Introduction

The North Sea Basin (NSB) has been suggested as a potential site for CO_2 storage (Element Energy 2010; EU 2009; 2011), due to its favourable geological setting, its proximity to sources, and pioneering operational experience storing CO_2 at the Sleipner injection site (Halland *et al.*, 2011, Arts *et al.* 2008). The shallow Neogene and Quaternary sediments of the NSB form the overburden and seal to these underlying CO_2 reservoirs but are under-researched, even though the NSB is a mature petroleum system, penetrated by hundreds of wells. The up-to 1000 metre-thick Quaternary sediments are in general bypassed to reach the profitable hydrocarbon resources located deeper in the succession.

Over the last 2.6 Ma the NSB has been subject to repeated cycles of glaciation and deglaciation (Gibbard et al. 2010). These Quaternary sediments have typically experienced rapid ice loading and unloading affecting the mechanical properties of the strata, fluid conductivity, and the effects of glacial erosion and deposition (e.g. incision by sub-glacial tunnel valleys). It is necessary to understand sedimentary architecture, compaction, cementation, and the role of connate fluids and microbial processes for CO_2 site characterisation. This increases confidence in secure containment of injected fluids.

The GlaciStore consortium was formed with the purpose of submitting a proposal to the International Ocean Discovery Program (IODP), for a drilling campaign addressing the following questions:

- Explore Earth's climate history over the last 2.6 Ma in an area where the most complete sequence is preserved.
- Better understand the geometry, dynamics, processes and wider impact of ice sheet development in the NSB.
- Understand fluid flow and its evolution (dissolved gases, salts and isotopes) during a period of fluctuating pressure conditions in shale-dominated basins and its implications for CO_2 storage.
- Understand the impact on the geomechanical properties of containment barriers (<1000 metres below sea floor (mbsf)) caused by cycles of glacial loading and unloading.
- Explore variations in microbial community within these shallow sedimentary sequences.

The Consortium comprises scientific, governmental and industrial partners from both UK and Norway. In this paper we will describe the detailed analysis and selection process forming the basis for drill site selections.

Data

Large seismic databases, predominantly from industrial sources, have allowed overarching basin infill, architecture, source areas and the environmental and glacial history of the NSB to be studied. Data available to the consortium included a number of shallow (maximum 220 metres deep) scientific boreholes (81/26, 77/02, and B2001) used for stratigraphic tie, TGS' North Sea Renaissance (NSR) seismic 2D lines that extend over most of the study area, regional merged 3D volumes (PGS Megamerge), and localised 3D seismic datasets. A lack of a robust chronology for the Quaternary section for the NSB, combined with sparse sedimentological data required the construction of a seismostratigraphic framework. Cores from the shallow wells, located in the rim of the NSB, representing dates back to Early Pleistocene, provided the chrono-stratigraphic framework for the core-to-seismic correlation. The regional seismostratigraphic interpretation also included the previously mentioned seismic data (Figure 1; Baig *et al.*, in prep, Hjelstuen *et al.*, in prep, Lamb *et al.* in prep). A number of seismic tie lines, traversing the NSB from west to east, were identified to facilitate correlation between the UK and Norwegian sectors (Figure 2).

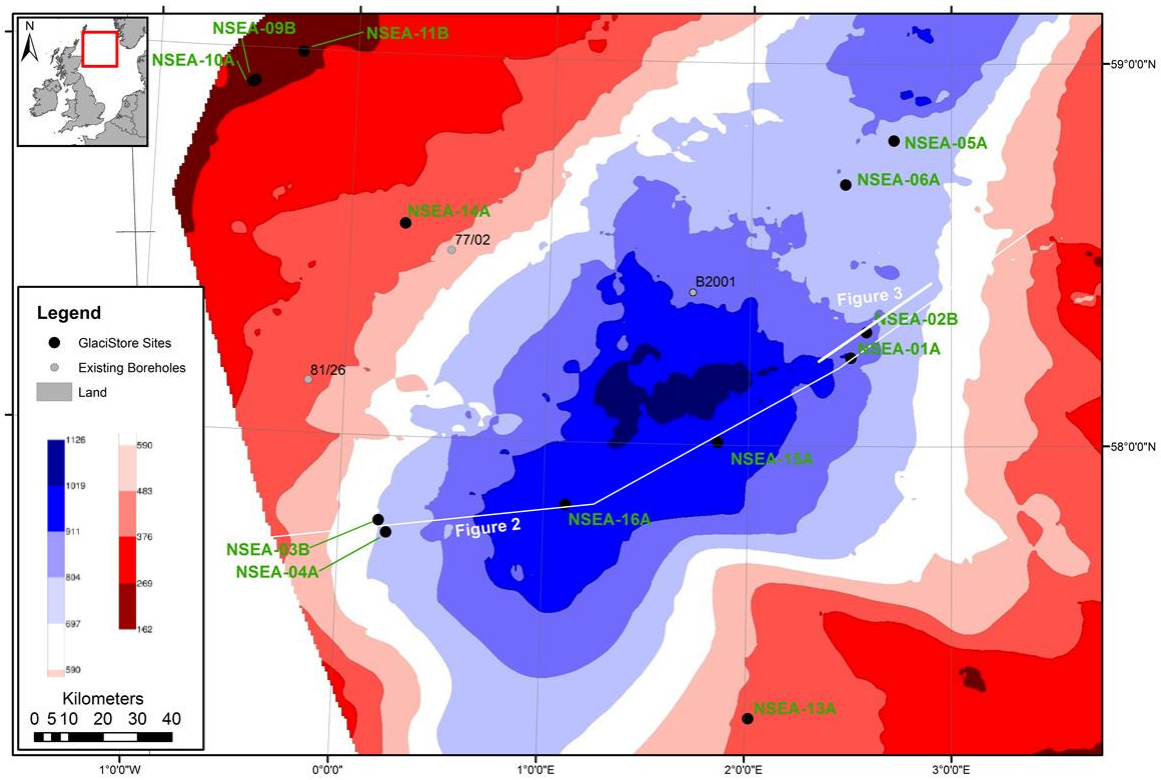

Figure 1 *Location map showing the proposed IODP drill sites, selected existing scientific boreholes and depth in Two Way Travel Time (ms) to the base Quaternary derived from seismostratigraphic interpretations (courtesy of University of Oslo and the Norwegian Petroleum Directorate).*

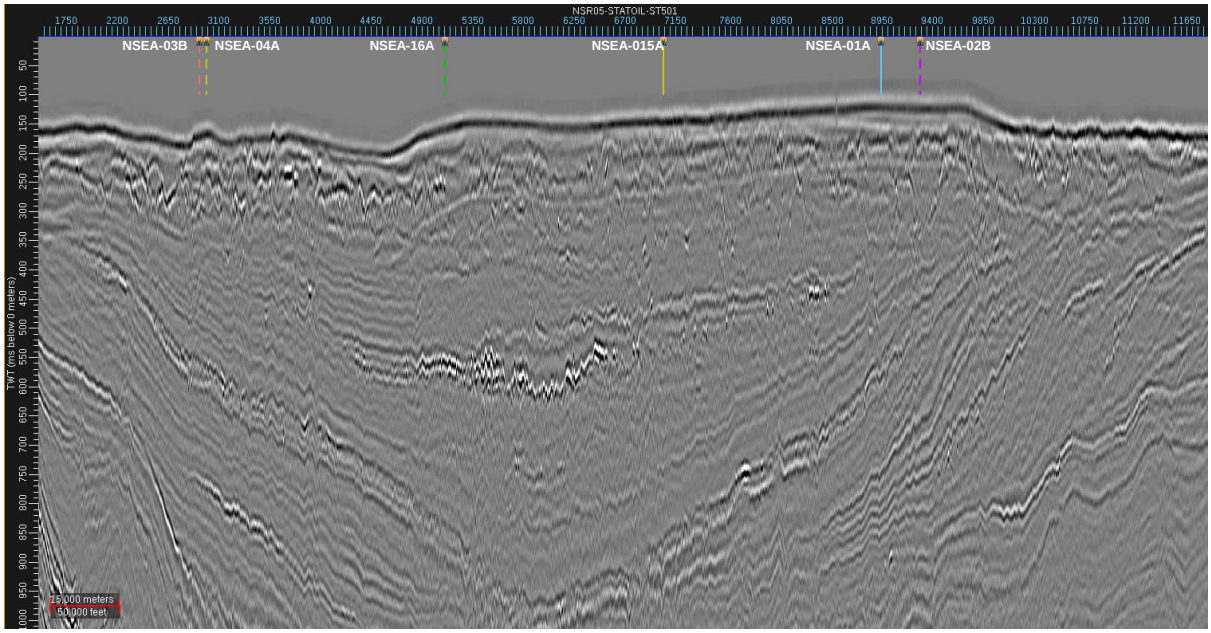

Figure 2 *Projections of indicated drill site locations on to the NSR tie line.*

Drill site selection

The criteria for drill site selection were based on the current understanding of the Quaternary stratigraphy and architecture as interpreted as part of the research of the GlaciStore consortium and addressed the objectives described in the *Introduction*. In addition, each drill site needed to pass a safety assessment. As the NSB is an active petroleum system, it was important to identify risks related *e.g.* to shallow gas. Most seismic data acquired in the area are focused on deeper targets and seismic resolution was consequently a challenge when performing shallow seismic interpretation.

Four primary drill sites were identified with nine back-up sites also presented. Two of the sites will be drilled to 800 mbsf in order to sample as complete a sedimentary record as possible; one will provide the most complete stratigraphy for the main depocentre of the central NSB, the other will test the oldest prograding unit from the east. The other two primary sites will focus on drilling sub-glacial tunnel valleys: the first will target the fill of a tunnel valley, a significant Quaternary unconformity, and three important glacial units; the second will target a sequence of intersecting, stacked, glacial channels. Such glacial channels and valley complexes exist all of over the study area and are important to understand, both with respect to glacial history, potential fluid flow pathways, and for optimising drilling targets. The contingency sites are targeted to achieve similar objectives and are included in the IODP proposal should the primary sites be compromised or a "composite hole" need to be constructed from a number of boreholes.

Example Site

Proposed site NSEA-02B (Figure 3) is located within Norwegian territorial waters around 175 kilometres west of Norway. The site targets in its deepest part a prograding unit which is predicted to comprise some of the earliest Quaternary deposits in the region, crucial to understanding the onset of cooler and glacial conditions in the region. The proposed dating work within the borehole sediments also aims to provide a more robust chronological framework for the Quaternary succession which is currently poorly understood. In the shallower section, the site will also penetrate a relatively shallow tunnel valley and core material will be used to investigate its infill; although dense networks of tunnel valleys are ubiquitous in the area, their fill remains largely unsampled. A good understanding of the tunnel valleys and the sediments within is key to the evaluation of migration pathways for CO2 storage sites, and to further understand the glacial history of the region. This presentation will examine the site in detail with an emphasis on the scientific objectives it will achieve.

Conclusion

Prospective CO_2 storage sites are located across all national sectors of the North Sea and form the great majority of potential CO_2 storage resource for industrial Europe (Element Energy 2010). Two storage sites are currently in operation in the NSB and a further three are planned. This study and subsequent investigation of these sediments through drilling by the IODP will thus benefit the main candidate CO_2 storage region for all of Europe. Deposition and diagenesis of the shallow Quaternary stratigraphy of the NSB was dominated by dynamic glacial processes and can only be understood once the nature and impact of the alternating glacial and inter-glacial episodes on the properties of the underlying strata and their component fluids are appreciated. The NSB preserves a unique record of glacial erosion and deposition from the Fennoscandian and British Ice Sheets, as well as sediment input from the large European river systems, and offers a unique possibility to study the onset, impact and temporal variability of Northern Hemisphere glaciations in detail.

Acknowledgments

The GlaciStore consortium consists of the British Geological Survey, CLIMIT, IFE, Lundin Petroleum, SINTEF Petroleum Research, Statoil ASA, University of Bergen, University of Edinburgh, University of Oslo, and UKCCSRC, which are all acknowledged for fruitful discussions throughout the submittal process and for their financial support. Statoil ASA is acknowledged for providing seismic data near location NSEA-02B. Rachel Lamb from the University of Edinburgh/BGS constructed the seismostratigraphic interpretation of the Quaternary for the UK sector, whereas Irfan Baig (UiO), Jan Inge Faleide (UiO), Hans Petter Sejrup (UiB), and Berit Hjelstuen (UiB) constructed the seismostratigraphic interpretation for the Norwegian sector.

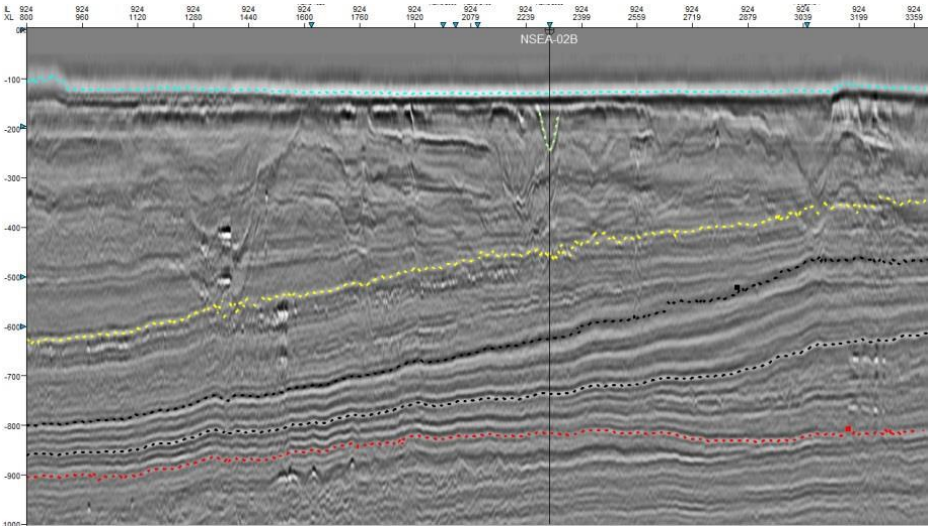

Figure 3 *Seismic example showing the location of proposed site NSEA-02B. Green shows the base of a tunnel valley, yellow the top of a prograding unit with black delineating other regionally identifiable units, red indicates the base Quaternary.*

References

Arts, R., Chadwick, A., Eiken, O., Thibeau, S., Nooner, S. [2008] Ten years' experience of monitoring CO_2 injection in the Utsira Sand at Sleipner, offshore Norway. First Break, **26,** 91-96.

Element Energy [2010] One North Sea, a study into North Sea cross-border CO_2 transport and storage. www.regjeringen.no/globalassets/upload/oed/onenortsea_fulldoc.pdf

EU [2009] The geological storage of carbon dioxide Directive 2009/31/EC. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

EU [2011] Implementation of Directive 2009/31/EC on the geological storage of carbon dioxide – Guidance document 2 – Characterization of the storage complex, CO_2 stream composition, monitoring and corrective measures.
http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd2_en.pdf

Gibbard, P.L., Head, M.J., Walker, M.J.C. [2010] Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. *Journal of Quaternary Science* **25**(2), 96-102.

Halland, E., Johansen, W. T., Riis, F. [2011] NPD CO_2 Storage Atlas Norwegian North Sea. Norwegian Petroleum Directorate. http://www.npd.no/global/norsk/3-publikasjoner/rapporter/pdf/co2-atlas-lav.pdf