DEVELOPMENTS IN MARINE GEOLOGY 2

ARCTIC OCEAN SEDIMENTS

PROCESSES, PROXIES, AND PALEOENVIRONMENT

RUEDIGER STEIN

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VOLUME TWO

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ARCTIC OCEAN SEDIMENTS: PROCESSES, PROXIES, AND PALEOENVIRONMENT

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Preface

Although it is generally accepted that the Arctic Ocean is a very sensitive and important region for changes in the global climate, this region is one of the last major physiographic provinces of the earth whose short- and long-term geological history is not very well known. Since the first recovery and description of deep-sea sediments during the famous 1893–1896 *Fram*-Expedition of Fridtjof Nansen (Nansen, 1897; Böggild, 1906), the progress in getting a better understanding of the Arctic Ocean system and its relationship to global change has been slow in comparison to studies in other ocean regions. This lack of knowledge is mainly caused by the major technological/logistic problems in reaching this permanently ice-covered region with normal research vessels and in retrieving long and undisturbed sediment cores. Prior to 1990, the available samples and geological data from the central Arctic Basins are derived mainly from drifting ice islands such as T-3 (e.g., Clark et al., 1980) and CESAR (Jackson et al., 1985), and a few ships expeditions such as *Ymer*-80 (Boström & Thiede, 1984), *Polarstern* ARK-IV/3 (Thiede, 1988), and *Polar Star*-1988 (Phillips et al., 1992). Comprehensive summaries about the knowledge on Arctic Ocean geology based on data available prior to 1990 were published in Herman (1989), Bleil and Thiede (1990), and Grantz et al. (1990).

In the following years, several international and multidisciplinary expeditions were carried out, for example, the *Polarstern/Oden* Expedition in 1991 (Fütterer, 1992), the *Polar Sea* Expedition in 1993 (Grantz et al., 1998), the *Louis St. Laurent/Polar Sea* Expedition in 1994 (Wheeler, 1997), the *Polarstern* expeditions in 1998, 2001, 2004, and 2007 (Jokat, 1999; Thiede, 2002; Stein, 2005; Schauer, 2008), and the *Akademik Federov* Expedition in 2000 (Kaban′kov et al., 2004), the *Oden* expeditions in 2001 and 2007 (Grönlund, 2001; Jakobsson, Polyak, & Darby, 2007b), and the *Healy/Oden* Expedition in 2005 (Darby et al., 2005). Furthermore, major multidisciplinary circum-Arctic research programmes and initiatives were developed, for example, SEARCH (The Study of Environmental Change; Morison et al., 2001), SBI (Arctic Shelf-Basin Interactions; Grebmeier & Harvey, 2005), APARD (Arctic Paleo-River Discharge; Stein, 1998), and ACD (Arctic Coastal Dynamics; Rachold, Are, Atkinson, Cherkashov, & Solomon, 2004b).

Prior to 2004, the geological sampling in the Arctic Ocean was restricted to obtaining near-surface sediments, that is, only the upper 15 m could be sampled by means of gravity and piston coring. Thus, all studies were restricted to the Late Pliocene-Quaternary time interval, with one exception. In four short sediment cores from Alpha Ridge where older strata are cropping-out, upper Cretaceous and lower Tertiary sediments could be sampled by gravity coring from an ice flow (see Chapter 7). That means, the old pre-Pliocene palaeoenvironmental history of the central Arctic Ocean was almost unknown. This situation changed with the first scientific drilling on Lomonosov Ridge, which was carried out in August/September 2004 within the framework of the Integrated Ocean Drilling Program (IODP). During this IODP–ACEX (Arctic Coring Expedition) expedition, which is a break-through for palaeoenvironmental research, a more than 400 m thick sedimentary sequence of Neogene, Palaeogene, and Campanian could be drilled successfully (Backman et al., 2006; Moran et al., 2006). This record will allow for the first time detailed multidisciplinary studies of the early Arctic Ocean history and its change from greenhouse to icehouse conditions.

During the past about two decades, numerous multidisciplinary studies of the data and sediment material collected during these ship expeditions and carried out in international cooperation have greatly advanced (and will further advance) our knowledge on Arctic Ocean palaeoenvironment and its variability through Cenozoic times. A comprehensive compilation of data on Artic Ocean palaeoenvironment and its short- and long-term variability based on the huge amount of new data including the ACEX drilling data, however, has not been available yet. Thus, the main scope of this book is to (partly) fill this gap in knowledge.

The book is divided into three parts: Part I (Chapters 1 and 2) gives (i) a short introduction into the Arctic Ocean system including the alarming story of recent Arctic climate change, the history of Arctic research, the tectonic evolution, and the glacial history of the High Latitudes, and (ii) a description of the characteristics of the modern Arctic Ocean. Part II (Chapters 3 and 4) is dealing with (i) glacio-marine sedimentary processes and (ii) marine-geological proxies and methods used for (palaeo-) environmental reconstructions in the Arctic Ocean. Some more general background information as well as examples of using these proxies in Arctic Ocean environmental studies are given. It should be mentioned that some of the described proxies have their main strength outside the polar ice-covered regions. Nevertheless, they are included here because they yield important information about (palaeo-) environmental conditions in the marginal ice-covered (Subarctic) zones or are used for palaeoenvironmental reconstructions of the old pre-glacial Arctic Ocean. A more detailed discussion of selected proxies is then included in Part III of this book (Chapters 5–7) where results of case studies dealing with reconstructions of modern and ancient Arctic Ocean environment are presented. Concerning Part III, I concentrate on themes such as, for example, the modern and ancient terrigenous input, the Quaternary glacial history as reflected in marine sediment cores, the organic-carbon record and its palaeoenvironmental significance, and the long-term climate history as reflected in the ACEX record, that is, themes in which I am personally more involved. Thus, neither the spatial coverage of records nor the major themes discussed in this book can be regarded as complete.

Although major progress in Arctic Ocean research has been made during the past decades, the knowledge of its short- and long-term palaeoceanographic and palaeoclimatic history as well as its plate-tectonic evolution is still behind that from the other world's oceans and coordinated multidisciplinary research projects are needed. In the final chapter of this book (Chapter 8), some key objectives of future Arctic geoscientific research are shortly presented and discussed.

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Ruediger Stein
Bremerhaven
April 2008

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List of Abbreviations

ACEX	Arctic Coring Expedition
AMS	Acceleration Mass Spectrometry
AO	Arctic Oscillation
BG	Beaufort Gyre
BIT	Branched and Isoprenoid Tetraether index
Cal. yr. BP	Calendar years Before Present
CCD	Carbonate compensation depth
DOC	Dissolved organic carbon
DSDP	Deep Sea Drilling Project
GDGT	Glycerol dialkyl glycerol tetraether
GIN Sea	Greenland–Iceland–Norwegian Sea
GLAMAP	Glacial Atlantic Ocean Mapping
HBI	Highly branched isoprenoid
HC	Hydrocarbons
IBCAO	International Bathymetric Chart of the Arctic Ocean
ICAM	International Conference on Arctic Margins
IODP	Integrated Ocean Drilling Program
IPY	International Polar Year
IRD	Ice-rafted debris
LGM	Last Glacial Maximum
LIS	Laurentide Ice Sheet
MIS	Marine Isotope Stage
MIZ	Marginal Ice Zone
MWP	Meltwater pulse
NADW	North Atlantic Deep Water
NAO	North Atlantic Oscillation
NGS	Norwegian-Greenland Seaway
NHG	Northern Hemisphere Glaciation
OAE	Oceanic Anoxic Event
OC	Organic carbon
ODP	Ocean Drilling Program
PETM	Palaeocene–Eocene Thermal Maximum
POC	Particulate organic carbon
PONAM	Polar North Atlantic Margin
QUAX	Quantitative phase analysis by X-ray diffraction
QUEEN	Quaternary Environment in the Eurasian North
SBIS	Svalbard-Barents Sea Ice Sheet
SCICEX	SCience ICe EXercise
SEM	Scanning electronic microscopy

SIC	Sea-ice cover
SIS	Scandinavian Ice Sheet
SSS	Sea-surface salinity
SST	Sea-surface temperature
TEX	Tetraether index
TOC	Total organic carbon
TPD	Transpolar Drift
TSM	Total suspended matter
UCM	Unresolved complex mixture of hydrocarbons
WSC	West Spitsbergen Current
XRD	X-ray diffraction
YD	Younger Dryas

Part 1: Introduction and Background

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CHAPTER ONE

Introduction to the Arctic: Significance and History

1.1. The Arctic Ocean and Its Significance for the Earth's Climate System

For several reasons, the Arctic Ocean (Figure 1.1) is unique in comparison to the other world oceans:

- it is surrounded by continents and the world's largest shelf seas, with limited connections to the Pacific and Atlantic Oceans via Bering Strait and Fram Strait, respectively, making the Arctic Ocean a "mediterranean" sea (Jakobsson, 2002);
- it is seasonally to permanently covered by sea ice;
- it is strongly influenced by huge river discharge which is equivalent to 10% of the global runoff (Aagaard & Carmack, 1989; Holmes et al., 2002);
- it has a strong seasonal forcing (runoff, ice formation, sunlight); and
- most of the terrestrial surface around the Arctic Ocean is occupied by permafrost.

These characteristics, which are outlined in more details in Chapter 2, have a large influence on the environment of the Arctic Ocean itself, the global Earth system, and climate change. The freshwater supply (see Chapter 2.5), for example, is essential for the maintenance of the low-salinity layer of the central Arctic Ocean and, thus, contributes significantly to the strong stratification of the near-surface water masses, encouraging sea-ice formation. Changes in the freshwater balance would influence the extend of sea-ice cover. The melting and freezing of sea ice result in distinct changes in the surface albedo, the energy balance, the temperature and salinity structure of the upper water masses, and the biological processes. Freshwater and sea ice are exported from the Arctic Ocean through Fram Strait into the North Atlantic. Changes in these export rates of freshwater would result in changes of North Atlantic as well as global oceanic circulation patterns. The interplay of the cold Arctic freshwater-rich surface-water layer and its ice cover with the relatively warm and saline Atlantic water is important for the renewal of deep waters driving the global thermohaline circulation (e.g., Broecker, 1997; Clark, Pisias, Stocker, & Weaver, 2002). Because factors such as the global thermohaline circulation, sea-ice cover and earth albedo have a strong influence on the earth's climate system, climate change in the Arctic could cause major perturbations in the global environment.

During the 1990s, it became widely recognized that the Arctic was undergoing dramatic change (Macdonald, 1996; Dickson et al., 2000; Morison,

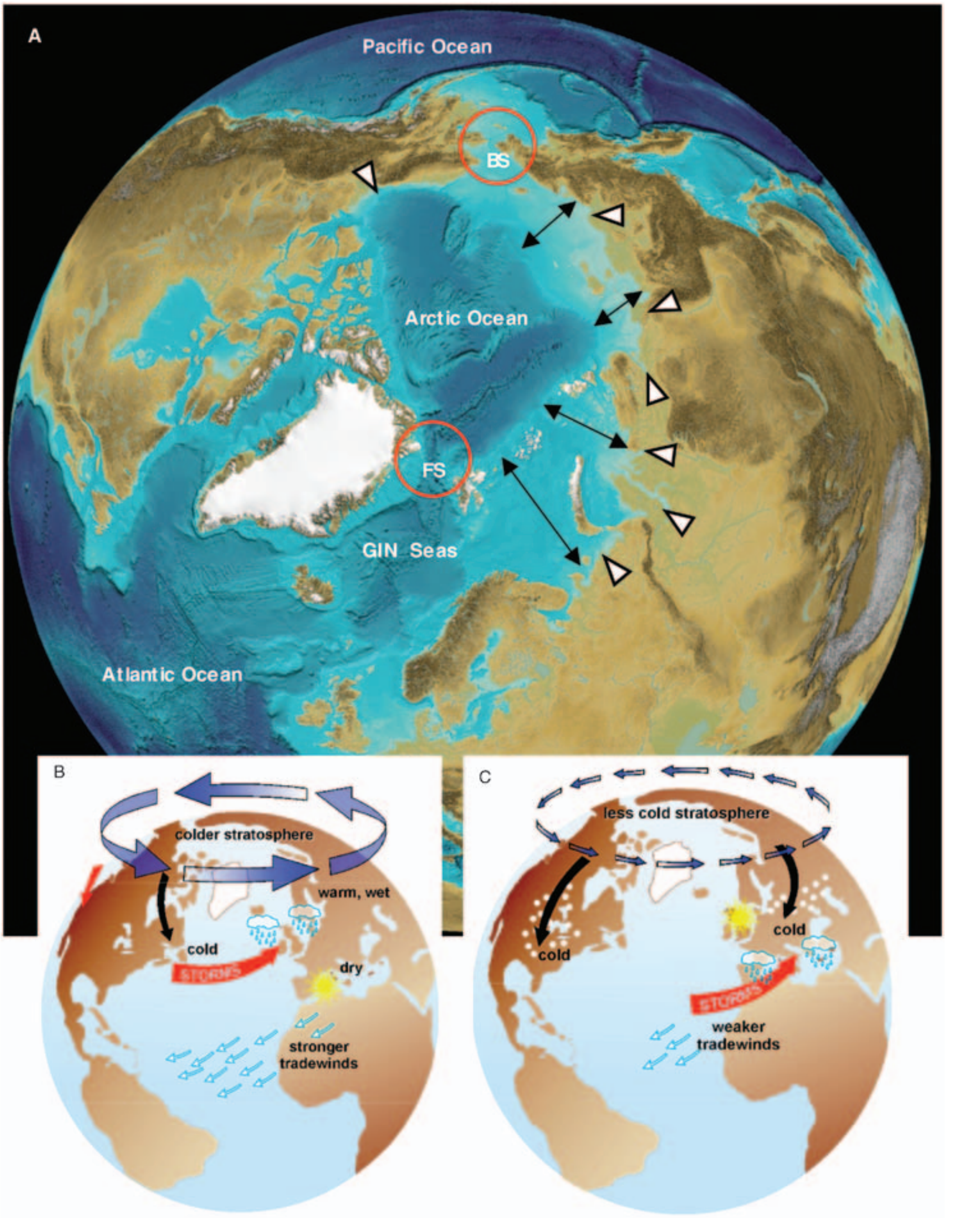

Figure 1.1 (A) Overview map of the Arctic Ocean (from Wille, 2005, supplemented). The connection to the Pacific and Atlantic Oceans, Bering Strait (BS), and Fram Strait (FS), respectively, loci of major riverine input (open triangles), and broad Eurasian shelf seas (black arrows) are highlighted. Schematic diagram of the polar vortex and North Atlantic storm tracks showing (B) the effect of the positive phase of the Arctic Oscillation and (C) the effect of the negative phase of the Arctic Oscillation (from Macdonald, Sakshaug, & Stein, 2004a; data source http://www-nsidc.colorado.edu/arcticmet/patterns/arctic.oscillation.html).

Aagaard, & Steele, 2000; Serreze et al., 2000; Moritz, Bitz, & Steig, 2002). Over the past decades, a significant increase in Siberian river discharge, associated with a warmer climate and enhanced precipitation in the river basins, has been observed (Semiletov et al., 2000; Serreze et al., 2000). At the same time, an increase in the amount and temperature of Atlantic water inflow into the Arctic, a reduced sea-ice cover, a thawing of permafrost, and a retreat of small Arctic glaciers are obvious (Dickson et al., 2000; Serreze et al., 2000). Reducing the sea-ice cover (see Chapter 2.3) causes a reduced albedo effect, and thawing of permafrost (see Chapter 2.6) may release greenhouse gases into the atmosphere, both positive feedbacks to further warming. Furthermore, increased glacial melt and river runoff add more freshwater to the ocean, raising global sea level and possibly slowing the global thermohaline circulation.

The Arctic sea ice, a key indicator and agent of climate change, affecting surface reflectivity, cloudiness, humidity, exchanges of heat and moisture at the ocean surface, and ocean currents, had been undergoing retreat over the past three decades (Figure 1.2), as recognized by the science community with some alarm (e.g., Johannessen et al., 2004; ACIA, 2004, 2005; Francis, Hunter, Key, & Wang, 2005; Serreze, Holland, & Stroeve, 2007; Stroeve, Holland, Meier, Scambos, & Serreze, 2007). Observed changes not only included a reduction in total area covered by sea ice (Maslanik, Serreze, & Barry, 1996; Johannessen, Shalina, & Miles, 1999; Johannessen et al., 2004; Parkinson, Cavalieri, Gloersen, Zwally, & Comiso, 1999; Vinnikov et al., 1999; Levi, 2000), but also an increase in the length of the ice melt season (Smith, 1998; Stabeno & Overland, 2001; Rigor, Wallace, & Colony, 2002), a loss of multiyear ice (Nghiem et al., 2007), and a general decrease in the thickness of ice over the central Arctic Ocean (Rothrock, Yu, & Maykut, 1999) (see Chapter 2.3 for more details).

On the basis of global coupled atmosphere–ice–ocean climate model simulations, Johannessen et al. (2004) predicted that the summer ice cover may be reduced by ~80% at the end of this century, i.e., the Arctic Ocean may nearly become ice-free during summer (Figure 1.3, lower records). The decrease in the summer ice cover is much greater than in the winter (Figure 1.3, upper records), or annual means modelled previously (Vinnikov et al., 1999; Johannessen, Shalina, Kuzmina, Miles, & Nagurnyi, 2001). The reduction of future sea ice may be even more rapid: an alarming record-low in minimum sea-ice cover was observed in September 2007, which is ~40% less than that of 1979, the start of sea-ice observation by satellites (Figure 1.2; Kerr, 2007). Such a minimum cover was forecasted by modelling to occur in the middle of this century (Figure 1.3; Johannessen et al., 2004).

All these environmental changes described above, seem to be related to a cyclic variation of the Northern Hemisphere/Arctic atmospheric circulation pattern, i.e., the "Arctic Oscillation (AO)" and the "North Atlantic Oscillation (NAO)" (Hurrell, 1995; Thompson & Wallace, 1998; Dickson et al., 2000; Peterson et al., 2002). With respect to changes in Eurasian arctic river discharge, Peterson et al. (2002) showed strong correlations with both global surface air temperature and the NAO index (Figure 1.4). During a positive NAO/AO Index phase, warm wet air is brought to Northern Europe and the Russian Arctic (Figure 1.1), causing increased precipitation in the drainage area of the Siberian rivers, which result in increased