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# The response of the Bering Sea Gateway during the Mid-Pleistocene Transition

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## ABSTRACT

The Mid-Pleistocene transition and the response of sea ice in the subarctic North Pacific are examined using a diatom record from the north eastern Bering Sea slope (IODP core U1344A). High percentages of diatom sea ice species in the assemblage foster the development of groupings specific to differing ice conditions. *Thalassiosira antarctica* var. *borealis* emerges as a key diatom species that delineates the development of thick multiannual sea ice and marks a series of advancements from 0.9 to1.2 Ma after which it dominates the assemblage until 0.6 Ma. The decline of *Neodenticula seminae*, indicative of Alaskan Stream water inflow, is in agreement with neighbouring core U1343E confirming the reduction of Bering Sea circulation after 0.9 Ma. We propose that during the MPT a stepped advancement of sea ice occurs in the Bering Sea as a response to increased moisture delivery to the high latitudes. An extended period of diatom productivity between 0.75 and 0.65 Ma, marks major deglacial conditions towards the end of the MPT by 0.6–0.55 Ma. The work highlights the important role played by sea ice and supports the contention of a colder MPT in the subarctic Pacific.

## 1. Introduction

Recent monitoring of diminishing sea-ice cover in the Arctic region agree with future scenarios of an ice-free Pole by the year 2040 or earlier (Comiso et al., 2008; IPCC, 2014; Overland et al., 2013; Stroeve et al., 2007; Wang and Overland, 2012). Sea ice plays an important role in climate dynamics, modifying temperature through ice-albedo feedbacks, ocean heat transfer, as well as the properties and formation rates of ocean deep water (Maslowski et al., 2012). However, due to the complex nature of the climate system the rate and regional responses to global warming are hard to predict (Nihoul and Kostianoy, 2009). As such, paleoarchives present a unique opportunity to study the subarctic ocean's response to past climate variability in the absence of anthropogenic forcing and improve modelling data for future forecasting.

High latitude regions, such as the Bering Sea, are important for monitoring past sea ice and ocean dynamics due to their sensitivity to the climate system. The Bering Sea is one of the world's most productive regions (Brown et al., 2011; Brown and Arrigo, 2013, 2012; Sambrotto et al., 1984; Springer et al., 1996; Whitledge and McRoy, 1988), with some of the highest primary production occurring at the Eastern Bering Shelf, referred to as the “green belt”. Diatoms dominate surface water productivity (Brown et al., 2011; Springer et al., 1996) and underlying sediments (Ren et al., 2014; Sancetta, 1982) and are established as a key proxy for paleoclimate reconstructions in this region (Jousé, 1971; Katsuki et al., 2003; Katsuki and Takahashi, 2005; Sancetta, 1982, 1981; Sancetta and Silvestri, 1986; Shimada et al., 2009). Diatoms are also found in sea ice and as such, can elucidate past sea-ice dynamics as well as surface water masses influencing a site (Caissie et al., 2010; Stroynowski et al., 2015).

The Bering Sea is the Pacific gateway to the Arctic and is a strategic paleoceanographic location in understanding the interaction between the two oceans. IODP Expedition 323 to the Bering Sea drilled 3 sites along the margin of the Eastern Bering Shelf in 2009, and recovered high resolution sedimentary sequences on the shelf slope and adjacently (Expedition 323 Scientists, 2011a). Located close to today's winter sea-ice edge, Site U1344A provides an opportunity to evaluate productivity in the “green belt” region since the early Pleistocene. Multiproxy records published from neighbouring Site U1343E, have revealed that sea ice extended past the site after ca. 0.9 Ma (323, 2009; Asahi et al., 2014; Teraishi et al., 2016), coinciding with the Middle Pleistocene Transition (MPT), when glacial/interglacial cycles switched from 40-kyr to 100-kyr frequency in the absence of marked changes in orbital forcing (Imbrie et al., 1993; Laskar et al., 2004; Pisias and Moore, 1981; Shackleton and Opdyke, 1977).

Several theories or driving mechanisms have been proposed for the MPT, as well as multiple feedback mechanisms that may have tipped

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the climate threshold to the asymmetrical sawtooth glacial-interglacial pattern held for the last 800 kyr. These can be summarized as: 1). a threshold response to a $p$CO$_2$-driven decrease in atmospheric temperature that led to gradual global cooling (Berger and Jansen, 1994; Raymo et al., 1996); 2). the regolith hypothesis, whereby progressive glacial erosion of bedrock allowed the buildup of larger ice sheets (Clark and Pollard, 1998), that in turn produced more unstable ice sheets and more abrupt terminations that characterise the last 600 kyr (Clark et al., 2006); 3). long-term deep ocean cooling as the driver of global temperature decline preceding the buildup of ice sheets (Bintanja et al., 2005), and 4). Antarctic abrupt ice volume growth at 900 kyr (MIS 24) caused by continued ice sheet growth during cold interglacial (MIS 23) and low insolation (Elderfield et al., 2012; Pollard and DeConto, 2009). Several authors have suggested that the MPT is the response to an earlier gradual strengthening of zonal and meridional circulation at ca. 1.8–2.1 Ma (Etourneau et al., 2010), through the cooling and expansion of polar water masses (Lawrence et al., 2010; Martinez-Garcia et al., 2010; McClymont et al., 2008; Rodríguez-Sanz et al., 2012), cooling in upwelling systems (Dekens et al., 2007; Dyez and Ravelo, 2014; Etourneau et al., 2009; Lawrence et al., 2006; Marlow et al., 2000), and/or evolving Asian monsoon strength (Heslop et al., 2002; Sun et al., 2006).

Here we present a continuous 1.93-Myr fossil diatom record from Site U1344A in the north eastern Bering Sea. Together with existing diatom data from nearby IODP Site U1343E, we develop on the possible scenarios of sea-ice evolution during this timeframe, in particular, the response during the MPT climate transition. On a broader scale, these sea-ice archives are compared to proxy sea surface temperature records in the Pacific and their relationship is discussed.

## 2. Oceanic setting and Pacific teleconnections

The Bering Sea (BS) is characterised by a shallow shelf edge (< 200 m) that extends along the Alaskan margin from north to south, covering close to half of the region (Fig. 1). The BS is semi-isolated from the North Pacific by the Aleutian Islands, where shallow passes allow the northward inflow of relatively warm, nutrient-rich Alaskan Stream (AS) waters. The shallow (< 80 m) and narrow (30 m) Unimak Pass on the far eastern side of the Aleutian Islands, provides the conduit for AS waters that enter over the shallow Bering Sea shelf. The bulk of AS waters enter through the deeper Amukta and Amchitka Passes in the central region of the Aleutian chain, at an estimated ~3 × 10$^6$ m$^3$/s, and form the eastward flowing Aleutian North Slope Current (ANSC) (Stabeno et al., 1999). In turn the ANSC feeds the northward flowing Bering Slope Current (BSC) that follows the bathymetry of the shelf break (Ladd, 2014; Stabeno et al., 1999). The BSC varies greatly, from a wintertime regular flowing current with speeds of up to 14 cm s$^{-1}$, to an ill-defined summer flow with eddies and meanders of < 1.5 cm s$^{-1}$ (Ladd, 2014). Eddies exhibit scales of 10–100 km horizontally (Stabeno et al., 1999), and > 1000 m vertically (Roden, 1995), and propagate during spring and summer under enhanced baroclinic instability (Mizobata et al., 2008).

The Bering Sea shelf water flows in a northward direction towards the Bering Strait, a narrow channel (50 m deep and 85 km wide), that provides 10–20% of oceanic heat and 1/3 of all freshwater to the Arctic (Serreze et al., 2006; Woodgate et al., 2010). However the amount exiting through the Bering Strait is minimal, at ~0.8 × 10$^6$ m$^3$/s and is caused by a pressure head difference of 0.4 m between the fresher, warmer, BS waters and comparatively cooler and more saline Arctic Sea (Coachman, 1993; Woodgate et al., 2005). Recent measurements have shown a doubling in the Strait's throughflow between 2001 and 11 in conjunction with weakened wind forcing, and the impact has been a substantial retreat in Arctic sea ice (Woodgate et al., 2012).

Recent studies have shown that the BSC current transport is significantly correlated with AS and Kamchatka Current transport (Panteleev et al., 2012), and in general, the BS ocean-atmosphere teleconnections are most evident in winter (e.g. Niebauer, 1988; Rodionov et al., 2007). Winter atmospheric circulation is mainly driven by the position, frequency and intensity of Aleutian lows, which in turn responds to global scale and Pacific-wide variations (Ladd, 2014; Niebauer, 1998). During El Niño events, the Aleutian low deepens and moves southeastward, warming the Bering Sea by advecting warmer North Pacific air. During La Niña phases, the Bering Sea is cooled by less intense Aleutian lows that move westward, allowing storms to track into the Bering Sea (Niebauer, 1988; Rodionov et al., 2007). Ladd (2014) found that winter BSC speeds were positively correlated to El Niño years, particularly between the Pribilof and Zhemchug Canyons. ENSO also plays a major role in the intensity of EASM/EAWM through several mechanisms, but principally through strengthening/weakening of Walker Circulation (WC). El Niño (La Niña) weakens (strengthens) the zonal pressure gradient of the WC, shifting the western Pacific Warm Pool eastwards (westwards) that in turn causes increased

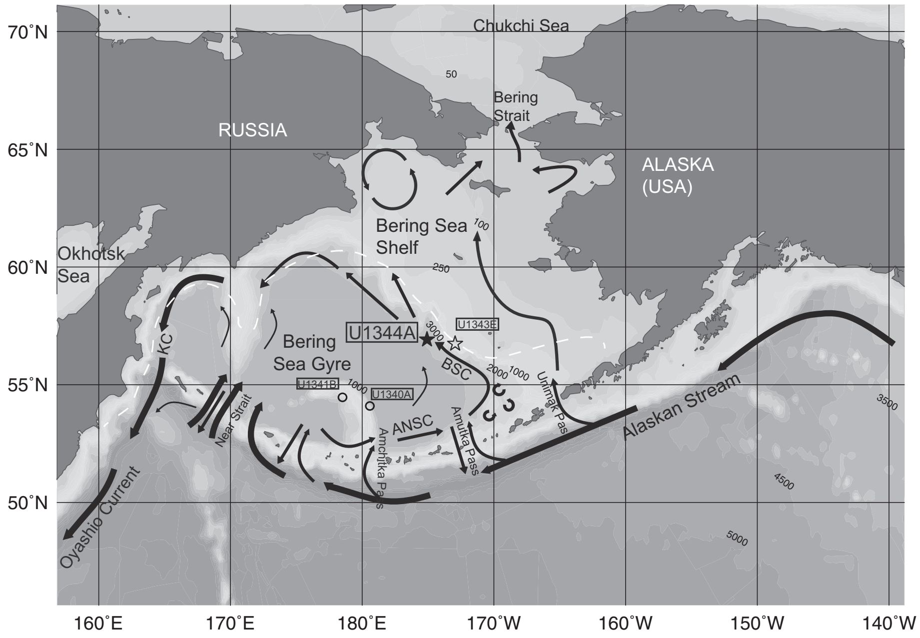

**Fig. 1.** Map of the North Pacific and Bering Sea with core locations IODP 323 sites U1340A and U1341B marked as empty circles. Study Site U1344A denoted with black star and U1343E with empty star. Generalised ocean circulation is shown detailing sea-surface currents (modified from Stabeno et al., 1999). Map generated on Ocean Data View: odv.awi.de.