Fire and Ice

Lorraine A. Manz

The surface of the land in most of northern and eastern North Dakota is littered with boulders (fig. 1). Many bear no resemblance at all to the local bedrock, or indeed to any of the Tertiary and Cretaceous sedimentary units that form the bedrock throughout most of the state. The great majority of these boulders, especially the larger ones, consist of a lithologically diverse assortment of very hard, igneous and high-grade metamorphic rocks. Most of the igneous rocks are granites (fig. 2), formed deep inside the earth's crust by the crystallization of molten rock as it slowly cooled over a period of thousands, perhaps millions of years. Some have a fine, granular texture, suggesting they cooled relatively quickly. In others, much slower rates of cooling have produced individual crystals that can be measured in inches. Many contain xenoliths – fragments of other rocks subsumed by the granite when it was still in its molten state.

Figure 1. Boulder-strewn pasture near Killdeer in Dunn County.

The metamorphic rocks are predominantly dark and light gray or pink gneisses (fig. 3). These rocks are formed at temperatures close to melting, which allows the light and dark minerals to separate into the layers that give gneisses their characteristic banded texture. Many are folded and/or cross-cut in all directions by granite intrusions, an indication of the close field relationship between these two types of rock. A few other lithologies are represented among the boulders including volcanic basalts and other high-grade metamorphics like greenstones and certain schists.

In spite of their durability, most of the boulders have been worn smooth, with rounded or planed and faceted surfaces. Sometimes the flatter surfaces are also striated: scratched with lines and grooves that are often aligned subparallel to one another (fig. 4).

The origin of the rocks these boulders are made of, where they (the boulders) came from and how they got here is a very long story: one that spans almost the entire length of the geologic record.

The world's oldest reliably dated rock, the Acasta gneiss in Canada's Northwest Territories, was formed a little over 4 billion years ago (Bowring and Williams, 1999). The Acasta gneiss is part of the Canadian Shield, a vast, roughly circular region of exposed Precambrian bedrock that extends over eastern, central, and northwestern Canada, most of Greenland and parts of northern Minnesota, Michigan, New York, and Wisconsin (fig. 5). The Canadian Shield is the heart of the North American Craton, the ancient, geologically stable portion of the earth's crust upon which the North American continent is built. Today, it is a topographically subdued region of deeply eroded, ice-scoured landscapes populated by caribou and polar bears. But the broken, deformed rocks in its Precambrian surface attest to an extremely violent past.

The North American craton is a remnant of one of Earth's earliest continents. Our planet was born about 4.6 billion years ago and was already half a billion years old by the time its surface had cooled sufficiently to allow a solid crust to form. Fueled by the tremendous heat released from Earth's still mostly liquid interior, repeated cycles of melting and solidification gradually separated this primitive crustal material into two components: the lighter fraction rising to the top to become the beginnings of the continents; and the heavier one ocean crust. The Acasta gneiss is a rare survivor of this turbulent period of tectonic and volcanic activity, which was far more intense than anything these processes could achieve today.

Figure 2. This particularly large granite boulder was unearthed on the capitol grounds earlier this year by crews working on the Heritage Center expansion. The side facing the camera measures about four by eight feet (note the lens cover used for scale)

Like its modern counterpart, Earth's crust in Precambrian time would have been broken up into a number of plates: great slabs of ocean crust with what would then have seemed little more than islands for continents embedded in them like logs frozen in river ice. Fierce convection currents circulating in the hot mantle below, would have kept the plates in constant motion in a kind of speeded-up version of present-day plate tectonics. New ocean crust was formed at spreading centers where plates were moving apart (the Mid-Atlantic Ridge is a modern example), and destroyed and recycled in subduction zones where they collided.

Exactly how the continents formed remains the subject of considerable debate (Petit, 2010; Nagel and others, 2012) but there is more than sufficient evidence to show that plate tectonics was (and still is) the primary mechanism. When two plates meet head-on, old, dense ocean crust is overridden by lighter, continental crust or, if two ocean plates collide, younger, less dense ocean

Figure 3. The dark-colored rock in this boulder outside the ND Oil and Gas Division's new office building in north Bismarck is gneiss (rhymes with "nice"). The thin layers of dark and light minerals that give gneisses their characteristic banded appearance can be clearly seen in this photo, as can several intrusions of pink granite that have cut across the mineral layers at various angles.

crust. The force of the collision may cause the overriding plate to buckle skywards and form mountains, while the denser plate is driven down (subducted) into the hot mantle where it causes the overlying rock to melt. The magma rises and is erupted from volcanoes in the mountains above. This is what is happening today along the west coast of South America, for example, where the Nazca oceanic plate is diving beneath Peru and Chile creating the Andes.

Things are a little different if both colliding plates are carrying a continent. Because continental crust is lighter and more buoyant than ocean crust, it is less inclined to subduct. Instead, the two landmasses simply plow into each other, shoving the land upwards into great mountain belts in a region-wide episode of faulting, folding, and general crustal deformation. Faults break the crust into huge thrust sheets that are stacked like dominoes as the force of the collision pushes them up and over one another. Bits of continental crust, chains of volcanic islands, sediments scraped off oceanic crust on the leading edge of the plate as it plunged in to the mantle, and any other crustal material caught between the approaching landmasses, are accreted to one or the other to end up as part of the towering mountain ranges that are the outcome of these titanic collisions. Deep below the surface metamorphism is widespread; mineral compositions, in rocks heated to the consistency of warm taffy and on the brink of melting, are changed while the rocks themselves are compressed and sheared by the tremendous pressure into elaborate patterns of folds and foliated minerals. Granitic magmas intrude into the overlying crust, forcing their way upwards by melting, fracturing, and breaking off chunks of solid rock as they rise. These magmas do not reach the surface but instead cool slowly at great depth to form batholiths, enormous bodies of coarse crystalline granite and other igneous rock that make up the mountains' core. This is what happened when, about 60 million years ago, the plate carrying the Indian subcontinent began to collide with the Eurasian plate and build the Himalayas. Moreover, India is not done yet and continues to ram into Asia at a rate of about 2 inches a year, which means these mountains are still growing.

Although some of its rocks are far older, the Canadian Shield itself was formed between about 2.5 and 1.2 billion years ago. Many of its rock assemblages show that much of it was constructed by processes very similar to the ones described above; including evidence of high mountain ranges that would have rivaled the Himalayas. The granites are the remains of their batholith cores, and along with the intensely folded gneisses and other high-grade metamorphic rocks, all that is left of their deep roots that hundreds of millions of years of weathering and erosion have gradually brought into the light of day.

Mountains are like icebergs – what you see above the surface is only a fraction of the whole. Regardless of its size, the relative proportion of ice or rock above the surface to what is below is always the same. Break a chunk of ice off the top of an iceberg and that delicate balance is upset. The 'berg will compensate by rising a little higher out of the water until its equilibrium is restored. Mountains are the same. The greater part of their mass is hidden underground where the enormous roots extend deep into the upper mantle, as much 30 miles below the surface. Over time, as a mountain range is slowly worn down, the whole structure, roots and all, rise imperceptibly upward as, bit by bit, the weight of billions of tons of rock is removed and washed away as sediment by rivers and streams or blown by the wind. By the end of the Silurian Period, around 420 million years ago, as subsidence was creating the depression that would later become known as the Williston Basin, the high mountain ranges of the Canadian Shield had already been eroded to within a shred of their present elevation (Percival and Easton, 2007); and for more than 400 million years little changed.

Figure 4. The planed and faceted surfaces indicated by the arrows on these two granite boulders are natural. The one on the left is also scratched or striated with dozens of fine, parallel lines.

What does any of this have to do with boulders in North Dakota? Only that it is one installment of their history. The granites and gneisses strewn across so much of the northern and eastern part of the state came off the Canadian Shield. They originated deep in the roots of a long-vanished mountain range that was built during one of the most violent periods in Earth's history. It is recorded in their composition and textures, in the xenoliths and the folded, broken rocks, which match others in the relict mountain terranes of North America's ancient heart. We don't know enough about the boulders to know exactly where on the Canadian Shield they came from but there are clues that help narrow down the possibilities.

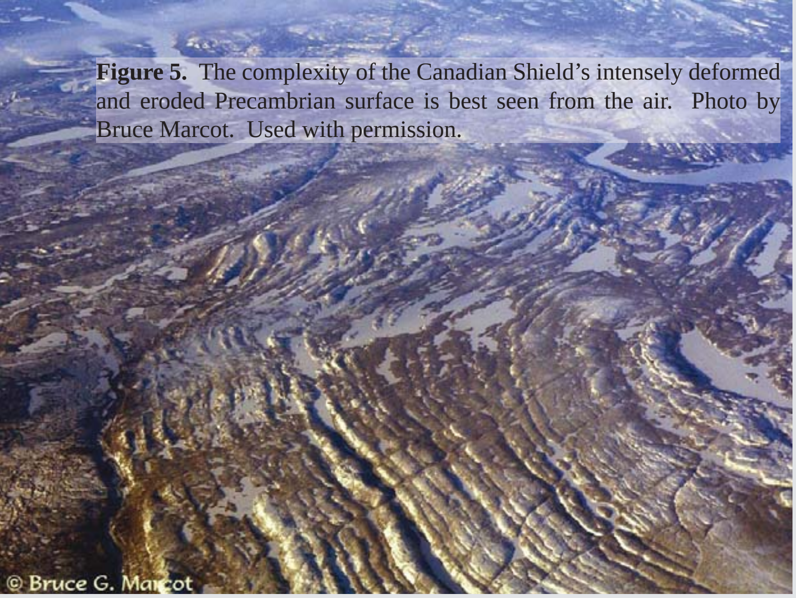

Figure 5. The complexity of the Canadian Shield's intensely deformed and eroded Precambrian surface is best seen from the air. Photo by Bruce Marcot. Used with permission.

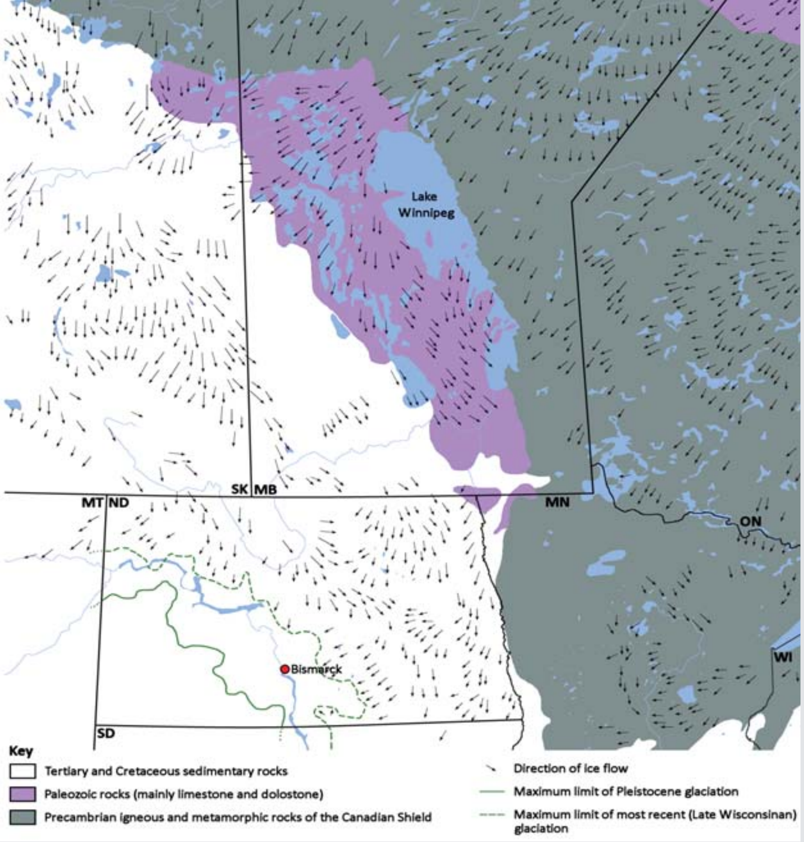

Figure 6. Map showing the general direction of ice flow and possible sources of the boulders and other geologic debris deposited in North Dakota by Pleistocene ice sheets. Regardless of where they came from, the extreme hardness and durability of the igneous and metamorphic rocks from the Canadian Shield almost always ensured that they would outnumber sedimentary lithologies at the boulder end of the till size scale. Modified from Clayton, Moran, and Bluemle, 1980; and Flint, 1971.

Getting a boulder-sized rock from the Canadian Shield to North Dakota, a distance of several hundred miles, requires more than just wind and water. And the only natural material capable of such a feat is ice in the form of a glacier. For the last 2.6 million years or so, Earth's climate has slipped in and out of long periods of cold, during which much of northern North America, Europe, and Asia were covered by enormous ice sheets, continent-sized glaciers like the ones in Greenland and Antarctica today. This interval of geologic time, which ended a mere 10,000 years ago, is called the Pleistocene Epoch, or "Ice Age."

The last time there were glaciers in North Dakota was between about 26,000 and 10,000 years ago, during the Late Wisconsinan glaciation, when ice spread into the state from a center somewhere west of Hudson Bay. As it grew and spread, the glacier advanced over parts of the Canadian Shield in Ontario, Manitoba, and Saskatchewan, leaving in its wake a bedrock surface swept clean of all loose material and gouged with lines and furrows marking the direction of its passage. Farther south, where the shield is overlain by younger, sedimentary rock, other lithologies were added to the mix: Paleozoic limestones and dolostones from formations north of Winnipeg; silty, sandy Cretaceous and Tertiary rocks from southern Manitoba, Saskatchewan, and northern and northwestern North Dakota, and shale from the eastern and northeastern part of the state (fig. 6). All along its path, the moving glacier plucked and entrained rocks, soil and unconsolidated sediment from the landscape and carried it away. Frozen within and to the base of the moving glacier, this jumbled mass of clay, silt, sand and gravel, pebbles, cobbles, and boulders was milled and abraded as the fragments ground past one another or were scraped over hard bedrock. Surfaces were rounded and worn smooth or planed flat and sometimes striated by smaller rocks. Striations scored in bedrock or when the ice flowed over a hard, stationary boulder were often in the form of parallel lines (fig. 4). Provided the rocks have remained as the glacier left them, these striations can be used to determine the direction from which it came long after the ice has disappeared.

Whether made of granite, limestone, sandstone or some other type of rock, any boulder that has been transported and deposited by a glacier is called an erratic. And North Dakota's countless igneous and metamorphic erratics have evidently come a long way: picked up off the Canadian Shield and carried for hundreds of miles by glaciers to where they are today, many exactly as the ice left them a little over 10,000 years ago. The other rocks and sediment that were brought with them and the parallel lines scratched into the erratics' planed surfaces hint at where on the shield they may have come from – northern Saskatchewan, Manitoba, Ontario, perhaps somewhere even further afield or a bit closer to home, Minnesota, for example.

Think about all this next time you see a pile of boulders in a field, a line of riprap or a lone specimen gracing someone's front yard. You may never look at them in quite the same light again.

References

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