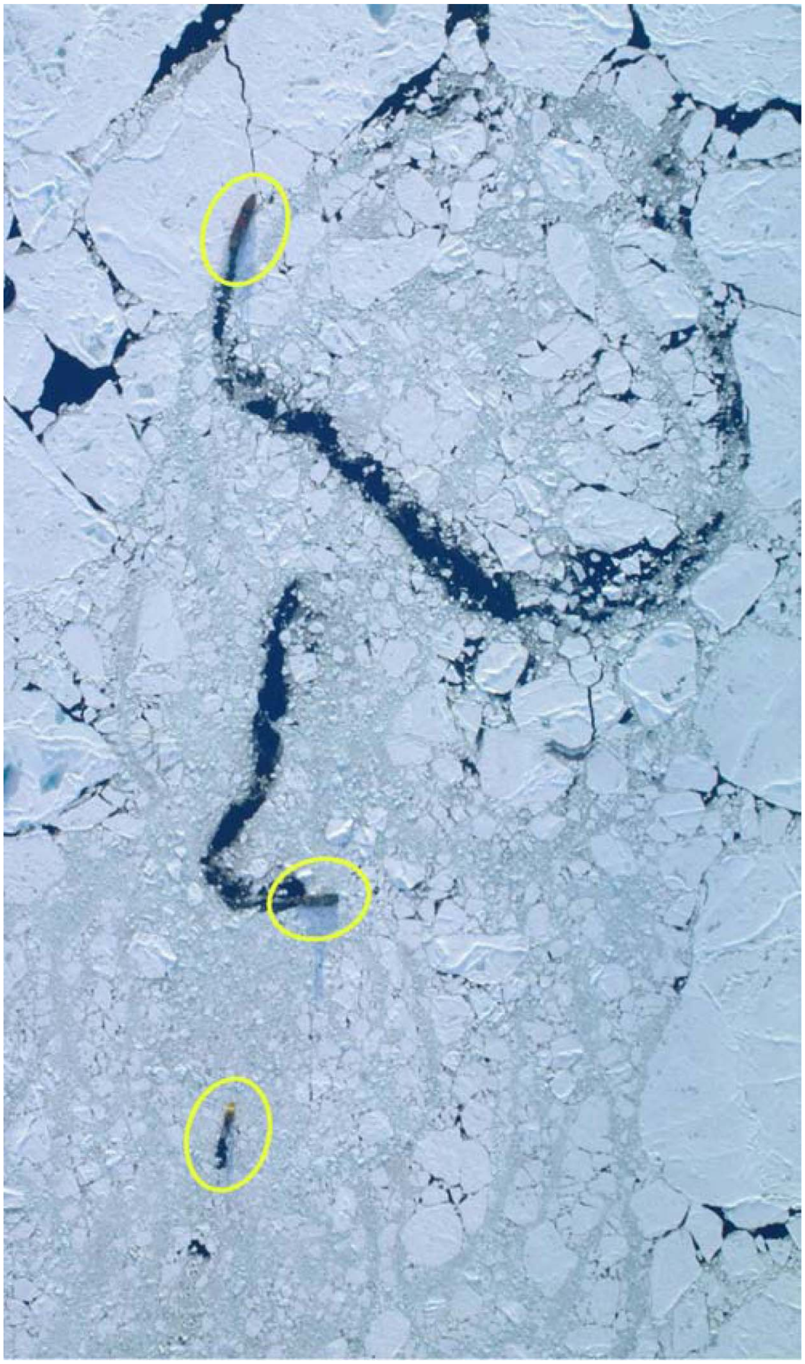

Figure F5. Plot of the *Vidar Viking's* position relative to Hole M0004A. Dark blue shows positions within 25 m, light blue within 50 m, and burgundy within 75 m. The maximum acceptable limit for the watch circle was 100 m. This positioning achievement was made over 9 continuous days (figure provided by M. Jakobsson). * = median value of calculated hole position.

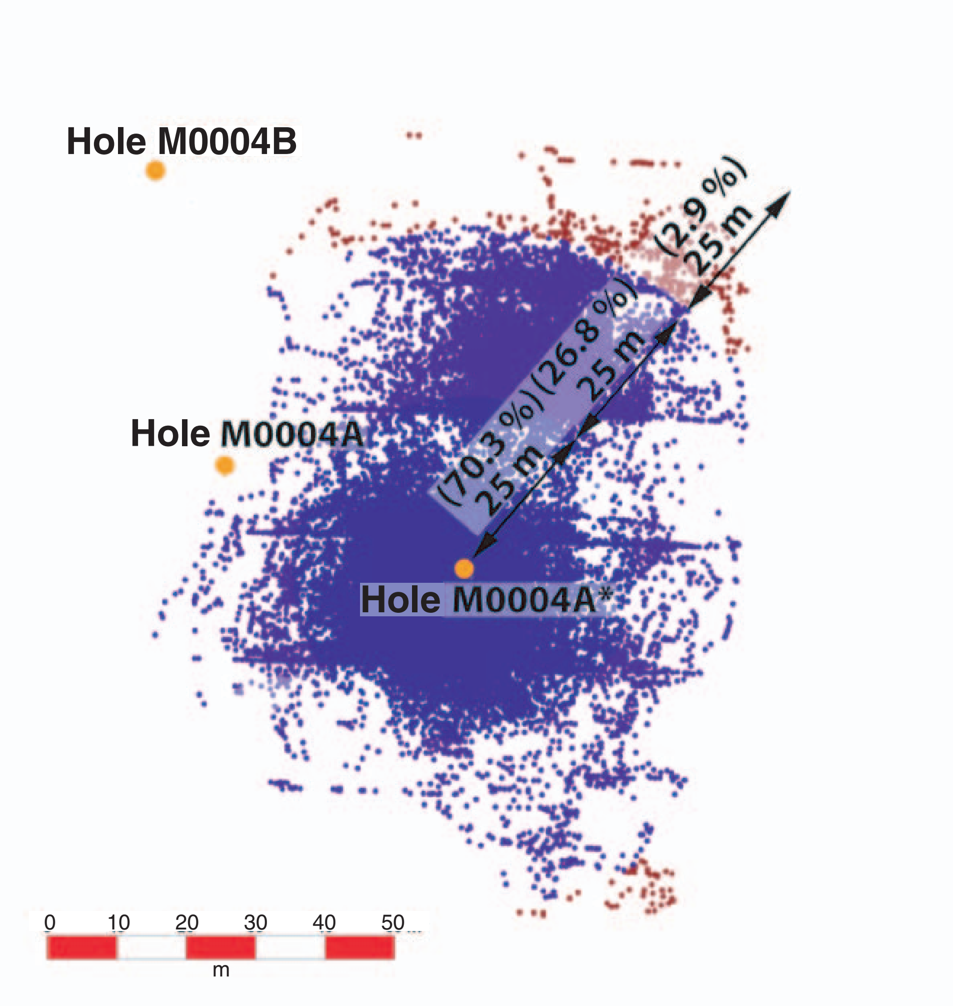

Table T1. Time breakdown of activities during Expedition 302 while on location.

Category	Hours	Percentage of time
Drilling operations	333.75	61.7
Waiting on ice	53.25	9.8
Transit	15.25	2.8
Breakdown	138.75	25.6