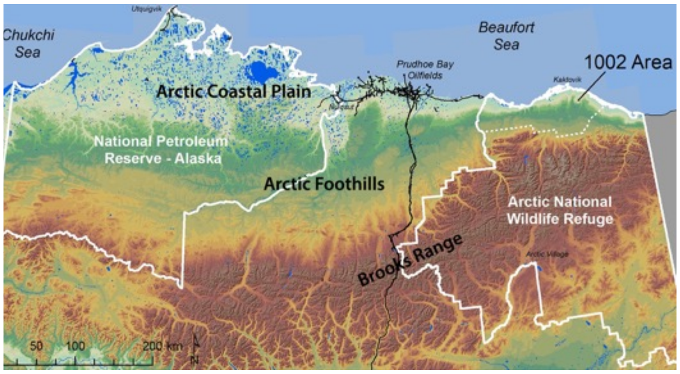
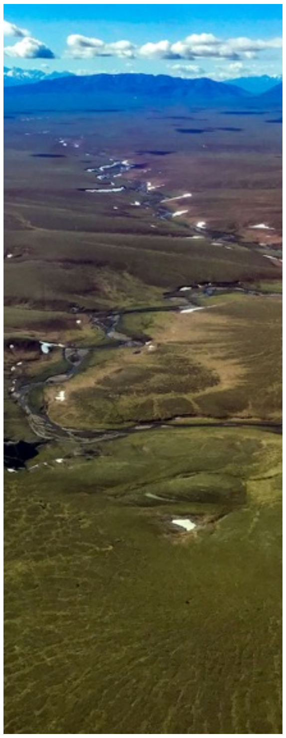
Likely impacts of proposed 3D-seismic surveys to the terrain, permafrost, hydrology, and vegetation in the 1002 Area, Arctic National Wildlife Refuge, Alaska





A White Paper by D. A. "Skip" Walker, M. Torre Jorgenson,
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On the cover

Clockwise from top left: (1) Location of the 1002 Area within the Arctic National Wildlife Refuge (ANWR) and northern Alaska. (2) Seismic camp move during the 1984-1985 2D-seismic surveys in the ANWR, courtesy: USFWS. (3) Hilly terrain of the 1002 Area. (4) Rubber-tracked Vibroseis or "thumper" vehicle. Credit: BLM. (5) Trails left by the Icewine seismic survey in spring 2018, courtesy: Heather Buelow.

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Skip Walker has conducted vegetation research and tundra disturbance-and-recovery studies in arctic Alaska and the circumpolar Arctic for 49 years. In 1981–82, he mapped the vegetation of the 1002 Area. He is currently the principle investigator of a National Science Foundation project to study the cumulative effects of arctic oil development in the Prudhoe Bay area with the goal of identifying practices for sustainable arctic infrastructure planning and design. He directs the Alaska Geobotany Center at UAF.

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Matt Nolan is a geophysicist and engineer who has spent 25 years studying the impacts of climate change on the landscapes of polar regions, primarily by developing new satellite, airborne, and field measurement techniques, including seismic exploration techniques used in Alaska, Siberia, and Antarctica. Since 2003, he has led the McCall Glacier project, a field study of climate-glacier-ecosystem interactions in the Arctic National Wildlife Refuge begun in 1957. He owns Fairbanks Fodar, a company specializing in measuring topographic change throughout Alaska using airborne photogrammetry.

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Martha Raynolds is a plant ecologist and mapper who has measured the effects of winter seismic exploration in the Arctic Refuge over three decades (1985–2009). She has analyzed cumulative geoecological effects of oil infrastructure and climate change in the Prudhoe Bay area. In 2003, she worked with an international team to create a circumpolar arctic vegetation map as a tool for vegetation scientists and land-use managers.

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Contents

Executive Summary

This white paper addresses the Bureau of Land Management's (BLM) plan for a 3D-seismic survey during the winters of 2018–2019 and 2019–2020 in the 1002 Area of the Arctic National Wildlife Refuge (ANWR).

The authors have long experience working in the Arctic, including combined decades of work in the 1002 Area. We present ten issues based on what is already known about the impacts of seismic activities to arctic tundra environments. We also identify several areas that require further research and evaluation to understand the potential consequences of 3D seismic exploration in the 1002 Area. The issues evaluated are limited to those related to our areas of expertise — Arctic snow, permafrost, hydrology, and vegetation — but we emphasize that these topics also have broad relevance to wildlife and the people who depend on the area for subsistence and recreation.

We conclude that there will likely be significant, extensive, and long-lasting direct, indirect, and cumulative impacts of 3D-seismic to the microtopography, hydrology, permafrost and vegetation of the 1002 Area. These warrant a more comprehensive environmental review before such activities are allowed in order to understand and mitigate potential long-term consequences through thoughtful planning and discussion. A thorough evaluation in the context of a full Environmental Impact Statement (EIS) should look at the interaction of these impacts with the ongoing and anticipated effects of climate change and the likely development within the 1002 Area that would follow the seismic surveys.

This white paper focuses on the following ten issues:

1. **The seismic plan will create a "checkerboard" of trails across the entire 1002 Area**. The proposed 3D-seismic methods would use fleets of heavy vehicles to create approximately 61,000 km (37,800 miles) of seismic lines spaced at approximately 200 m (660 feet) intervals, that would directly impact an estimated 610 km^2 (150,000 acres) with likely long-term impacts on some substantial fraction of this.
2. **The 1002 Area of the Arctic National Wildlife Refuge is internationally recognized for its intact ecosystems, biological diversity, and its value to wildlife, local people, and the world.** It is one of the most biologically diverse protected areas in the circumpolar Arctic and is highly vulnerable to the impacts of 3D-seismic surveys.
3. **The 1002 Area is significantly different from the Arctic Coastal Plain to the west of it and requires a different approach to seismic exploration.** The area is steeper, more incised, and includes more river systems compared to predominantly flat areas further west where extensive 3D-seismic surveys have been conducted. The different topography strongly affects the snow, hydrology and permafrost regimes of this generally hilly region and increases the potential for significant impacts from seismic exploration.
4. **3D-seismic technology has not been sufficiently developed to prevent significant damage to arctic tundra.** Detailed microtopographic transects across existing 3D-seismic trails show that there is compression of the tundra vegetation mat that is up to 20 cm. These changes to microtopography within the track cause other changes to snow, hydrology, and thermal regimes, which make the tracks visible from the air and set the

stage in some areas for thermokarst and thermal erosion. Changes in the micro-topography and compression of the vegetation mat also would have likely large consequences to habitats of many species of plants, insects, small mammals, and birds.

5. **Snow conditions of the 1002 Area are too heterogeneous to allow for an extensive and regular grid of closely spaced seismic lines.** Generally, low amounts of winter snowfall, strong winter winds, and the hilly terrain in the 1002 Area combine to create substantial areas of very thin and unpredictable snow cover, such that much of this area would be damaged by seismic surveys.
6. **The upper permafrost in the 1002 Area contains large amounts of ground ice, which may result in widespread thermokarst in the seismic trails.** Permafrost conditions within the 1002 Area are relatively understudied compared to other regions of northern Alaska, but it is known that the soils are almost universally ice rich with large thaw-settlement potential. Exceptionally ice-rich silt deposits blanket much of the 1002 Area. Furthermore, climate-related arctic permafrost warming and feedbacks over time will create pathways for flowing water in this steeper terrain, increasing thermokarst and thermal erosion along the tracks left by the seismic survey equipment.
7. **It will be difficult to avoid significant long-term impacts to the tundra vegetation.** Evidence from past seismic surveys in the 1002 Area in the 1980s indicates that there have been long lasting changes to vegetation in the trails. We summarize the impacts from previous 2D-seismic surveys with respect to vehicle type, snow, permafrost, vegetation, and time since disturbance. We also review the existing evidence of impacts from previous 3D-seismic surveys elsewhere.
8. **Camp moves are the most damaging aspect of the 3D-seismic surveys with respect to the terrain and vegetation.** The technology and available equipment used in camp moves has not changed sufficiently to avoid permanent, significant impacts. Bulldozers and strings of heavy sleds are used for the camp moves and create the most damaging impacts. Some of the camp-move trails created during the 1980s are still visible on aerial photographs and satellite images.
9. **It is likely that 3D-seismic impacts will combine with other future impacts related to climate change and infrastructure expansion to create widespread and unpredictable cumulative effects to the terrain and vegetation of the 1002 Area.** Ongoing climate change will exacerbate seismic impacts. Anticipated oil and gas development will also add to seismic impacts, extending them far beyond the currently projected 2000-acre infrastructure footprint. A realistic adaptation strategy should account for cumulative effects of climate change and realistic scenarios of the direct and indirect impacts that would accompany plans for oil- and gas-field exploration, development and production.
10. **Major data gaps need to be filled to permit sound decisions regarding 3D-seismic exploration in the 1002 Area.** These include (1) detailed characterizations of the surficial geomorphology, microtopography, vegetation, snow, and ground ice, which would also serve as the basis for detecting long-term changes; and (2) data regarding the long-term environmental effects of 3D seismic, which are necessary to understand the resistance and resilience of the various terrain and vegetation types to past and future 3D-seismic disturbance.

1 Introduction

The Bureau of Land Management (BLM) has issued a "Coastal Plain Oil and Gas Leasing Program Draft Environmental Impact Statement[1]" (referred to here as the "Draft Leasing EIS") pursuant Public Law 115-97, enacted Dec. 22, 2017 (the "Tax Act") [2]. The "Coastal Plain" area considered in the Draft Leasing EIS is also referred to as the "1002 Area" of the Arctic National Wildlife Refuge (ANWR), which is the term we use throughout this document. The scoping document for the Leasing EIS describes the purpose of the assessment:

> "The Leasing EIS will inform the BLM as it implements the Tax Act, including the requirement to hold multiple lease sales and to permit associated post-lease activities. The program includes **seismic** and drilling exploration, development, and transport of oil and gas in and from the Coastal Plain. Specifically, the **Leasing EIS considers and analyzes the environmental impact of various leasing alternatives**, including the areas that will be offered for sale, and the lease stipulations and required operating procedures to be applied to leases and associated oil and gas activities. **These are intended to properly balance the proposed program with surface resources protection**. The alternatives also **limit the footprint of production and support facilities on federal lands to no more than 2,000 surface acres"**.[3] [Bolding added by the authors to emphasize issues discussed in this paper].

Parties interested in bidding for the leases will likely want modern seismic data to evaluate which tracts to bid on. Towards this anticipated interest, SAExploration Inc., Arctic Slope Regional Corp. (ASRC), and Kaktovik Iñupiat Corp. (KIC) have filed a plan with the BLM for a proposed 3D-seismic survey program in the 1002 Area titled "Marsh Creek 3D",[4] The proposed plan would survey the entire approximately 1.53 million-acre (6327 km^2) 1002 Area beginning in the winter of 2018–2019.

1.1 Intent of this paper

The main goals of this paper are 1) to urge BLM to conduct a comprehensive environmental review of the likely environmental consequences of 3D seismic within the 1002 Area as part of the Final Leasing EIS, and 2) to inform other stakeholders and the public of these potential consequences. We highlight key statements with italics for emphasis.

Based on the authors' knowledge of the 1002 Area, the available literature, and our observations of impacts from previous seismic surveys, the proposed seismic program will have extensive short-term and long-term direct, indirect, and cumulative impacts to the 1002 Area. A thorough review is required in light of what is already known about the detrimental impacts of seismic surveys in the Arctic and to identify gaps in our knowledge. This will help in the development of

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[1] Bureau of Land Management. 2018a. Seismic Exploration of the Coastal Plain. Retrieved from https://eplanning.blm.gov/epl-front-office/eplanning/projectSummary.do?methodName= renderDefault ProjectSummary&projectId=111085

[2] Tax Cuts and Jobs Act of 2017, Public Law 115-97

[3] Bureau of Land Management. 2018b. Coastal plain oil and gas leasing program draft environmental impact statement. Retrieved 21 Dec 2018 from https://eplanning.blm.gov/epl-front-office/projects/nepa/ 102555/164448/200585/Coastal_Plain_Draft_EIS_Volume_1.pdf

[4] SAExploration, Inc. 2018. Marsh Creek 3D plan of operations winter seismic survey. Retrieved from https://eplanning.blm.gov/epl-front-office/projects/nepa/111085/153349/187888/Marsh_Creek_Plan_ of_Operations_Submitted_May2018.pdf

guidelines to assure maximum protection of the terrain and vegetation of the 1002 Area. As stated in the scoping report for the Leasing EIS, seismic activities are part of the overall program of planned exploration and development of the 1002 Area.

1.2 The 3D-seismic plan for the 1002 Area

3D-seismic activities are part of the overall program of planned exploration and development of the 1002 Area. The following descriptions of 3D methods are taken primarily from the BLM action plan for exploration of the coastal plain and the plan of operations submitted by SAExploration Inc.[5] More detailed descriptions of vibroseis seismic methods are in the USFWS report on the 1984–1985 2D-seismic exploration in the 1002 Area,[6] and the National Research Council's 2003 review of cumulative effects of oil and gas development on Alaska's North Slope.[7]

Using the vibroseis method, seismic surveys gather subsurface geological information by recording reflected impulses from artificially generated acoustic waves created by a seismic vibrator pad mounted between the front and rear treads of a large tracked vehicle (Appendix 1, Fig. A1). The vibrator pad (about 1.2 m^2) is lowered to the ground, and vibrations are triggered electronically from a recorder truck. The shock waves travel into the Earth's surface and are reflected off subsurface geological formations. The reflected signals are detected by arrays of vibration detectors (geophones) connected to recorder trucks that receive and record the signals.

It is necessary to survey a grid of closely-spaced seismic source lines and receiver lines in order to create 3D views of the subsurface. *In the proposed 1002-Area survey, both source and receiver lines would be spaced approximately 660 foot (200 m) apart.* Numerous vehicles would move up and down this grid to create the vibroseis signals and to place or move geophones. The vibrator source signals would be taken at 41.25-foot (12.6-m) intervals along source lines, and the recorder trucks and geophones would be spaced at 165 ft (50.2 m) intervals along the receiver lines. *Two teams would conduct the surveys supported by two mobile camps, containing portable housing units, kitchens, and other facilities for approximately 150 workers each.* The camps are moved every 2–3 days as the surveys progress across the tundra.

Impacts to the tundra terrain generated by these two principal types of activities and vehicles include: 1) Grids of seismic trails created by tracked vibrator units, tracked receiver vehicles, geophone carriers, and tracked personnel carriers (Appendix A, Figs. A1–A2); and 2) Camp-move trails created by 8–10 strings of 5–8 camp and fuel sleds pulled by large tractors (Appendix A, Figs. A3–A8). The camp sites are areas of concentrated vehicle trails covering somewhat larger areas.

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[5] Ibid.

[6] Garner, G. W., and P. E. Reynolds. 1986. Surface and seismic exploration. Page 494-522 *in* Arctic National Wildlife Refuge Coastal Plain resource assessment: final report baseline study of the fish, wildlife, and their habitats. U.S. Fish and Wildlife Service, Alaska region, Anchorage, Alaska, US.

[7] National Research Council. 2003. Cumulative environmental effects of oil and gas activities on Alaska's North Slope (p. 183). National Academies Press, Washington, DC, US.

2 Major issues

The authors address ten issues regarding the likely environmental impacts of the planned 3D-seismic program along with detailed explanation of their concerns.

The authors are all scientists who have spent most of their careers in Arctic Alaska, much of them in the Arctic National Wildlife Refuge, studying the ecosystems and environments of the region. We limit our concerns to those related to our areas of expertise — Arctic snow, permafrost, hydrology, and vegetation — but we also emphasize that these topics have broad relevance to the wildlife and the people who depend on the 1002 Area for subsistence and recreation.

2.1 The seismic plan will create a "checkerboard" of trails across the entire 1002 Area.

Figure 1. Grid of trails required to do a 3D-seismic survey to cover the entire 1002 Area at 1300-ft (400-m) intervals.[8]

The Marsh Creek 3D-seismic plan calls for 200-m spacing between the seismic source and receiver lines (twice the density of trails displayed in Figure 1). This would create approximately 61,000 km (37,800 miles) of trails — 30.5 times the approximately 2000 km of trails that were created by the 1984–1985 2D-seismic surveys in the 1002 Area,[9] *which were generally spaced at 5–10-km intervals. If the proposed 200-m spacing is used for the entire 1002 Area, the seismic trails would directly affect approximately 610 km² (150,000 ac) of the approximately 6327 km² (1,563,500 ac) 1002 Area, assuming an average trail width of 10 m.*

The trail locations and spacing could, however, vary depending on the final permitted action. 3D-seismic surveys in northern Alaska typically create grids of trails that are generally at least as dense as those in Figure 1. For example, Figure 2 shows a pair of Radarsat-1 synthetic-aperture radar (SAR) images taken during a wintertime survey south of the Point Lonely DEW Line station. The images show a network of camp-move trails and camps that were used to

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[8] Nolan, M. 2018a. Latest view of 2018 seismic exploration impacts near the 1002 Area. http://fairbanksfodar.com/latest-view-of-2018-seismic-exploration-impacts-near-the-1002-area

[9] Garner and Reynolds 1986

support a survey of 3D-seismic trails spaced at approximately 400 m , which is representative of the spacing indicated by the grid of trails shown in Figure 1. The Marsh Creek 3D plan proposes a grid twice as dense as shown in Fig. 2.

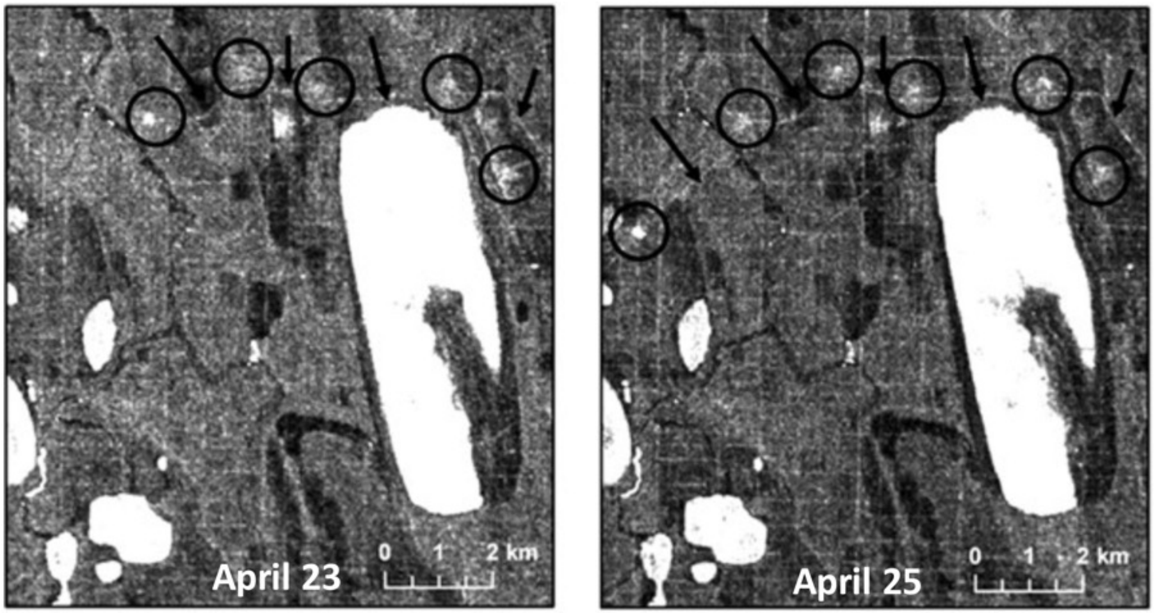

Figure 2. Radarsat-1 SAR images from 23 April and 25 April 2006, showing a faint grid of seismic lines spaced at approximately 400 m, and a progression of camp moves (black circles) associated with a 3D seismic survey near a large elliptical ice-covered lake south of the Lonely DEW Line Station in the NPR-A. A new campsite was added between the 23 and 25 April. Note: the more intense radar signal associated with the camps and camp move trails (black arrow), which corresponds to the generally more intense disturbance caused by these activities.[10]

Seismic surveys create a "checkerboard" of trails clearly visible on aerial photographs. Figure 3 is from a 2018 survey on west side of the Canning River, adjacent to the 1002 Area with seismic lines spaced at 400-m x 200-m intervals. The individual trails are 5–30 m wide. Figure 4 shows a network of seismic trails from a site south of Prudhoe Bay where the trails are spaced only tens of meters apart. In Sections 2.7 and 2.8, we summarize evidence from studies of previous 2D- and 3D-seismic surveys that some of these trails will likely persist for decades.

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[10] Jones, B. M., R., Rykhus, Z. Lu, C. D. Arp, and D. J. Selkowitz. 2008. Radar imaging of winter seismic survey activity in the National Petroleum Reserve-Alaska. Polar Record **44**:227–231 [doi:10.1017/S0032247407007206].

Figure 3. Tracks left by a 3D seismic survey conducted in winter of 2017–2018 on State of Alaska lands along the western boundary of the Arctic National Wildlife Refuge 1002 Area, near the delta of the Canning River. The spacing of the trails is 200 m x 400 m. Top photo shows the grid of trails in early June during snowmelt.[11] *The bottom photo shows the trails in midsummer 2018. Although the trails are much fainter in midsummer, they are easily detected because of several factors compared to the adjacent tundra, including differences in the local microtopography (Fig. 7), the amount of standing-dead plant material, and local hydrology (wetter trails). These differences are likely to persist and have long-term ecosystem consequences that will affect the soils, hydrology, permafrost, and plant species.*[12]

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[11] Nolan, M. 2018b. Detecting tire tracks in the 1002 Area with Fodar. http://fairbanksfodar.com/detecting-tire-tracks-in-the-1002-area-with-fodar

[12] Nolan 2018a

Figure 4. Trails left by the Icewine seismic survey in Spring 2018, approximately 40 km south of the Prudhoe Bay oilfield and 20 km west of the Dalton Highway. The survey consisted of seismic lines spaced 37.5 m to 150 m apart and covered approximately 518 km^2.[13]

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[13] Alaska Department of Natural Resources. 2018. MLUPNS 17-002, Geokinetics Inc., Icewine 2018 3D, Geophysical Exploration Permit Approval. (Letter from Alaska Department of Natural Resources). Retrieved 11 Nov 2018 from http://dog.dnr.alaska.gov/Documents/Permitting/NorthSlope/MLUP/2018/MLUPNS_17-002_Geokinetics_Icewine_2018_3D_GeophysicalExplorationPermitApproval.pdf. Photo courtesy of Heather Buelow.

2.2 The 1002 Area of the Arctic National Wildlife Refuge is internationally recognized for its intact ecosystems, biological diversity, and value to wildlife, local people, and the world.

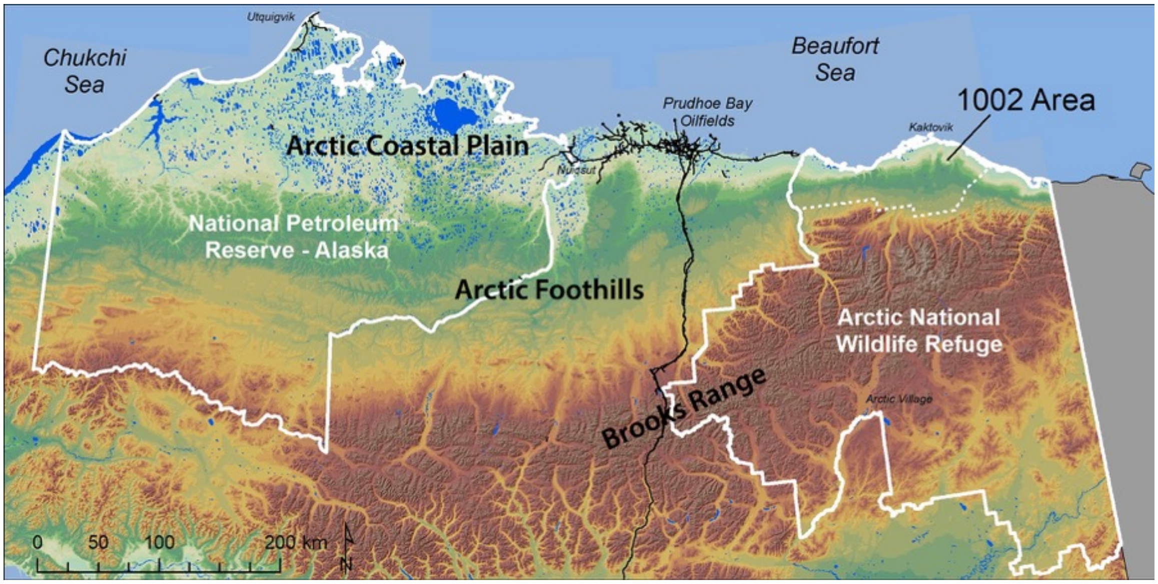

Figure 5. Location of the 1002 Area within the Arctic National Wildlife Refuge (ANWR) and northern Alaska. Note the northward bend in the Brooks Range along the western boundary of the ANWR and the much steeper topographic gradient between the mountains and the Beaufort Sea within the 1002 Area compared to areas further west. This results in a lack of large lakes, dominance of hilly terrain, and limited extent of flat coastal plain within the 1002 Area compared to the northern part of NPR-A and the Prudhoe Bay oil fields.

The landscapes of the 1002 Area are the biological heart of the Arctic National Wildlife Refuge (Fig. 5). *The World Wildlife Fund recognizes this region as having one of the most diverse examples of arctic tundra in the circumpolar Arctic.* The Brooks Range just south of the 1002 Area is the highest mountain range within the circumpolar Arctic with mineral-rich granite and limestone bedrock and glaciers that feed the numerous rivers and floodplains that pass through the 1002 Area. "It is the center of activity for caribou, migratory birds, polar bears, and other wildlife. Together with two Canadian national parks adjoining the refuge, this intact ecosystem protects the migrations of the largest international caribou herd in the world—the Porcupine Caribou Herd—and contains the herd's sensitive birthing and nursery grounds."[14]

While the Tax Act authorized an oil and gas leasing program in the 1002 Area, Congress passed the tax reform bill with assurances that the environmental quality of this region will be maintained. As discussed below, the terrain and vegetation of this region are highly vulnerable to the impacts of 3D-seismic surveys, the cumulative impacts of development that would follow, as well as the impacts of climate change. A more thorough evaluation of potential cumulative

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[14] World Wildlife Fund. Protection of the Arctic National Wildlife Refuge: Key to managing one of the World's most biologically valuable ecoregions, the Arctic Coastal Tundra. Retrieved 13 Oct 2018 from http://web.mit.edu/12.000/www/m2007/teams/editing/Environment/anwr_position.pdf

effects of 3D seismic surveys is needed to understand the full potential consequences of moving forward with seismic.

2.3 The terrain of 1002 Area is significantly different from the Arctic Coastal Plain to the west of it in ways that increase sensitivity to seismic exploration.

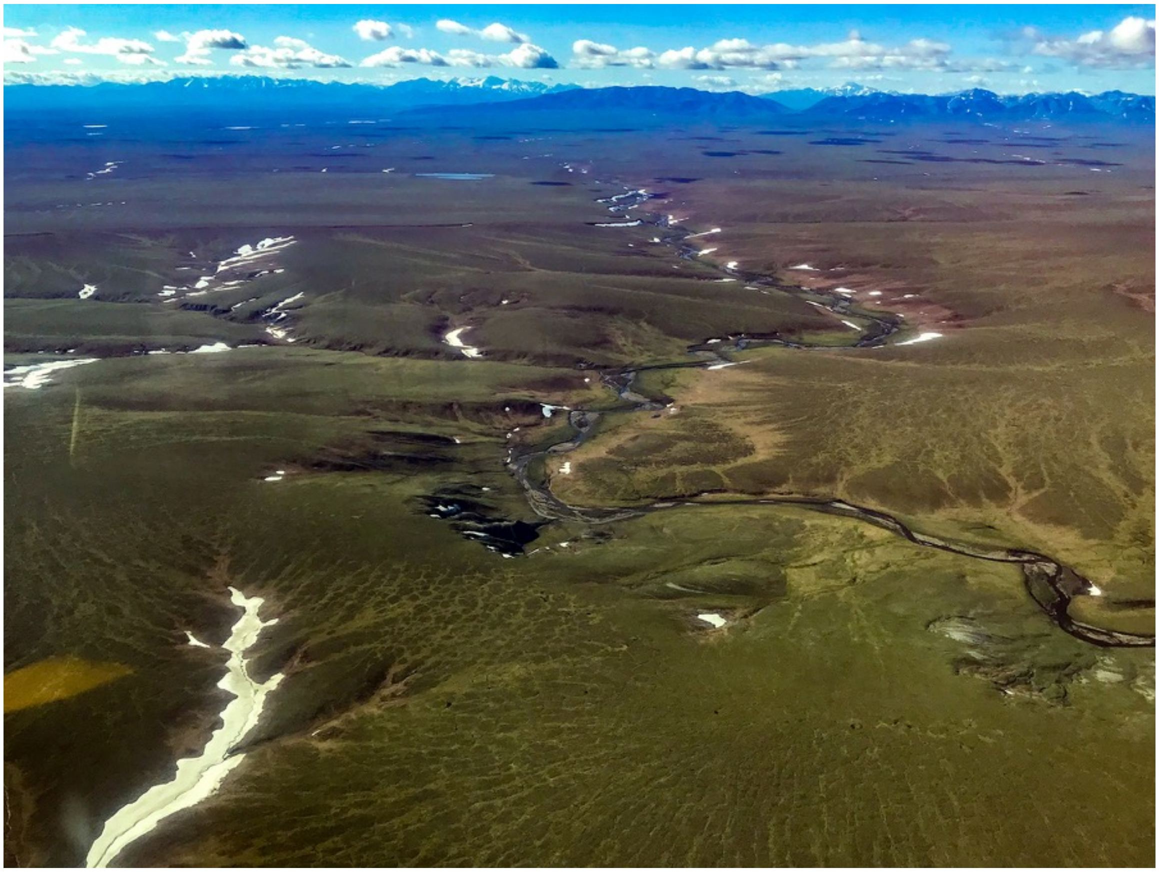

Figure 6. Hilly terrain of the 1002 Area. Snow and hydrology regimes of this area are highly variable and will cause considerable problems for seismic teams as they survey a grid of seismic lines spaced approximately 200 m apart while trying to minimize impacts to the tundra.[15]

The title of the Draft Leasing EIS, "Coastal Plain Oil and Gas Leasing Program Draft Environmental Impact Statement", as well as the maps, descriptions of the physiography, and general script of the Draft EIS create a misperception that the 1002 Area is a generally flat landscape, similar to the coastal plain to the west of the ANWR. Within the Refuge, the Brooks Range takes a broad swing northward to within 30–50 km of the Arctic Ocean (Fig. 5), all but eliminating the flat coastal plains within the 1002 Area. Most of the 1002 Area was originally mapped in 1965 as part of the White Hills Section of the Arctic Coastal Plain[16], which includes the White Hills and Franklin Bluffs and is quite different from the Teshekpuk Lake Section,

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[15] Nolan, M. 2018c. Acquisition of 1002 Area complete! http://fairbanksfodar.com/acquisition-of-1002-area-complete

[16] Wahrhaftig, C. 1965. Physiographic divisions of Alaska. U.S. Geological Survey, Professional Paper 482.

which is dominated by thaw lakes, drained thaw-lake basins, and vast areas of wet low-centered ice-wedge polygons. A 1982 map of the "terrain types" of the 1002 area better portrays the topographic contrasts within the 1002 Area (Appendix 2, Figure A9)[17], which is dominated by foothills (45%) (Fig. 6), hilly coastal plain (22%), and river floodplains and deltas (25%). A small portion of the 1002 Area is part of the Sadlerochit Mountains (0.03%). *Flat thaw-lake plains, such as those typical in the northern portion of the National Petroleum Reserve-Alaska (NPR-A) and the Prudhoe Bay region, comprise only about 3% of the 1002 Area. The steep topographic gradients in the 1002 Area are reflected in the geology, soils, snow regimes, and vegetation that create a mosaic of habitats that allows for the high biological diversity of the region. The rivers and streams draining the mountains form broad braided floodplains and deltas in some areas and deep ravines and gullies in others that also affect snow distribution, hydrology, permafrost and vegetation of the region.*

2.4 3D-seismic-survey technology has not been sufficiently developed to prevent significant damage to the arctic tundra.

Claims have been made that current 3D-seismic methods leave no impact to the tundra. While it is true that compared to impacts from early 2D surveys in the 1960s and 1970s, improved methods have lessened damage to tundra vegetation from individual vehicle passes, there is considerable evidence that 3D-seismic surveys still leave damaged and compressed trails. *The much larger area impacted by proposed trails, larger sizes of vehicles, and difficult terrain assure that the total impacts will be greater during the proposed surveys than during the 1984–1985 2D-seismic surveys.* The vibrator units (Appendix A, Fig. A1) and camp-move vehicles (Appendix A, Figs. A3–A9) are of particular concern because of their large size, high ground pressures, and the fact that 3D techniques require larger crews in more vehicles.

To illustrate the impacts of current seismic methods, we examined trails left by a 2018 3D-seismic survey just west of the 1002 Area along the Canning River (Figs. 3 and 7). The trails are clearly delineated by snow that remained in the track depressions after snow melted from areas between the trails. Late summer images of the same area show no snow and a grid of faint but clear trails.[18] Figure 7 (top aerial photo) shows a representative microtopographic transect (red line) across one of the trails shown in Figure 4. *Microtopography within the seismic line is depressed about 20 cm below the minimum levels on either side of the seismic line (Fig. 7, bottom chart). Microtopographic variability within the trail is also much less than variability on either side of the trail (10–25 cm within the trail compared to 20–40 cm on both sides of the trail). A more statistically rigorous evaluation is needed to fully evaluate the range and variability of impacts of past 3-D surveys in different snow conditions, terrain types, surface-landform types, and vegetation types.*

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[17] Walker, D. A., W. Acevedo, K. R. Everett, L. Gaydos, J. Brown, and P. J. Webber. 1982. Landsat-assisted environmental mapping in the Arctic National Wildlife Refuge, Alaska. CRREL Report 82-37. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, US.

[18] Fountain, H. 2018. How oil exploration cut a grid of scars into Alaska's Wilderness. New York Times. Retrieved from https://www.nytimes.com/2018/08/03/climate/alaska-anwr-seismic-testing-tracks.html

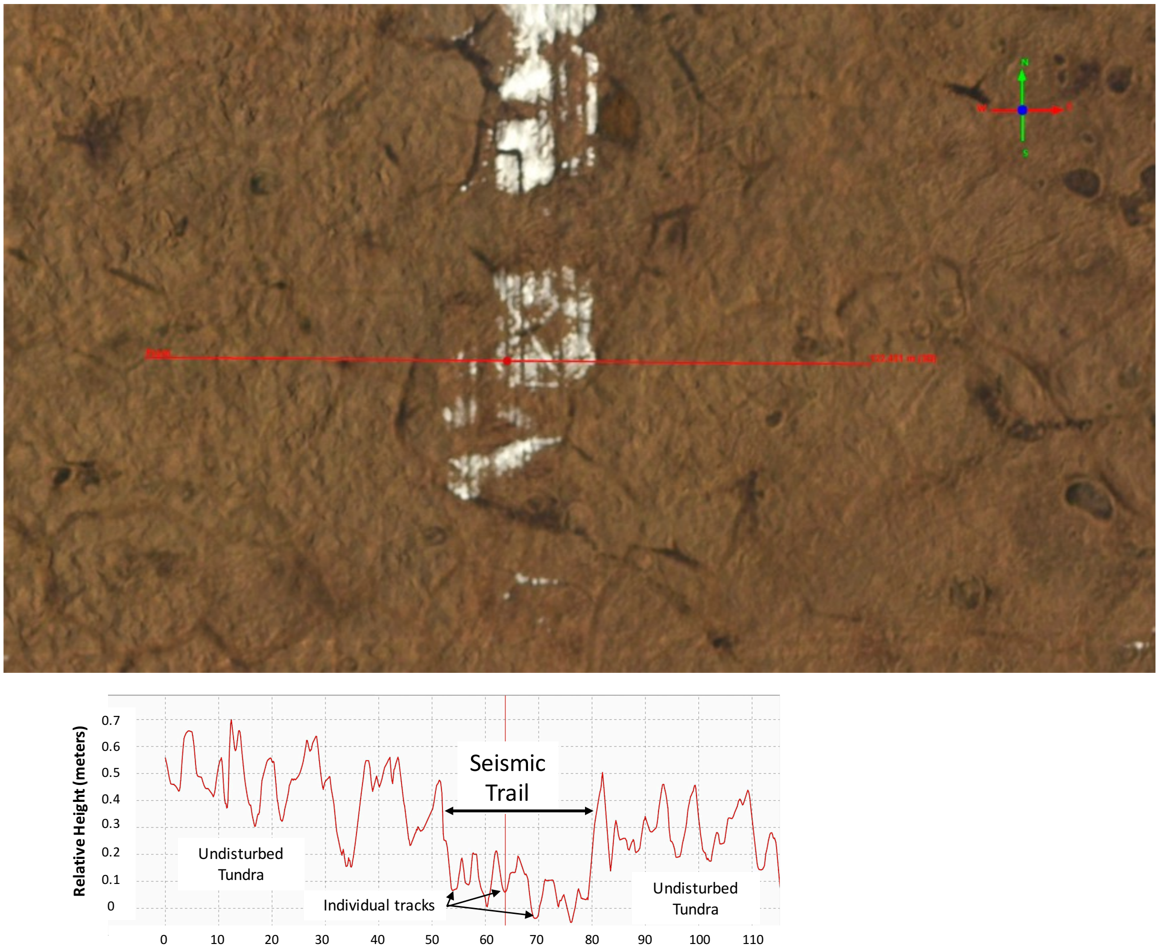

Figure 7. An airborne photogrammetric analysis of compression of tundra surface in one of the seismic lines from a 2018 3D-seismic survey near the Canning River (Fig. 3). The ***upper aerial orthophoto*** *shows a corridor of vehicle trails with compacted late-melting snow and several deep tracks left by numerous tracked vehicles. The horizontal red line denotes a 115-m digital topographic transect used to extract elevations from the digital elevation model created to study these impacts. The transect includes approximately 50 m of undisturbed tundra on the left side and 35 m on the right side of the 30-m wide seismic line. The red dot denotes the center of the seismic line at approximately 63 m along the transect. The* ***lower chart*** *shows the elevations along the 115-m transect. The spacing of the horizontal gridlines depicting microtopographic variation is 10 cm, and the spacing of the vertical gridlines depicting distance along the transect is 10 m. The vertical red line corresponds to the elevation at the approximate center of the seismic line at the red dot. There are approximately 20–40 cm of topographic variability associated with moss hummocks, tussocks, and ice-wedge polygon rims and troughs on both sides of the seismic line. Within the seismic trail, the tundra is compressed approximately 20 cm below the adjacent level on either side of the trail and generally has approximately 10–25 cm of topographic relief from individual vehicle tracks.*[19]

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[19] Nolan 2018b

Why do these difference in microtopography matter? Studies at Prudhoe Bay,[20] Toolik Lake,[21] Barrow,[22] and elsewhere[23] have shown that variations in microtopography account for much of the variation in biological diversity and ecosystem function of tundra landscapes. *Compressing the tundra eliminates much of the microtopographic diversity, which is important to the distribution of numerous plant species, insects, small mammals, and birds. The depressions can change the character of vegetated surfaces by compressing the snow and tundra, leading to increased snow accumulation in the tracks. During the spring lingering snow and water in the trails can promote ponding of water on the tundra surface, and channel water along the tracks. This alters the micro-surface energy balance, which affects the active-layer and permafrost conditions. In some sensitive landscapes, this can trigger melting of ice in the permafrost[24] leading to thermokarst and thermal erosion of the trails* (explained further in Section 2.6).

Water tables are near to the surface even on slopes over 5%. A naturally uneven permafrost table that is close to the tundra surface often acts as a barrier to down-hill water drainage. *Small meso- and micro-topographic differences affect a wide range of environmental factors that raise serious concerns about the overall sensitivity and response of the landscape to 3D-seismic surveys.* How will the perched wetlands of the 1002 Area, separated by only decimeters to meters, be affected by a gridwork of shallow seismic trails, centimeters to decimeters deep? Will this lead to new surface drainage networks that will effectively drain these wetlands and therefore change this habitat? Are the criteria and stipulations used for determining significant impacts in NPR-A and flatter portions of the Arctic Coastal Plain west of ANWR suitable in the much different landscapes of the 1002 Area? We have seen no studies addressing these concerns about potentially serious impacts.

2.5 Snow conditions in the 1002 Area are too heterogeneous to allow for an extensive and regularly spaced network of seismic lines.

The 1002 Area has seen little systematic study of the snow cover. Here we discuss what we do know about the spatial and temporal trends in snow cover as this relates directly to

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[20] Walker, D. A. 1985. Vegetation and environmental gradients of the Prudhoe Bay region, Alaska. CRREL Report 85-14. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, US.

[21] Chapin, F. S. I., K. Van Cleve, and M. C. Chapin. 1979. Soil temperature and nutrient cycling in the tussock growth form of *Eriophorum vaginatum*. Journal of Ecology **67**:169–189.

[22] Zona, D., D. A. Lipson, R. C. Zulueta, S. F. Oberbauer, and W. C. Oechel. 2011. Microtopographic controls on ecosystem functioning in the Arctic Coastal Plain. Journal of Geophysical Research Atmospheres **116**: 3128 [doi:10.1029/2009JG001241].

[23] Ohlson, M., and B. Dahlberg. 1991. Rate of peat increment in hummock and lawn communities on Swedish mires during the last 150 Years. Oikos **61**:369 [doi:10.2307/3545244].

[24] Jones B. M., C. L. Amundson, J. C. Koch, and G. Grosse. 2013. Thermokarst and thaw-related landscape dynamics: annotated bibliography with an emphasis on potential effects on habitat and wildlife. US Geological Survey Open-File Report **2013-1161**:60.

whether or not the areas affected by proposed seismic surveys will have sufficient snow cover to protect the tundra.[25],[26],[27]

Routine monitoring in the region has suffered from changing stations and data gaps. A 41-yr (1948–1989) period of continuous measurements from Kaktovik shows annual maximum snow depths varying from 20 to 120 cm (Fig. 8), a six-fold variation that probably reflects as much the difficulty of measuring snow in this windy region as any true variations in the snow cover. Nonetheless, the record is the only long-term one available from the 1002 Area.

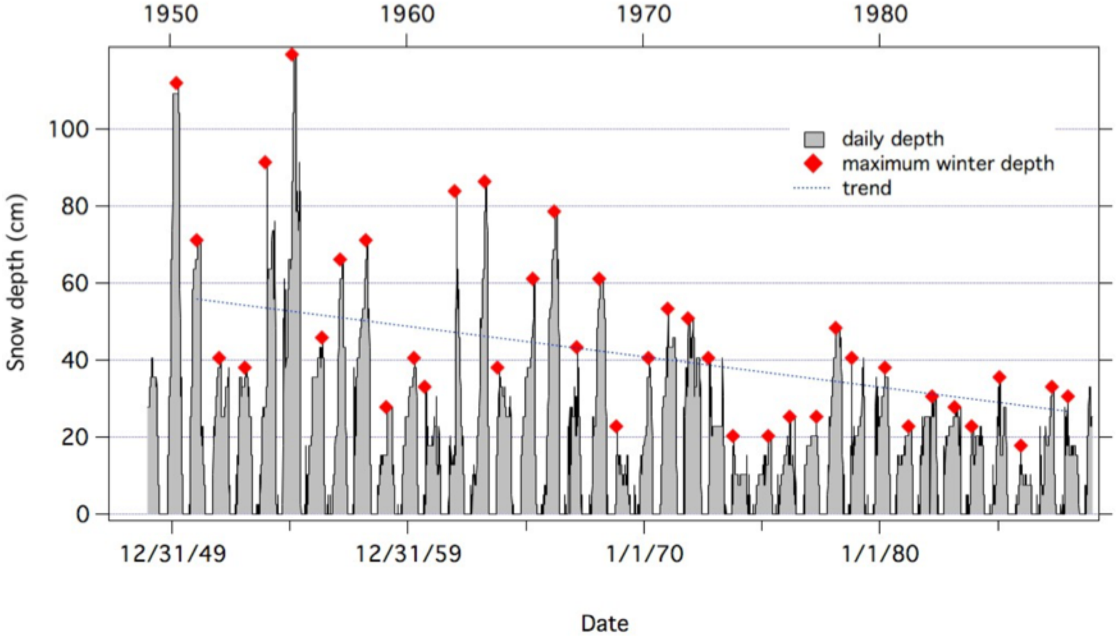

Figure 8. Snow depth records from Kaktovik Alaska, 1948-1988. (National Weather Service records).

Snow distribution measurements were also made in 1984 and 1985 during the initial seismic exploration,[28] and in 2014 new snow studies were begun.[29] The former study showed that snow depths in excess of 25 cm produced better protection of the underlying tundra than shallower snow depths. Wind-slab snow was much denser and an even better predictor of protection. Slab snow was found in large drift deposits in the cut banks and bluffs that are common throughout this area (see further discussion of vegetation-snow relationships in Section 2.7).

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[25] Nolan, M., C. Larsen, and M. Sturm. 2015. Mapping snow depth from manned aircraft on landscape scales at centimeter resolution using structure-from-motion photogrammetry. The Cryosphere **9**:1445-1463 [doi:10.5194/tc-9-1445-2015].

[26] Felix, N. A., and M. K. Raynolds. 1989a. The role of snow cover in limiting surface disturbance caused by winter seismic exploration. Arctic **42**:62–68.

[27] Urban, F. E., and G. D. Clow. 2018. DOI/GTN-P climate and active-layer data acquired in the National Petroleum Reserve–Alaska and the Arctic National Wildlife Refuge, 1998–2016. Data Series 1092, U.S. Geological Survey [doi:10.3133/ds1092]. [Supersedes USGS Data Series 1021.]

[28] Felix and Raynolds 1989a

[29] Nolan et al. 2015

Consistent, continuous, accurate records are needed for the 1002 Area. The only additional snow information available comes from the public data produced by the weather stations operated by the USGS,[30] where wind speed and local snow depth have been collected by autonomous instruments. Unfortunately, no overlap exists between the older weather records and new data being collected by the USGS at its three climate monitoring stations in the Arctic National Wildlife Refuge, hence identifying any recent trends in snow depth is not possible, though the data still indicate a similar level of variability. This difficulty highlights the need for long-term field-based monitoring of basic climatic parameters including snow depth. While sonic depth-sounder measurements (which record depth rather than snow-water equivalent) offer an inexpensive way to monitor the snow, unshielded gauges like these are notoriously inaccurate and can report a station as a drift one year and a scour zone the next. Some recent papers have suggested that with the reduction in Arctic Ocean sea ice, there should be an increase in October–December precipitation[31],[32],[33] but other predictions are that the increased precipitation will fall mainly as rain.[34]. *What we do know about snow in the 1002 Area is that it is generally thin (<50 cm) with large areas of wind-scour with even less snow in mid-winter and large drifts 2–5 m deep along the banks of the incised streams and rivers.*

The spatial distribution of the snow cover reflects the power of the wind in this region. A photogrammetrically produced snow-depth map from April 2018, made by subtracting a digital elevation model (DEM) of the summer ground surface from a winter snow surface[35], demonstrates the range of snow depths (Fig. 9) and the lack of sufficient snow cover for the proposed seismic work. The map was created in April 2018 using methods described here at a nearby location showing similar results and validated using ground measurements of snow depth collected within that study area.

When examining the map, it is important to note that the all-time deepest snow recorded for the area occurred in 2018, yet vast areas of this study area were snow free in 2018 and even larger areas had less snow than the current Alaska Division of Natural Resources (ADNR) permit guidelines of 23 cm (9 in) for any off-road vehicle travel over snow in state-owned North Slope foothills. From the map, it is apparent that drifts in excess of 100 cm depth (blue) are found immediately adjacent to scoured areas where the snow depth is less than 25 cm deep (red and orange). In fact, it is best to think of these thin and thick areas of snow as conjugates, produced by wind removing snow from large areas of tundra and depositing it in much smaller areas of riparian zones.

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[30] Urban and Clow 2018

[31] Higgins, M. E., and J. J. Cassano. 2011. Northern Alaskan land surface response to reduced Arctic sea ice extent. Climate Dynamics **38**:2099–2113 [doi:10.1007/s00382-011-1095-0].

[32] Carne, A. R. 2017. The impact of reduced arctic sea ice extent on cryospheric snowfall. M.S. thesis, University of Nebraska, Lincoln, US.

[33] Cai L., V. A. Alexeev, C. D. Arp, B. M. Jones, A. K. Liljedahl, and A. Gädeke. 2018. The Polar WRF Downscaled Historical and Projected Twenty-First Century Climate for the Coast and Foothills of Arctic Alaska. Frontiers of Earth Science **5**:111 [doi:10.3389/feart.2017.00111].

[34] Bintanja, R., and O. Andry. 2017. Towards a rain-dominated Arctic. Nature Climate Change **7**:263–267 [doi:10.1038/nclimate3240].

[35] Nolan et al. 2015

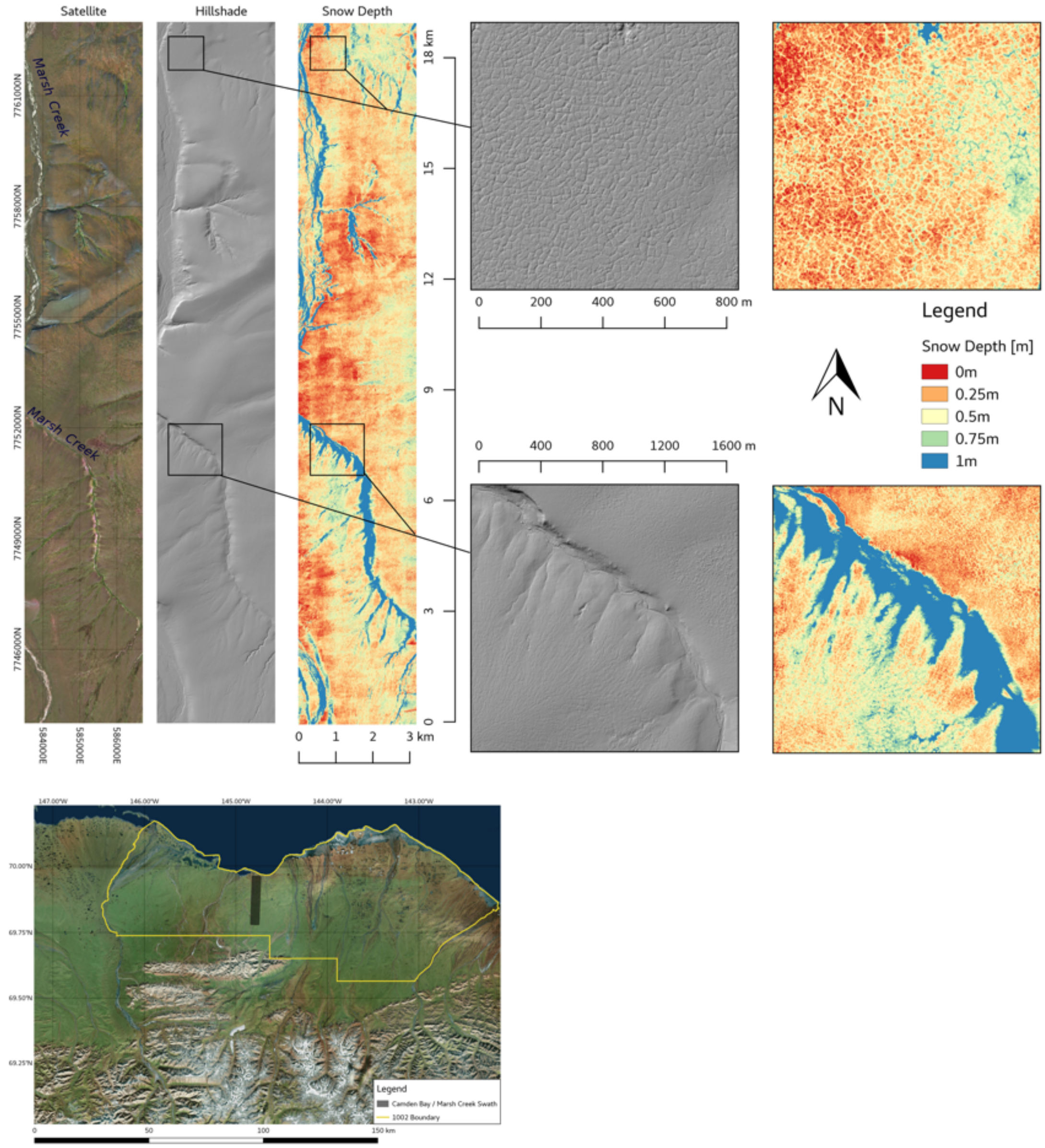

Figure 9. Topography, snow-depth, and terrain of a 6-km x 24-km area centered on Marsh Creek in the 1002 Area[36]. The snow map was created using structure-from-motion techniques[37]. The black rectangle in the bottom figure shows the location of the study area within the 1002 Area. Note on both high-resolution inset maps the pattern of deep snow (>1 m depth, blue color) in creek channels and shallow snow (0–50 cm red to yellow colors) on the creek bluffs. High-centered ice-wedge polygons with very shallow snow are abundant along the creek bluffs and extend more than 3 km upwind on the (east) side of the creek with no snow to shallow snow (< 25 cm, red to orange colors) on the raised polygon centers and somewhat deeper snow (to 50 cm, yellow colors) in the polygon troughs. The areas with <25 cm of snow are particularly susceptible to high disturbance by 3D-seismic surveys.

While an in-depth analysis of winter wind speeds in the 1002 Area has not been done, there is a common understanding that blizzard winds are stronger in this eastern part of the North Slope than farther west in the NPR-A. *Currently, we lack comprehensive records of where scour*

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[36] Figure by Charles Parr and Matthew Sturm.

[37] Nolan et al. 2015

and drift are most or least intense, and we have little information on how often excessive scour takes place in winter and how widespread it is when it does occur, nor how a variety of snow-related factors may be affected by rapid climate change. (See Section 2.7 for discussion of vegetation-snow relationships and the depth of snow needed to protect the tundra.) We do know that areas such as those shown in Figs. 9 and 10 are not unique within the 1002 Area and that even in high-snow years there is simply no way a 200 m x 200 m grid of trails can be established to avoid zones with too little snow to protect the tundra.

Figure 10 was photographed in April of 2017, a year with less snow and more wind than 2018. The view is northeast from the Hulahula River across the 1002 Area. It is evident that 9 inches (23 cm) of snow does not exist in most of the field of view, nor is there a route through this area with snow sufficient to meet the minimum requirement for any over-snow vehicle operation in state-owned Arctic Foothills.[38] Even in the heavy snow year of 2018, the 9-inch minimum was not met over large parts of the mapped area (orange areas in Fig. 9). *Spatial snow distribution studies are needed to clarify the extent and frequency of snow scour in the 1002 Area.*

Figure 10. Aerial photo taken in April 2017 looking NE from the Hulahula River showing extensive areas of wind scour over most of the image, especially along ridge lines and topographic high points. Shallow snow drifts, generally less than 1 m deep, occur in a few shallow drainage channels and other depressions.

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[38] Alaska Department of Natural Resources. 2015. Fact Sheet: off-road travel on the North Slope on state land. Retrieved 29 Dec 2018 from http://dnr.alaska.gov/mlw/factsht/land_fs/off-road_travel.pdf

2.6 The upper permafrost in the 1002 Area contains large amounts of ground ice, which may result in widespread thermokarst in the seismic trails.

The presence of permafrost greatly increases the complexity of ecological responses to disturbance in the Arctic. Protection of the underlying permafrost is, thus, a key consideration for any activity that could alter the insulative layer of vegetation[39],[40]. During early seismic activities in the 1960s, the tundra mat was bulldozed, which exposed the tops of the ice wedges to rapid melting and extensive thermokarst formation (Fig. 11). *Thermokarst* refers to the process by which characteristic landforms, such as thermokarst pits, ponds, and thaw lakes, form as a result of permafrost thaw and the subsidence of the land surface (thaw settlement). *Thermal erosion* refers to processes where flowing water is involved in the thawing and removal of ice-rich materials resulting in forms such as thermo-erosional gullies.[41]

Large near-surface ice wedges are extremely vulnerable to thermokarst and thermal erosion.[42],[43],[44] Rapid climate change or surface disturbance may cause ice-wedge degradation and formation of ponds in areas with flat terrain. In the foothills, deep gullies may form very fast as a result of thermal erosion along ice wedges. The formation of deep troughs between ice-wedges occur as the tops of ice wedges thaw, and these deepend troughs can serve as efficient new drainage networks[45] or sites for ponded water to collect as in Figures 11 and 13. For example, rapid development of new drainage systems occurred in ice-wedge-polygon tundra with a gentle 0.6° slope, at rates of up to 5 m/day, creating a 750-m-long and 4-m-deep gully system in four years at a site with a mean annual temperature of -15 °C.[46] Increased precipitation is also documented to destabilize ice-rich permafrost terrain.[47]

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[39] Jorgenson, M. T., V. Romanovsky, J. Harden, Y. Shur, J. O'Donnell, E. A. G. Shuur, M. Kanevskiy, and S. Marchenko. 2010. Resilience and vulnerability of permafrost to climate change. Canadian Journal of Forest Research **40**:1219–1236.

[40] Jorgenson, M. T., M. Z. Kanevskiy, Y. Shur, N. G. Moskalenko, D. R. N. Brown, K. Wickland, R. Striegl, and J. Koch. 2015. Role of ground ice dynamics and ecological feedbacks in recent ice wedge degradation and stabilization. Journal of Geophysical Research: Earth Surface **120**:2280–2297 [doi:10.1002/2015JF003602].

[41] Jones *et al.* 2013

[42] Jorgenson, M. T., Y. L. Shur, and E. R. Pullman. 2006. Abrupt increase in permafrost degradation in Arctic Alaska. Geophysical Research Letters **25**:L02503.

[43] M. T. Jorgenson *et al.* 2015

[44] Kanevskiy, M., Y. Shur, T. Jorgenson, D. R. N. Brown, N. G. Moskalenko, J. Brown, D. A. Walker, M. K. Raynolds, and M. Buchhorn. 2017. Degradation and stabilization of ice wedges: implications for assessing risk of thermokarst in northern Alaska. Geomorphology **297**:20-42 [doi:10.1016/j.geomorph.2017.09.001].

[45] Liljedahl, A. K., *et al.* 2016. Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. Nature Geoscience **9**:312–318 [doi:10.1038/ngeo2674].

[46] Fortier, D., M. Allard, and Y. Shur. 2007. Observation of Rapid Drainage System Development by Thermal Erosion of Ice Wedges on Bylot Island, Canadian Arctic Archipelago. Permafrost and Periglacial Processes **18**:229-243 [doi:10.1002/ppp.595].

[47] Kokelj, S. V., J. Tunnicliffe, D. Lacelle, T. C. Lantz, K. S. Chin, and R. Fraser. 2015. Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. Global and Planetary Change **129**:56-68.

Figure 11. One of many bladed tractor trails just west of the Canning River left from seismic exploration in the 1960s, photographed in 2018. Note the extensive thermokarst and ponding of water along the trail and around the gravel drilling pad near the center of the photo.[48]

Although the invasive seismic practices that created the impacts seen in Figure 11 no longer occur, thermokarst and thermal erosion initiated by old seismic activity continue, as observed in long-term studies of the 1984–1985 2D-seismic surveys in the 1002 Area (see section 2.7).

While less damaging, vehicle tracks from 3D-seismic surveys can initiate similar processes due to the impacts on the ground surface topography and soil thermal regime even without changes in air temperature and precipitation. *As shown in Figure 7, the heavy vehicles used in 3D-seismic surveys leave shallow depressions that collect snow and surface water. These seemingly minor disturbances can initiate thaw settlement and lead to water impoundment, decreased surface albedo, and increased heat flux, which in turn cause increases in the active-layer thickness and subsequent thaw settlement.*[49]

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[48] Nolan, M. 2018a

[49] Lawson, D. E. 1986. Response of permafrost terrain to disturbance: a synthesis of observations from northern Alaska, US. Arctic and Alpine Research **18**:1-17.

Figure 12. Ice wedge at the Beaufort Sea coast, northern Alaska. Wedge ice is one of the most common forms of massive ground ice in permafrost, which is responsible for the prominent ice-wedge polygons visible in aerial photographs of the region. Good examples of ice-wedge polygons are visible in Figures 3, 4, 7, and 13. This ice wedge is approximately 4 m deep and over 5 m wide at the top. A warming climate is causing loss of ice at the top surface of ice wedges on most upland surfaces of the 1002 Area, resulting in thermokarst pits such as those shown in Figure 13. Disturbance to the microtopography and vegetation mat can exacerbate thermokarst and lead to thermal erosion, greater loss of ice, and major landscape changes.[50]

Increased hydrologic connectivity due to new drainage networks can produce impacts to the landscape beyond the initial disturbance area as the trough or gully systems continue to expand. Accordingly, *the ground compaction by seismic vehicles, combined with the projected increases in temperatures and precipitation for the region, increase the risks for long-term hydrological impacts and widespread destabilization of ice-rich permafrost terrain.*

Disturbance to permafrost from seismic exploration is a substantial concern because the upper layer of permafrost just below the seasonally-thawed active layer tends to be extremely ice rich with large thaw-settlement potential[51],[52],[53] (Fig. 12). Ice content of the permafrost, and

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[50] Photo: M. Kanevskiy

[51] Pullman, E. R., M. T. Jorgenson and Y. Shur. 2007. Thaw settlement in soils of the Arctic Coastal Plain, Alaska. Arctic, Antarctic, and Alpine Research **39**:468-476.

[52] M. T. Jorgenson *et al.* 2015

[53] Kanevskiy, M., Y. Shur, M. T. Jorgenson, C. L. Ping, G. J. Michaelson, D. Fortier, E. Stephani, M. Dillon, and V. E. Tumskoy. 2013. Ground ice in the upper permafrost of the Beaufort Sea coast of Alaska. Cold Regions Science and Technology **85**:56–70 [doi:10.1016/j.coldregions.2012.08.002].

therefore the potential for thaw subsidence, varies greatly between areas.[54] Permafrost characteristics are still inadequately studied in the 1002 Area. The permafrost conditions are much better documented in the central portion of the Beaufort Coastal Plain by environmental studies associated with oil development in the Colville River delta and the eastern NPR-A, where the total ground-ice volume (including wedge ice, pore ice, and lenses of segregated ice) in the upper permafrost often exceeds 70% of the soil volume. Moderate surface disturbance in these areas can lead to seasonal thaw depths increasing to an equilibrium depth of 80 cm with typical thaw settlement potential of 10–40 cm depending on terrain type.

But the 1002 Areas are substantially different fom areas to the west. Extremely ice-rich, wind-blown silt deposits, called *yedoma*, that are abundant throughout the 1002 Area (Fig. 13). These deposits can be more than 40 m thick and contain large ice wedges that span the whole yedoma sequence with potential thaw settlement of 10–20 m or more if the deposits were to thaw completely.[55],[56] While disturbance from winter seismic exploration is highly unlikely to lead to complete degradation of yedoma, there is a high potential for partial thawing of ice wedges with formation of deep troughs and development of active-layer-detachment slides on slopes, as occurred after fire in the Anaktuvuk River area[57]. *The extremely high ice content of yedoma is of special concern, and its distribution and characteristics have not been evaluated in the 1002 Area. Degradation of ice wedges in yedoma deposits and other ice-rich deposits caused by thermokarst and/or thermal erosion can result in extensive ecosystem changes, can pose dangers to infrastructure, and can be very difficult—if not impossible—to mitigate.*

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[54] National Research Council 2003, p. 65

[55] Kanevskiy, M., Y. Shur, D. Fortier, M. T. Jorgenson, and E. Stephani. 2011. Cryostratigraphy of late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure. Quaternary Research **75**:584-596 [doi:10.1016/j.yqres.2010.12.003].

[56] Schirrmeister, L., D. Froese, V. Tumskoy, G. Grosse, and S. Wetterich. 2013. Yedoma: Late Pleistocene ice-rich syngenetic permafrost of Beringia. Encyclopedia of Quaternary Science, 2nd Edition **3**:542–552.

[57] Jones, B. M., G. Grosse, C. D. Arp, E. Miller, L. Liu, D. J. Hayes, and C. F. Larsen. 2015. Recent Arctic tundra fire initiates widespread thermokarst development. Scientific Reports **5** [doi:10.1038/srep15865].

Figure 13. Thermokarst pits in undisturbed ice-rich probable yedoma terrain of the 1002 Area east of the Jago River. The numerous small thermokarst ponds are caused by melting of the upper surface of ice wedges that separate the ice-wedge polygons. Thermokarst such as this has recently become widespread across large areas of undisturbed tundra in northern Alaska, and is now very common on upland surfaces of the 1002 Area.[58]

Rapid climate change has resulted in significant warming of the permafrost in northern Alaska. North Slope permafrost borehole temperatures at 20-m depth have increased steadily since about 1990 and show some of the strongest increases anywhere in the Arctic. For example, permafrost temperatures at Deadhorse increased 3 ˚C between 1977 and 2016.[59] Data from a borehole at Kaktovik indicate a warming of about 2–3 ˚C from 1985 to 2004.[60]

In recent years, ice-wedge thermokarst has become much more widespread in undisturbed tundra landscapes across the circumpolar Arctic that correspond to recent increases in permafrost temperatures,*[61]. Ice-wedge degradation with flooded thaw pits became common after about 1990 in the central and eastern parts of the North Slope. and is also seen in the*

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[58] Nolan 2018a

[59] Romanovsky, V. E., S. L. Smith, K. Isaksen, N. I. Shiklomanov, D. A. Streletskiy, A. L. Kholodov, et al. 2017. Terrestrial permafrost. *In*: Arctic Report Card Update for 2016. Retrieved from https://www.arctic.noaa.gov/Report-Card/Report-Card-2017/ArtMID/7798/ArticleID/694/Terrestrial-Permafrost

[60] Osterkamp, T. E., and J. C. Jorgenson. 2006. Warming of permafrost in the Arctic National Wildlife Refuge, Alaska. Permafrost and Periglacial Processes **17**:65–69 [doi:10.1002/ppp.538].

[61] Liljedahl *et al.* 2016

landscapes of the 1002 Area (Fig. 13). Ice-wedge degradation started earlier in portions of the Arctic Coastal Plain west of the Colville River.[62] The likely reasons for the differences in the timing of the onset of widespread ice-wedge degradation include differences in ground-ice content, regional climate gradients from west (maritime) to east (continental), and regional differences in the timing and magnitude of extreme warm summers after the Little Ice Age. *At present, it is not known how future seismic activities will affect these regional thermokarst patterns, but it can be assumed that the landscapes will be much more heterogeneous than they were during the 1980s and that ice wedges will be more sensitive to degradation.*

2.7 It will be difficult to impossible to avoid significant long-term impacts to the tundra vegetation from the proposed 3D-seismic plan.

Most of the known effects of seismic exploration to tundra vegetation come from US Fish and Wildlife Service studies of trails that were left from the 1984–1985 seismic surveys in the 1002 Area. USFWS personnel accompanied the seismic teams during winter and established long-term study plots to observe the snow conditions and impacts[63],[64],[65] and then followed up with periodic observations of recovery that continued to 2018. *Although the effects of individual seismic trails generally were at low levels, nearly a third of the trails had initial medium to high levels of disturbance. The long-term effects are extensive when the entire network of trails is considered and vary greatly in relationship to snow cover, permafrost conditions, site moisture, microtopography, and vegetation characteristics.*[66] This section summarizes vegetation impacts with respect to vehicle type, snow, permafrost, vegetation type, and recovery time since disturbance.

Vehicle types: Table 1 summarizes vehicles used historically and currently for seismic surveys in northern Alaska. *Camp move trails were made by vehicles with higher ground pressure than seismic lines and had more initial damage and slower recovery.*[67]

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[62] Frost, G. V., T. Christopherson, M. T. Jorgenson, A. K. Liljedahl, M. J. Macander, D. A. Walker, and A. F. Wells. 2018. Regional patterns and asynchronous onset of ice-wedge degradation since the mid-20th century in arctic Alaska. Remote Sensing **10**:1312. [doi:10.3390/rs10081312].

[63] Felix, N. A., and M. K. Raynolds. 1989b. The effects of winter seismic trails on tundra vegetation in northeastern Alaska, US. Arctic and Alpine Research **21**:188-202.

[64] Felix, N. A., and M. T. Jorgenson. 1984. Effects of winter seismic exploration on the coastal plain of the Arctic National Wildlife Refuge, Alaska. Arctic National Wildlife Refuge, U.S. Fish and Wildlife Service, Fairbanks, Alaska, US.

[65] Felix, N. A, M. K. Raynolds, J. C. Jorgenson, and K. E. DuBois. 1992. Resistance and resilience of tundra plant communities to disturbance by winter seismic vehicles. Arctic and Alpine Research **24**:69-77.

[66] Jorgenson, J. C., J. M. Ver Hoef, and M. T. Jorgenson. 2010. Long-term recovery patterns of arctic tundra after winter seismic exploration. Ecological Applications **20**:205–221 [doi:10.1890/08-1856.1].

[67] Ibid.

Table 1. Seismic survey vehicle, ground pressure (psi, pounds per square inch) and number of units for one survey crew. Two crews operating at one time are proposed for the 2019 survey in the 1002 Area. Data are summarized from Jorgenson et al. *(2003)*[68] *plus 2017 from table in BLM's Greater Moose's Tooth EA (2016) and 2019 from table in SAE Plan of Operations for ANWR (2018).*[69] *Ground pressure values are probably for empty vehicles, for example fuel tanks without fuel.*

Vehicle type	psi	1984	1985	1996	1999	2000	2001	2017	2019
		ANWR 2D	ANWR 2D	COLVILLE 3D	NPR-A 3D	W OF COLVILLE 3D	W OF COLVILLE 3D	NPR-A GMT 3D	ANWR 3D
Camp vehicles									
D7 Caterpillar tractor	10.3 psi	6	6	6	4	4	3	4	2
Challenger or Case tractor	4.5 psi	0	0	0	0	0	1	10	9
Camp sled on skis	6 psi	14	12	~20	~25	24	33	38	~50
Caterpillar 977 Loader	10 psi	0	0	0	2	2	1	1	1
Nodwell with crane	3 psi	1	1	0	0	0	0	0	0
Fuel tanks on vehicles or sleds	6 - 8 psi	3 to 6	4	3	3	2	7	8	11
Vibrators & other vehicles for line work & crew transport									
psi <5	1 - 5 psi	23	20	16	18	16	2	34	38
psi >5	8 - 15 psi	0	0	2	8	6	10	12	12
TOTAL # OF UNITS-APPROXIMATE		48	43	47	60	54	57	107	~123

Impacts caused by exploration during the 1980s are still relevant today because medium to high levels of damage from seismic exploration are still occurring. While there have been some improvements in vehicles, fleet sizes for current exploration more than double those of previous surveys and many vehicles are heavier. A study of impacts to upland tundra from current exploration on the MacKenzie River Delta, Canada, reported that initial impacts are similar to or somewhat greater than those reported from 2D surveys in the same area 30 years previously.[70],[71] *A recent BLM Environmental Assessment for seismic surveys in northern Alaska stated that "seismic exploration may vary from having no observable effects in some situations to damaging vegetation to the extent that it may take years or even decades to heal. These impacts occur despite existing stipulations on operations, and cannot be further mitigated, given the types of equipment currently used."*[72]

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[68] Jorgenson, M. T., J. E. Roth, T. C. Cater, S. F. Schlentner, M. J. Emers, and J. S. Mitchell. 2003. Ecological impacts associated with seismic exploration on the central Arctic Coastal Plain. Final Report for ConocoPhillips Alaska, Inc. ABR, Inc., Fairbanks, Alaska, US.

[69] Bureau of Land Management. 2012. National Petroleum Reserve-Alaska Integrated activity Plan environmental impact statement. Arctic District, BLM, Fairbanks, Alaska, US.

[70] Kemper, J. T., and S. E. Macdonald. 2009a. Directional change in upland tundra plant communities 20-30 years after seismic exploration in the Canadian low-arctic. Journal of Vegetation Science **20**:557–567 [doi:10.1111/j.1654-1103.2009.01069.x].

[71] Kemper, J. T., and S. E. Macdonald. 2009b. Effects of contemporary winter seismic exploration on low arctic plant communities and permafrost. Arctic, Antarctic, and Alpine Research **41**:228–237 [doi:10.1657/1938-4246-41.2.228].

[72] Bureau of Land Management. 2008. Environmental assessment: Conduct 3-D seismic, Anadarko. BLM EA #93476. Anchorage, Alaska, US.

Snow: The tundra surface needs to be thoroughly frozen and have sufficient snow cover to protect it from damage by seismic vehicles. During 1984–1985 2D-seismic surveys in the 1002 Area,[73] USFWS monitors travelled with the seismic crews measuring snow depths and observed vehicle impacts to vegetation and soils (Fig. 14).

Figure 14. Trail made by D-7 Caterpillar tractors and ski-mounted trailers in March 1984. This site was still highly disturbed in 1994.[74] By 2018 the trail here had subsided into a large pond due to melting of ice wedges. Based on the amount of bare ground exposed, it is clear that there was insufficient snow to protect the tundra.[75]

Snow versus disturbance data were analyzed for the two most common vegetation types, Tussock Tundra and Moist Sedge-willow Tundra. *The thickness of a wind-slab layer (a harder, usually wind-packed layer that often sits on top of softer snow) was a better predictor of the degree of vegetation disturbance than total snow depth.* A wind-slab depth of 20 cm (8 inches) above a soft depth-hoar layer (a very loose layer consisting of large crystals that forms at the base of a cold snowpack) appeared to be sufficient to prevent most disturbances from seismic vehicles, but not from the camp-moves.[76],[77] *Actual snow depths were usually less than one foot (30 cm) and did not provide complete protection from vehicle damage.* Medium-level disturbance occurred at snow depths to 25 cm (10 inches) in Tussock Tundra and to 35 cm (14 inches) in Sedge-willow Tundra. Measurable vegetation disturbance was recorded in Tussock Tundra with as much as 45 cm (18 inches) of snow and 72 cm (28 inches) in Sedge-willow Tundra.

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[73] Felix and Raynolds 1989a

[74] Jorgenson, J. C., B. E. Reitz, and M. K. Raynolds. 1996. Tundra disturbance and recovery nine years after winter seismic exploration in northern Alaska. Arctic National Wildlife Refuge, U.S. Fish and Wildlife Service, Anchorage, Alaska, US.

[75] Photo: U.S. Fish and Wildlife Service

[76] Felix and Raynolds 1989a

[77] Felix and Raynolds 1989b

Currently BLM does not have a stipulated standard for snow depth but uses a "performance based" system whereby the operator decides when there is enough snow,[78] *but the effectiveness in preventing tundra damage by such a system has not been established in any rigorous way.* Climate change is causing further complications for determining the date to open the tundra. Delayed winter seasons, earlier snowmelt in spring, and late freeze-up in fall have resulted in shortened ice-road and tundra-travel seasons[79],[80].

Permafrost: Trails with medium to high levels of disturbance typically had thaw depths 10–15 cm (4–6 inches) deeper than adjacent control reference areas, indicating that thaw had penetrated into ice-rich layers to cause some thaw settlement.[81] Plots with greater amounts of ice in the upper permafrost tended to have greater soil subsidence and higher disturbance ratings.[82] Thaw settlement induced by the trail disturbance led to changes in surface hydrology and caused recovery patterns to shift away from the original site conditions toward new plant communities that made some trails visible for decades.

Much of the persistent disturbance on seismic trails was associated with degrading ice wedges. Thermokarst troughs and pits frequently became larger after medium- and high-level disturbance, especially in Sedge–Dryas Tundra and Sedge–willow Tundra (Fig. 15). Thaw settlement can occur even at moderate levels of disturbance; damage can increase gradually over long periods; stabilization may take decades; and the depressions formed due to the upper permafrost degradation may persist for centuries. The effects of climate fluctuations further complicate the evaluation of the effects of seismic trail because ice wedges throughout the region have been degrading in response to occasional years of unusually warm and wet weather (see Fig. 13). [83],[84],[85] *Better knowledge of ground-ice distribution is needed so that the impacts of seismic work—and especially impacts from camp moves and the heavier vehicles—on sensitive terrains can be more fully understood and mitigated.*

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[78] Bureau of Land Management. 2013. National Petroleum Reserve-Alaska integrated activity plan record of decision. Retrieved 9 Nov 2018 from https://eplanning.blm.gov/epl-front-office/projects/nepa/ 5251/ 42462/45213/NPR-A_FINAL_ROD_2-21-13.pdf. [See C-2 Best Management Practice, p. 54.]

[79] National Research Council 2003, p. 86

[80] Bader, H. R., and J. Guimond. 2006. Alaska North Slope Tundra Travel Model and Validation Study. Final Report to Alaska Department of Natural Resources. Fairbanks, Alaska, US. Retrieved 3 Nov 2018 from http://www.osti.gov/servlets/purl/881572-u4fQuI

[81] J. C. Jorgenson *et al.* 2010.

[82] Ibid.

[83] Jorgenson *et al.* 2006

[84] Raynolds, M. K., D. A. Walker, K. J. Ambrosius, J. Brown, K. R. Everett, M. Kanevskiy, G. P. Kofinas, V. E. Romanovsky, Y. Shur, and P. J. Webber. 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. Global Change Biology **20**:1211–1224 [doi.org:10.1111/gcb.12500].

[85] Liljedahl *et al.* 2016

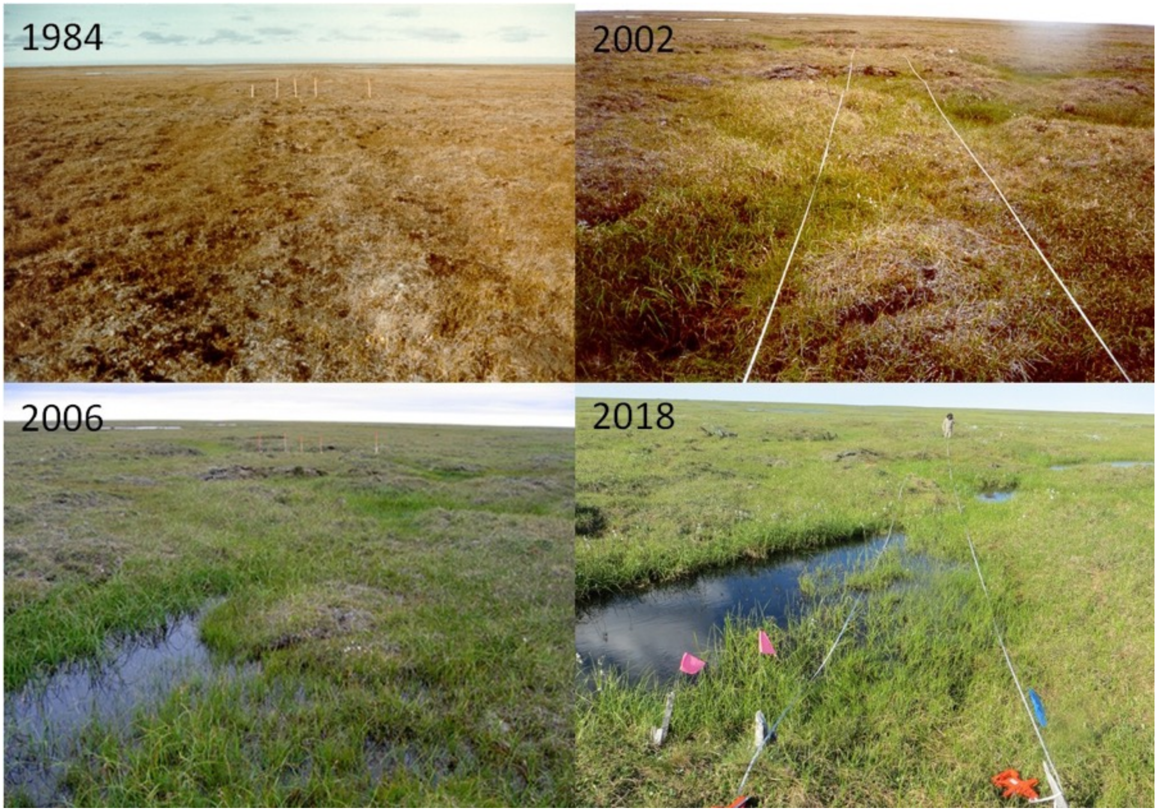

Figure 15. Repeat photographs of a study plot affected by thermokarst on a camp move trail on Sedge-Dryas Tundra (updated from Jorgenson et al. *2010). Parallel ruts and crushed vegetation were evident in 1984, the summer following disturbance (top). By 2002, a network of sedge-filled troughs had developed where melting ice wedges caused ground subsidence, which was not seen in the reference control plot off the trail. The thermokarst pits continued to expand and deepen through 2018.*[86]

Vegetation type: *Moist and dry vegetation types were most strongly affected and slowest to recover, whereas wet vegetation types recovered relatively quickly.* Moist tundra includes Tussock Tundra, which is the most common vegetation type in the 1002 Area and is susceptible to damage because of the considerable microtopographic relief associated with the tussocks, which can be up to 25 cm (10 in) tall.

Tussock Tundra, Shrub Tundra, and Dryas Terrace vegetation were the vegetation types with the highest initial disturbance.[87] About one half of the plots in these areas had medium- or high-level disturbance in 1985, while only one-third of Sedge-Dryas Tundra and Sedge-willow Tundra did. Medium and high-level disturbance occurred in less than 10% of the Wet Sedge Tundra plots and in partially vegetated areas and riparian shrublands, which tend to collect deeper snow.

Species were also differentially sensitive to vehicle disturbance. Some vascular-plant and moss species appear to be particularly sensitive to compression of the "depth hoar" snow layer at

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[86] Photos: U.S. Fish and Wildlife Service

[87] J. C. Jorgenson *et al*. 2010

the base of the snowpack.[88] The plant species with poor potential for recovery if damaged included cotton-grass tussocks (*Eriophorum vaginatum*), evergreen shrubs [including Labrador tea, (*Rhododendron decumbens*), low-bush cranberry (*Vaccinium vitis-idaea*), and mountain avens (*Dryas integrifolium*)], deciduous shrubs [including dwarf birch (*Betula nana*) and dwarf willows (e.g., *Salix phlebophylla, S. reticulata, S. arctica*)], some mosses (particularly *Sphagnum* spp. and *Tomentypnum nitens*), and all lichens.[89]

Recovery time: During the initial summers following the 1984–1985 2D-seismic surveys, most trails had at least some scuffing of vegetation and soil. Medium- to high-level disturbance occurred on almost one-third of the trails About 14% of plots on the trails had no detectable disturbance; 57% had low-level disturbance; 27% had medium-level disturbance; and 2% had high-level disturbance.[90] Recovery was rapid in the first decade as the percentage of disturbed plots decreased from 79% in 1985, to 48% in 1989, and to 11% in 1993. Overall, vegetation recovery reached a plateau after about a decade. After 10 years (1984–1994), the active layer (depth of summer thaw) was deeper on about 50% of the disturbed plots than on adjacent control areas indicating that deeper soil and ecosystem changes were still ongoing. *Measurable disturbance remained on 5% of trails in 2009*[91] *and 3% in 2018,*[92] *33 years after the initial disturbances. The soil subsidence and alterations to vegetation remaining on the trails in 2018 indicate that disturbance will persist for decades more.*

Studies of 3D seismic impacts: *Much less information on recovery is available for 3D-seismic surveys compared to 2D seismic*[93],[94]*. One study from a 1996 3D-seismic-exploration program on Alaska's North Slope found that 6% of 3D-seismic lines and 29% of camp-move trails had at least medium-level disturbance initially.*[95] *A study of disturbance from 1998 3D-seismic exploration by the Bureau of Land Management*[96] *found that 4% of seismic lines and 63% of camp-move trails were still disturbed after six years.* A study of repeated 2D exploration in the Colville River delta in 1992, 1993, and 1995 and from 3D work in 1996 found high levels of disturbance on 1% of the sites surveyed.[97] *The same study found a much higher density of trails associated with the 3D operations and difficulty in quantifying the number of random stray*

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[88] Walker, D. A., D. Cate, J. Brown, and C. Racine. 1987. Disturbance and recovery of arctic Alaskan tundra terrain: a review of recent investigations. CRREL Report 87-11. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, US.

[89] National Research Council 2003, p. 84

[90] Felix and Raynolds. 1989b

[91] J. C. Jorgenson *et al*. 2010

[92] Jorgenson, J. C. 2018. Tundra disturbance and recovery on winter seismic trails in the Arctic National Wildlife Refuge, monitored from 1985 to 2018. Arctic National Wildlife Refuge, U.S. Fish and Wildlife Service, Fairbanks, Alaska, US.

[93] Bureau of Land Management 2008

[94] Bureau of Land Management 2012

[95] Jorgenson *et al.* 2003

[96] Bureau of Land Management 2012

[97] Jorgenson, M. T., and J. E. Roth. 1996. Reconnaissance survey and monitoring of seismic trail impacts on the Colville River Delta, 1997-1998. Prepared for ConocoPhillips Alaska, Inc. ABR, Inc., Fairbanks, Alaska, US.

trails that were not part of the seismic lines or camp-move trails. Some areas were surveyed several times by different companies, resulting in a maze of seismic trails, camp trails, and ice roads that were difficult to identify by type and year of origin. Multiple 3D surveys of the same area are partially related to 4D analyses that examine time-series of changes to known hydrocarbon deposits. Some repetition is also caused by the proprietary nature of most surveys, setting the stage for different companies to gather data and conduct analyses independently.

2.8 Camp moves are the most damaging aspect of the 3D surveys with respect to the terrain and vegetation. Technology and available equipment used in camp moves has not changed sufficiently to avoid these impacts.

During the 1984-1985 2D-seismic surveys in the 1002 Area, camp trailers pulled by tractors caused more long-term damage than seismic survey vehicles (Figs. 16 & 17).[98] By 1989, 32% of the seismic trails were still disturbed compared to 64% of camp-move trails, including 41% of the camp move trails at medium- and high-level disturbance levels. Multiple vehicles travelling in the same narrow track caused more damage than when vehicles were spread out.[99] Measurable disturbance remained on 10% of camp-move trails in 2009[100] and 5% in 2018.[101]

Camp-move trails for 3D seismic surveys traverse far less ground than the seismic lines (for example, compare seismic trails versus camp move trails in Figure 2). Whereas 3D-seismic lines must stick to a rigid grid pattern, camp-moves have more leeway in route selection. During one seismic survey, a single seismic crew created over 3,200 km of seismic trails and approximately 200 km of camp-move trails (roughly 6% of the seismic trail distance).[102] *The impact from the camp moves is, however, far more damaging than the seismic lines due to the many tractors and sleds on skis, some of which are Caterpillar bulldozers with steel treads.* A recent analysis of trails visible on high-resolution satellite images on Google Earth revealed that approximately 47 km of trails from the 1950s and 1980s within the 1002 Area are still visible. These included 11.4 km of old tractor trails from the 1950s. *Of the 35.8 km of trails from the 1980s that are still visible on satellite images, three quarters are camp moves and one quarter seismic lines. All are in the western, hillier portion of the 1002 Area.*

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[98] J. C. Jorgenson *et al.* 2010

[99] Felix and Raynolds 1989a

[100] J. C. Jorgenson *et al.* 2010

[101] Jorgenson 2018

[102] Bader and Guimond 2006

Figure 16. Camp-move trail photographed in 1994, 10 years after it was made. This trail remained visible due to trail subsidence, a decrease in shrubs and mosses, and increase in standing dead sedge leaves.[103]

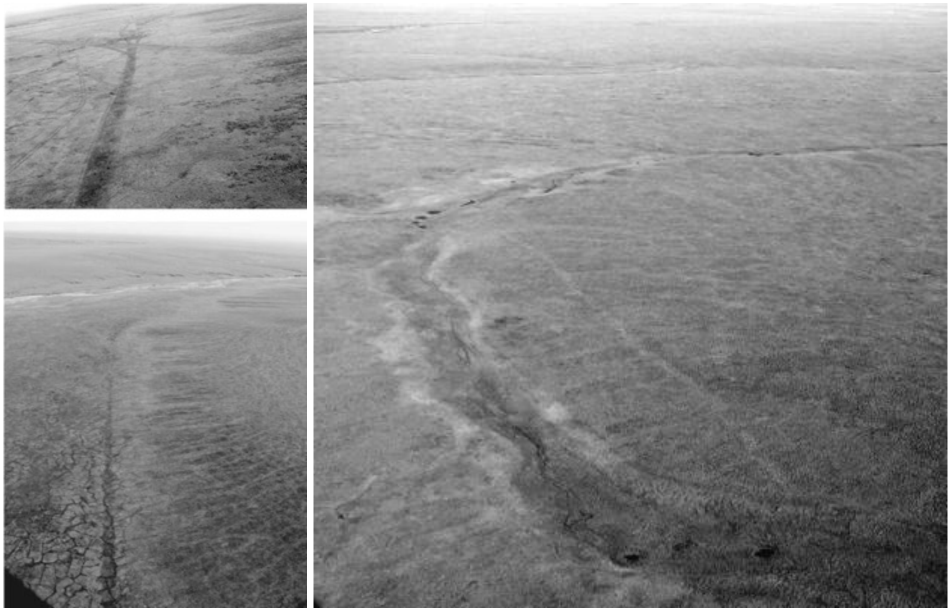

Figure 17. Trails in the 1002 Area made by camp-move vehicles during 2D seismic surveys in 1984 and 1985. The top-left image was taken in July 1985 of a trail through ice-rich permafrost terrain; the lower-left image is of the same trail taken in July 2007. An undisturbed reference plot to the left of the trail had a soil excess ice content of 28% in 1985. Thawing of soil ice and ice wedges led to trail subsidence. The trail remained wetter and greener than surrounding tundra in 2007. The right image shows a trail created in 1984 and photographed in 2005. The trail is still visible after 21 years because it had fewer evergreen shrubs and more sedges than the surrounding tundra.[104]

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[103] J. C. Jorgenson *et al.* 1996

[104] J. C. Jorgenson *et al.* 2010

2.9 Cumulative effects of 3D seismic need to be thoroughly evaluated.

The impacts of seismic exploration are the most geographically extensive direct impact of any aspect of oil exploration and development but have been largely ignored in assessments of the long-term consequences of oil development. Seismic exploration has been conducted every winter on the North Slope of Alaska since at least 1976, and trails in various stages of recovery are visible from the air during the summer in most areas surveyed. *The proposed 61,000 km of seismic trails for the 1002 Area would exceed the 51,500 km of total trails that the National Research Council estimated were made on the North Slope in 10 years between 1990 and 2001 and the 43,450 km were predicted to be surveyed in the following 10 years.*[105]

Cumulative impacts are the incremental impacts of the proposed action added to other past, present, and reasonably foreseeable future actions[106]. Cumulative impacts can be notably difficult to quantify and predict but must be considered in documents prepared under the National Environmental Policy Act (NEPA) regulations. *Cumulative effects of 3D seismic to lands in the 1002 Area include direct and indirect impacts from the proposed survey, possible future repeated 3D-seismic surveys, future "nibbling" and fragmentation of the landscape by expanding networks of infrastructure associated with oil and gas exploration development and production, and climate change.*

The proposed seismic plan especially needs to consider the changing climate, such as the issues related to thawing permafrost and changing hydrologic regimes, as described elsewhere in this report. Warming during the past two decades has exacerbated some of the thawing on trails established in earlier decades[107]. Numerous recent studies in northern Alaska and elsewhere in the Arctic have revealed that recent warming of the Arctic is causing thermokarst to expand over extensive areas[108],[109], which exacerbates ponding caused by seismic surveys. Warmer and longer thaw seasons are also reducing the length of time when off-road travel is permitted on the tundra.

Another cumulative-impact concern is how to evaluate the long-term consequences that would follow seismic surveys. *Estimates of impacts from future 3D-seismic surveys should not be based on old data from previous 2D-seismic surveys that could either vastly over- or under-estimate the long-term impacts. Instead, they should be based on current knowledge from recent 3D-surveys and more realistic scenarios of the total direct and indirect impacts of exploration, development and production including gravel mines, ice roads, and temporary trails and roads associated with pipelines and power lines, and the indirect impacts of infrastructure-related*

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[105] National Research Council 2003, pp. 81-88, 183-184

[106] Council on Environmental Quality. 1997. Considering cumulative effects under the National Environmental Policy Act. Executive Office of the President, Washington, DC, US.

[107] J. C. Jorgenson *et al.* 2010

[108] Jorgenson *et al.* 2006

[109] Liljedahl *et al.* 2016

flooding and thermokarst, road dust, and off-road vehicle trails, including new seismic surveys that will likely be needed to refine the search for pockets of hydrocarbons.[110],[111],[112],[113]

2.10 Major data gaps exist regarding environmental conditions within the 1002 Area and the impacts of 3D seismic.

Monitoring the consequences of seismic exploration should become routine in all surveys — past and future. For example, monitors' measurements of snow depths were a critical element in the analysis of impacts following the 1002-Area 2D surveys in 1984 and 1985. The long-term monitoring of terrain and vegetation recovery that followed these surveys resulted in most of what we know about impacts of seismic in the Arctic. Currently, fly-by inspections for fuel contamination, garbage, and trail damage are done to assess impacts soon after exploration, but little on-the-ground-monitoring of snow and terrain conditions is done during the surveys or following the surveys to determine short- or long-term terrain and vegetation recovery, and little documentation is available to the public.

Although evaluating disturbance and recovery associated with wintertime seismic surveys in tundra vegetation is difficult, the current approach is insufficient to provide a scientific basis to assess the outcomes of current practices. Two main approaches have been used previously to observe and monitor changes to vegetation caused by seismic surveys in northern Alaska. ADNR used an experimental approach[114] to develop criteria and models for determining the dates for opening and closing the tundra to wintertime cross-tundra travel.[115] The main focus of the ADNR studies was to determine the resistance to compression of easily measured abiotic factors such as thaw depth, soil moisture, and the tundra mat. The results were used to establish the present ADNR snow-depth and soil-temperature thresholds for opening and closing dates on the coastal plain and foothills. The studies also resulted in a change in the methods used to determine frozen-surface hardness. The studies did not examine the most damaging vehicle configurations used in camp-moves, nor did they address the issue of ecological resilience (ability to recover) following high levels of disturbance. Spatial variability of vegetation and site factors rarely can be controlled to provide an optimal statistical design for analyzing such patterns across a range of conditions.[116]

The approach used during and following the 1984—1985 2D-seismic surveys in the 1002 Area included monitoring during the wintertime seismic activities followed by long-term

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[110] Walker, D. A., P. J. Webber, E. F. Binnian, K. R. Everett, N. D. Lederer, E. A. Nordstrand, and M. D. Walker. 1987. Cumulative impacts of oil fields on northern Alaskan landscapes. Science **238**:757–761 [doi:10.2307/1700351].

[111] National Research Council 2003

[112] Arctic Monitoring and Assessment Programme (AMAP). 2010. Assessment 2007: Oil and Gas Activities in the Arctic—Effects and Potential Effects. Vols. 1-2. Oslo, Norway.

[113] Raynolds *et al.* 2014

[114] Bader and Guimond 2006

[115] Bradwell, P., A. Maclady, and S. Wall. 2004. History of the Alaska Department of Natural Resources, Tundra Travel Management 1969–2003. Alaska Department of Natural Resources. Appendix D in H. R. Bader, and J. Guimond 2006. Retrieved 3 Nov 2018 from http://www.osti.gov/servlets/purl/881572-u4fQuI

[116] Ver Hoef, J. M. 2002. Sampling and geostatistics for spatial data. Ecoscience **9**:152–161.

studies of the vegetation and permafrost responses.[117] Winter observations recorded snow and terrain conditions.[118],[119],[120] Long-term summer observations included measurements of species cover and site factors on disturbed plots within the seismic trails[121],[122],[123] and control reference plots in undisturbed plots adjacent to the trails.[124] The plots were monitored six times from 1984 to 2002 and continue to be monitored up to the present by the original authors. These observations resulted in models that predict the effects of vegetation type and initial disturbance levels on recovery patterns of the different plant growth forms as well as soil thaw depth.[125] The studies found that severe impacts to tundra vegetation persisted for more than two decades after disturbance under some conditions and that recovery to pre-disturbance communities was not possible where trail subsidence occurred due to thawing of ground ice.

Applying similar approaches to previously authorized seismic work, particularly in terrain similar to the 1002 Area, would help establish the necessary rigorous baseline of information for evaluating seismic work in the 1002 Area. *3D-seismic sensitivity maps and models are needed, based on detailed knowledge and maps of surficial geomorphology, microtopography, spatial and temporal variation of snow and ground ice, and projections of the effects of climate change on snow, permafrost, hydrology, and vegetation.*

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[117] J. C. Jorgenson *et al.* 2010

[118] Felix and Raynolds 1989b

[119] Felix and Raynolds 1989a

[120] Raynolds, M. K., and N. A. Felix. 1989. Airphoto analysis of winter seismic disturbance in northeastern Alaska. Arctic **42**:362-367.

[121] Jorgenson, J. C. 2001. Tundra disturbance and recovery during 16 years after winter seismic exploration in the Arctic National Refuge, Alaska. Arctic National Wildlife Refuge, Fairbanks, Alaska, US.

[122] J. C. Jorgenson *et al.* 1996

[123] J. C. Jorgenson *et al.* 2010

[124] Jorgenson, J. C., M. K. Raynolds, J. H. Reynolds, and A.-M. Benson. 2015. Twenty-five year record of changes in plant cover on tundra of northeastern Alaska. Arctic, Antarctic, and Alpine Research **47**:785–806 [doi:10.1657/AAAR0014-09].

[125] J. C. Jorgenson *et al.* 2010

3 Conclusions

Congress passed the tax reform bill that permitted oil development in the 1002 Area of the Arctic National Wildlife Refuge with assurances that the environmental quality of this region will be maintained. The justification and approaches for using 3D seismic for exploration are clearly different in the 1002 Area, where the terrain and biological conservation values are extremely high, than in many areas of the U.S. where the lands are already degraded by other land-use pressures. Without greater attention to the potential impacts specific to the unique terrain and vegetation of the 1002 Area, the benefits of 3D seismic will come with considerable costs of environmental impacts to the 1002 Area. The purpose of this white paper is to make clear that potentially severe consequences to the terrain, vegetation, and environmental quality of the 1002 Area will occur unless sufficient care is taken in how 3D-seismic surveys are conducted. Toward this goal, we summarize our major conclusions:

1. *Of greatest concern is the magnitude and location of the proposed activity which is unprecedented in arctic Alaska. The proposed surveys would create approximately 61,000 km of seismic trails in one of the most sensitive protected areas in the circumpolar Arctic. If the goal is to reduce the likelihood of significant, long-lasting impacts, the blanket 3D-seismic coverage of all of the 1002 Area needs to be thoroughly reevaluated. Under the proposed activity, the seismic surveys could occur in the winter of 2018–2019, before careful planning and land-management guidelines can be developed to address this unique situation. More time is needed for a thorough environmental review. Any new plan will require new and well-thought-out stipulations and guidelines.*

2. *The 1002 Area is topographically and biologically distinct from the rest of the North Slope. The diversity of geology, topography, soils, snow regimes, and vegetation create a mosaic of habitats that accounts for the high biological diversity of the 1002 Area. The impacts from surveys in this terrain will likely have long-term significant impacts to the area's hydrology, permafrost, vegetation, and ecosystems.*

3. *The technology of 3D-seismic surveys makes it likely that the impacts of the proposed activity would be more severe than from the 1984–1985 2D-seismic surveys. Even though some improvements have been made in seismic methods since the 1984–1985 surveys, much denser and more extensive networks of 3D-seismic trails, larger camps, and more numerous and larger vehicles would increase the risks of damage to the steeper and more heterogeneous tundra terrain in the 1002 Area.*

4. *Evidence from high-resolution microtopography surveys of the 3D-seismic trails near the 1002 Area indicate that 3D-seismic trails compress the tundra vegetation mat in a way that will likely have long-lasting and far-reaching consequences to the hydrology, permafrost, vegetation, and wildlife that depend on the microtopographic irregularities of the tundra surface.*

5. *Very strong winds and varied topography in the 1002 Area create a heterogeneous snow environment that will make it difficult to find routes for the surveys that can meet minimum snow-cover standards aimed at protecting tundra vegetation and permafrost. How 3D-seismic efforts could be conducted in such a patchwork of snow depths is not apparent to us.*

6. *Thermokarst and thermal erosion are likely to occur along new seismic trails. The permafrost environment of the 1002 Area is not well known, but recent studies suggest that*

near-surface massive ground ice is present nearly everywhere. Thermokarst and especially thermal erosion are particularly likely in the hillier portions of the 1002 Area, which have thick ice-rich silt deposits with large ice wedges (yedoma), and where severe disturbances will be difficult or impossible to mitigate once they occur. These unfavorable permafrost conditions combined with a warming climate will likely lead to degradation of the upper permafrost along seismic and camp-move trails.

7. *Significant impacts to the vegetation can be expected from the seismic-survey vehicles and especially camp moves. Significant surface disturbances have lasted over 30 years after the 1984–1985 2D-seismic surveys in the 1002 Area. A majority of the disturbances disappeared gradually, but many impacts to tundra vegetation persist up to the present. The persistent disturbances are most evident in areas with ice-rich permafrost, low snow cover, and terrain with considerable micro-relief, such as areas of frost boils and tussock tundra. Thaw settlement can occur even at moderate levels of disturbance; damage can increase gradually over long periods; stabilization may take decades; and the degradation of surface permafrost may be permanent.*

8. *The most severe and long-lasting impacts of past surveys were caused by camp moves. The camps often are pulled by D7 bulldozers in steep terrain or deep snow and are transported on sleds with steel runners that cut into raised features such as hummocks, tussocks, frost boils, and elevated rims of low-centered ice-wedge polygons.*

9. *The cumulative effects of 3D-seismic surveys to the terrain and vegetation are difficult to predict unless thoroughly evaluated. There is a need to develop realistic scenarios of future impacts. These scenarios need to include piecemeal fragmentation of terrain by successive steps of exploration and development and spreading impacts from seismic trails. Expanding networks of infrastructure have invariably followed discovery of oil and gas resources elsewhere. Significant impacts will very likely spread beyond the predicted 2000-acre footprint indicated in the Draft Leasing EIS. There will likely be direct and indirect impacts of the surveys combined with the effects of climate change. The effects of regional climate change include uncertain future snow, hydrology, and permafrost conditions, which complicate the evaluation of the effects of seismic surveys. Ice wedges throughout the region have already been degrading in response to periodic increases in the depth of seasonal thawing during unusually warm and wet summers.*

10. *A rigorous program of integrated scientific monitoring and research is needed for transparent assessment of the wide range of potential environmental impacts from 3D-seismic surveys. The program needs to include a better understanding of the long-term effects of 3D seismic to ecosystems within and beyond trails, including microtopography, snow, hydrology, permafrost, and vegetation conditions. If 3D-seismic surveys do occur, given the 1002 Area's location and conditions, a robust monitoring program will be needed to assess compliance with regulations and guide remediation.*

11. *Knowledge gaps include a 3D-seismic adaptive land-use strategy that should be based on 1) detailed information regarding how much snow is needed to fully protect the tundra; 2) terrain sensitivity to 3D seismic maps based on consideration of topography, snow regimes, hydrology, permafrost, and vegetation; and 3) detailed long-term monitoring of terrain, vegetation, snow depth, and ecosystem recovery for past and future 3D-seismic surveys*.

Appendix 1. Vehicles and equipment in 1002 seismic survey plan of operations

The Marsh Creek 3D plan of operations submitted by SAExploration in May 2018 proposed the following vehicles and equipment for use in a winter seismic survey of the 1002 Area.[126] Not all of the vehicles and equipment listed are shown in photos.

Table A1. The Marsh Creek 3D plan of operations specifies the equipment list for each survey crew, with two crews operating at one time.

Equipment list	# per crew	Details
Tucker Snow Cat	12	1644
Tucker Ice Cat	8	1644
Tucker Personnel Carrier	3	1600
GPS Base Station	3	Hagglund
Vibe Tender	2	Tucker Trailer
Mechanic Field Shop	1	Tucker Trailer
Node Charging Shack	3	Tucker Trailer
Recorder	1	Tucker Trailer
Taco	6	Trailer
Survival Trailer	2	Tucker Trailer
GSX Nodes	TBD	GSX-1
Batteries	TBD	BX10
Sensor	TBD	Arctic Base
AHV-IV Vibrators	12	Commander (PLS-364)
Sleigh Camp	1	150 Man
Fuel Tanks/Fuel Stations	7	3,000 / 4000 Gallon
Long Haul Fueler	4	4,000 Gallon
Rolligons	1	
Case/Steiger Tractors	9	535
CAT Dozer	2	D7G
CAT Loader	1	977H

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[126] SAExploration, Inc. 2018

Vehicles and equipment used in seismic operations

Figure A1: ConocoPhillips rubber-tracked Vibroseis (or "thumper") is a truck-mounted seismic vibrator used to inject low-frequency vibrations into the ground. The vibrator pad is located between the front and rear treads of the vehicle. The plan of operations includes 12 Inova AHV-IV Vibrators per crew. (Photo: Bureau of Land Management)

Figure A2: Tucker Sno-Cat, a cleat-tracked vehicle used to transport workers, prepack snow, and other uses not requiring a heavy vehicle. The plan of operations includes 12 Tucker Sno-Cats, eight Tucker Ice Cats, three Tucker personnel carriers, and a variety of Tucker trailers per crew. (Photo: Alaska Department of Natural Resources)

Vehicles used in camp moves

Figure A3: Steiger tractor used to haul camp trailers and other vehicles and equipment . The plan of operations anticipates nine Case/Steiger tractors per crew. (Photo: Alaska Department of Natural Resources)

Figure A4: Rolligons are vehicles with large low-pressure tires used by the oil industry in Canada and Alaska. The plan of operations lists one Rolligon per crew. (Photo: Alaska Department of Natural Resources)

Figure A5: Caterpillar D7 dozer, steel-tracked vehicle used to haul camps and equipment. The plan of operations includes two CAT D7G per crew, but 4 per crew were used at GMT 3D in 2017 and that area was flat, compared to the hilly 1002 where D7s will likely be in high demand. (Photo: Alaska Department of Natural Resources)

Figure A6: Caterpillar 977H tracked loader. One 977H per crew is anticipated in the plan of operations. (Photo: Purple Wave Auction, https://www.purplewave.com/auction/140515/item/H6548)

Figure A7: Cat train with sled-mounted camps pulled by a D7 dozer during the 1984–1985 surveys. The plan of operations proposes one 150-person sleigh camp per crew. The vehicles required for the mobile camps consist of 8–10 strings of 5–8 sleds pulled by large tractors. (Photo: U.S. Fish & Wildlife Service)

Figure A8: Five strings of Cat trains with sled-mounted camps during 3D seismic exploration in foothills terrain near Kavik, AK, 2001. The three Cat trains in background apparently required two tractors per train to travel in this hilly terrain, while the two in the foreground were waiting for tractors to return for them. (Photo: U.S. Fish & Wildlife Service)

Appendix 2. Terrain types of the 1002 Area

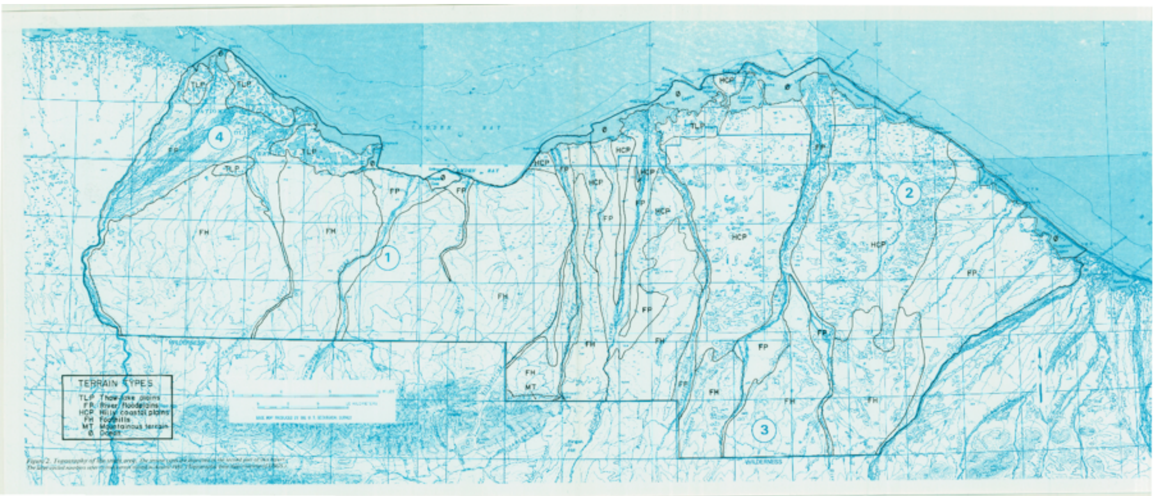

Figure A9: Topography of the 1002 Area with boundaries of primary terrain units according to Walker et al. *(1982).*[127] *(Topographic Base Map: USGS). The areas of the map units in order of dominance are: FH, Foothills (45%); River floodplains and deltas (25%); HCP, Hilly coastal plains (22%); TLP, Thaw-lake plains (3%); Mountainous terrain (0.03%).*

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[127] Walker, D. A., K. R. Everett, W. Acevedo, L. Gaydos, J. Brown, and P. J. Webber. 1982. Landsat-assisted environmental mapping in the Arctic National Wildlife Refuge, Alaska. CRREL Report 82-37 (p. 68). U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, US. Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a123440.pdf

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