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See table of contents

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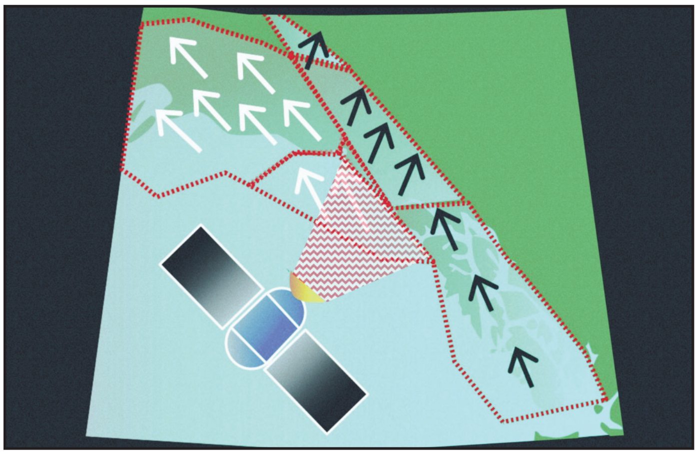

EON-ROSE* and the Canadian Cordillera Array – Building Bridges to Span Earth System Science in Canada

***Earth-System Observing Network - Réseau d'Observation du Système terrestrE**

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"*The significant problems we face cannot be solved at the same level of thinking we were at when we created them*" (Albert Einstein, New York Times 1946).

SUMMARY

EON-ROSE (Earth-System Observing Network - Réseau d'Observation du Système terrestrE) is a new initiative for a pan-Canadian research collaboration to holistically examine Earth systems from the ionosphere into the core. The Canadian Cordillera Array (CC Array) is the pilot phase, and will extend across the Cordillera from the Beaufort Sea to the U.S. border. The vision for EON-ROSE is to install a network of telemetered observatories to monitor solid Earth, environmental and atmospheric processes. EON-ROSE is an inclusive, combined effort of Canadian universities, federal, provincial and territorial government agencies, industry, and international collaborators. Brainstorming sessions and several workshops have been held since May 2016. The first station will be installed at Kluane Lake Research Station in southwestern Yukon during the summer of 2018. The purpose of this report is to provide a framework for continued discussion and development.

RÉSUMÉ

EON-ROSE (Earth-System Observing Network - Réseau d'Observation du Système terrestrE) est une nouvelle initiative de collaboration de recherche pancanadienne visant à étudier de manière holistique les systèmes terrestres, depuis l'ionosphère jusqu'au noyau. Le Réseau canadien de la cordillère (CC Array) en est la phase pilote, laquelle couvrira toute la Cordillère, de la mer de Beaufort jusqu'à la frontière étasunienne. L'objectif d'EON-ROSE est d'installer un réseau d'observatoires télémétriques pour suivre en continu les processus terrestres, environnementaux et atmosphériques. EON-ROSE est un effort combiné et inclusif des universités canadiennes, des organismes gouvernementaux fédéraux, provinciaux et territoriaux, de l'industrie et de collaborateurs internationaux. Des séances de remue-méninges et plusieurs ateliers ont été tenus depuis mai 2016. La première station sera installée à la station de recherche du lac Kluane, dans le sud-ouest du Yukon, au cours de l'été 2018. Le but du présent rapport est de fournir un cadre de discussion et de développement continu.

Traduit par le Traducteur

INTRODUCTION

The purpose of this article is to engage and inform the Canadian geoscience community about the exciting opportunities represented by EON-ROSE (Earth-System Observing Network - Réseau d'Observation du Système terrestrE), a proposed new initiative to develop a pan-Canadian research collaboration capable of holistically examining Earth systems from the ionosphere through the Earth's surface and into the core. The fundamental component is a uniformly-spaced grid of observation stations, successively covering different areas of Canada. The initial component is the proposed Canadian Cordillera Array (CC Array), spanning the Cordillera of western Canada from the Beaufort Sea to the United States border. The CC Array will build upon the unprecedented opportunities for technical, methodological, and scientific knowledge transfer presented by the coming completion of the US EarthScope program (www.earthscope.org), which currently has a grid of several hundred telemetered seismic, Global Navigational Satellite System (GNSS) and associated instruments across Alaska and northwestern Canada. The resulting scientific advances in studies of the solid Earth structure, dynamics and hazards enabled by such large-scale integrative networks of geophysical and other scientific instruments provide a strong foundation for driving innovative Earth science. EON-ROSE and the CC Array offer much potential for new breakthroughs in scientific research.

EON-ROSE proposes to formally explore and pursue linkages between solid Earth, surface and atmospheric processes. Although the EON-ROSE initiative came from the solid Earth geoscience community, such a network would be a unique opportunity for many other disciplines, and it has broadened to a truly multidisciplinary effort. It is envisioned as a combined effort of Canadian universities, federal and provincial government agencies, industry, and international collaborators (including those involved in the US EarthScope program and German Helmholtz Association). The US EarthScope program has been very successful but focused on mainly seismic, infrasound GNSS, and magnetotelluric instrumentation.

Here, we propose that progress in understanding complex changes in Earth's energy budget, the carbon cycle, the water cycle, and human influence within these systems requires consideration of global processes from the ionosphere and atmosphere, through the Earth's lithosphere, and deep into the mantle. Such an effort requires novel data collection and analysis approaches that would be greatly enhanced by multidisciplinary collaborative research networks bridging Earth System Science. In the spirit of the exceptionally successful Canadian multidisciplinary geoscience Lithoprobe program (1984–2005; e.g. Clowes 2010) the EON-ROSE program will include a wide range of associated and collaborative geoscience research. One key objective is to examine connections between surface geology and the deep structures and dynamics of the crust and upper mantle.

The vision of EON-ROSE is to expand upon the scientific momentum in North America gained from the Lithoprobe and EarthScope research and data collection initiatives. The specific vision for the CC Array is to install a network of mainly telemetered observatories (Fig. 1), each equipped with a suite of sensors such as broadband seismometers (including ocean bottom seismometers in the Beaufort Sea and the eastern Pacific Ocean), GNSS equipment, meteorological sensors, permafrost monitors, atmospheric gas sensors, shallow borehole temperature and moisture sensors, riometers (to monitor the electromagnetic-wave ionospheric absorption in the atmosphere), and magnetometers. Many of the stations will be in place temporarily for up to three years (longer for the GNSS

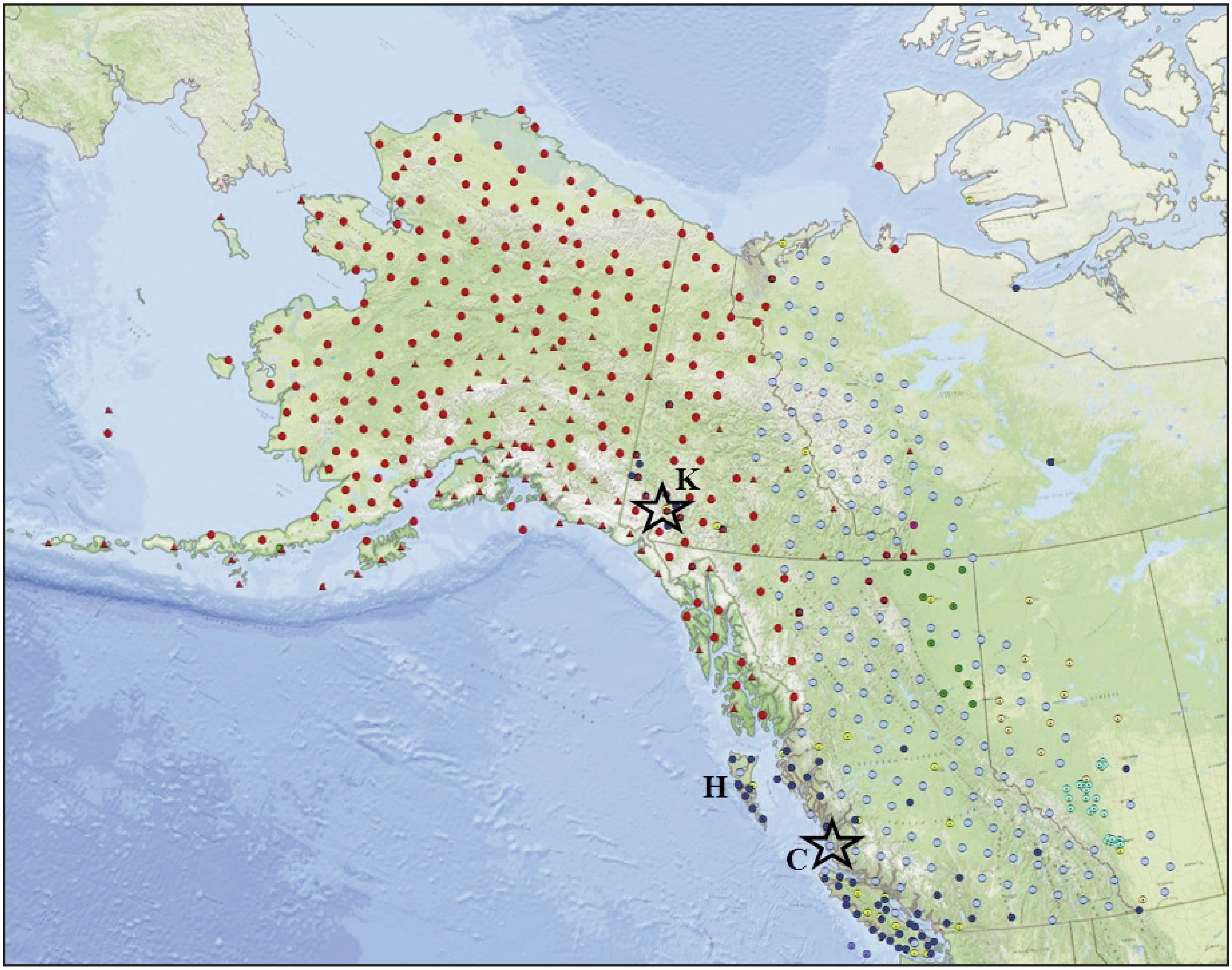

Figure 1. Proposed distribution of Earth observation stations for the Canadian Cordillera Array (CC Array) at an 85 km spacing. The red circles and triangles are current distribution of the 193 Transportable Array (TA) and 87 cooperative seismic, meteorological, and infrasound US TA stations in Alaska and northwestern Canada. The light blue circles are the ~ 165 proposed Earth observation stations for the CC Array. The various other colours and symbols are broadband seismometers from a variety of academic and federal government groups (courtesy of S. Azeveda and R. Busby). K – Kluane Lake Research Station, C – Calvert Island, H – Haida Gwaii Islands.

equipment), but the intention is to leave some stations in place for long-term Earth and environmental monitoring and science research across Canada. Although the initial network is proposed to be on an approximately uniformly-spaced grid, it is expected that there will be more detailed follow-up in areas of special interest with more closely spaced station distributions (as with the EarthScope Flexible Array), coupled with seismic and other geophysical surveys (as with Lithoprobe), and on-ground geological surveys and studies.

Benefits of Multiple Sensors at Each Station

Recent scientific and technical advances of the EarthScope program and its associated integrative instrumentation developments and science goals (e.g. Aster and Simons 2015) provide a strong foundation for developing the methodology for EON-ROSE and CC Array. Many modern geophysical instruments make measurements that benefit multiple fields of research, allowing a multidisciplinary approach to observation networks and the exploration of cross-disciplinary scientific problems. Examples from EarthScope support the power of combining several sensors in one station.

Infrasound signals (i.e. low-frequency sound undetectable by humans) were detected by the EarthScope seismic and infrasonic sensors (e.g. de Groot-Hedlin et al. 2008, 2011; Hedlin et al. 2010; Walker et al. 2011). These infrasound signals can be used to study wind and temperature structure in the atmosphere. When the US Transportable Array (TA) was located in the 'tornado alley' of the US Midwest, dedicated infrasound sensors were added to exploit this potential for research. Using Delauney triangulation (a computational technique that created a triangular grid pattern with the TA stations such that no station was isolated by itself in one of the triangles), de Groot-Hedlin et al. (2014) developed the capacity to track the motion of atmospheric gravity waves across the TA from slow-moving, long-period pressure pulses. Weather-related gravity waves describe the disturbance of fluids (or gases) from an equilibrium state. Propagating gravity waves can develop from the outward moving wind gusts at the leading edge of thunderstorms (Miller 1999; Knupp 2006). Gravity waves are of interest to numerical weather modellers and atmospheric scientists because they play a vital role in the transfer of energy and momentum between atmospheric layers and in global-scale circulation patterns (Holton et al. 1995). The TA sensors have also been used to study outward moving wind gusts at the leading edge of thunderstorms (Tytell et al. 2016). It remains of interest to determine how these sensors could improve modelling of weather processes in an operational setting and improve forecasting.

Another example that illustrates the benefits of co-locating sensors occurred recently in Nevada and California (Smith et al. 2016a). The co-location of seismometers and cameras offered real-time support to situational awareness for first responders monitoring wildland and interface fires. Due to the vast and remote nature of Canadian territory at risk from wildfires, this could be of great value in the early detection and real-time analysis of wildfires.

Integration of Solid Earth Geosciences with Space Weather, Numerical Weather Modeling, Critical Zone Science and Climate Change Research

A key objective of the proposed EON-ROSE and CC Array initiatives is to integrate solid Earth geoscience research with space weather observations, numerical weather modelling, critical zone science and climate change research.

Space weather refers to the changes caused by energetic particles and fluctuating magnetic fields above the thermosphere, which is the uppermost layer of the atmosphere that can be considered a continuous gas. The thermosphere is located above the stratosphere and is about 100 km above the troposphere, where day-to-day weather occurs. The Sun regularly emits giant clouds of ionized gas with 10^{16} g or more of hot plasma per event, causing geomagnetic storms that form the aurora and can severely disturb communications systems (Lanzerotti 2001), disrupt electric power grids (Boteler 2001), as well as cause significant damage to Earth-orbiting spacecraft.

Numerical weather modelling enables forecasts that account for dynamic, thermodynamic, radiative, and chemical processes working on temporal and spatial scales from seconds to weeks and hundreds of metres to thousands of kilometres (Bauer et al. 2015; Brunet et al. 2015). Recent experiences with extreme weather events such as Hurricanes Harvey, Irma and Maria have demonstrated the continued critical need for accurate numerical weather prediction. Although technological and scientific advances have permitted accurate global weather forecasting capabilities to extend by about one day per decade, there remain several challenges including obtaining physically consistent initial conditions by observations, and in better evaluating the accuracy of forecasts through ensemble predictions, i.e. sensitivity modelling exercises in which initial parameters are varied (Bauer et al. 2015; Brunet et al. 2015).

The *critical zone* (e.g. as defined by the US National Research Council in 2001) forms the complex region that is essential for supporting life, i.e. from the top of the forest canopy through the soil to the bottom of the deepest weathering and the base of aquifers (Wymore et al. 2017). Critical zone science includes investigation of crucial societal issues, such as access to potable drinking water, the impact of climate variability on soil development, the evolution and sustainability of soils and soil biomes, carbon sequestration in the near-surface and landslide studies (Goddéris and Brantley 2013).

Climate change and related issues such as population growth, increased vulnerability, and opportunities to increase resiliance, to natural hazards, and the need for long-term sustainability of resources (including minerals, energy, water and food) demand new approaches to integrated Earth System Science (e.g. Zoback 2001). Many aspects of the response to these challenges hinge on progress in Earth System Science, which will be aided by the multidisciplinary approach to Earth monitoring embodied by the EON-ROSE concept.

Call for Collaboration

This report presents an overview of our vision for EON-ROSE (Table 1) including a discussion of the potential application of this proposed holistic interdisciplinary approach to the development of exploration models for mineral deposits. It also includes a summary of 'white papers' (listed in Table 2) that were presented at a series of recent developmental workshops. These documents are essentially scoping studies that outline proposals for specific areas or scientific themes that could be investigated as part of the proposed project. Table 2 contains a listing of white papers prepared as part of this process, and we refer to these specifically in the last part of the paper. They are not listed in the references that conclude the paper.

Many of these white papers are available from a website set up as part of the CC Array initiative (www.ccarray.org). The purpose of this report is to provide a framework for continued discussion and development of this proposed national initiative. Interested readers are welcome to contact any of the authors, other authors of white papers, workshop participants (Table 3), or other people mentioned in the organizational chart on the CC Array website.

EON-ROSE AND CANADIAN CORDILLERA ARRAY CONCEPT INITIATION

The EON-ROSE concept arose from discussions at the 2015 EarthScope workshop related to potential new initiatives to follow the planned completion of the decadal-scale US EarthScope program by September 2020. Although the final phase of EarthScope has now placed instruments across Alaska and parts of northwestern Canada, there were no formal plans in Canada to start an 'EarthScope-like' program prior to 2015. The idea was first presented at the October 2015 annual Council of Canadian Chairs of Earth Science Departments meeting in Ottawa. Subsequent consultations resulted in letters of sup-

Table 1. Timeline for EON-ROSE* Project and the Canadian Cordillera Array (CC Array)

Date	Event	Advances
February 2013	Meeting to develop 'BC Array' at PGC	TA Array stations placed in NW Canada
June 2015	EarthScope Workshop	Idea emerged to bring EarthScope-like program to Canada
October 2015	First CCCESD Presentation	First white papers developed at McGill University
March 2016	NGSC Presentation	Start of buy-in from Geological Survey of Canada (GSC)
May 2016	CGU/CMOS Presentation	Start building community
May 2016	GAC-MAC Workshop	Continue building community
August 2016	SGT Forum Presentation and Poster	Reach out to US community
August 2016	Calgary and Ottawa brainstorming workshops	CC Array separated out as pilot project
October 2016	Second CCCESD Presentation	Report on brainstorming workshops
November 2016	Planning Meeting	Dave Eaton agreed to be Director; developed organization chart
December 2016	GeoPRISMS-sponsored Workshop at American Geophysical Union	Need for letter of interest to IRIS and UNAVCO (delivered in January); Expanding community to Critical Zone Science (CZS) and Space Physics
December 2016	Meeting with Director General of Geological Survey of Canada after EarthScope Townhall	Expand GSC support and interest
February 2017	Cordilleran Tectonics Workshop	Met with Hakai Institute
March 2017	GNSS – Focused Workshop	Proposed draft for GNSS receiver deployment; Building connections with CZS and Space Physics
March 2017	SWARM Conference	
April 2017	First CC Array Townhall	Report on NSERC SPGN LOI submission; present website
May 2017	CC Array Workshop at EarthScope 2107 Workshop	Establish connections with NSF Program Officers; Connect with the Chinese SinoProbe program
June 2017	CC Array Planning Meeting and Session at GSA Rocky Mountain Section Meeting	Developed first draft of proposed critical zone stations for CC Array
August 2017	CC Array Scientific and Planning Meeting	Report on first station installation spring 2018; Developed first draft of proposed distribution of weather stations for CC Array; Final report to be start of scientific strategic plan

*EON-ROSE - Earth-System Observing Network - Réseau d'Observation du Système terrestrE
BC Array - British Columbia Array (now combined with Yukon as CC Array), CC Array - Canadian Cordillera Array
CCCESD - Canadian Council of Chairs of Earth Science Departments, CGU - Canadian Geophysical Union, CMOS - Canadian Meteorological and Oceanographic Society
GNSS - Global Navigational Satellite System, IRIS - handles seismic data for EarthScope and other North American groups, NGSC - National Geological Surveys of Canada
NSERC SPGN LOI - National Science and Engineering Research Council of Canada Strategic Partnership Grants Letter of Intent, NSF - US National Science Foundation
SWARM - European Space Agency satellite mission to measure Earth's magnetic field, SGT - Structural Geology and Tectonics
TA - transportable array, UNAVCO handles the GPS data from the Plate Boundary Observatory of EarthScope

port for the concept from the Yukon Geological Survey, Repsol, Nanometrics Inc., and Environment and Climate Change Canada. The first white papers outlining research opportunities under a future EON-ROSE program were coordinated by Christie Rowe at McGill (Amos et al.; Liu et al.; see Table 2).

All of the white papers were first summarized at information sessions at the Canadian Geophysical Union/Canadian Meteorological and Oceanographic Society (CGU/CMOS) meeting (Fredericton, May 29, 2016) and the GAC-MAC meeting (Whitehorse, May 31, 2016), with further calls for interest to these communities. Subsequently, two brainstorming workshops were held at Mount Royal University in Calgary (August 17–19, 2016) and at the University of Ottawa (August 21–23, 2016; participants listed in Table 3). One major theme that emerged from these first workshops was the need to broaden the research community engaged in EON-ROSE; these efforts resulted in a workshop sponsored by GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins; www.geoprisms.org) at the Fall 2016 AGU meeting. A subsequent section will summarize the key points of these white papers (see Table 2 for further information about the white paper authors and subject material).

SEPARATION OF THE CANADIAN CORDILLERA ARRAY FROM THE EON-ROSE UMBRELLA AS A PILOT PROJECT

A significant outcome from the Ottawa workshop in August 2016 was a proposal to separate the Canadian Cordillera Array (CC Array) from the wider umbrella of EON-ROSE in order

Table 2. White papers submitted for the EON-ROSE* brainstorming workshops. These documents are not included within the reference list, but can be obtained from the Canadian Cordillera Array website (www.ccarray.org) or from the authors.

Authors	**Topic**
Amos, Harrington, Kirkpatrick, Leonard, Levson, Liu, Morell, Regalla, Rowe	Active faults of the Cascadia forearc: Implications for seismic hazard and tectonic evolution
Barnes	Canadian Environmental Change Research Network (CECRN): analysis and mitigation of global change and major natural hazards
Brunet	NEWP – Numerical Environmental and Weather Prediction
Colpron	Nature of the crust in North Yukon?
Elliott	Strain distribution across eastern Alaska and western Canada
Frederiksen, Eaton, Morozov	The Trans-Hudson Underlying Mantle Project (THUMP): a proposed teleseismic project for EarthsCAN
Freymueller	Distributed plate boundary deformation in the Northern Cordillera
Godin	Faults, tectonic inheritance, fluids, and seismicity: Towards an integrated Canadian Fault Atlas
Hyndman, Schaeffer, Audet, Aster, Schutt, Schmidt	Consequences of margin plate interactions in the Canadian Cordillera: BC Array concept
Kushner	Community Geoscience projects
Liu, Harrington, Darbyshire	Structure, seismicity and earthquake triggering in the St-Lawrence rift system
McCormack, Adams	Monitoring natural phenomena
Miller, Else, Sastri, Williams, Papakyriakou, Melling	CO_2 Fluxes and transformations in the Arctic marine system: A node in the Global Carbon CycleCO_2 Fluxes and transformations in the Arctic marine system: A node in the Global Carbon Cycle
Molnar	Transportable seismic arrays for ambient noise tomography imaging: Toward physics-based wave propagation modeling of earthquake scenarios
Myers	Towards integrated ocean observing systems, with the Atlantic as an evolving example
Ndimovic, Audet, Bostock, Calvert, Darbyshire, Dosso, Frederiksen, Liu, Liu, Welford	National facility for seismic imaging
Risk	Gas mapping as a geospatial resource for collaborative science
Scherwath, Dewey, Pirenne, Moran, Heesemen	Ocean Networks Canada and its role in Earth observing systems
Snyder	Semi-permanent stations for multi-azimuthal teleseismic studies of anisotropy and structure
Stevenson	Geological maps as historical documents
Stevenson, Darbyshire, Rizo, de Souza	Mapping the lithospheric mantle
Unsworth, Ferguson, Jones, Craven and Farquharson	Magnetotelluric imaging of the Canadian lithosphere: A historical perspective and future opportunities in EarthsCAN

*EON-ROSE - Earth-System Observing Network - Réseau d'Observation du Système terrestrE

to move forward more quickly and take advantage of the time-limited opportunities presented by the EarthScope US Array Transportable Array (TA) instruments currently located in Alaska and northwestern Canada (Fig. 1). Timing is crucial for deployment of the CC Array because these EarthScope TA instruments will be removed in the summers of 2019 and 2020 and installing new stations in isolated regions such as eastern Alaska and northwestern Canada is logistically challenging. To take advantage of the trained EarthScope installation teams and expertise and the investment in permitting and installation expertise already funded by the US National Science Foundation, the CC Array must move forward on a faster timeline than the nationwide EON-ROSE initiative. The general consensus was that combining the proposed Yukon array (white paper by Colpron; Table 2) and British Columbia array (white paper by Hyndman et al.; Table 2) as the CC Array would make a good proof of concept for EON-ROSE and provide an effective stepping stone to a successful national program. It is important to keep the pan-Canadian goal of EON-ROSE in the forefront of planning and strategic thinking, and to build the national initiative on a time schedule that would allow the full EON-ROSE instrumental network to roll out across Canada in an efficient manner.

SUMMARY OF WHITE PAPERS

After the initial two white papers, more detailed white papers were submitted for the information sessions and the brainstorming workshops (Table 2). Of these white papers, 14 are

Table 3. List of participants at the Calgary and Ottawa EON-ROSE* brainstorming workshops.

Position	Affiliation	Name
Calgary Workshop		
Coordinator	Mount Royal University	Boggs, Katherine
Presenter	Geological Survey of Canada / University of Victoria	Hydman, Roy
	Ocean Networks Canada, University of Victoria	Scherwath, Martin
	Purdue University	Elliott, Julie
	Repsol Inc.	Hsieh, Jean
	University Alaska Fairbanks, DENO	Freymueller, Jeff
	University of British Columbia	Clowes, Ron
	University of Saskatchewan	Llewelyn, Ted
	University of Toronto	Kushner, Paul
	University of Victoria	Morell, Kristin
	Yukon Geological Survey	Colpron, Maurice
Participant	Alberta Geological Survey	Schultz, Ryan
	Association of Professional Geoscientists of Alberta	Sneddon, Tom
	Carbon Management Canada Research Institute	Osadetz, Kirk
	Mount Royal University	Droboth, Jason#
		Fornwald, Connor#
		Gopal, Saha
		Witvoet, Leela#
	Simon Fraser University	Calvert, Andy
	University of Calgary	Bao, Xuewei#
		Dettmer, Jan
		DiCaprio, Lydia
		Eaton, Dave
		Else, Brent
		Ferguson, Ron
		Gilbert, Hersh
		Lauer, Rachel
		Weir, Ron#
	University of Copenhagen	Leth, Maria#
	University of Victoria	Leonard, Lucinda
		Nissen, Edwin
	Yukon Geological Survey	Relf, Carolyn
Ottawa Workshop		
Coordinator	Mount Royal University	Boggs, Katherine
	University of Ottawa	Audet, Pascal
Presenter	Canadian Geodetic Survey	Klatt, Calvin
	Canadian Hazards Information Services	Adams, John
	Geological Survey of Canada	Snyder, David
	Geological Survey of Canada / University of Victoria	Wang, Kelin
	McGill University	Liu, Yajing
	Nanometrics Inc.	Spriggs, Neil
	Oxford University	Sigloch, Karin
	Queens University	Godin, Laurent
	St Francis Xavier University	Baillie, Jennifer
	University of British Columbia	Clowes, Ron
	University of Ottawa	Schaeffer, Andrew
	Université du Québec á Montréal	Stevenson, Ross
	University of Toronto	Kushner, Paul
	University of Victoria	Barnes, Chris
	Western University	Molnar, Sheri
Participant	Canadian Geodetic Survey	Craymer, Mike
	Geological Survey of Canada	Ackerley, Nick
	University of Ottawa	Montsion, Rebecca#
	Université du Québec á Montréal	Darbyshire, Fiona
		Pinti, Daniele
	University of Toronto	Murray-Bergquist, Louisa#

= student participants
DENO - Director of the EarthScope National Office; *EON-ROSE - Earth-System Observing Network - Réseau d'Observation du Système terrestrE

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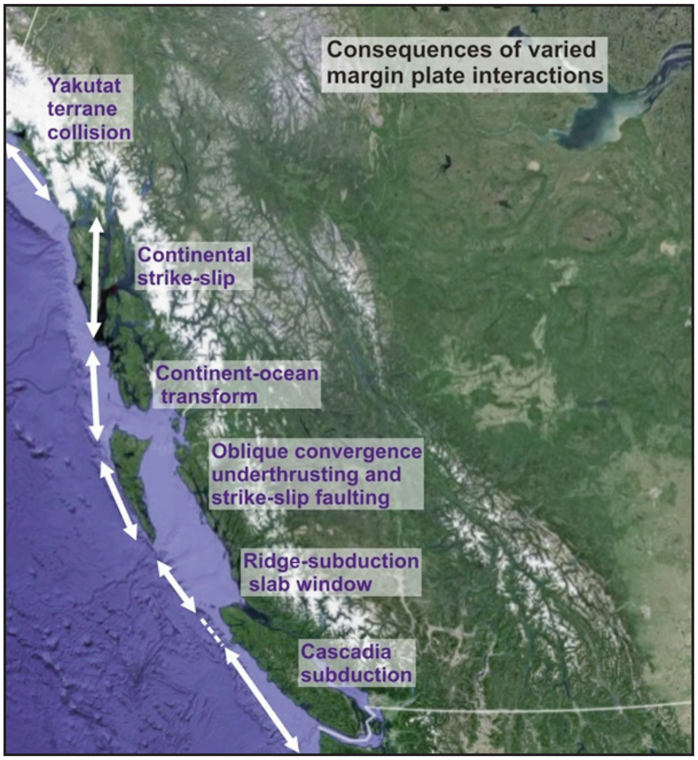

Figure 2. Tectonic characteristics off the west coast of Canada.

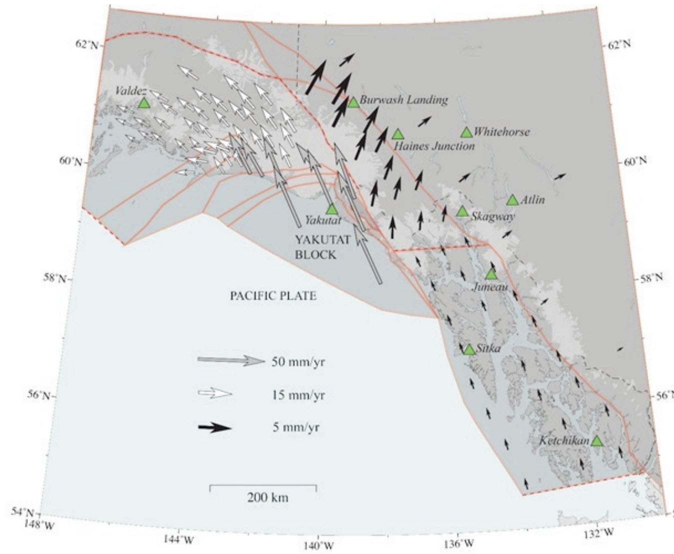

Figure 3. Global Navigational Satellite System (GNSS) - derived model predictions of block motions (relative to stable North America) in southeastern Alaska and western Canada. Red lines show boundaries between blocks; dashed lines indicate uncertain boundaries. Model from Elliott et al. (2016). More information about the model blocks and data used can be found in Elliott et al. (2010; 2013).

related to solid Earth geosciences, 3 to oceanography, 2 to atmospheric gases, 1 to climate change and 1 to weather modelling. This indicates that the solid Earth geosciences are presently over-represented, due in part to the background and expertise of the proponents and because the Canadian geoscience community is familiar with the successes of the Lithoprobe and EarthScope programs. Ongoing efforts to build a truly multidisciplinary EON-ROSE initiative and research community will focus on expanding the role of studies outside solid Earth geoscience, to hopefully make the whole greater than all the individual parts. The proposals contained in the white papers can be grouped in part on the basis of geography, but some proposals are of a more thematic nature.

CC Array – Western Canada with Adjoining Arctic Canada

Several white papers focused on western Canada (Amos et al., Colpron, Elliott, Freymueller, Hyndman et al., Miller et al., Nedimović et al., and Scherwath et al.; see Table 2) and outlined the need for the CC Array. Colpron pointed out that the US Array stations only cover the western half of the “Yukon Stable Block” (YSB; located in north central Yukon Territory). The YSB has some interesting and enigmatic features, such as the underlying Paleoproterozoic Wernecke Group, which is only found in this region of the Northern Cordillera, and Cretaceous and Cenozoic structures that are deflected around the YSB. The white paper by Hyndman et al. (see Table 2) describing the proposed BC Array emphasized the need to better understand the plate structure and seismicity of the complex tectonic setting off the west coast of British Columbia, which includes normal subduction, slab windows, ridge triple junctions, possible incipient subduction, transform faulting, and terrane collision (Fig. 2). GNSS data, seismicity and modelling (Elliott et al. 2010, 2013, 2016) show that deformation along this active margin is spread over a broad region. Haida Gwaii (off the west coast in northwestern BC) and the adjacent mainland coastal areas appear to be moving towards the north (Mazzotti et al. 2003). Further north, the Yakutat Block is colliding with southern Alaska, resulting in ~3 cm/year of convergence that is accommodated over ~ 100 km (Elliott et al. 2010, 2013, 2016; Fig. 3). This oblique collision appears to be transferring strain to the north and northeast, causing active deformation across the Richardson and Mackenzie mountains (Mazzotti and Hyndman 2002; Leonard et al. 2007; Leonard et al. 2008). One intriguing question is to what extent the strain transfer occurs diffusely across hundreds of kilometres, as opposed to being accommodated by rigid blocks and a few discrete faults. Although a portion of this active margin was covered by the EarthScope US Array stations, the distribution of continuous GNSS sites is extremely sparse. A well-distributed seismic and continuous GNSS network is necessary for measuring the active tectonics. The GNSS network is also needed to measure the deformation associated with glacial isostatic adjustment and would also be beneficial for assessing environmental parameters such as hydrological cycle loading (Rocken et al. 1993, 1995; Bevis et al. 1994), soil moisture (Larson et al. 2005; 2008; Larson and Small 2013) and snow depth (Larson and Nievinski 2012; Larson and Small 2013; McCreight and Small 2014). Signals from glacial isostatic adjustment (e.g. Larsen et al. 2005) and these environmental effects are mixed together in the crustal motions recorded by GNSS, and measurements from complementary terrestrial and satellite sensors are necessary in order to separate them successfully. The EON-ROSE project could provide terrestrial data to complement remote sensing data such as those provided by the

GRACE-FO (Gravity Recovery and Climate Experiment – Follow On) satellite soon to be launched by NASA.

In the area of the CC Array there is a need for studies of recent (neotectonic) fault activity, especially on southern Vancouver Island (Morell et al. 2017) and potentially across much of southwestern British Columbia. For example, using a multidisciplinary approach that incorporates geophysics, LIDAR images and field work, Morell et al. (2017) demonstrated that the Leech River Fault (southern Vancouver Island) experienced at least 3 earthquakes greater than magnitude 6 during the last 15,000 years. Studies of neotectonic activity are rare in Canada compared to the United States due to sparse instrumentation, sparse high-resolution imagery, and a sparse fault database. Canada needs to improve in this regard because these faults do not stop at the international boundary and active fault identification supports local seismic hazard characterization. Studies of neotectonic processes will also be necessary across the Richardson and Mackenzie mountains to understand how strain is so broadly distributed through this region from the collision with the Yakutat Block, as discussed above.

The white papers by Unsworth et al. (on magnetotellurics; see Table 2) and by Risk (on gas mapping for collaborative science; see Table 2) outlined two diverse sensor types for inclusion in the CC Array Earth observation stations. Magnetotelluric (MT) data have proven useful for 3-D studies of potential geothermal prospects in fault zones and volcanic settings in British Columbia, the Yukon and elsewhere (Unsworth et al. white paper). MT has also been used effectively for mineral exploration including porphyry copper (Hubert et al. 2016) and some other types of sulphide deposits (Jones et al. 2014). The white paper by Risk outlines how various gas sensors could also have multiple applications ranging from monitoring volcanic activity (e.g. radon, CO_2, CH_4, volatile organic compounds) to environment and health (e.g. oxygen, nitrogen and sulfur oxides, radon) and permafrost thawing and impact of climate change (e.g. CH_4, CO_2).

Ground motion visualizations that have emerged from the EarthScope project have made it possible for the first time to develop earthquake wave visualizations fields at continental scales (e.g. https://www.iris.edu/hq/programs/epo/visualizations). Natural hazard mitigation and risk assessment in areas where strong ground motions would be expected were significant components of discussions during the brainstorming workshops in both Ottawa and Calgary. In Canada, the Canadian Hazard Information Services (CHIS) monitors and provides information on hazards including earthquakes, volcanoes, tsunamis, landslides and geomagnetic storms. CHIS management proposed possible collaborations ranging from providing archival storage and data dissemination to sharing their expertise on sensors and deployment.

The white paper by Molnar (see Table 2; also Molnar et al. 2014a, b) proposed that earthquake simulation techniques provide one of the best methods for addressing uncertainty for future ground-shaking estimates in order to better evaluate earthquake response and planning. She proposed using an equivalent to the EarthScope Flexible Array to improve the sedimentary velocity model for the Georgia Basin in the Metro Vancouver area by improving the resolution beyond the current coarse spacing (~ 250 m to 1 km). The possibility of increasing the site density of seismographic, GNSS, and other instrumentation in areas of special interest was also proposed by the Hyndman et al. white paper (Table 2). This approach is similar to that employed for the EarthScope Flexible Array component, as currently deployed across the Mackenzie Mountains (Witt et al. 2017).

Central Canada

Although the details of EON-ROSE beyond the proposed CC Array have not been established, the white papers by Frederiksen et al. (on the Trans-Hudson Underlying Mantle Project) and by Liu et al. (on the St. Lawrence Rift Valley) proposed some deployment possibilities for future phases of EON-ROSE. Frederiksen et al. proposed filling in a significant gap in broadband seismometers across Saskatchewan and Manitoba to examine the tentative attribution of a local seismic cluster near Esterhazy in southeastern Saskatchewan to dissolution collapse in evaporite deposits. As outlined by Liu et al., the St. Lawrence rift system in eastern North America is the highest seismic hazard region in eastern Canada due to the Lower St. Lawrence, Charlevoix and Western Quebec seismic zones. Seismicity along the St. Lawrence rift system is enigmatic, as the state of stress inferred from earthquake focal mechanism solutions deviates significantly from interpretations based on regional borehole measurements. Although the earthquakes are generally associated with reactivated late Proterozoic Iapetus rift structures, the seismicity appears to scatter around the major rift faults instead of clustering on them. A network of monitoring stations would aid our understanding of this complex region and its seismic hazards.

Atlantic Canada

One intriguing tectonic target in Atlantic Canada was outlined by Pollock et al. (2015) in their study of Avalonia in southeastern Newfoundland and southern Cape Breton. Their preferred model was for one Late Precambrian arc with significant compositional, tectonic and structural variation along strike. An EarthScope-like array could determine whether this arc formed as a 180° orocline bend similar to the Sunda-Bonda arc (van Staal et al. 1998) or a cognate arc system similar to the Tonga-Kermadec-New Zealand arc system (Pearce et al. 1999).

The most catastrophic tsunami in recorded Canadian history was triggered by a 7.2 magnitude earthquake on the southern edge of the Grand Banks on 18 November, 1929 (Murty 1977; Piper et al. 1988; Evans 2001; Clague et al. 2003). A submarine slope failure in excess of 200 km^3 was triggered, which became a turbidity current that broke all 12 telegraph cables along the continental slope south of Newfoundland (Heezen and Ewing 1952; Fine et al. 2005). Twenty-seven people were killed in Newfoundland and one in Nova Scotia (Cranford 2000; Clague et al. 2003). The possible consequences of another event of this type in the 21st century provide an obvious rationale for improved monitoring of seismic activity and other indicators.

The first deployment of the new ocean bottom seismometer facility proposed for EON-ROSE will be in the Atlantic Ocean (white paper by Nedimovic et al.; Table 2). The white paper by Myers (Table 2) described the collaborative approach for the integrated Atlantic Ocean Observatory.

Oceanography and Atmospheric Sciences

Multidisciplinary collaborative opportunities were outlined in white papers by Kushner, Nedimovic et al., Sherwath et al., and Miller et al. (Table 2). The Nedimovic et al. white paper described a Canadian Foundation for Innovation application to fund an ocean bottom seismometer facility that could be available for deployment off the west coast of British Columbia or in the Beaufort Sea as early as 2020, after initial deployment in the Atlantic Ocean. The Sherwath et al. white paper (Table 2) described potential collaborations with Ocean Networks Canada (ONC), including the Neptune and Venus cabled ocean observatories that already collect data on geological, biological, chemical and physical aspects of the oceans and seafloor. The Kushner white paper proposed following the model of the Climate Change and Atmospheric Research program of NSERC and infrastructure collaboration in the area of advanced research computing across the disciplines represented by this initiative.

Pacific, Arctic and Atlantic Oceans

The Arctic Ocean is a precarious net sink of atmospheric CO_2 (white paper by Miller et al.; Table 2). To predict magnitudes and directions of carbon fluxes through the Arctic Ocean, data at much greater temporal and spatial resolutions are required, and the necessary observations are not currently possible with conventional camp- or ship-based chemical oceanography. Presently there is one functioning observatory in Cambridge Bay (operated by ONC) equipped with CO_2 system sensors coupled with an air-sea CO_X flux tower on a small island offshore in Dease Strait (south of Victoria Island, Nunavut), with plans for a second in southwestern Hudson Bay. The Miller et al. white paper suggested linking efforts from multiple countries to monitor the Arctic Ocean through the EON-ROSE initiative and perhaps using this proposed research network to strengthen collaborative research on the Arctic Ocean. Although the Myers white paper (Table 2) focused on the Atlantic Ocean, the proposed collaborative approach to an Integrated Atlantic Ocean Observing System could also be applied to the Pacific Ocean or the Arctic Ocean.

POSSIBLE APPLICATIONS TO MINERAL EXPLORATION

As with Lithoprobe, we envision that funding will be available to support diverse geoscience studies, such as field-based research, geochemistry, geochronology and other more detailed geophysical studies, such as seismic reflection and refraction experiments. Technological advances from the Lithoprobe program were beneficial for improving images of base-metal deposits (e.g. Sudbury impact structure, Creighton 402 Orebody; Eaton et al. 2010), uranium deposits (e.g. Athabasca Basin, McArthur River Mine; Hajnal et al. 2010), and diamondiferous kimberlites (e.g. Diavik, A154 pipe; Snyder and Grütter 2010). Today, a new frontier is to improve our understanding of the subcontinental lithospheric mantle (SCLM), which is considered an important source reservoir for diamonds (Shirey et al. 2002; Malkovets et al. 2007), rare earth elements (Smith et al. 2016b) and other metals (Au, Cu, Mo, Pb, Zn; Pettke et al. 2010; Groves and Santosh 2015). Mantle influence and/or sources are suggested for REE deposits hosted by both alkali syenites (Kramm and Kogarko 1994; Stevenson et al. 1997) and carbonatites (Simonetti et al. 1995; Yang et al. 2011; Baatar et al. 2013; Moore et al. 2015). The US EarthScope program (Long et al. 2014) has greatly improved imaging of the SCLM under the US Cordillera (Becker et al. 2014; Refayee et al. 2014; Meqbel et al. 2014; MacCarthy et al. 2014; Lekić and Fischer 2014; Hopper et al. 2014; Porritt et al. 2014), but the Canadian Cordillera lacks the same SCLM resolution.

Recently, Groves and Santosh (2015) emphasized the need to expand traditional exploration models to include common tectonic settings to improve discovery rates for greenfield exploration. Groves and Santosh (2015) specifically referred to recent models for iron oxide-copper-gold (IOCG) deposits, intrusion-related gold systems and Carlin-type gold deposits, all of which suggest common controls by craton margins or suture zones with sub-Moho magma chamber sources. Changing exploration foci to consider lithospheric boundaries could aid in discovering other associated deposit types, such as komatiite-associated Ni–Cu–PGE deposits (Begg et al. 2010; Maier and Groves 2011; Groves and Santosh 2015). A similar exploration model would also be appropriate for giant porphyry-type Cu–Mo–Au deposits such as the Bingham Canyon deposit, as demonstrated using Pb isotopes by Pettke et al. (2010). Such exploration strategies require an integrated multidisciplinary approach among field-based geological, isotopic and geophysical studies; an approach which will be possible through the proposed CC Array program.

The Australian PACE Program: An Example of Interdisciplinary Approaches for Mineral Exploration

The Australian PACE (Plan for Accelerating Exploration) initiative provides several interesting examples that illustrate the positive benefits of interdisciplinary approaches to mineral exploration (Scott and Jones 2014). Khamsin and Carrapateena are two new copper-gold discoveries that are directly attributed to the PACE program, along with 14 other significant new discoveries that resulted from the collaborative drilling program associated with the PACE initiative (Scott and Jones 2014).

A separate collaborative drilling and geophysics program with accompanying detailed geochronology, geochemistry and petrographic studies led to significant refinements to the formation model for the supergiant Olympic Dam IOCG (iron oxide–copper–gold) deposit. Specifically, the influence of sedimentary basins on uranium deposition is now better understood (e.g. Cherry et al. 2017). The Olympic Dam mine is located in the Olympic IOCG Province along the eastern margin of the Gawler Craton (Skirrow et al. 2007) in south-central Australia, and is one the largest copper and gold resources in the world (Ehrig et al. 2012).

It is now recognized that the Olympic Dam deposit formed in a multi-stage hydrothermal-tectonic setting (Oreskes and Einaudi 1990; Reeve et al. 1990). Recent Partially Preserved Amplitude (PPA) processing of seismic data revealed steeper tectonic structures than had been imaged previously (Wise et al. 2016). This PPA processing also outlined several kilometre-scale sub-vertical zones in the vicinity of several IOCG deposits that correspond with features indicated by magnetotelluric modelling of deep conductivity. These conductive features could have been formed by hydrothermal alteration or partial-melt migration (Wise et al. 2016).

Although Canada does not currently have any producing IOCG deposits, they are strategically and economically attractive exploration targets due to their polymetallic and nuclear energy resources (Corriveau et al. 2007). The non-magmatic end-member IOCG-bearing Wernecke Breccias in the Yukon Territories (Hunt et al. 2007) fall within the proposed footprint for the CC Array. The proposed CC Array and its potential for tomographic imaging and other related projects could provide a geological and geophysical framework conducive to future economic IOCG discoveries, in the same way that the PACE program assisted in the discovery of new deposits in Australia.

THE FUTURE OF THE EON-ROSE CONCEPT

The development of the EON-ROSE initiative is concurrent with corresponding initiatives in atmosphere-related research focused on weather, climate, and air quality, such as the *ad hoc* working group on Atmosphere-Related Research in Canadian Universities (ARRCU; Kushner et al. 2015). There is also a university-focused effort in ocean science (the Canadian Consortium of Ocean Research Universities – C-CORU: http://www.oceannetworks.ca). The Canadian Mountain Network is focused on sustainability of mountain environments and communities. All of these initiatives have identified areas for interdisciplinary connections between different research communities. To our knowledge, however, EON-ROSE is the first initiative to formally explore and pursue linkages between solid Earth, surface and atmospheric processes.

Experience shows that strategic planning initiatives like EON-ROSE develop over a multi-year timescale. As such, they need to be separated from the relatively short timeline of research infrastructure opportunities like the CC Array. Nevertheless, the CC Array initiative provides timely opportunities for coordinating with other scientific communities to build a nationwide program. Currently we are reaching out to solicit interest and ideas for other approaches towards using this opportunity to create new research networks aimed at understanding the coordinated working of the Earth system.

We hope that a network such as EON-ROSE will help fill many research gaps, and bring about unanticipated discoveries. It is also hoped that a broad community will be galvanized to participate and work together to maximize efficiency and consider some related 'grand challenge' questions. For example, what are the science questions that are likely to drive research in Earth System Science for the next 10–20 years? How can these questions be approached using new national infrastructure networks and collaboration between researchers? What new opportunities would a network of monitoring stations and other multidisciplinary approaches offer research and how might they improve the management of resources and address societal issues? These are critical questions that face the geoscience community. We believe that an inclusive, collaborative, multidisciplinary approach within a unifying initiative is the best way forward.

If you are interested, have suggestions or questions, please contact any of the authors or other people identified on the CC Array website (ccarray.org).

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