Why can the breakup of the continental lithosphere take different paths?
Understanding the transition from magmatic to amagmatic rifting

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Overview
The combination of land and marine instruments in the Amphibious Array makes it an ideal tool to investigate the Nova Scotia and adjoining offshore region where key questions of continental evolution and oceanic formation can be probed. In this region, a clear transition from volcanic (aka magma-rich) to non-volcanic (aka magma-poor) lithospheric breakup that took place during the opening of the Atlantic Ocean is well recognized. The two different modes of lithospheric breakup offshore Nova Scotia may be linked to tectonic inheritance from past rifting and orogenic episodes, or else they may be completely independent, and instead represent a 3D evolution of the process in time (i.e., magmatic and amagmatic stages of breakup could be diachronous). It is notable that this along strike variation in magmatic activity observed offshore appears to agree with onshore syn-rift magmatic activity associated with the Central Atlantic Magmatic Province (CAMP) which extends only as far north as the Bay of Fundy and SW Nova Scotia, but it contrasts with an apparent continuity of tectonic fabric onshore as major terranes of the Appalachian orogeny continue along the entire length of Nova Scotia.

The deployment of the broad band ocean bottom seismometer (BB OBS) Amphibious Array here can address a fundamental question of the plate tectonic theory: Why can the breakup of the continental lithosphere take different paths?

Nova Scotia region is a designated “research focus area” of the GeoPRISMs initiative (ENAM site, RIE component, Figure 1), essential for addressing the following programmatic goals:
• The role of magmatism in rifting, breakup, and post-rift lithospheric evolution
• The along-strike transition from magma-rich to magma-poor extension at breakup
• The evolution of segmentation from initial rifting to mature seafloor spreading

Figure 1. Location of the northern corridor within the ENAM focus site of the GEOPRISMS program. Adapted from the RIE ENAM Implementation Plan (http://www.geoprisms.org/science-plan.html).
The region boasts several data sets both on land and offshore, as well as a number of ongoing and planned experiments (see subsequent sections). The most significant data “gap” in this area is the paucity of passive seismic data, especially offshore, and until recently - onshore. As a consequence, the large-scale architecture of the margin is known only in places where seismic refraction studies were undertaken (SMART, OETR, OCTOPUS, Figure 2). As the processes shaping the margin were three dimensional, understanding them requires observational coverage that can resolve 3D variations in large-scale structure, spanning both onshore and offshore regions. An ongoing cooperative passive seismic deployment (Rutgers, LDEO, University of Quebec – Montreal, Imperial College – London) is improving the regional sampling on land, however lateral resolution possible with the present configuration of the sites (temporary, to operate for 2 years) is insufficient to address questions outlined above.

Figure 2. Location of the controlled source seismic survey planned by the Canadian scientists and existing seismic lines offshore Nova Scotia. Regional MCS reflection lines are shown as solid black lines (Lithoprobe and Frontier Geoscience Program), dashed black lines (NovaSpan Project of ION-GXT) and yellow lines (UNCLOS Project). OBS refraction profiles (SMART Lines 1-3, OCTOPUS and OETR) are marked by orange lines. Jurassic salt over the Slope Diapiric Province is indicated by white patches. The red box indicates the proposed regional 3-D controlled source OBS survey area with instrument spacing of ~15 km.

Challenging to image salt areas in the north-eastern corner are covered by the 2013 Shell wide-azimuth MCS survey (dashed yellow box), the results of which Shell agreed to share with us for research purposes. The red dashed line shows the proposed detailed 2-D OBS transect with instrument spacing of only 1 km. The location of the proposed surveys is based on the available data, in particular on the Smart Lines 2-3 and the ION-GXT line 5100 which gives insight to where the main variations in the crustal structure along the margin occur.

**Offshore: Available data and an ambitious plan for a new OBS facility**

Canadian researchers have proposed to build a National Facility for Seismic Imaging (NSFI) equipped with 160 compact, low-cost, next-generation ocean bottom seismometers (OBS), each covering all the applications of a conventional short-period OBS and a limited number of the applications of a broadband instrument. The first experiment to be carried out with this facility is a 3D controlled source wide-angle reflection/refraction OBS study focused on the transition from magmatic to amagmatic rifting found offshore SW Nova Scotia (see red box in Figure 2). This experiment will provide unprecedented insight into the structure of the crust and the uppermost few km of the mantle if this area.

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Onshore: Passive seismic observations in conjunction with the eastern deployment of the Earthscope TA

A small number of permanent seismic observatories exist in Nova Scotia region. The Earthscope Transportable Array (TA) on the Atlantic coast did not extend into Canadian Maritimes, thus its ~75 km lateral sampling of the region ends at the US-Canada border. A cooperative US-UK effort in New Brunswick and Nova Scotia did add a number of sites in the region (Figure 3), although coverage is sparser. All temporary observatories will collect a 2-year long data set. A number of sites in Maine will likely remain operational through 2017 under the auspices of the Central and Eastern US Network (CEUSN, www.usarray.org/ceusn).

![Map of Earthscope TA deployment](image)

**Figure 3.** A present (September, 2014) configuration of continuously operating land seismic observatories in Maine, Quebec and Canadian Maritimes. Permanent US and Canadian stations - red and white boxes. Temporary seismic array (Summer 2013 through Summer of 2015): Earthscope TA (white circles), Earthscope FlexArray QMIII (blue circles), SEIS-UK array (purple diamonds). Inset –CEUSN sites in New England.

A task for the Amphibious Array

As outlined in more detail in the GeoPRISMS RIE Implementation plan, a deployment of the shoreline-crossing seismic observatory system would lead to the development of a truly 3D model of the margin on lateral scales of 10s to 100s of km. To obtain unambiguous constraints, an area centered on the East Coast Magnetic Anomaly weakening at ~43°N/64°W and ~200-km wide in a N-S direction would need to be imaged (Figure 4). The eastern (seaward) boundary of the corridor needs to be at least 400 km offshore to include true oceanic lithosphere. The western (landward) extent of the proposed corridor has to extend onshore, ideally including the Appalachian front (i.e., area west of the St. Lawrence River). A uniform grid of broadband land sites and OBSs with a spacing ~100 km (i.e., similar to that of the Earthscope TA) would be the key additional component, providing the necessary resolution on the lithospheric scale. Using the USAArray strategy, additional details in areas of special interest would be obtained by active source studies (like the one discussed above), and by denser deployments similar to those employed in Cascadia and the GeoPRISMS community experiment. One significant challenge for the use of regularly spaced OBS is the width of the shallow shelf...
offshore Nova Scotia, which increases their risk of being disturbed. Use of shielded instruments will likely alleviate the challenge.

Figure 4. An example plan for the layout of the passive BB OBS array in Nova Scotia region. The yellow outline corresponds to the shape of the “Northern Corridor” in GeoPRISMS ENAM Implementation plan. Permanent and long-term land observatories are shown by white and red symbols, proposed Amphibious Array elements are shown by circles: red – land stations, black – deep-water OBS, purple – shielded OBS. A 2-year observatory campaign with this configuration would be sufficient for resolving lithospheric structures on ~100 km scale.