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The European Plate Observing System and the Arctic

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ABSTRACT. The European Plate Observing System (EPOS) aims to integrate existing infrastructures in the solid earth sciences into a single infrastructure, enabling earth scientists across Europe to combine, model, and interpret multidisciplinary datasets at different time and length scales. In particular, a primary objective is to integrate existing research infrastructures within the fields of seismology, geodesy, geophysics, geology, rock physics, and volcanology at a pan-European level. The added value of such integration is not visible through individual analyses of data from each research infrastructure; it needs to be understood in a long-term perspective that includes the time when changes implied by current scientific research results are fully realized and their societal impacts have become clear. EPOS is now entering its implementation phase following a four-year preparatory phase during which 18 member countries in Europe contributed more than 250 research infrastructures to the building of this pan-European vision. The Arctic covers a significant portion of the European Plate and therefore plays an important part in research on the solid earth in Europe. However, the work environment in the Arctic is challenging. First, most of the European Plate boundary in the Arctic is offshore, and hence, sub-sea networks must be built for solid earth observation. Second, ice covers the Arctic Ocean where the European Plate boundary crosses through the Gakkel Ridge, so innovative technologies are needed to monitor solid earth deformation. Therefore, research collaboration with other disciplines such as physical oceanography, marine acoustics, and geo-biology is necessary. The establishment of efficient research infrastructures suitable for these challenging conditions is essential both to reduce costs and to stimulate multidisciplinary research.

Key words: solid earth; Arctic; EPOS; research infrastructure; seismology; tectonics

RÉSUMÉ. Le système European Plate Observing System (EPOS) vise l'intégration des infrastructures actuelles en sciences de la croûte terrestre afin de ne former qu'une seule infrastructure pour que les spécialistes des sciences de la Terre des quatre coins de l'Europe puissent combiner, modéliser et interpréter des ensembles de données multidisciplinaires moyennant diverses échelles de temps et de longueur. Un des principaux objectifs consiste plus particulièrement à intégrer les infrastructures de recherche existantes se rapportant aux domaines de la sismologie, de la géodésie, de la géophysique, de la géologie, de la physique des roches et de la volcanologie à l'échelle paneuropéenne. La valeur ajoutée de cette intégration n'est pas visible au moyen des analyses individuelles des données émanant de chaque infrastructure de recherche. Elle doit plutôt être considérée à la lumière d'une perspective à long terme, lorsque les changements qu'impliquent les résultats de recherche scientifique actuels auront été entièrement réalisés et que les incidences sur la société seront claires. Le système EPOS est en train d'amorcer sa phase de mise en œuvre. Cette phase succède à la phase préparatoire de quatre ans pendant laquelle 18 pays membres de l'Europe ont soumis plus de 250 infrastructures de recherche en vue de l'édification de cette vision paneuropéenne. L'Arctique couvre une grande partie de la plaque européenne et par conséquent, il joue un rôle important dans les travaux de recherche portant sur la croûte terrestre en Europe. Cependant, le milieu de travail de l'Arctique n'est pas sans défis. Premièrement, la majorité de la limite de la plaque européenne se trouvant dans l'Arctique est située au large, ce qui signifie que des réseaux marins doivent être aménagés pour permettre l'observation de la croûte terrestre. Deuxièmement, de la glace recouvre l'océan Arctique, là où la limite de la plaque européenne traverse la dorsale de Gakkel, ce qui signifie qu'il faut recourir à des technologies innovatrices pour surveiller la déformation de la croûte terrestre. C'est pourquoi les travaux de recherche doivent nécessairement se faire en collaboration avec d'autres disciplines comme l'océanographie physique, l'acoustique marine et la

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géobiologie. L'établissement d'infrastructures de recherche efficaces capables de faire face à ces conditions rigoureuses s'avère essentiel, tant pour réduire les coûts que pour stimuler la recherche multidisciplinaire.

Mots clés : croûte terrestre; Arctique; EPOS; infrastructure de recherche; sismologie; tectonique

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INTRODUCTION

European earth scientists have played a major role in the study of plate tectonics during the past 50 years, opening new horizons within the fields of plate dynamics and deformation processes at many scales. European research infrastructures (RI) have gathered vast amounts of geological and geophysical data, largely on national scales. These data have led to an improved understanding of natural hazards (e.g., earthquakes, volcanic eruptions, landslides, and tsunamis) and reduced their negative impact on society. The Arctic covers a significant portion of the European Plate and hence plays an important role in solid earth research in Europe.

The European Plate Observing System (EPOS, www.epos-eu.org/) is a pan-European initiative (European Strategy Forum on Research Infrastructures [ESFRI] Roadmap project) that aims to integrate the European Research Infrastructures for solid earth science through a multidisciplinary approach. Integrating infrastructures that capture deformation at various spatial and temporal scales is a key challenge for solid earth science. Integration of existing RIs within the fields of seismology, geodesy, geophysics, geology, rock physics, and volcanology at a pan-European level is one of the primary objectives of EPOS. The work environment in the Arctic is difficult, and data collection in the Arctic requires collaboration. EPOS provides a tool to streamline this collaboration.

The European Plate boundary in the Arctic (Fig. 1) is important not only to plate deformation and the associated earthquake hazard, but also to the natural resources in this region, especially hydrocarbons and minerals, both offshore and on land. The Arctic dimension is an area with significant geographical extent within the European Plate. It includes the plate boundary in the northern North Atlantic along Iceland and Jan Mayen, which has active volcanoes, and its continuation in the Arctic Sea, as well as the Barents Sea region, the Svalbard area, and the Norwegian continental shelf.

Arctic interests within EPOS are concerned with fundamental scientific issues related to geodynamic processes. Closely related to these are the natural hazards in the region and the exploration, exploitation, and management of natural resources, fields in which geodynamic processes play a significant role. In this context, the Nordic monitoring networks (e.g., seismological and geodetic stations; Fig. 2) have a significant geographical responsibility in the North Atlantic and the European Arctic and hence provide a substantial contribution to the main objectives of EPOS.

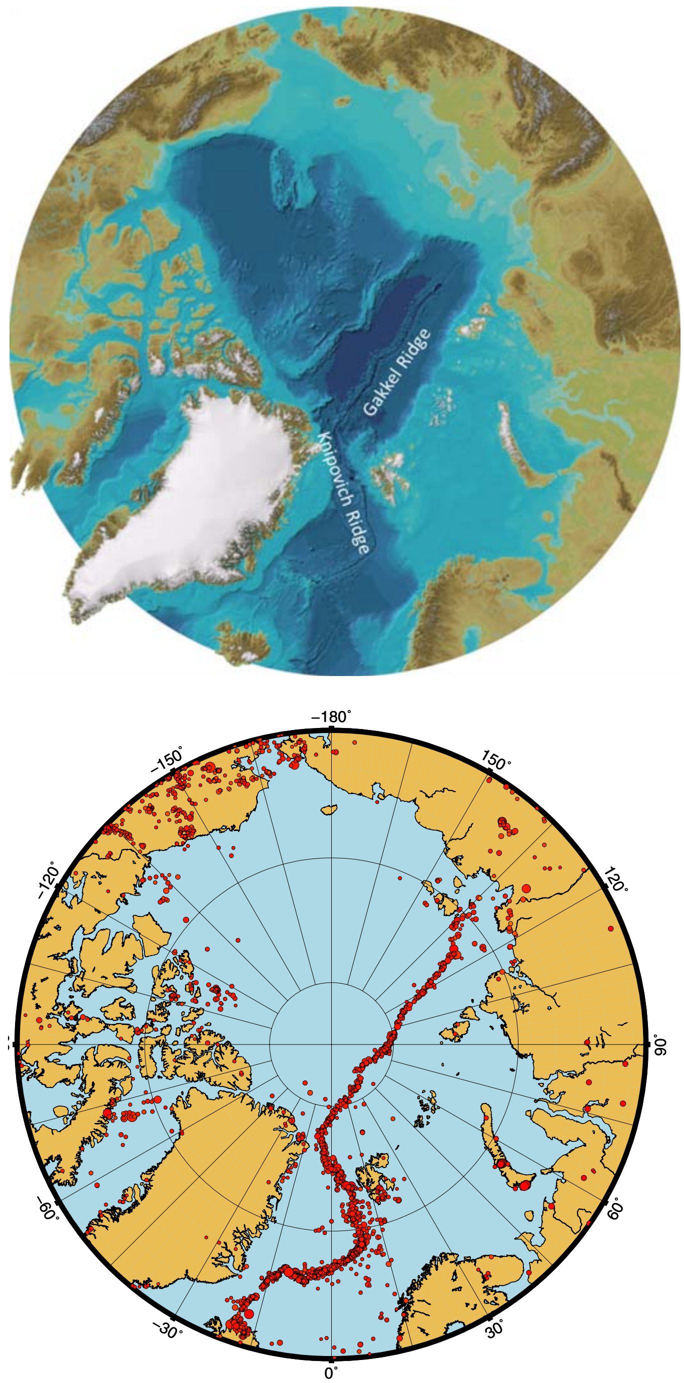

FIG. 1. Top: Bathymetric and topographic map of the Arctic (NOAA, 2013). Bottom: Seismicity of the Arctic with magnitude 4 or higher in the period 1900–2013 (data from USGS). The pronounced linear trend of the seismicity clearly indicates the European Plate boundary in the Arctic through the Knipovich Ridge west of Svalbard and the Gakkel Ridge in the Arctic Ocean. (Courtesy of Dr. M. Raeesi, 2013.)

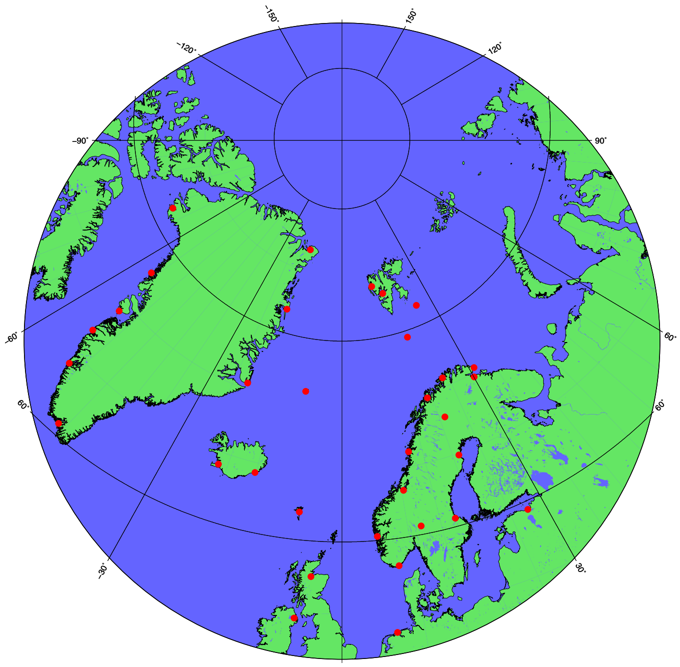

FIG. 2. Northern European GPS stations in the Arctic Testbed network.

RESEARCH NEEDS AND RELEVANCE

Scientific Questions

Understanding the dynamic and complex solid earth system requires a systematic approach to the deformation processes that takes into account both their causes and their consequences. The approach attempts first to understand the causes of lithospheric deformation, namely, the stress-generating mechanisms at different tectonic settings and scales, and then to understand the processes of stress build-up and release through phenomena at many physical and temporal scales. Final outcomes of these processes are the consequences such as earthquakes, volcanic eruptions, slope instabilities, and tsunamis. At the downstream end of the natural hazards and risks are the impacts on society of these consequences, which need to be understood, analyzed, and treated. The scientific questions are therefore structured according to four issues, namely, the *causes*, the *processes*, the *consequences*, and the *societal impacts* of deformations of the European Plate. Here we present some scientific questions that are not yet properly understood in the Arctic and northern European context.

The earth's crust is deforming as a result of different processes and on different time and spatial scales. The most prominent and easiest deformation to observe is the large-scale and long-term movement of the tectonic plates. Local deformation (such as along continental margins) is similarly interesting, but more challenging to observe. We can now measure deformation in terms of stress and strain accumulation before and after occurrence of earthquakes, as well as the co-seismic displacement itself, provided that the earthquake is large and shallow enough to be picked up in the seismic and GPS data (see Fig. 2). Different loads are also affecting the earth's crust. The viscoelastic response of the earth after the last ice age is well known, and it explains most of the large uplift we observe in Fennoscandia and North America today. Together with geological evidence, geodetic measurements of this uplift, absolute gravimetry included, have been the main data to constrain the viscoelastic parameters of the earth's mantle. Remaining differences between modeled and measured uplift can lead us to improved knowledge of the inertia of the earth.

The elastic response of the crust can also be measured on shorter time scales. Surface loads (such as water, ice, and atmosphere) and gravity loads (e.g., from the sun and the moon) deform the earth on time scales from hours to years. Precise measurements of these deformations constrain the earth's elastic part and are mandatory to separate the viscoelastic from the elastic response of the solid earth. The smaller scales, up to some tens of kilometres, are also important here, expressed, for example in terms of seismic and geodetic anomalies that result in the earthquake swarms experienced repeatedly in northern Norway.

Causes of Crustal Deformation of the Earth

The lithospheric stress-generating mechanisms are the key to our understanding of plate deformations. Their causes vary widely with scale (plate-wide, regional, or local); however, these causes (forces) are additive, and stress may also propagate efficiently over long distances, so at any particular location there will be multiple sources of stress to account for.

It is well established that post-glacial isostatic uplift may trigger seismic activity. Precise Global Positioning System (GPS) measurements provide information on the local deformations and may therefore be useful to determine the strain accumulation since the last glacial maximum. In addition, we observe a large loss of ice mass in many of the ice-covered areas in the world (e.g., Greenland, Svalbard, and other Arctic areas) due to current climate change. In this regard, the elastic response of the solid earth on melting of the ice sheets shows large temporal and spatial variations. Such variations of stress may be observed through dense GPS networks operating over longer time periods. In Scandinavia, rapid deglaciation occurred over the period 18 to 10 ka BP. The resulting isostatic rebound had led to significant earthquake activity in northern Scandinavia, including also large-scale submarine slope instabilities. Detailed studies of this specific episode may help in understanding the deformational processes associated with the current climate change and its long-term implications in the future.

One can take advantage of using geological, seismological, geodetic, and geo-technical methods simultaneously when mapping and measuring stresses in the lithosphere. In addition, different time scales need to be taken into account. The current level of precision in GPS measurements makes it possible now to quantify surface deformation in low-strain-rate crustal interiors as well, even if the permanent networks are still not dense enough to pick up deformations on shorter wavelengths.

One of the main challenges when measuring stress and interpreting its causes is that what we measure is strongly affected by structural (crustal) variations and inhomogeneities, again at many scales, so that it is difficult to identify or differentiate among the various contributing causes. What we see is therefore the result of a complexity of sources, propagation paths, and site conditions that all contribute at the same time. This situation clearly calls for advanced multidisciplinary tools (such as combined measurements of ground motions through broadband, high-resolution seismograph stations, satellite geodetic measurements including GPS, Interferometric Synthetic Aperture Radar, or InSAR, and gravity and magnetics) and competence within numerical modeling, keeping account of a range of both spatial and temporal scales, as well as sophisticated data acquisition and processing.

Processes Leading to Deformation of the Earth

The earth's deformation, caused by plate tectonic processes, is responsible for the varied topography on the earth, from deep ocean basins and trenches to various types of mountain chains. The formation of the topography is related to cooling and convection processes that take place deep into the earth's mantle, as well as to erosion and sedimentation on the earth's surface. For example, recent research has revealed that the mantle below southern Norway is unusually warm, but the possible relation between this temperature and the formation of the mountain chain is not well understood. Nor do we know whether the mantle below the northern part of the country is more "normal" or if the northern part of the Scandinavian mountains has the same origin as the southern part. It is likely that the mountain formation has a relation to the processes that formed the adjacent continental margin and the oil and gas-bearing basins that it contains. A detailed mapping of the crust/mantle structure is necessary to understand these issues better. The mapping of the crust and mantle offshore is of particular importance for understanding the relation of the present topography to the opening of the Atlantic Ocean and the formation of the continental margin, and it is also relevant to the other continental margins of the Arctic.

Geodetic data, as well as paleo-sea-level data, are useful in determining the glacial-isostatic adjustments (GIA) in Fennoscandia, even though it is still a major challenge to separate between tectonic and GIA processes and to determine which of these processes are the primary driving mechanisms for earthquakes. Together with a precise knowledge of ice evolution, geodetic data may also be used to investigate crustal and mantle structure of the earth. However, it is not yet possible to uniquely constrain the earth's viscosity structure. It can therefore be useful to combine seismology with GPS measurements to better understand land motion, ice evolution, and crustal and mantle structure in Fennoscandia and in the Arctic. Further constraints on crustal deformation are provided by strain maps (e.g., http://gsrm.unavco.org/intro/).

Consequences of Crustal Deformation of the Earth

Earthquakes are sometimes called "instant geology" because of their abrupt effects in the ground. While each larger earthquake can tell us a lot about driving mechanisms and forces, the collective ensemble of the earthquakes, accumulated over time, can reveal a lot more about the underlying causes and processes.

In seismically active areas, the history of earthquakes helps to reveal the potential for large earthquakes. However, for low-seismicity regions, where the time between large events may be tens of thousands of years, other approaches are needed. In northern Scandinavia, a series of post-glacial fault scarps, such as the Stuoragurra Fault in Norway (Olesen, 1988; Olesen et al., 1992) and the Landskjärv Fault in Sweden (Lagerbäck et al., 1990), showing evidence of large ($M > 7$) surface-rupturing earthquakes, were studied using paleoseismological methods. On mainland Norway, the largest observed historical earthquake (at Lurøy in 1819) had a magnitude of 5.8, whereas the largest offshore event, on the continental shelf southeast of Spitsbergen, had a magnitude of 6.1. The largest event recorded on the plate boundary along the Jan Mayen Fracture Zone occurred recently, on 30 August 2012, with a magnitude of 6.6. However, the geology could allow for an M7+ event. In this regard, combining data on past seismicity with crustal movement rates and geological and tectonic data will help to answer this question.

A geologic fault is classified as active if it has moved within the last 10 000 years. In slowly deforming areas, detecting the likely occurrence of large earthquakes requires integration of multidisciplinary data. So far, the large surface-rupturing post-glacial faults have been observed only in northern Scandinavia. It is unknown, however, to what extent similarly recent ruptures, only deeper and hidden, might have occurred elsewhere, including on the continental margin. Integrating available geological, seismological, GPS, and InSAR data would facilitate the detection of such faults, if they exist, and allow us to determine whether such structures are active today. It is important to realize that slow deformation processes in combination with short observation periods can lead to misinterpretation of deformation potentials, as low or no seismicity does not necessarily mean stability. This fact also reinforces the need for long and stable observation platforms.

In scientific studies of natural hazards and their consequences, the potential hazards to a region are often treated separately. However, one hazard can trigger another, thereby leading to cascading multiple events, which can have much more severe consequences than if the hazardous events would occur independently. Common examples are the triggering of landslides by severe precipitation or earthquakes, generation of tsunamis by earthquakes, landslides, or volcanic eruptions, and triggering of earthquakes by volcanic eruptions. Whereas it is well known that the different hazards are interconnected, there is still a lack of understanding of the details of some of these connections. For example, what are the requirements for an earthquake to trigger landslides or submarine slides? In what way are triggering and run-out of landslides related to the fault type and mechanical parameters of the soil? What are the mechanisms behind tectonic earthquakes triggered by volcanic activity? And how successful are we in simulating these hazards numerically? Merging the available data and competence on these topics within EPOS will bring us a step closer to answering these questions.

The plate boundary at the Mid-Atlantic Ridge is important for Norway because it hosts its only active volcano, the Beerenberg volcano on Jan Mayen. Mid-oceanic ridges are composed of spreading segments, offset by fracture zones with transcurrent motion, and Jan Mayen is located near such a fracture zone. EPOS will contribute to an improved understanding of mid-oceanic ridge processes through the integration of GPS, seismicity, InSAR, and geological data. The activity of the Beerenberg volcano is not well understood, despite its potential threat to the limited island population—as well as to European air traffic, as demonstrated in 2010 during the volcanic eruption of Eyjafjallajökull in Iceland. Improved monitoring will reveal new knowledge about magmatic processes leading to eruptions and their possible linkage to surface deformation and earthquake activity. All this information can be combined to deduce new information about the location and size of the magma chamber.

RESEARCH INFRASTRUCTURE

Long-term monitoring of earthquake activity, in conjunction with geological and other geophysical research, will form the basis for understanding the crustal deformation patterns offshore and onshore in the Arctic (Fig. 3), which in turn is important for understanding the development of petroleum resources and natural hazards in general. The earthquake hazard in the northern North Sea and along the continental margin farther north is high enough to be potentially damaging for critical constructions. The offshore industry realized this already in the early 1970s and consequently decided to help improve both earthquake monitoring and research. In addition, the ideas discussed above for a multidisciplinary use of seismological data under EPOS will significantly expand the potential usefulness of these data in the future.

The Norwegian National Seismic Network (NNSN) consists of 32 stations (Fig. 4). In addition, NNSN receives data from NORSAR, which operates three seismic arrays and one single seismic station with the purpose of nuclear test ban treaty monitoring through the Comprehensive Nuclear Test-Ban Treaty Organization. In the future, earthquake monitoring needs to continue without interruption and with an improved capacity through a denser network, reflecting both the scientific visions in this document and more practical purposes related to increased offshore investments and other industrial and societal activities.

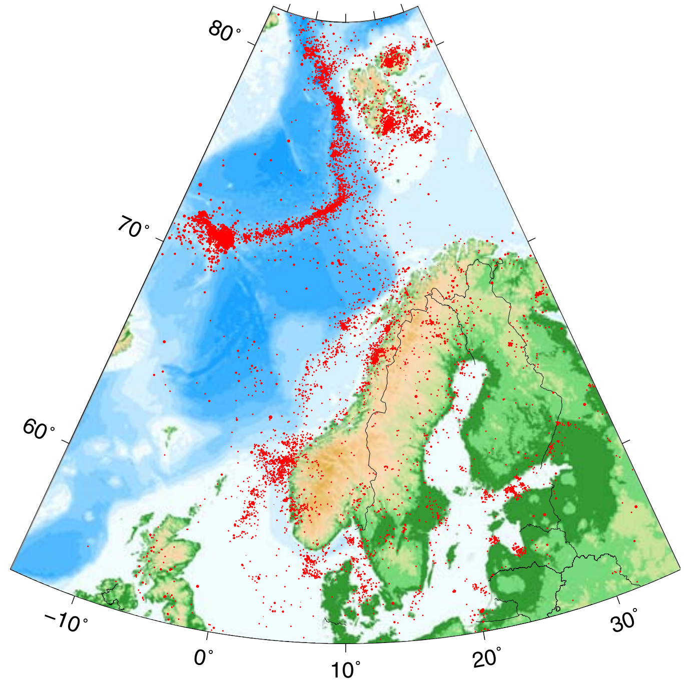

FIG. 3. The seismicity of Norway and adjacent areas for the period 1980–2010 (data largely from the Norwegian National Seismic Network (NNSN), which is operated by the Department of Earth Science, University of Bergen).

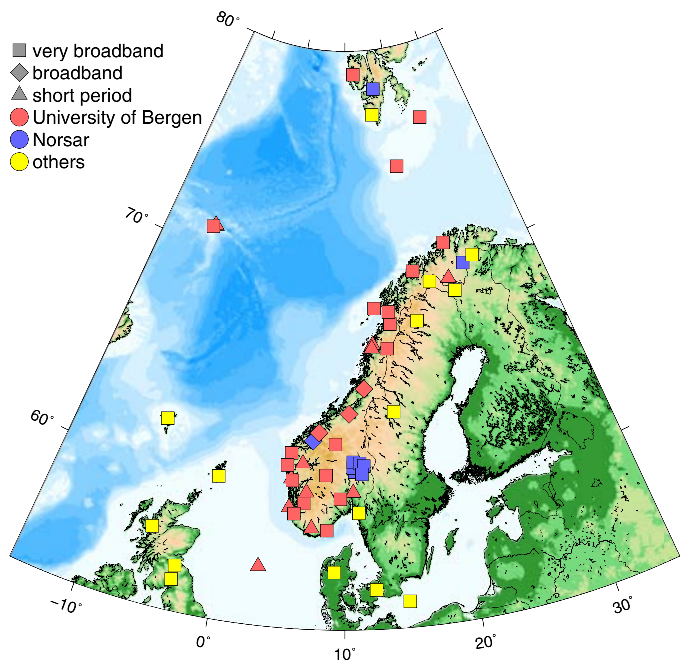

FIG. 4. NNSN stations operated by the University of Bergen are shown in red symbols. Also shown are stations from NORSAR arrays (blue symbols) and neighbouring countries (yellow symbols) that are used in the seismic data analyses.

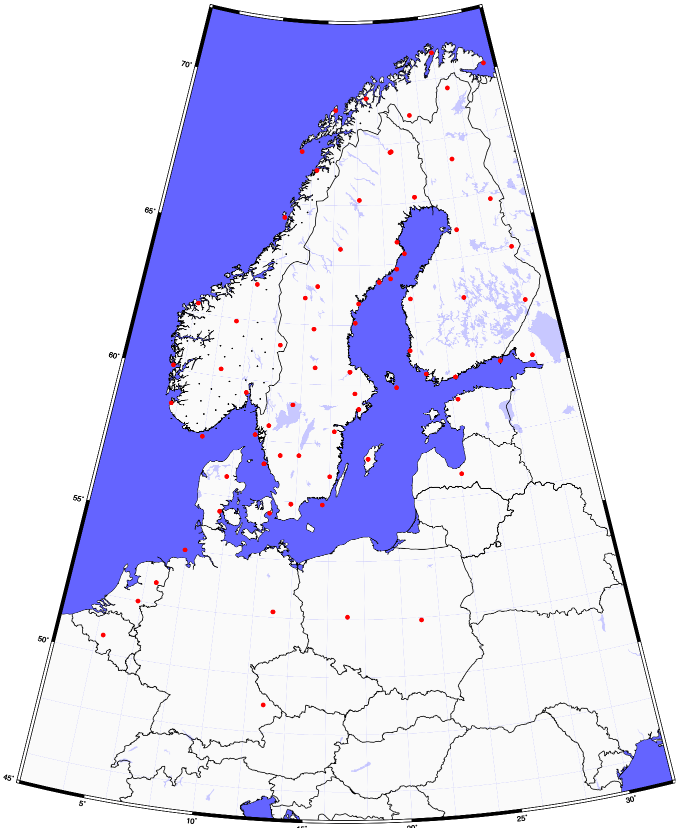

FIG. 5. Continuously recording GPS stations in Nordic and Baltic countries (red dots). Additional GPS stations exist on Jan Mayen and Bjørnøya, and on Hopen and elsewhere in the Svalbard Archipelago. The small black dots in Norway indicate permanent GPS receivers built mainly for navigational purposes, which generally provide data of similar quality.

The geodetic networks are diverse and include space geodesy, GPS, Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging, relative and absolute terrestrial gravity measurements, and gravity satellite missions like the Gravity Recover and Climate Experiment (NASA, 2014).

In Norway, the Norwegian Mapping Authority (NMA) is responsible for the space geodetic networks, which now consist of more than 130 continuously operating GPS stations on the Norwegian mainland (Fig. 5), as well as stations on Jan Mayen and Bjørnøya, and on Hopen and elsewhere on Svalbard. There is also one VLBI telescope at Ny-Ålesund. The NMA is also responsible for networks of absolute gravity points in Norway and, together with the Geological Survey of Norway (Norges geologiske undersøkelse), for the relative gravity data.

The NMA has collected and analysed geodetic data for many scientific purposes and practical applications, and there is significant cooperation among the Nordic countries on these issues. With its location close to the Arctic, the NMA has had a special focus on factors influencing the geodetic observations there. The elastic responses of the melting glaciers have been studied in detail—especially on Svalbard—and give valuable information on both glacial melting and the earth's crust.

In order to achieve the necessary quality of the geodetic observing system for these applications, global, high quality homogeneous networks of the geodetic techniques are needed and should be considered together with increased network density on both regional (for instance, the Nordic Geodetic Observing System) and local scales.

One main idea of EPOS is that from a societal perspective, one single infrastructure for solid earth sciences will have concrete advantages:

- Creating a single portal for information and scientific data, facilitating significantly easier access to these data.
- Providing a baseline before the exploration, exploitation, and management of natural resources.
- Addressing a variety of geohazard-related issues of societal importance.
- Improving research-based education by providing the relevant data through a single research infrastructure.

COLLABORATION

EPOS is a timely initiative responding to the current European need for a comprehensive and integrated solid earth RI. EPOS will constitute the solid earth science component that is currently lacking and will complement other large-scale RIs studying the planet earth in the Global Earth Observation System of Systems and Global Monitoring for Environment and Security initiatives. Examples include the European Space Agency satellites, European Multidisciplinary Seafloor Observation systems, including the deep-sea observatory HAUSGARTEN (Soltwedel et al., 2005), and other ESFRI initiatives such as the Svalbard Integrated Arctic Earth Observing System (SIOS).

The solid earth science presented in this paper is linked to numerous Arctic Observing Summit (AOS) white papers on Arctic observations in various scientific areas, including those of Lee et al. (2015) on observing networks, Ellis-Evans et al. (2013) on SIOS, Forest et al. (2013) on bio-moorings, Jakobssen et al. (2015) on Arctic bathymetry mapping, Mikhalevsky et al. (2015) on ocean acoustic networks, Orcutt et al. (2013) on a cabled observatory, Scambos et al. (2013) on multidisciplinary ocean system monitoring, and Tannerfeldt et al. (2013) on research icebreakers.

It would be very beneficial to study the practical requirements (e.g., location(s), duration, power, real-time vs. non real-time) of these different types of data acquisition. For example, not all EPOS-related acquisition has to be done in real time. However, in certain situations, such as when earthquakes occur or for early tsunami warning systems, real-time data acquisition would be very advantageous.

CONCLUSIONS

One of the main challenges of solid earth data collection in the Arctic is the existence of the ice sheet. Seismological measurements in the Arctic are dependent on direct coupling with the seabed. Installation of relevant instruments on the sea bottom under the thick ice cover is a common challenge for other types of instrumentations relevant to oceanography, biology, and climate research. In addition, communication between instruments deployed on the seabed and those on the ice is a common challenge for data collection and transfer and the associated logistics. Ice drift adds another important complexity that makes data collection in the Arctic difficult. Geodetic measurements need to be made on stable surfaces, not on ice or in the sea. Such areas are limited in the Arctic, and installation, maintenance, and data collection at such sites are obviously also difficult.

Technical solutions for these challenges will have mutual benefits for a variety of research groups, even if they may have different scientific objectives. Joint efforts combining various scientific groups from different disciplines will help to address these common problems. In some cases, such as ocean acoustics and seismology, the multidisciplinary collaboration is likely to result in sharing of research tools and joint research projects. Other technical solutions, such as cabled systems on the sea floor, ice floating systems, icebreakers, helicopters, gliders, autonomous underwater vehicles, planes, and hovercraft, can also be used to overcome the common logistical challenges.

There is an increased need for denser monitoring networks in the Arctic. Since much of the Arctic consists of ice-covered ocean, land-based observational networks do not contribute much to our understanding of the underlying processes in this region. There is therefore an urgent need to find mechanisms of collaboration between the various scientific groups working in the Arctic, including also financial mechanisms for permanent deployment of Arctic monitoring systems. EPOS is ready to contribute to the solid earth science dimension of such collaboration.

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