The consequences of climate change in the Arctic and implications for natural resource utilisation

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History of the Northwest Passage sea route, recent climate change, global warming and the opening of the Northwest Passage

The Northwest Passage is a shipping route linking the Atlantic Ocean with the Pacific Ocean, much shorter than current traditional routes via the Suez or Panama Canals (Figure 1). For example, from New York to Tokyo via the Northwest Passage is approximately 14'000 km (7'560 nautical miles) compared to 18'200 km (9'830 nautical miles) for the equivalent transit via the Panama Canal. A counterpart route via the North coast of Russia, the Northeast Passage (sometimes also known as the Northern Sea Route) similarly provides a shortened transit – passage via the Suez Canal for Hamburg to Tokyo is 21'000 km (11'340 nautical miles) in comparison to 13'000 km (7'020 nautical miles) along the Northeast Passage. Whilst the suitability of the Northeast vs the Northwest Passage depends on the port of departure (Europe vs eastern seaboard of North America), overall the much shorter distances available to shipping travelling via Arctic routes significantly saves both time and money and reduces emissions. For

example, it has been estimated by Fednav – the shipping company behind the first cargo ship to travel solo through the Northwest Passage in September 2014 carrying Ni-ore from Deception Bay in Canada to Bayuquan in China (without an escort from icebreakers) – over 1'000 tonnes of greenhouse gas emissions were saved by this shorter route for this voyage alone. Besides the obvious environmental benefit saving fossil fuels, this also significantly reduced the cost of fuel for the journey and avoided expensive escort and port fees required along more mainstream canal routes.

Historically exploration for the Northwest Passage was led by a desire to find a shortcut from Europe to Asia by travelling west (rather than the eastern trade routes) and dates back to the 15th Century. In 1497, John Cabot's expedition ultimately led to his landing on the eastern seaboard of Canada (historians debate whether this was Cape Breton, Nova Scotia, Newfoundland or Labrador) although he failed to find a passage to Asia (Hunter 2011). This was followed by subsequent exploration by Martin Frobisher (1576 to 1578), Henry Hudson (1609), William Baffin and Robert Bylot (1615-1616) amongst others. The 18th Century saw a break in such expeditions but after the Napoleonic Wars, Captain John Ross undertook his first Arctic expedition to explore for a Northwest Passage in 1818. Perhaps most famously, these historic voyages culminated with Sir John Franklin's fateful expedition in 1845, again instigated to shorten the sea route between Europe and Asia, thereby linking the Atlantic Ocean with the Pacific Ocean through the Arctic Ocean (Hutchinson 2017). The dramatic failure of Sir John Franklin's expedition ended in the loss of his two ships, H. M. S. *Erebus* and H. M. S. *Terror* near King William Island (Figures 2 and 3) and the deaths of the 129 men on board, despite his expedition being the best equipped Arctic expedition of the time. The inaccuracy of charts and maps of the area (where available for some portions of the eastern part of the passage) and the fact that enormous areas located west of Baffin Island and north of Greenland were uncharted, is largely thought to have been responsible for the failure of these expeditions (Figure 3). At the time, there was also a belief that there was open water between North Greenland and the North Pole. Over the years, 52 search expeditions across extensive areas of the Arctic were organized to try to find Sir John Franklin and his crew – ironically this led to a significant improvement in knowledge and mapping culminating in final threading of a passage through the labyrinthine seaways (McGoogan 2002). Finally in 2014, the ship *Erebus*, followed by the *Terror* in 2016, were found at the bottom of Arctic waters on the west coast of the King William Island (Figure 3) – both were well-preserved [1].

The allure of an Arctic seaway to connect the Pacific and Atlantic Oceans in the northern hemisphere has endured beyond Sir John Franklin, whether for commercial, security or touristic reasons. But what are the consequences of an ice-free or seasonably shippable Northwest Passage in terms of exploration and exploitation of natural resources? There has been a recent increase of interest in land-based mineral resources in proximity to the Northwest Passage in the vicinity of Greenland and Arctic Canada. How will interest in such future activities manifest and what considerations are needed in relation to its socio-economic impact and growing concerns for climate change?

With Arctic shipping routes becoming more popular, other considerations between the choice of Northeast and Northwest Passages come to the fore including; the abundance and longevity of sea ice each year; permitting and fees (presently for the Northeast Passage only); the remoteness of the route (there are several ports and bases on the Northeast Passage but very few on the Northwest Passage, with none along the central portions of the passage); and geopolitics (from tensions over sovereignty and national seaways vs international waters, to wild speculation from Trump's intent to 'buy' Greenland). Further geopolitical focus has been recently raised when the Swiss Polar Institute's 'Greenland Circumnavigation Expedition', intended to navigate around Greenland by sea, was cancelled due to it not receiving the relevant permissions from the Danish Department of Foreign Affairs, possibly due to unease about the role of Russian partners on the expedition (Anner 2019). Whilst the legal, political and maritime complexities embroiled in Arctic sea routes such as the Northwest Passage is beyond the scope of this article, which instead seeks to highlight the topic for discussion within the natural resources community, it ultimately underpins the feasibility of trade and the development and extraction of natural resources in the region.

Seasonable ice coverage in the Arctic has changed dramatically over the past 40 years (Figure 1). It is conceivable that the Northwest Passage will be ice free in late summer in the near future (e.g., Boé et al. 2009) expanding the September navigability for common open-water ships (Smith & Stephenson 2013) further opening the Northwest Passage as a route through the Arctic. Figure 4 provides photographs of the examples of summer ice in the Arctic Ocean showing large areas covered by pack ice in the Smith Sound in North Greenland. Evidence of a warmer climate in Greenland is clearly seen from the shrinking of glaciers – for example the glacier in Qaamarujuk Fjord (Figure 5) located near the (now mothballed) Black Angel mine in central-West Greenland, North of the settlement of Uummannaq (Schlatter 2016; Georgi 1933). It is the perception from personal observations of the first author during 15 seasons of field work in the Greenlandic Arctic that the summer air temperatures have tangibly risen since

the mid-1990s, and crucially such observations are widely supported by scientific studies and literature (Jardine 2019).

The recent recorded warming of oceans and rising air temperatures in the Arctic are paired with melting of sea-ice, glaciers and the inland ice – melting in the period 2007 to 2011 has been estimated as 262 Gt/year with the greatest extent of melting seen in the inland ice of the extreme North of Greenland (van As et al. 2016). Warming of air temperatures is also demonstrated by reconstructions for the past ~200 years showing that positive temperature anomalies have predominantly been recorded since the end of the Little Ice Age at about 1860, especially in the areas located in the northern hemisphere (Figure 6). Given Sir John Franklin's legendary expedition came to an end because of the sea ice conditions towards the end of the Little Ice Age, then the present conditions would likely have facilitated his success.

Geology and natural resources

The seaboard of much of the Northwest Passage in Greenland and the western portions of the Canadian Arctic comprises crust of Proterozoic and Archean ages as well as terranes of Cretaceous-Tertiary and the Mesoproterozoic ages (Figure 7); (Kolb et al. 2016). Such terranes are proven to be prospective for mineralisation of precious metals, diamonds, base metals, and ferrous metals for examples from large resources in Western Australia and South Africa (Cawood and Hawkesworth 2015; Robb 2005). Some of these prospective geological terranes have been (and continue to be) explored in the Canadian and Greenlandic Arctic and in Alaska, and (were) actively mined (e.g., Black Angel, Mary River, Raglan, Ekati and Diavik– see Table 1). These are also prospective regions for rare earth elements (e.g., the Gardar Intrusive Suite in southern Greenland, (Kolb et al. 2016) as well as other critical metals, important in the global move towards "green" technology and sustainable growth (Table 1, Figure 2); (Kolb et al. 2016; Petrov and Smelror 2015). Younger crustal regions, such as those along the western seaboard of the Canadian Arctic and Alaska are prospective for mineralisation of base metals (e.g., Red Dog, Table 1). Somewhat controversially, both the eastern and western portions of the Northwest Passage lie along onshore and offshore oil deposits. Table 1 provides a summary of grade and tonnages of significant mines and mineral exploration projects that are located in the vicinity of the Northwest Passage (Figure 2). For further details, the reader is encouraged to refer to the detailed compilation by Boyd et al. (2016) who provide a comprehensive inventory of mineral resources in the Arctic. The Arctic regions, including those along the Northwest Passage seaboard, are widely considered one

of the last frontiers on the planet, and with increasing interest and accessibility to the region, more mineral occurrences will undoubtedly be found in these largely underexplored areas. Furthermore, market drivers such as increasing oil and gas prices and unrest in the Middle East may see growing (and certainly contentious) exploration efforts to locate and potentially extract hydrocarbon resources.

Beyond these more 'traditional' natural resources, additional opportunities may be identified. The accelerated melting of the Greenland Ice Sheet as well as glaciated areas along the Northwest Passage seaboard and its impeccable quality of water presents a potential for capture as mineral water, agricultural water and industry usage. Further opportunities may come from hydropower (especially with augmented capacity from the melting of the inland-ice) and other sources of renewable energy such as tidal, wind and wave power. Mud and glacial rock flour produced by the Greenland Ice Sheet represent another natural resource, highly valued as a cropland additive due to its fertilizing properties for improving arable land quality (Bennike et al. 2019; Gunnarsen et al. 2019), and intriguingly with the potential to be used as a carbon-sink for CO_2 capture and storage (e.g., Sarkar et al. 2018). This mud was also successfully tested for producing bricks and expanded clay aggregates and as cement-replacing filler for local construction material production (Belmonte 2015). Together, the natural resources (including metals, water and wind, and industrial minerals such as the anorthosite mined by Hudson Resources Inc. in West Greenland) of the Arctic, particularly along the Northwest Passage, could play an important role in the near future. However, in times of irreversible and overturning climate change comes responsibility – both to the environment and society on a local and global scale. On the one hand, the Northwest Passage and other Arctic sea routes are becoming more viable to access allowing for more efficient communication and trade links globally, which itself could reduce carbon emissions by shortening transportation routes as well as allowing for increased production of key mineral and metal resources to facilitate global development towards a 'green economy' and even carbon capture and sequestration. Yet on the other hand, growing access to the Arctic sea routes would inevitably cause further ecological stress (e.g., Miller and Ruiz 2014) and likewise cause further societal pressure on ingenious peoples (e.g., Kaiser et al. 2018) possibility exacerbating geopolitical instability.

Socio-economic and environmental aspects

144 The first encounter between the indigenous peoples of North-West Greenland and Captain John Ross took place in
145 1818 at Cape York (Malaurie 1992). Captain John Ross did not expect to find people living in such a remote area
146 and so far north whereas the indigenous peoples were not aware of other civilizations. Since this historical and non-
147 violent encounter, Arctic regions have become further populated with most habitants located in the Russian Arctic
148 (population approximately 2 million, after "The Arctic Institute Center for Circumpolar Security Studies",
149 Washington [2]) and comparatively few in the Canadian Arctic (population more than 100'000, Canadian High
150 Commission in London [3]) and Greenland (population less than 60'000, after Statistics Greenland [4]) with most being
151 situated on the west coast while the east coast and northern areas remain very sparsely populated. In Greenland, there
152 are fewer hunters each year and this traditional way of living is diminishing – this is in part due to the dramatic loss
153 of the sea-ice on which hunters for seals and halibut fishing are reliant for access by dog sledges and skidoos (Ford
154 and Goldhar 2012). Other consequences of the warming are the melting of permafrost and frozen sediment on which
155 many houses in the Arctic are built, resulting in twisted houses and structural instability of buildings as recently seen
156 in Qaanaaq in North Greenland (personal communication by Ole Christiansen, 2019) and in other parts of the Arctic
157 (Welch and Orlinsky 2019). In the Canadian Arctic, ice roads and airport runways have become unusable due to
158 melting permafrost causing problems with transportation, infrastructure, communication and trade, including at the
159 Jericho mine – a diamond mine located in Canada's Nunavut territory now under care and maintenance; the short
160 season of the ice roads in 2006 was one of a number of factors that led to its closure (Sevunts 2012).
161
162 In recent years, there has been rapid growth in a market for cruise ship tourism in arctic areas (e.g., Stewart et al.
163 2013) as well as yachts, and this has particularly been the case along the Northwest Passage. Aside from the
164 increased CO_2 and other emissions from this expansion in activity, it is possible that this will have a negative impact
165 in the form of waste overboard and littering although legislation is generally very effective for larger commercial
166 shipping required to adhere to the International Convention for the Prevention of Pollution from Ships (MARPOL [5]).
167 A recent study has already highlighted the presence of microplastic in sea ice (Peeken et al. 2019) although this is
168 likely also sourced from local industry and habitation. From a socio-economic perspective, there are only a few
169 larger towns that are located north of 65° latitude, such as the town of Murmansk on the Northeast Passage, and
170 therefore cruise ships along the Northwest Passage will more likely visit very small Arctic communities with
171 populations generally of less than 100 habitants. For example, the settlement of Siorapaluk in North-West Greenland
172 has basic infrastructure, is one of the world's northernmost inhabited settlements and the northernmost settlement

inhabited by indigenous people (Figure 8). Consequently, such ‘invasions’ of (increasingly more frequent) cruise ship-based tourists pose new challenges to the people, infrastructure and environment – including impact on the fauna and flora of the region.

The very small population of the Arctic regions will also present radical challenges to the likely growth and development of natural resources along the seaboard of the Northwest Passage, and vice versa. This applies to all phases from mineral exploration through to mining and rehabilitation. With the development of any large mining project, a large number of workers are needed throughout the ramp-up to production and thereafter during mining and via the multiplier effect. Policies could be put in place to preferentially seek to employ local and indigenous peoples for the work force, but the balance of numbers involved in such operations together with the need for highly specialised roles means that it is most likely that workers from outside of the region would also be needed. It is questionable how well a relatively large foreign workforce will integrate with the indigenous population, and what proportion of the total workforce could be indigenous people for future mining operations. What considerations do such radical changes in immigration and emigration require? How do local people envision their roles and future lives in potential sites of exploitation? What steps should be taken so that the voices of indigenous peoples are heard in democracies such as Greenland and Canada (Nuttall 2012)? In a pre-emptive move, the public of Greenland discussed how an influx of approximately 3000 Chinese workers, in connection with the opening of a future Isua iron-ore mine, could affect the Nuuk region. In particular, the considerations around salaries were discussed. Whilst Chinese companies could abide by the minimum wage criteria of Greenland, it is possible that such companies could also deduct food, clothing and other expenses from this salary. This arrangement was formalised in a law intriguingly called “the Chinese law”, although officially this law was given the Danish name for large-scale project legislation: Storskalaloven (Nuttall 2012). However, a fierce debate ensued when this law was passed by the Greenland parliament (Kalaallit Nunaanni Inatsisartut) in 2012, making it possible to accommodate foreign labour under special conditions (Gad et al. 2018).

The sensitivities of this and accordingly the social licence to operate is one that is crucial to the viability and success of any future projects. The mineral industry must also abide by their responsibility to the environment, especially when operating in such sensitive Arctic areas. Coupled, regulators must have a place in forming practical legislation for the exploration and mining industry tailored to the polar region. Nonetheless, legislation passed by regulators must have the full support of citizens, unlike the case highlighted in Greenland.

Closing statement

The Arctic regions have undergone significant changes since Captain John Ross and Sir John Franklin's expeditions towards the end of the Little Ice Age and the search for the Northwest Passage. Since then, the indigenous population has encountered significant cultural, technological, environmental and climatic changes, challenging traditional hunting and fishing activities and ways of life. With the continued opening of the Northwest Passage further changes and challenges are to be expected, such as a new trade route between Europe and the western Americas with China and other Asian and Australasian consumers of minerals and raw materials. Yet there are likely to be commercial beneficiaries, such as shipping and cruise line operators that could utilize a sea ice-free Northwest Passage making such routes logistically feasible and profitable. Increased local commerce and opportunities will likely also come with this. In particular, the opening of the Northwest Passage will almost certainly open up areas for increased exploration for mineral resources and raw materials, with access via this seaway and other Arctic sea routes bringing commodities to market and the prospect of wealth to the associated seaboard (Schlatter et al. 2018; 2019). The opening of the Northwest Passage on the one hand points to new commercial possibilities that may be harnessed for a greener global economy, but on the other hand exemplifies the problems of climate change caused by industrialisation and such commercialization. We ask, what are the socioeconomic and environmental factors at play in this scenario? Are there means by which careful and sympathetic use of the Northwest Passage can facilitate a positive side-effect of ice loss caused by the global warming? Such means would require an open and interdisciplinary discussion between researchers, policy makers, industry, and above all, local communities, on all aspects of benefit and disadvantages.

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Footnotes

1) The successful searches for *Terror* and *Erebus* were led by the Arctic Research Foundation and subject of a recent exhibition at the National Maritime Museum in Greenwich, UK (Hutchinson, 2017, Palin, 2018).

2) https://www.thearcticinstitute.org/countries/russia/

3) https://www.canadainternational.gc.ca/united_kingdom-royaume_uni/bilateral_relations_bilaterales/arctic-arctique.aspx?lang=eng

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5) http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx

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Figure captions

Fig. 1: Location of the Northwest Passage and the Northern Sea Route. Route via Greenland, Northern Canada, US, the Northwest Passage in blue; Route via the North coast of Russia; the Northeast Passage in brown. September is the month when yearly Arctic minimum sea ice extent is reached. In the year 2019, the lowest extent of sea ice was 3.8 million square kilometers (on 3rd, and 14-18th September). The sea ice concentration is derived daily from satellite data with the method described by Spreen et al. (2008). The figure also shows the dramatic decrease of the sea ice that recorded during the period 1981-2010. Sea-ice data and figures are used with the permission of the University of Bremen (https://seaice.uni-bremen.de/arctic-sea-ice-minima/). The small scale bar refers to the proportion of ice (white) and water (blue).

Fig. 2: Location of the Northwest Passage and the most important settlements with ports and airports, and past and active mines near the Northwest Passage. Modified from Wikipedia: https://en.wikipedia.org/wiki/Northwest_Passage#/media/File:Northwest_passage.jpg. Popular Northwest Passage routes. Based on a NASA image that is in the public domain.

Fig. 3: (A) NASA satellite image of summer Arctic ice coverage reveals that there is no open waters North-West of Greenland. (Data source: Satellite observations. Credit: NASA Scientific Visualization Studio, copyright-free NASA image) (B) Photograph of the globe of the world from 1845 showing open water in a large area around the North Pole (modified after Hutchinson 2017). Arrows on A and B shows the location on King William Island. It was North of this island that the ships of Sir John Franklin were abandoned, recently found in Terror Bay South of King

William Island (wreck of the *Terror*) and West of Adelaide Peninsula (wreck of the *Erebus*). The image "GLP0081 (S0361), Terrestrial table globe" is printed with the permission of the National Maritime Museum, Greenwich, London.

Fig. 4: Photograph of the pack-ice in North Greenland taken on board of the sailing vessel Rembrandt van Rijn in 2015 when the first author was also part of the crew. Photograph by courtesy of Plana; published with the permission of the photographer.

Fig. 5: The same glacier of the Qaamarujuk Fjord. (A) Photograph during summer of 1930, see Georgi (1933). (B). Photographs during summer 2012, see Schlatter (2016). While this glacier has almost reached the ocean in 1930 and Alfred Wegener crossed this glacier to reach the inland ice, in 2012 large portions of the glacier has melted.

Fig. 6: History of the temperature of the last 200 years. Extended annual mean surface air temperature (SAT) record for the Atlantic Arctic boundary region based on composite land station records. Ninety-five percent confidence limits are shown. Decadal-scale variations are emphasized with a two-way Butterworth low-pass filter constructed to remove frequencies higher than 0.1 cycles per year (black line). The early 20^{th} century warming episode and the recent temperature increase are evident. Figure and figure caption modified from Overland et al. (2011); superimposed is the instance of the winter 1846/1847 when Franklin's ship got trapped in the ice. Figure is used with the permission from Open Academia, registered in Sweden with Company Number 559109-1383.

Fig. 7: Distribution of the continental crust and its ages. Superimposed, the approximate route of the Northwest Passage. Modified after Kerrich and Polat (2006). Figure is used with the permission from Elsevier, Licence Number 4703710320540.

Fig. 8: Photograph of the village of Siorapaluk in North-West Greenland taken in 2015 on board of the sailing vessel Rembrandt van Rijn when the first author was also part of the crew. Photograph by courtesy of Plana (2015); published with the permission of the photographer.

Table caption

Tab.1: List of mines and mineral exploration projects located near the Northwest Passage, providing the mined/explored commodities, their grades and tonnages as well as information regarding the shipping of the

385 commodities. The location of the mines and mineral exploration projects can be found in the Figure 2. Data from
386 Boyd et al. (2016), Goodfellow (ed.) (2007), Melia et al. (2017); * shipping information, personal communication
387 John L. Pedersen, 2019; Mt=million tons.

Fig. 1

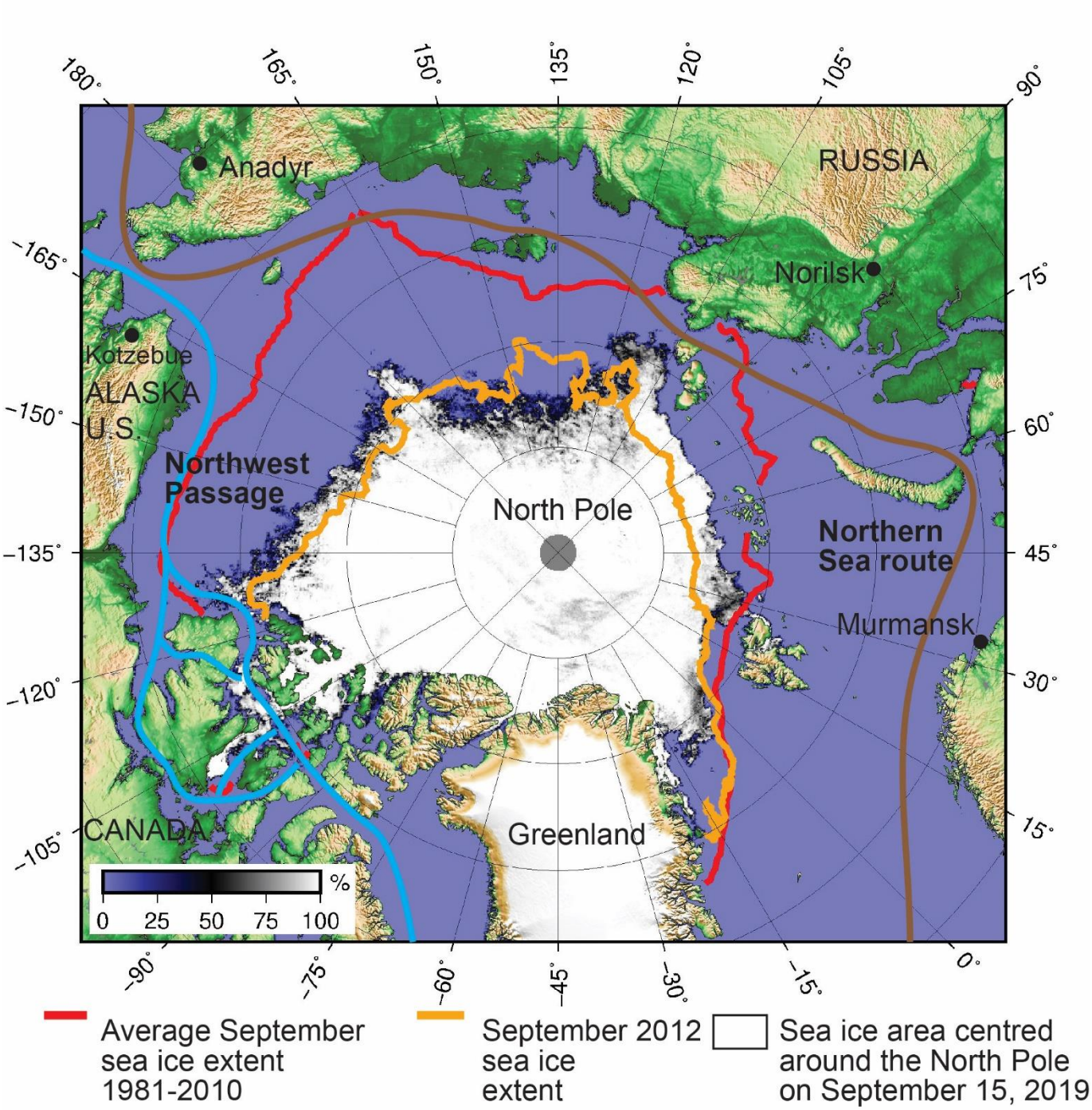
180°
165°
150°
135°
120°
105°
90°
75°
60°
45°
30°
15°
0°
-165°
-150°
-135°
-120°
-105°
-90°
-75°
-60°
-45°
-30°
-15°
Anadyr
RUSSIA
Norilsk
Kotzebue
ALASKA
U.S.
Northwest
Passage
North Pole
Northern
Sea route
Murmansk
CANADA
Greenland
%
0 25 50 75 100
Average September sea ice extent 1981-2010
September 2012 sea ice extent
Sea ice area centred around the North Pole on September 15, 2019

Fig. 2

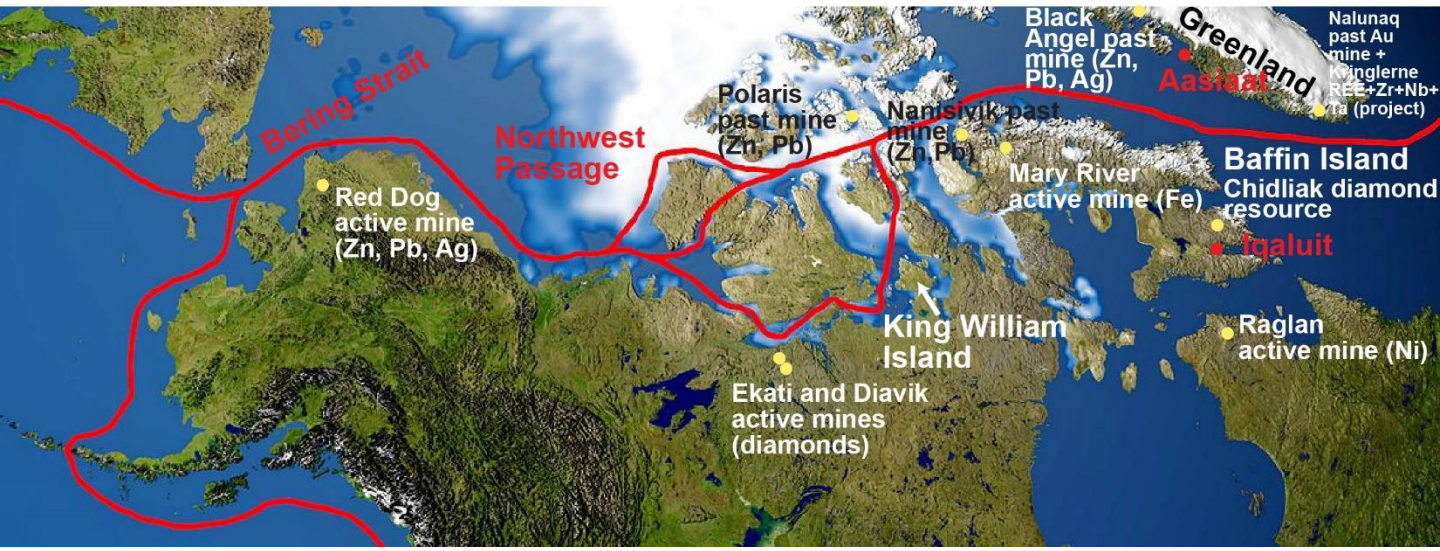
Bering Strait
Northwest Passage
Red Dog active mine (Zn, Pb, Ag)
Polaris past mine (Zn, Pb)
Nanisivik past mine (Zn, Pb)
Black Angel past mine (Zn, Pb, Ag)
Greenland
Aasiaat
Nalunaq past Au mine + Kringlerne REE+Zr+Nb+Ta (project)
Mary River active mine (Fe)
Baffin Island
Chidliak diamond resource
Iqaluit
King William Island
Raglan active mine (Ni)
Ekati and Diavik active mines (diamonds)

Fig. 3

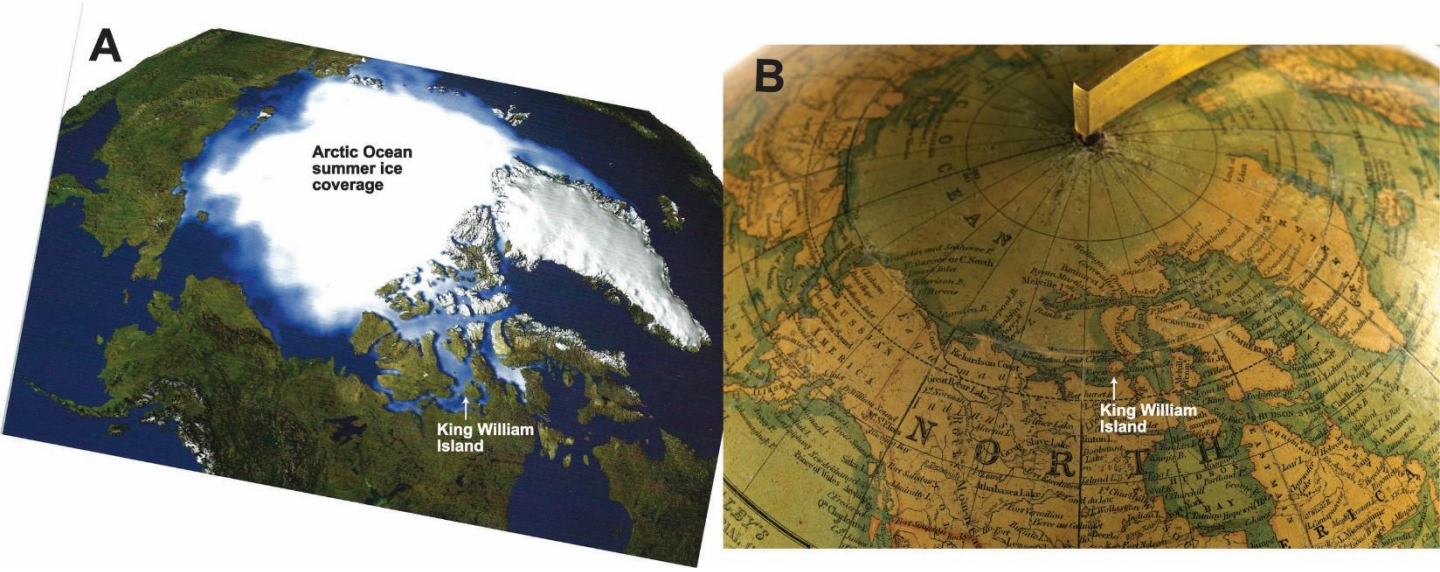
A
Arctic Ocean
summer ice
coverage
King William
Island
B
King William
Island

Fig. 4

Fig. 5

Fig. 6

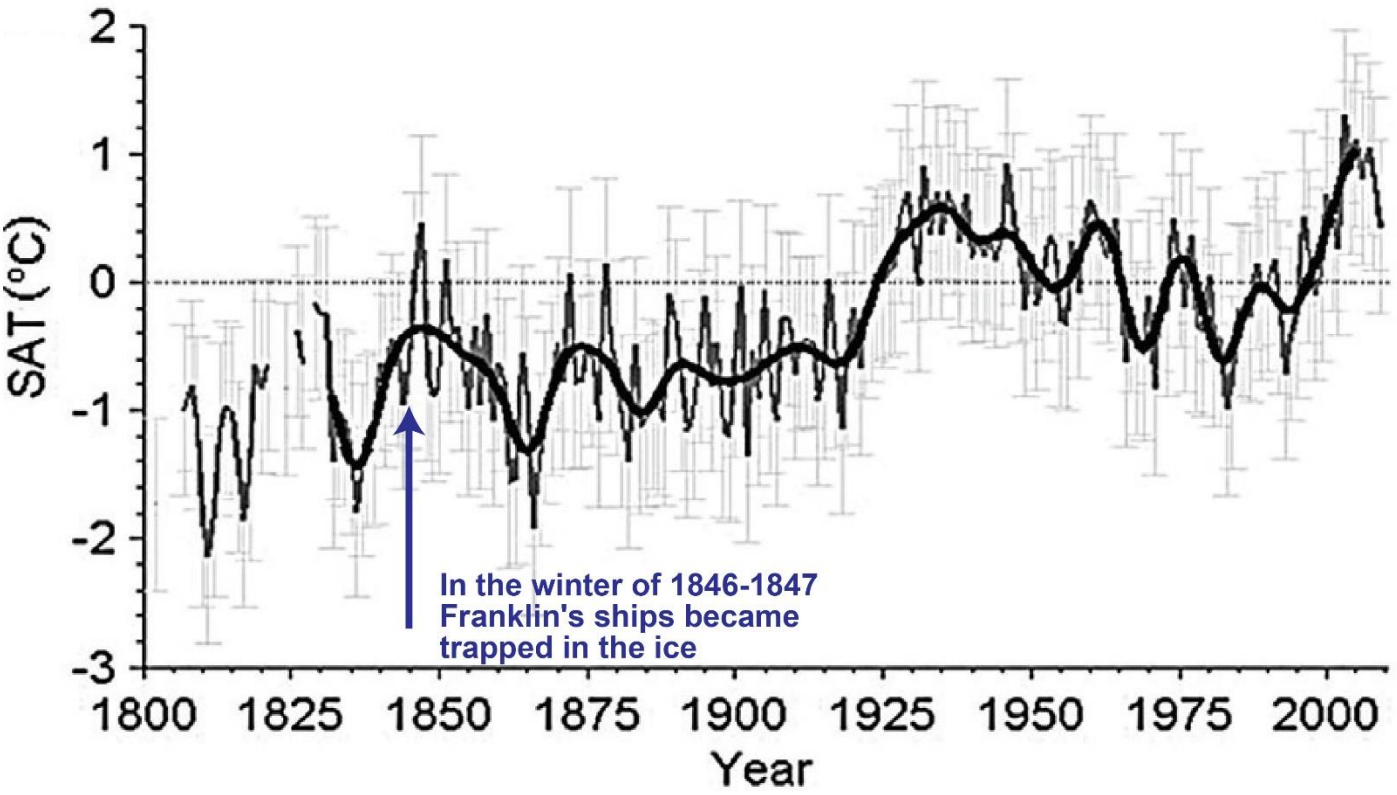
SAT (°C)
2
1
0
-1
-2
-3
1800
1825
1850
1875
1900
1925
1950
1975
2000
Year
In the winter of 1846-1847
Franklin's ships became
trapped in the ice

Fig. 7

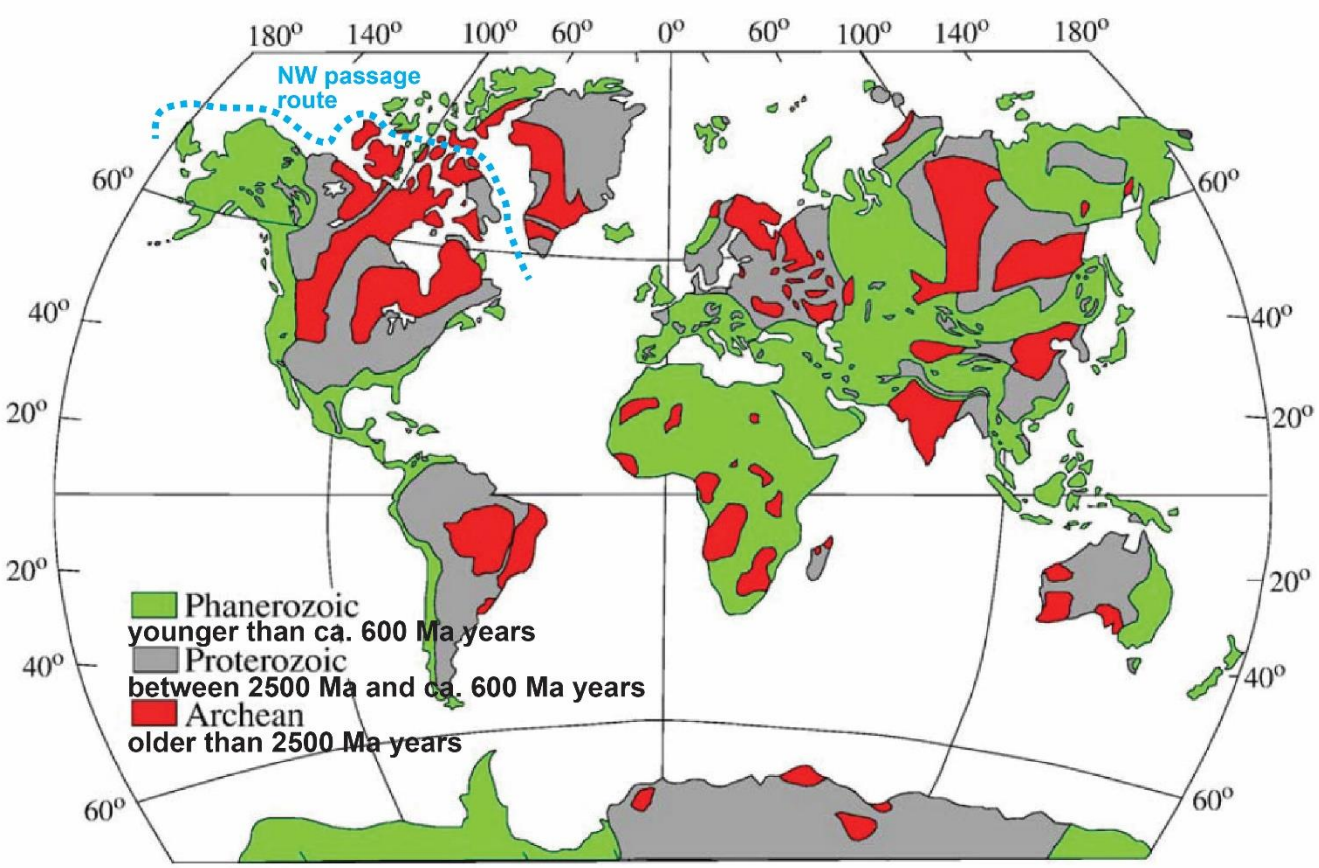
180°
140°
100°
60°
0°
60°
100°
140°
180°
NW passage route
60°
40°
20°
20°
40°
60°
Phanerozoic
younger than ca. 600 Ma years
Proterozoic
between 2500 Ma and ca. 600 Ma years
Archean
older than 2500 Ma years

Fig. 8

Table 1

Country	Project	Main commodity	Date	Shipping season	Shipping demand
Canada	**Polaris**	Zinc 20.1 Mt @13.4% Zn, 3.6% Pb	1971-2002	3 months	1 ice-breaking bulk carrier
Canada	**Raglan**	Nickel >1000 Mt @1.2% Ni	1997-present	8 months	1 ice-breaking bulk carrier
Canada	**Mary River** Milne Inlet	Iron ore >400 Mt @65% Fe	2015-present	Year-round	estimated 3 ice-breaking bulk carriers
Canada	**Ekati**	Diamonds >50 million carats of diamonds	1998-present	Access by winter road	no access to water
US/Alaska	**Red Dog**	Zinc >11 Mt @20% Zn, 5.6% Pb, 90 g/t Ag	1987-present	4 months	23 ship calls/year
Greenland	**Black angel**	Zinc 13.6 Mt @12.3% Zn, 4% Pb, 29 g/t Ag	1973-1990	7 months	1 bulk carrier * (4 to 5 ships/year)
Greenland	**Nalunaq**	Gold 0.713 Mt @15 g/t gold	2004-2014	Gold doré produced on site and sent out by air	ships for infrastructure in the summer season
Greenland	**Kringlerne**	Tantatalum, niobium, REE, zircon 4300 Mt @0.65% Total Rare Earth Oxide, 0.2% Nb_2O_3, 1.8% Zr_2O_5 *(inferred resource)*	*exploration*	*under investigation* *exploitation license under review*	*under investigation* *exploitation license under review*
Russia	**Norilsk** Talnakh groups of deposits	Nickel 1309 Mt @ 1.77% Ni, 3.57% Cu, 0.061% Co 9.5 g/t PGE (including 1.84 g/t Pt, 7.31 g/t Pd)	1930s-present	Year-round since 2005	5 ice breaking container ships