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A two-millennium dinoflagellate cyst record from Gullmar Fjord, a Swedish Skagerrak sill fjord

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ABSTRACT

Gullmar Fjord, a sill fjord on the Skagerrak coast of western Sweden, contains a valuable sedimentary archive for the last 2500 years. This archive encompasses a temporal record from the Roman Warm Period, the Dark Ages, the Medieval Warm Period, the Little Ice Age and into the modern warm period. A high resolution dinoflagellate cyst analysis has been completed on this archive using material from two cores taken from the deepest part of the fjord, Alsbäck Deep. The recovered dinoflagellate cysts have provided a quantitative temporal record that has been used to construct a dinoflagellate cyst spectrum and has been subjected to both Q-mode cluster analysis and CABFAC factor analysis with varimax rotation. In addition the heterotrophic ratio and both the thermophilic and cryophilic ratios have been calculated to assist with the interpretation of the results. Well preserved and diverse dinoflagellate cyst assemblages have been recovered throughout the sedimentary sequence and have been used to explore surface water conditions within the fjord over this time interval. Although a clear link is observed between the cyst assemblages and the climate phases of the Subatlantic, established from previous stable isotope work, there was little change in the cyst populations and indeed they reflect the known modern cyst floras. However a major change was seen in the incoming of *Gymnodinium nolleri* during the Dark Age and its reduction to a relict species towards the end of the Little Ice Age. Comparisons to other published work confirm the regional nature of this dinoflagellate cyst event but its ecological preferences remain enigmatic. A second major change was also recognised around the late 1960s/early 1970s and was associated with differences in nutrient availability from either a diminution in upwelling, as the NAO changed from a negative phase to a positive, or from marine pollution or a combination of both. Otherwise the dinoflagellate cyst assemblages can be grouped, using the factor analysis, into F1 *Protoperidinium* spp. indet. (round, brown cysts); F2 *G. nolleri* and F3 *Lingulodinium polyedrum* and *Protoceratium reticulatum*. The cluster analysis shows a similar subdivision into units closely associated with the recognised climate phases of the Subatlantic. Possible climate environments have been explored, but because of the relatively minor variations in the assemblages and the lack of autecological information, only relatively small scale changes were recognised except for the clear, but complex nature of the recent warm period.

1. Introduction

The Holocene, as presently defined, is the second epoch of the Quaternary Period, notwithstanding the introduction of the Anthropocene (Zalasiewicz et al., 2010, 2011). It is the most recent interval of geological time and the present-day interglacial. The base of the Holocene has proved difficult to define, in traditional depositional sequences, based upon evidence for contrasting climatic conditions. Walker et al. (2009) proposed that the base be defined on the basis of the NGRIP ice core reflecting the first signs of climate warming at the end of the Younger Dryas/Greenland Stadial 1 cold phase. This boundary was placed at 11,700 ± 99 yr b2K (before AD 2000).

Various attempts have been made to sub-divide the Holocene following the use of the Blytt–Sernander pollen climatostratigraphy (Sernander, 1908). Although with its limitations, such as the proven diachroneity of pollen zones (Smith and Pilcher, 1973), its conceptual framework was eventually redefined to provide a chronostratigraphical scheme constrained by radiocarbon ages (Mangerud et al., 1974). The presence of climatic fluctuations within the Holocene provides a link between changes occurring on a millennial timescale to those that are much shorter i.e. representing centennial or decadal variations. Within the Subatlantic, the last 2500 yr BP, the recognition of several climatic phases such as the Roman Warm Period (RWP), the Dark Ages (DA), the Medieval Warm Period (MWP) and the Little Ice Age (LIA) (Lamb, 1995) has proved to be important. These climatic phases are key to the study of the various forcing factors affecting climate at a time when summer solar insolation was and is declining (Wanner et al., 2011), resulting largely from changes within the precession of the equinoxes. Among other driving forces involved are changes in solar activity

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(Mauquoy et al., 2002), volcanism (Sicre et al., 2011; Miller et al., 2012), the state of the North Atlantic Oscillation (Trouet et al., 2009; Olsen et al., 2012) and changes in the Gulf Stream (Lund et al., 2006). In addition, changes in the Atlantic Meridional Overturning Circulation (AMOC) are implicated with significant climate impacts throughout the Holocene (Hoogakker et al., 2011). This climatic variability within the Subatlantic and its phases is suggested to have rather weak amplitude, estimated at ca. 2 °C for sea surface temperatures (Bond et al., 1997).

In order to understand the present day climate, and the controls that force change, it is necessary to detail the recent past. The study of the Holocene is paramount in this respect. This is especially true given the concerns about the present climate change, global warming and the marked increase of atmospheric carbon dioxide since the start of global industrialisation. Carbon dioxide levels in the atmosphere breached 400 ppm in 2013, http://www.esrl.noaa.gov/gmd/index.html, in sharp contrast to the pre-industrial level of 280 ppm. There is increasing evidence that already there have been regime shift changes within the North Atlantic circulation in the 1920s and 1930s (Drinkwater, 2006) and more recently in the 1980s (Beaugrand et al., 2002) and further changes are feared (Reid and Valdés, 2011).

Gullmar Fjord on the west coast of Sweden provides an ultra-high resolution archive of sediment encompassing the Subatlantic phase of the Holocene including the RWP, the MWP and the LIA together with a record of modern warming. It is one of the most studied marine areas in the world with the first hydrographical measurements being taken as early as 1869. It is also the site of one of the world's oldest marine research stations founded by the Royal Swedish Academy of Sciences in 1877. In particular Gullmar Fjord is a sill fjord (Fig. 1A, B) and as such is a site of net sediment accumulation. Negligible tidal activity and high sedimentation rates of 0.7–1.4 cm a^{-1} (Filipsson and Nordberg, 2004) result in Gullmar Fjord becoming a high resolution environmental archive (Howe et al., 2010a). In addition, the hydrography of the fjord, the stratified water column (Fig. 1C) and the long residence time of the deep water together with high oxygen consumption from the decay of organic material results in severe hypoxia. In turn this affects the benthic communities and increases the likelihood of nil or low activity within the bottom macrobenthos leading to a concomitant lack of bioturbation. These fine-grained sediments deposited in low oxygen environments, often undisturbed by bioturbation and deposited in high accumulation environments, are ideal for the preservation of a high-resolution dinoflagellate cyst temporal record.

Finally Gullmar Fjord is ideally placed within the Skagerrak/Kattegat to reflect changes in the North Sea and further connections to the North Atlantic, and particularly to monitor changes in the geographical ranges of temperate dinoflagellate cysts and the input of cysts more usually found in the sub-arctic/arctic regions. Hence the provision of a high-resolution temporal record over the last two millennia, at a time when a number of climate phases are known but not well understood, can only enhance the understanding of this time interval. In this paper we provide new data on the recovered dinoflagellate cyst record in order to detail changes within the surface waters of the fjord. This is part of a larger study that encompasses sedimentology, bulk sediment geochemistry and stable isotope analysis (Filipsson and Nordberg, 2010) together with benthic foraminiferal stratigraphy (Filipsson and Nordberg, 2004; Polovodova et al., 2011; Polovodova Asteman et al., 2013) and dinoflagellate cysts (Harland et al., 2006).

2. Materials and methods

This study is based on two sediment cores: GA113-2Aa and 9004, which were both collected at 116 m water depth in the deepest basin

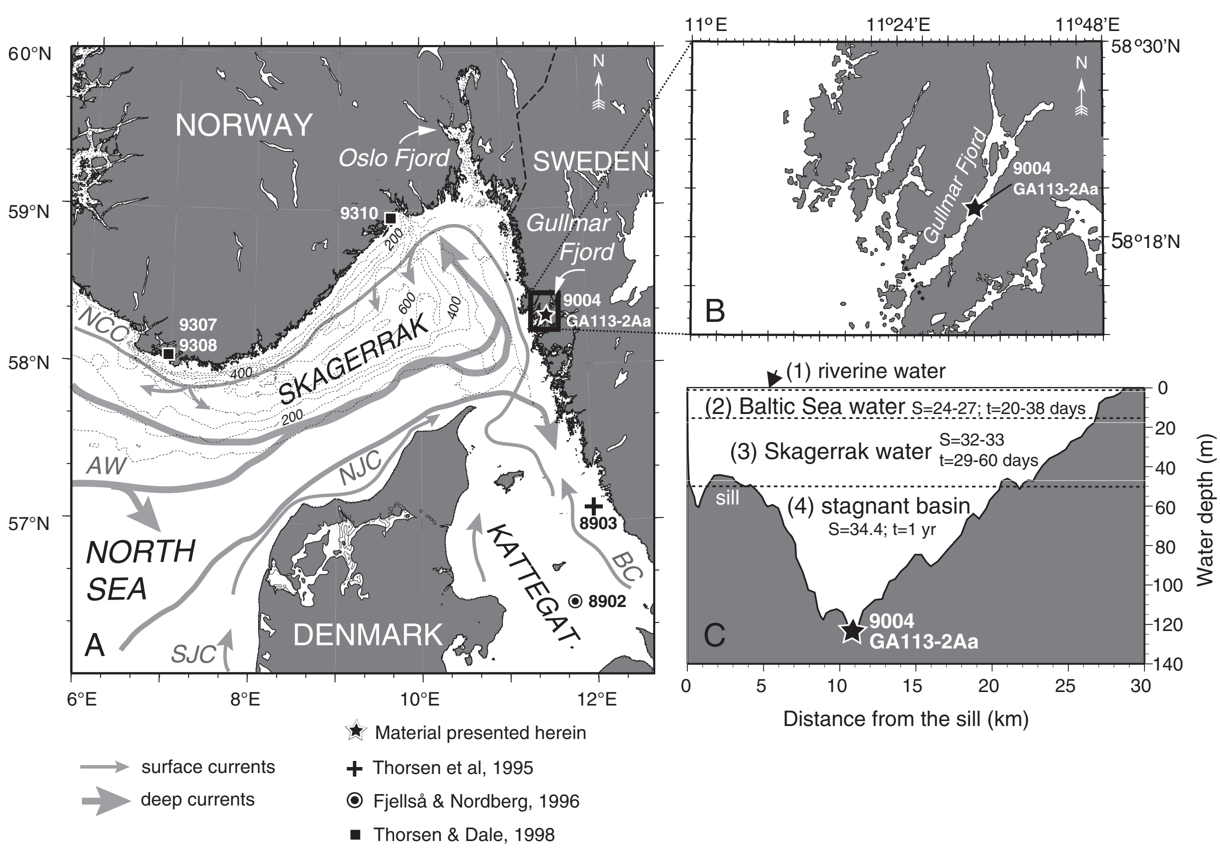

Fig. 1. Location of the Gullmar Fjord within the Skagerrak (A) and at the Swedish west coast (B) and stratification of the fjord's water masses with salinity ranges (s) and residence times (t) following Arneborg, (2004) (C). Star indicates a sampling site for cores GA113-2Aa and 9004; dashed line in the outer part of the Gullmar Fjord shows location of a sill at 42 m water depth; whereas abbreviations AW, SJC, NJC, NCC and BC stand for Atlantic Water, South Jutland Current, North Jutland Current, Norwegian Coastal Current and Baltic Current, correspondingly.