Andrew Macumber received a B.Sc. degree in neuroscience; he change direction and entered the geology M.Sc. program at Carleton University (Ottawa, Canada); his research work was so impressive that his advisor (R. Tim Patterson) encouraged him to upgrade the work into a Ph.D. dissertation.

Thesis Title: High-resolution multi-proxy paleoclimatic reconstruction of the southern Northwest Territories (NT) using lake sediments from the Tibbitt to Contwoyto Winter Road (TCWR), NT, Canada.

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Project Rationale: The Tibbitt to Contwoyto Winter Road (TCWR) is the sole overland route that services mines and exploration activities in the Northwest Territories (NT) (including the Diavik Kimberlite Mine) and in Nunavut. It is the world's longest heavy haul ice road, and is critical to the economy of the region with more than $500 million per year in goods passing over it, and essential for the operation of an industry which comprises over 30% of the gross territorial product. Without the TCWR important mine sites would most likely never have been developed, and current expansion of mining activity would not be possible. Cold winter temperatures are critical to the viability of the TCWR, since the majority (495 km, 87%) of its length is comprised of frozen lakes. Recent climate variability has resulted in changing ice stability, thickness, and duration of ice cover. This has greatly impacted the use of the road particularly as large highway semi-tractor trailers require ice thicknesses in excess of 100 cm for safe operation. Mild and stormy winter conditions during the 2006-2007 season, related to an El Niño/Southern Oscillation (ENSO) event, shortened operations to 26 days below average, resulting in only 6841 loads going north (in contrast to 10,922 loads north in 2007). With the current rate of expansion of this system it is expected that loads north will need to exceed 14000 by 2013. Resource managers lack sufficient records of this region's natural climate variability that are needed in order to make a critical review of the viability of current and future infrastructure. In order to estimate the impacts that future climate change will have on both the aquatic and terrestrial environments, there

needs to be deep understanding of how this region has responded to climate variability.

The purpose of this study is to reconstruct the climatic variability and identify climate phenomenon (i.e. ENSO) that have impacted the southern Northwest territories over the last 3500 year period during which the modern climate became established. A high temporal resolution sub-sampling methodology will provide a resolution useful (i.e. sub-decadal to decadal) to resource managers in their assessment of the viability of current and future infrastructure.

Areas of the NT have seen annual temperatures warm by ~2^{o}C since the 1940s, when instrumental records were first kept. Meteorological data show that northern regions continue to warm at a rate twice as fast as the rest of the world and general circulation models predict that the NT may become 2-3^{o}C warmer over the next 50

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years. Since the 1980s there has been a realization that rapid climate change on the scale of human life was possible. That it may be related to atmospheric increases in anthropogenically produced greenhouse gases has provided a major impetus for research into climate change. There is also the realization that human induced climate change is only a subset of possible climate system behaviour, and that rapid climate change as a result of natural climate variability may also present a significant challenge to our civilization. A long term perspective is necessary to identify how the environment has responded to similar climatic conditions and identify decadal to centennial oscillation of climate phenomenon that impact this region.

Modern atmospheric-oceanic conditions became established along the Pacific coast of North America between 4200 and 3000 yr BP. The warmer and dryer conditions that characterized the mid-Holocene gave away to the cooler and wetter conditions of the Late Holocene. Instrumental and geologic records of climatic conditions have shown decadal oscillations in the North Pacific and the interior North America are linked to global climate phenomenon such as the Pacific Decadal Oscillation (PDO), and ENSO variability. Fluctuations in precipitation on a decadal scale have been correlated to changes in North East Pacific sea surface temperatures that are in turn correlated to regime shifts associated with positive and negative phases of the PDO. The PDO is long lived ENSO-like pattern of Pacific climate variability, which has two periodicities: 15-25 years and 50-70 years. According to the Nyquest sampling theorem, in order to capture the oscillations of a climate cycle, such as the PDO, we must subsample at a temporal frequency that is two times greater than that of the climate cycle of interest. To be able to look for the PDO specifically our temporal resolution needs to be 15 or 25 years. A large body of palynological research has occurred in the NT, but mostly focussed on the tree line or the Mackenzie region. Very few multi-proxy studies of environmental change have been conducted in the central NT and the temporal resolution of this previous work is relatively coarse (centennial scale). This scale is far too coarse to capture high frequency oscillations of climate systems

that may be impacting the region. Understanding which climate systems impact the NT is necessary to understand the regions natural climate variability.

Project Methodology: The entire region was glaciated during the last glacial maximum and as a result the landscape shows abundant glacial erosional features. This and the influence of permafrost have disrupted drainage patterns resulting in an abundance of lakes. Lake sediments archive continuous records of environmental change and are arguably the most complete records available of aquatic and terrestrial change. Lake beds contain natural archives of limnological, atmospheric temperature and precipitation conditions and changes. Utilizing both microfossil and sediment proxies a high resolution paleoclimatic record will be reconstructed. Enumeration of arcellaceans, a well fossilized and abundant benthic protest, will allow for the interpretation of current

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and ancient lake conditions. Variation in precipitation and snow volume leads to variation in catchment energy and variations in size of grains washing into lacustrine systems. Analyzing grain size changes at a millimetre resolution using time series analysis will identify significant frequencies that can be correlated with previously identified climate phenomenon. Understanding which climate phenomenon impact this region is critical in modelling how this region will respond in the future to climate change. Detailed core analysis will be restricted to portions deposited within the last 3500 years which encompasses the Late Holocene when modern circulation and climatic conditions developed.

Three lake sediment cores will be studied, each from a different climatic zone. The first from below the tree line, the second at the tree line and third will be located within the arctic tundra. This will complete a 2^{o}C climatic gradient. A freeze corer will be used to collect a complete and undisturbed record, including the soupy sediment water interface which reflects modern conditions. Freeze corers are ideal in low sedimentation regimes, and the frozen slabs are easy to handle and subsample. All cores will be x-rayed, and described sedimentologically. Cores will be dated using ^{210}Pb & ^{137}Cs isotopes for times scales less than 100 years linking the geological record to the instrumental record which began only 40 years ago. Cores will be dated using $_{14}$C isotopes for longer time scales. Bayesian age-depth modelling will be used to associate depth with time and the accuracy of this process (i.e. the number of dates) is essential for time series analysis and accurate interpretations of the regions climate history.

Using a slab microtome Late Holocene sediments will be accurately subdivided into 1 mm thick slabs suitable for high resolution grain size analysis. Composites of slices will be used for more labour intensive. Organic content of lake sediments, as measured by loss-on-ignition, have been correlated with lake and watershed productivity, and positively correlated to temperature in the NT. The relative concentration of biogenic silica in northern lakes is related to the productivity of siliceous diatoms and chrysophytes, which is in turn most likely correlated to the NT summer

temperatures and consequently to the length of the ice free period. Thecamoebians (testate amoebae) are mostly benthic protists that are abundant in lacustrine habitats, and possess tests that fossilize well in Holocene sediments. Variation in thecamoebian assemblages reflect environmental changes such as: eutrophication, pH, temperature, and oxygen levels. They have been used previously to reconstruct paleoclimate throughout North America, including the NT.

Project Objectives: The data will be used to construct a high resolution (decadal) and multi-proxy description of climate variability for this economically important corridor, spanning a 2^{o} latitudinal gradient. Understanding how this system has responding in the past will facilitate inference of what affect future climate variability will have on aquatic and terrestrial environments in the central NT. We will recognize cycles and trends in

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the late Holocene using time series analysis. In this way we can quantify the dominant paleoclimate cycles and trends, and correlate them with known continental climate signals recorded elsewhere in North America. This will provide resource managers with the dynamic baseline conditions for this region, greatly facilitating and lending guidance in their evaluation of the viability of current and future infrastructure practices.