# A Review of Paleomagnetic Studies from Northern Alaska and Yukon: Implications for Terrane Reconstructions

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**Abstract**

Here we present a comprehensive overview of available paleomagnetic studies and datasets from northern Alaska, USA, and Yukon, Canada. Most studies in this region were conducted when our understanding of best-practices paleomagnetism was still developing; as a result, many do not meet modern standards of data quality and many interpretations of the paleomagnetic data – though valid at the time – are now also outdated. In this review, we assess what data are reliable, what interpretations have stood the test of time, and what the existing data can constrain about the tectonic history of this region. We find that although a Middle to Late Cretaceous overprint pervades much of this area, many sites still retain primary remanence directions, some dating as far back as the Neoproterozoic. Studies that found complete overprinting in the Cretaceous also typically analyzed poor lithologic recorders of paleomagnetic directions, such as carbonates. Based on our assessment of the most reliable data from the study region, relative motion between the examined outboard terranes and Laurentia was not yet complete by the Middle Cretaceous. We also find that 'high latitude' dinosaur fossil sites were more northerly than today, confirming previous assumptions about the paleolatitudes at these sites. Finally, we discuss how the widely cited Jurassic–Cretaceous counterclockwise rotation hypothesis for the Arctic Alaska terrane is no longer supported by the existing paleomagnetic data, and the validity of this hypothesis should be critically reexamined.

**Key Words:** Paleomagnetism, Tectonics, Yukon, Alaska, Brooks Range, Koyukuk, Farewell, Cordillera, Arctic

## 1. Introduction

The tectonic history of the northernmost North American Cordillera and Arctic is still mired in uncertainty (e.g. Lawver and Scotese 1990, Johnston 2001, Colpron and Nelson 2009, McClelland et al. 2021). One data type that is notably sparse in this region is paleomagnetic data. Such data are key to tectonic reconstructions in most other regions of the world, as they can determine the paleolatitude and rotation of a terrane with more precision than other techniques (e.g. Van der Voo 1988, Tauxe et al. 2010). Furthermore, paleomagnetic datasets are abundant in other regions of the Cordillera (e.g., the western United States), but they notably dwindle in abundance above ~65°N latitude. Of the paleomagnetic data that is available from this region, it is decidedly of mixed quality. Some studies were at the forefront of paleomagnetic methodologies and techniques, were executed with great competence, and the data were interpreted with significant care and thought. Their only flaw is that many of these studies were conducted when our understanding of paleomagnetism was rapidly developing and our methods to extract the best data possible were not yet optimized (e.g. Gubbins and Herrero-Bervera 2007, Lowrie 2021). There are also numerous paleomagnetic studies from this region that are simply lacking in major components, such as a small number of samples, incomplete data reporting, and/or missing sample location data. There are useful data to be found in these studies, but care must be taken to sort through the details.

In this study, we first briefly review how to evaluate the quality of paleomagnetic data (Section 2). Then, we review all the known paleomagnetic data from the northernmost Cordillera in Alaska and Yukon (Section 3). While doing so, we address several misconceptions involving these data, re-assess their quality, and determine which data are usable. We also present new paleomagnetic data from flood basalts in this region. Finally, we comment on how the existing data supports or refutes current tectonic reconstructions and comment on opportunities for high-impact studies in this region in the future (Section 4).

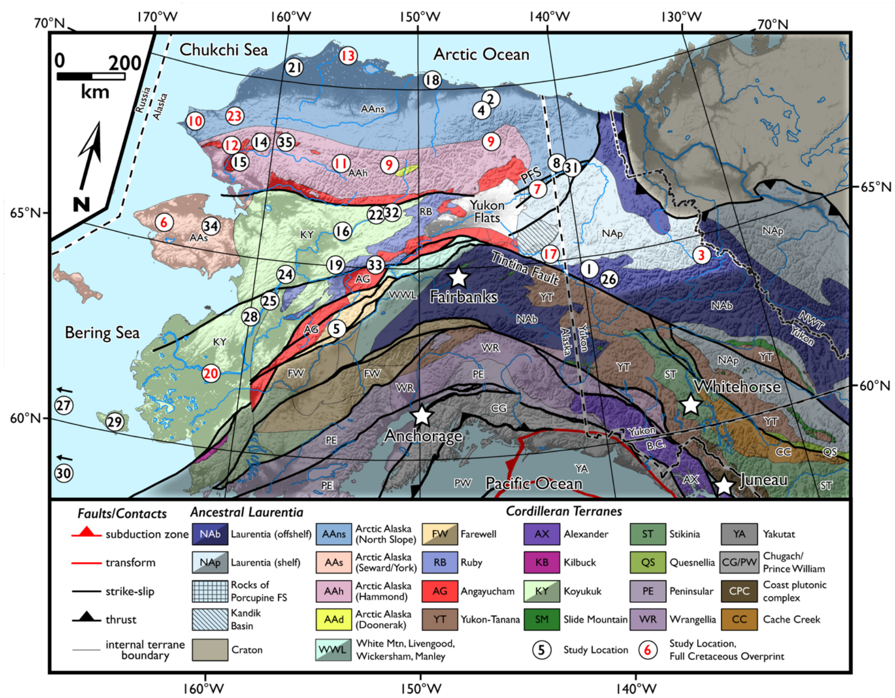


**Figure 1.** Simplified terrane map of Alaska and Yukon modified from the Yukon Geological Survey (2020). Dark-shaded area is outside the scope of this review. Numbered locations on the map correspond to locations described in Section 3. Previous studies found complete Cretaceous overprinting at the red-numbered locations. Koyukuk = combined Yukon-Koyukuk basin and Koyukuk arc.

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### 1.1 Scope of Review

The geographical boundaries of our review are shown in Figure 1. This encompasses most areas north of the Kaltag and Tintina fault systems and south of the Canada Basin of the Arctic Ocean. The units in this study area (debatably) share a common Mesozoic tectonic history associated with the onset of regional Cordilleran deformation (e.g. Nelson et al. 2013, Moore and Box 2016). Southern Alaska and Yukon are excluded from this review, as other paleomagnetic reviews of that region are already available (Coe et al. 1985, Harbert 1990, Enkin 2006). St. Matthew Island and the Pribilof Islands (Locations 27 & 30, Figure 1) are also included in this review, as they do not fall neatly into other review areas.

We cover studies that range from Quaternary unconsolidated sediment to Precambrian crystalline rocks. Particular attention is paid to Mesozoic units due to active debates about their tectonic history. We also include studies that were 'published' via conference abstracts because a significant portion of the paleomagnetic data from this region only reached this stage. If we restricted ourselves only to primary literature published datasets, this review would be ineffectively brief. Critically, this is not a review of northern Cordilleran tectonics. The main purpose of this review is to assemble all the available paleomagnetic studies into one manuscript and present an assessment of the reliability and quality of these data. In doing so, we hope that this study will be useful to geologists who may not be as familiar with paleomagnetic data and for paleomagnetists who will see opportunities for further study.

### 1.2 Geologic Background

The study region broadly transitions westward from the autochthonous margin of Laurentia into a variety of terranes now embedded within the northern Cordillera, including their younger Cenozoic overlap assemblages (Figure 1). The primary examined terranes consist of the Arctic Alaska, Angayucham/Tozitna, Ruby, Kilbuck, and Farewell terranes, as well as allochthonous to parautochthonous rocks of the Porcupine River area. Note that some of these areas have been referred to with other terrane nomenclature (e.g. Silberling et al. 1994). Several review papers that cover the foundational geologic background of the study region are available (Moore et al. 1994, Patton et al. 1994a, 1994b, Decker et al. 1994, Dover 1994, Hyndman et al. 2005, Nelson et al. 2013, Moore and Box 2016), but we will only cover the basic history here.

Precambrian rocks in this region are not well characterized west of the Yukon-Alaska border area, partially due to a lack of study and partially due to the lack of abundant rocks of this age throughout Alaska. The oldest known unit in Alaska is the Paleoproterozoic Idono Complex of the Kilbuck terrane on the southeastern edge of the Yukon-Koyukuk Basin, which is correlative with the Kanektok Complex south of the study area (Figure 1; Miller et al. 1991). The Idono Complex comprises a supracrustal succession of amphibolite and metasedimentary rocks with minor orthogneiss bodies that have been dated to ca. 2.06 Ga, with similar ages reported from the Kanektok Complex (Miller et al. 1991, Miller and Bundtzen 1994, Turner et al. 2009, Bradley et al. 2014, Dumoulin et al. 2018a). The Farewell, Ruby, and Arctic Alaska terranes and Porcupine River area all host younger Proterozoic basement complexes, (meta)sedimentary

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successions, and/or (meta)igneous rocks (Patton et al. 1994b, Roeske et al. 1995, Amato et al. 2009, 2014, Bradley et al. 2014, Cox et al. 2015, Hoiland et al. 2018a, 2018b, Strauss et al. 2019b, 2019a, Faehnrich et al. 2021), the details of which are beyond the scope of this review. Pertinent rocks related to this study are referenced in greater detail below.

In the autochthonous portion of Yukon, the oldest dated unit is the ca. 1.71 Ga Bonnet Plume River intrusions and Slab volcanics in the Wernecke Mountains (Laughton et al. 2001, Thorkelson et al. 2001, 2005), which are part of the Paleoproterozoic–Mesoproterozoic Wernecke Supergroup (Delaney 1981, Furlanetto et al. 2016). Throughout the Ogilvie and Wernecke Mountains and Yukon-Alaska border region, the Wernecke Supergroup is overlain by a diverse assemblage of younger Mesoproterozoic and Neoproterozoic sedimentary and igneous rocks of the Mackenzie Mountains and Windermere supergroups (Young 1982, MacDonald et al. 2011, MacDonald and Cohen 2011, Macdonald et al. 2012, Strauss et al. 2015, Cox et al. 2018). These rocks are interpreted to record polyphase extension associated with the development of the early Paleozoic passive margin of northwestern Laurentia (Macdonald et al. 2012, Moynihan et al. 2019, Busch et al. 2021).

A more substantial portion of the study region is covered by diverse Paleozoic units of both the Laurentian autochthon and adjacent accreted terranes. Paleozoic strata of the Laurentian margin are distinguished by platformal and basinal sedimentary successions with minor volcanic rocks that reflect maturation of the passive margin, including the development of the deeper-water Selwyn basin and associated offshore region along the Yukon-Alaska border (Figure 1; Morrow 1999, Pyle 2012 and references therein). The Farewell, Ruby, and Arctic Alaska terranes (and potentially the Kilbuck terrane, Bradley et al. 2014) also host thick Paleozoic successions characterized by fault-bounded platformal and basinal sedimentary rocks (e.g. Decker et al. 1994, Roeske et al. 1995, Dumoulin et al. 2002, 2018b, 2018a, Strauss et al. 2013, 2019b, 2019a, Hoiland et al. 2018b). Many of these rocks are penetratively deformed and metamorphosed, particularly in the Ruby and southern Arctic Alaska terranes. Polydeformed Paleozoic sedimentary rocks along the Porcupine River area are likely fault slivers of both allochthonous and parautochthonous portions of the Laurentian margin (e.g. Faehnrich et al. 2021 and references therein). Discontinuous belts of Cambrian and Ordovician mafic volcanic rocks are exposed in off-shelf areas of the autochthonous Laurentian margin (e.g. Goodfellow et al. 1995). Early Paleozoic mafic intrusive rocks and volcanics are also located in various locations throughout the Brooks Range of the Arctic Alaska terrane (Amato et al. 2014, Strauss et al. 2017, Johnson et al. 2019 and references therein), in addition to widespread Middle to Late Devonian mafic and felsic plutonic rocks (e.g. Moore et al. 1997, Ward et al. 2019 and references therein). The lower thrust sheet of the allochthonous Angayucham terrane, a large ophiolitic belt, also appears to be Paleozoic in age (Harris 2004, Fredriksson and Pease 2022).

Mesozoic units and associated terranes have received the most study, in part because of their widespread exposure and economic value. Discontinuous exposures of Mesozoic sedimentary successions in the autochthonous and parautochthonous portions of northwestern Laurentia broadly provide a record of Cordilleran orogenesis. Mesozoic sedimentary units of the North Slope/Colville Basin on Arctic Alaska were deposited in the foreland basin of the Jurassic to Cenozoic Brookian Orogeny (Lease et al. 2014, Moore et al. 2015, Hoiland et al. 2018b) and are significant producers of oil and natural gas (Bird and Molenaar 1992). The Brookian Orogeny is thought to result from collision of the Koyukuk arc with the passive margin of Arctic Alaska, causing widespread compression and the creation of a fold-thrust belt. This collision began during or before the middle Jurassic and metamorphism peaked (and therefore Arctic Alaska and the Koyukuk arc were conjoined) by the Albian (e.g. Box and Patton 1989, Pallister et al. 1989, Moore et al. 1993, Lawver et al. 2002, Biasi et al. 2020).

Only one location in this review (Location 16) is unambiguously part of the Koyukuk arc. The remaining studies in the 'Koyukuk' area of Figure 1 were focused on Yukon-Koyukuk basin units. Here we will typically focus on the history of the Yukon-Koyukuk basin, but when referring to the combined arc and basin we will use the term 'Koyukuk terrane'. Eventually contraction was replaced by widespread regional extension, exposing the metamorphic core of the southern Brooks Range and leading to the opening of the Yukon-Koyukuk basin (e.g. Law et al. 1994, Little et al. 1994).

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By the early to middle Cenozoic, it appears that remnant Cordilleran contraction was highly localized, northern and southern Alaska had been combined, and the strike-slip tectonic regime that characterizes most of Alaska today became dominant (Redfield et al. 2007, Haeussler 2008, Nelson et al. 2013). The magnitude of regional strike-slip offsets is one of the most controversial topics in Cordilleran tectonics – some argue that many terranes have been transported northward for thousands of kilometers based on paleomagnetic constraints (e.g. Tikoff et al. 2023), while others argue that these terranes experienced minimal strike-slip displacement based on other datasets (e.g. Dickinson and Snyder 1978, Humphreys 2009).

Given what we know (or do not know) about the geologic history of this region, paleomagnetic data could help to resolve several ongoing debates, including:

- The paleolatitudes and relative positions of terranes prior to widespread Mesozoic and Cenozoic deformation
- The possible rotation of the Arctic Alaska composite terrane
- The long-term behavior of the geomagnetic field at high latitudes
- The paleolatitude of various invertebrate and vertebrate fossil sites found in northern Alaska
- The development and associated provenance of sedimentary basins in this region

After compiling all the available paleomagnetic information, we assess whether there is enough reliable data to weigh in on any of these issues.

## 2. Evaluating Paleomagnetic Data

We assume here that the reader has a basic understanding of paleomagnetism as it applies to tectonic reconstructions, and we devote most of this section to selected topics that are most relevant to this review. Interested readers who need more background information are referred to Butler (1992) for an introduction to paleomagnetism and Tauxe (2010) for more thorough explanations of specific topics within the field.

There are several methods to assess paleomagnetic data, both informal (Table 1) and formal (Table 2). Van der Voo (1990) introduced the ‘quality’ factor (Q), which grades a paleomagnetic study on seven criteria, including the number of samples, field tests (Figure 2), presence of reversals, and the existence of a well determined age. A study with a Q-score of zero cannot be relied upon, while a study with a Q-score of seven is completely reliable. These criteria have recently been updated by Meert et al. (2020) to form a new ‘reliability’ score (R). Their criteria are similar to Van der Voo (1990) but more strict; again, the most reliable studies have criteria with an R-score of seven.

None of the studies discussed in this review have a Q- or R-factor of seven and most have low quality scores between one and four (Table 2). This does not mean that they are unreliable; low Q- or R-factor scores are more common when dealing with terranes or continental/oceanic fragments. Therefore, we also focus on more informal indicators of data reliability (Table 1).

**Table 1.** Informal indicators of paleomagnetic data quality.

| | Best | Better | Good | Fair | Poor |
|---|---|---|---|---|---|
| **Data Availability** | Measurement-level | Sample-level | Site-level | Study-level | Polarity Only |
| **Methodology** | Rock Magnetic Measurements | Multiple Demagnetizations | Thermal or AF Demagnetization | Chemical Demagnetization | No Demag. |
| **Field Tests** | Multiple passing tests | Single passing test | Mixed test results | Unclear test results | No field tests |
| **Age of Magnetization** | Known age of magnetization | Overprints determined | No age constraints | | |

AF = alternating field; Demag. = demagnetization

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Of the criteria outlined in Table 1, the most important indicator of data reliability are the field tests. These tests, illustrated in Figure 2, attempt to constrain the age of magnetization. For example, magnetization that pre-dates folding will pass the fold test, while magnetization that was imparted after folding (and hence an overprint magnetization) will fail the fold test (Graham 1949, McElhinny 1964). Most of the field tests were established early in the development of paleomagnetism, and modern field tests, such as the fold and reversal tests, must meet rigorous statistical standards (e.g. Enkin 2003, Heslop and Roberts 2018).

It is important to note that almost all the studies in this review lack sufficient samples to meet these modern standards of statistical significance (Watson and Enkin 1993, Enkin 2003). Therefore, we determine the 'passing' or 'failing' of a field test more informally in this review. To fully confirm if a field test is passed, any future studies of these same sites will need to collect many more samples. It is important to note that the criteria above, as well as the Q- and R-factors (Table 2), all attempt to determine if the data are reliable. They make no evaluation of whether the data are correctly interpreted.

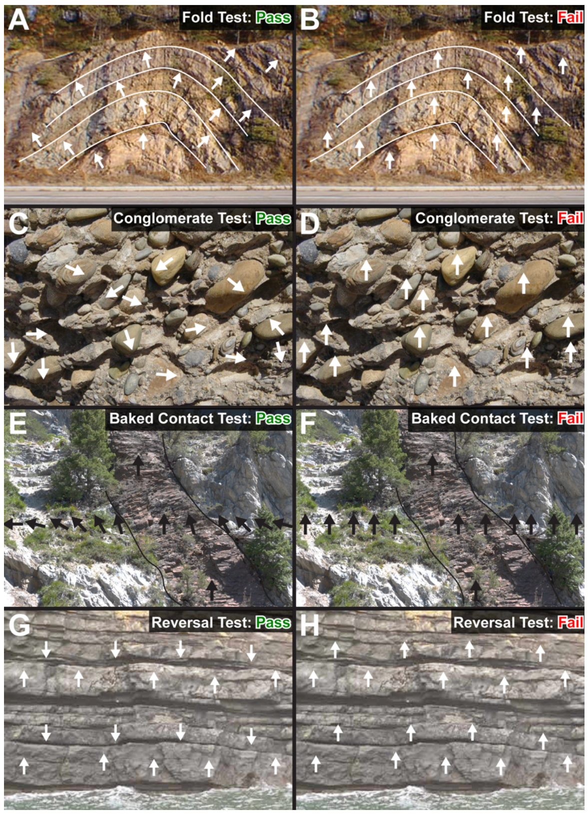


**Figure 2.** Arrows symbolize measured paleomagnetic directions. Left column: examples of passing (also called 'positive') paleomagnetic tests. Right column: examples of failing (negative) paleomagnetic tests. A,B) The fold test is used to determine if magnetization occurred before or after deformation. C,D) The conglomerate test  is used to determine if the magnetization is primary. E,F) The baked contact test is used to determine if an igneous intrusion has been reset. This test cannot determine if the wall-rock magnetization is primary. G,H) The reversal test is used to determine if a stratigraphic succession retains primary magnetization. Secondary remagnetization events typically impart only one polarity at the outcrop scale (Buchan et al. 1977, Dunlop and Buchan 1977), destroying reversal-stratigraphy in the process. Image credits: A,C,G: Wikipedia (public domain). E: J. Biasi.

**2.1 (Re-)Interpretations**

For each study in this review, we provide an interpretation that falls into one of three categories:

- The original interpretation was correct at the time and remains valid today.
- The original interpretation is no longer valid due to advances in paleomagnetism.
- The original interpretations is no longer valid due to advances in local/regional geologic knowledge.

The most common reason for invalidating an earlier interpretation involves how the position of Laurentia, as constrained by more recent paleomagnetic studies, has changed over time. Great efforts have been made to improve our understanding of the paleogeography of Laurentia, and the apparent polar wander (APW) paths from the 1980s are significantly different from the APW paths available today (e.g. Harrison and Lindh 1982, Torsvik et al. 2012). Most comparisons of paleomagnetic poles to the earlier Laurentian APW paths have been reinterpreted in this review using the most current APW paths for Laurentia (Beck and Housen 2003, Kent and Irving 2010, Torsvik et al. 2012, Merdith et al. 2021, Müller et al. 2022).

Despite these advancements, there are still competing hypotheses in the paleomagnetic literature about the position of Laurentia, particularly in the Triassic–Jurassic. Global plate reconstructions require that Laurentia remains at high latitudes throughout the Mesozoic (Kent and Irving 2010, Torsvik et al. 2012, Müller et al. 2022). In contrast, other models that only consider data from Laurentia place the continent at lower latitudes until the middle-early Cretaceous (e.g. Beck and Housen 2003). The disparity between these APW paths is as high as c. 1900 km in the middle Jurassic. However, all APW paths converge from 120 Ma – present, with typical disparities between the paths being <300 km during this time.

All models agree that North America was at a 'standstill' in the Middle to Late Cretaceous (Figures 4, 5, 6) and thus the APW paths do not show significant movement of Laurentia during this time (Beck and Housen 2003, Kent and Irving 2010, Torsvik et al. 2012, Müller et al. 2022). Most of the paleomagnetic controversies covered in this review concern this younger time period when the paths are in general agreement. In this review, all rotation and translation calculations will reference the APW path of Torsvik et al. (2012). The APW path of Beck and Housen (2003) will also be included in some figures as a point of comparison. For Precambrian units, we reference the paleolatitude constraints from Merdith et al. (2021), which covers the last 1 Ga.

The paleolatitude of a terrane can have significant uncertainty due to the phenomenon of *hemispheric ambiguity*. Rocks that are magnetized in the northern hemisphere during a normal polarity period will have positive inclination. However, rocks that are magnetized in the southern hemisphere during reversed polarity will also have a positive inclination. Unless the polarity of the rock is already known, its paleolatitude is subject to this ambiguity (see Hillhouse (1977) and Panuska & Stone (1981) for examples from southern Alaska). Large continental blocks or cratons like Laurentia have a better constrained geologic and paleomagnetic history, and their paleolatitude is therefore easier to determine using this additional context. Older, smaller, and more far-travelled terranes are most susceptible to hemispheric ambiguity due to a relative lack of supporting data (Butler 1992).

At the time that many of the studies in the northern Cordillera were conducted, *inclination flattening* was not well understood. This phenomenon occurs in sedimentary rocks where compaction during lithification can cause the magnetic minerals to record a lower inclination than originally acquired (King 1955). The effect of inclination flattening is most prominent when platy hematite is the main magnetic carrier (Kodama 2012). Sedimentary rocks with equant magnetite grains are less susceptible to inclination flattening. The flattening effect is most prominent at moderate inclinations (mid-latitudes) and less prominent at equatorial or high latitudes (Tauxe 2005, Li and Kodama 2016). Inclination flattening generally produces 'far-sided' poles, where the site artificially appears to have formed at a lower paleolatitude than should be recorded.

Other common reasons for reinterpretation include better paleomagnetic statistics/pole calculations, better age constraints on studied units, and a better understanding of the timing of regional orogenesis. Overall, we found that almost all studies made the best interpretation that they could at the time, but this does not mean that their interpretations should continue to be trusted in perpetuity.

### 2.3 Use of Paleomagnetic Data in the Northern Cordillera

Apart from its remoteness, the main reason that paleomagnetic data is so sparse from this region stems from a common misconception. Early paleomagnetic studies found pervasive overprints with a steep-downward direction and no primary remanence directions (e.g. Newman et al. 1977, Hillhouse et al. 1980, Hillhouse and Grommé 1983, 1988, Coe et al. 1985). This steep overprint was attributed to a widespread thermal resetting event in the Jurassic–Cretaceous Cordilleran Orogeny, and we agree about the general nature of this interpretation. Laurentia was at a high latitude at this time (e.g. Beck and Housen 2003, Kent and Irving 2010), which certainly accounts for the steepness of the overprint. However, this review shows that complete overprinting is not as common as initially suspected, and many sites retain primary remanence directions (black locations in Figure 1). Complete overprinting can happen to any rock type (e.g. Burmester et al. 2000), but is most easily accomplished in sedimentary rocks with weak paleomagnetic signals, such as carbonates (e.g. McNeill and Kirschvink 1993). In addition to widespread overprinting of the majority of carbonates from this region, coarse-grained sedimentary rocks - such as conglomerates and coarse-grained sandstones - are often also fully overprinted. In contrast, igneous units (intrusive or extrusive) and fine-grained sedimentary rocks (shales and siltstones) have generally escaped full resetting and often preserve primary remanence directions (Section 3).

## 3. Review of Previous Studies

Here we summarize previous paleomagnetic studies from the northern Cordillera and comment on the quality, quantity, reliability, and interpretation of the data. The studies are grouped by the age of the host lithologies (oldest to youngest), not the age of magnetization. The location numbers in Figure 1 correspond to the location numbers given below in Table 2.

**Table 2: Summary of Available Paleomagnetic Data**

| Location | Data Source | Lithology | Unit Age | Fully Reset? | Q | R |
|---|---|---|---|---|---|---|
| | | | ***Precambrian*** | | | |
| 1 | P, T | Mafic Volcanics | c. 720 Ma | No | 6 | 6 |
| 2 | New | Mafic Volcanics | c. 720 Ma | No | 5 | 5 |
| 3 | P | Dolostone, Sandstone | Ediacaran | Yes | 2 | 2 |
| | | | ***Cambrian - Jurassic*** | | | |
| 3 | P | Quartzite | Cambrian | Yes | 4 | 3 |
| 4 | A | Carbonates | Cambrian-Permian | No | 2 | 2 |
| 5 | T | Carbonates | Ordovician-Devonian | No | 5 | 4 |
| 6 | A | Carbonates | Ordovician-Silurian | Yes | 2 | 2 |
| 7 | P | Carbonates | Silurian-Permian? | Yes | 2 | 2 |
| 8 | P | Granitoid | Late Devonian | No | 1 | 1 |
| 9 | P | Conglomerate | Devonian-Mississippian | Yes | 2 | 3 |
| 10 | A | Sed. Rocks | Devonian-Triassic | Yes | 1 | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 11 | P | Limestone | Mississippian | Yes | 3 | 2 |
| 12 | P | Zn-Pb Deposit | Carboniferous | Yes | 4 | 2 |
| 13 | P | Siliciclastics | Triassic | Yes | 2 | 3 |
| 14 | A | Mafic Volcanics | Middle Jurassic | No | 1 | 1 |
| 15 | P | Mafic Plutonic Rocks | Middle Jurassic | No | 3 | 2 |
| No Location | A | Carbonates | Unknown | No | 2 | 2 |
| | | ***Cretaceous*** | | | | |
| 16 | P, T | Misc. Volcanics | Early Cretaceous | No | 3 | 1 |
| 17 | P | Argillite | Early Cretaceous | Yes | 3 | 2 |
| 18 | P | Siliciclastics | Early Cretaceous | No | 5 | 5 |
| 19 | P, T, A | Siliciclastics | Early-Middle Cretaceous | No | 1 | 0 |
| 20 | P | Mafic-Int. Tuffs | Hauterivian | Yes | 4 | 4 |
| 21 | Report | Siliciclastics | Early Cretaceous | No | 4 | 4 |
| 22 | P, T, A | Volcanics and Seds. | Middle Cretaceous | No | 4 | 2 |
| 23 | P, T | Siliciclastics | Albian | Yes | 5 | 4 |
| 24 | P, T, A | Volcanics and Seds. | Middle-Late Cretaceous | No | 5 | 3 |
| 25 | P, T, A | Siliciclastics | Late Cretaceous | No | 4 | 2 |
| 26 | P | Seyenite/Monzonite | Turonian | No | 4 | 3 |
| 27 | P, T | Misc. Igneous Rocks | Late Cret. to Paleogene | No | 4 | 4 |
| 5 | T | Granitoid | Maastrichtian | No | 2 | 2 |
| | | ***Paleogene-Neogene*** | | | | |
| 5 | T | Mafic-Int. Volcanics | Late Cret. to Paleogene | No | 4 | 3 |
| 28 | P, T, A | Mafic-Int. Volcanics | early Paleogene | No | 4 | 3 |
| 25 | P, T, A | Misc. Igneous Rocks | early Eocene | No | 4 | 3 |
| 7 | P, A | Basalt and Tuff | Miocene | No | 5 | 3 |
| | | ***Quaternary*** | | | | |
| 20 | P, T | Mafic Volcanics | <5 Ma | No | 6 | 6 |
| 30 | P | Mafic Volcanics | <2.2 Ma | No | 6 | 6 |
| 31 | P, A | Tephra and Sediments | <210 Ka | No | 6 | 6 |
| 32 | P | Old Crow Tephra | <210 Ka | No | 3 | 3 |
| 33 | P, A | Fluvial Sediments | <210 Ka | No | 5 | 4 |
| 34 | P, T | Lacustrine Sediments | <150 Ka | No | 4 | 5 |
| 35 | P, T, A | Lacustrine Sediments | <37 Ka | No | 5 | 5 |
| 36 | T, A | Lacustrine Sediments | <21 Ka | No | 5 | 5 |

Note: Location column corresponds to Figure 1 and Section 3. Q = quality index of Van der Voo (1990); R = reliability index of Meert et al. (2020); P = publication; T = thesis; A = conference abstract; Ma = mega-annum; Ka = kilo-annum; Cret. = Cretaceous; Int. = intermediate

**3.1 Precambrian**

**Location 1** – Mount Harper Volcanics, Ogilvie Mountains, Yukon, Autochthonous Laurentia, publications and thesis – Mafic volcanic flows and tuff of the Mount Harper Volcanics are exposed ~60 km north of Dawson, Yukon, and are well-characterized paleomagnetically by

Brunet (1986), Park et al. (1992), and Eyster et al. (2017). The volcanics are bimodal in composition and have been dated to ca.719–717 Ma via U-Pb chemical abrasion-thermal ionization mass spectrometry (CA-TIMS) on zircon (Macdonald et al. 2010, 2018), highlighting an important link to the larger Franklin large igneous province (LIP) of northern Laurentia. Park et al. (1992) collected block samples from hematized and non-hematized flows, as well as samples from an interbedded siltstone unit, and paleomagnetic data were collected with a spinner magnetometer. Samples were variably subjected to alternating field (AF), thermal, and chemical demagnetization (acid-leaching). Later work by Eyster et al. (2017) used newer methodologies (cryogenic magnetometer), more samples, and better sample statistics (Kirschvink 1980) on the same units. Eyster et al. (2017) also conducted rock-magnetic experiments (hysteresis, isothermal remanent magnetization (IRM) acquisition, thermal and AF demagnetization of saturation IRM) and concluded that the primary carrier in most cases is pseudo-single-domain magnetite. They found the same primary direction as Park et al. (1992) but with lower error. They also identified three other overprints, at least one of which is due to Cretaceous metamorphism. Results from both studies are in good agreement despite the differing methodologies, and both concluded that this part of the Yukon block rotated ~50-60° clockwise relative to the Mackenzie Mountains and Laurentia between the Neoproterozoic and today. The timing of this rotation remains unknown, but overlying Neoproterozoic–Mesozoic strata are unambiguously tied to the Laurentian margin (e.g. Norris 1997, Morrow 1999, Moynihan et al. 2019). The study by Eyster et al. (2017) fulfills six out of seven Q-factors of Van der Voo (1990), while the study by Park et al. (1992) fulfills three of the Q-factors. These concurring results illustrate how paleomagnetic studies that do not conform to modern standards (e.g. Park et al. 1992) can be successfully reproduced and often contain data that should not be dismissed (Beck et al. 2001).

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**Location 2** – Kikiktat volcanic rocks, Sadlerochit Mountains, Alaska, Arctic Alaska terrane, new data – These preliminary data are from ca. 720 Ma Franklin LIP-associated lava flows in the Sadlerochit Mountains of the northeastern Brooks Range, Arctic Alaska terrane (Figure 1; Cox et al. 2015). Full results will be reported in a future study, but preliminary results are shown here for completeness of the review. Seventy samples were taken from 12 sites within a ~450 m thick succession of flood basalt flows, breccias, and volcaniclastic strata. A volcaniclastic interval in

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the Kikiktat volcanics were dated with U-Pb zircon chemical abrasion-thermal ionization mass spectrometry (CA-TIMS) to 719.47 +/- 0.29 Ma and are consistent with correlation with the Franklin LIP of northern Laurentia (Cox et al. 2015). Samples were measured using a 2G 755-4K superconducting rock magnetometer at Massachusetts Institute of Technology using both AF and thermal demagnetization. Directions were calculated using principal-component analyses best-fits (no origin, minimum four data points; Kirschvink 1980). While some sites did not yield meaningful directions, other sites yield coherent directions. Both reversed and normally magnetized sites were found, but there is currently insufficient data to pass a reversal test. There is considerable scatter of directions between sites (Figure 3), but not within many of the sites themselves. This is probably due to local rotations that have not been corrected for accurately in the preliminary dataset. Collection of rock-magnetic data is ongoing, but unblocking temperatures suggest that the primary carrier is magnetite. We suspect that the magnetization at some sites is primary but more data are needed to confirm this. The average paleolatitude from the reliable sites is 17.8° +/- 15.5°, which is the expected paleolatitude of Laurentia and the North Slope subterrane of Arctic Alaska at ca. 720 Ma (Figure 4; Strauss et al. 2019a). Other components of this pole (latitude, longitude) should not be used given the uncertainty in local rotations.

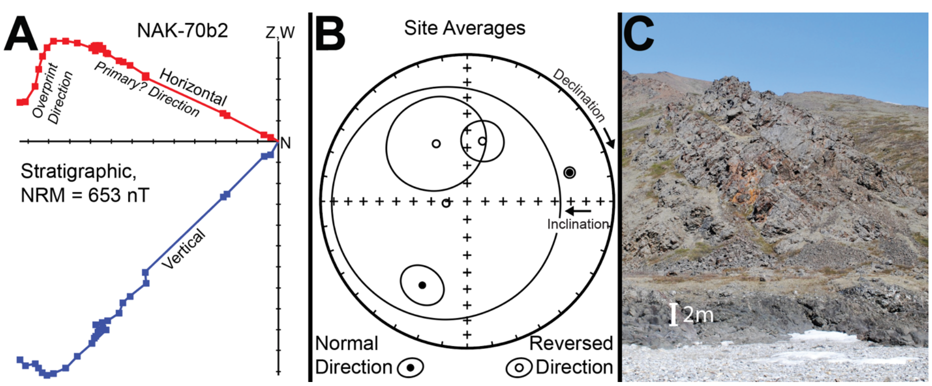


**Figure 3.** Preliminary unpublished results from the Kikiktat volcanics (Franklin LIP) in the Sadlerochit Mountains, Arctic Alaska terrane. A) Orthogonal projection showing a representative demagnetization result. B) Equal area projection showing site averages. C) Field photo showing a representative outcrop of the Kikiktat volcanics. Image Credit: J. Strauss.

**Location 3** – Risky Formation, Wernecke Mountains, Yukon, Autochthonous Laurentia, publication – The late Ediacaran Risky Formation was studied by Park (1995) in the Wernecke Mountains of eastern Yukon (Figure 1). Sampled lithologies include dolostones, dolomitic sandstones, and quartz-rich sandstones, and a spinner magnetometer was used in conjunction with both AF and thermal demagnetization. This study also employed magnetic anisotropy and susceptibility measurements to determine magnetic mineralogy. The fold tests were inconclusive and several overprint directions were identified. 'Component D' in this study most likely corresponds to the Cretaceous overprint. The dolostones yielded a 46 ± 16 °S paleolatitude, which Park (1995) interpreted as primary; however, based on current low-latitude northerly Ediacaran reconstructions of Laurentia (~9°N; Merdith et al. 2021), this is most likely an overprint direction as well (Figure 4a). If hemisphere ambiguity is invoked (Section 2.1), the paleolatitude is instead farther north than expected (Figure 4a). It appears that no primary remanence directions were found in this study.

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**3.2 Cambrian–Jurassic**

**Location 3** – Backbone Ranges Formation, Wernecke Mountains, Yukon, Autochthonous Laurentia, publication – Quartzites of the early Cambrian (Terreneuvian) Backbone Ranges Formation lie stratigraphically above the Risky Formation (see above) and were sampled at the same location by Park (1992). Samples were measured using a spinner magnetometer and demagnetized using a combination of AF, thermal, and chemical methods. Magnetic mineralogy was characterized with optical microscopy and miscellaneous petrological techniques. Steep inclinations were found after removing signals from abundant secondary hematite. This study found one reversal high in the section, which appears to be robust. Park (1992) argued this area had not rotated significantly because the data conforms with other age-equivalent paleomagnetic data from the adjacent Mackenzie Mountains, suggesting that the arcuate geometry of Proterozoic rocks in the Mackenzie and Wernecke Mountains is an inherited structure, not the product of Cordilleran oroclinal bending. The Backbone Ranges Formation passes the fold test in this study, and Park (1992) concluded that this area was at 69 ± 11 °S during early Cambrian sedimentation. Hemisphere ambiguity (Section 2.1) allows for the paleolatitude to instead be at 69 ± 11 °N (Figure 4b). Again, modern paleomagnetic reconstructions place this portion of the continent just south of the equator at this time (Figure 4b; Merdith et al. 2021), so the primary direction in this study is probably another overprint; however, it is difficult to reconcile this conclusion with the reversal and positive fold test that was found in this section, and a new study of this unit is warranted.

**Location 4** – Lisburne and Nanook groups, Shublik and Sadlerochit Mountains, Alaska, Arctic Alaska terrane, abstracts – Multiple studies by Plumley and Tailleur (1985, 1986) are only available in abstract form, so there are few details to assess the quality of these data. The authors discuss paleomagnetic results from unknown carbonate outcrops of the Carboniferous Lisburne Group and Cambrian–Ordovician Nanook Group. For the Lisburne Group, thermal demagnetization yielded two components: a younger steep-down direction (probably Cretaceous), and an older pre-folding reversed direction. It is unclear if the reversed direction is the primary direction or a pre-folding overprint. No directional data were given in the abstract, but the authors suggest that 40° of clockwise rotation could have occurred locally. We cannot verify this without the data. Results from the Nanook Limestone (now Black Dog Formation of the Nanook Group; Strauss et al. 2019b) also has a pre-folding component with shallow inclination, although we cannot verify this without any data. Overall, this area of the Brooks Range is promising for future paleomagnetic studies.

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**Location 5** – Novi Mountain, Telsitna, and Whirlwind Creek formations, Mystery Mountains, Alaska, Farewell terrane, thesis – Plumley (1984) studied various carbonate units of the Nixon Fork subterrane of the Farewell terrane as part of his PhD dissertation. Based on results from 558 paleomagnetic cores, these carbonates are among the oldest sedimentary rocks in this review that still preserve a primary remanence direction (Dumoulin et al. 2018a). Samples were measured on a spinner magnetometer and demagnetized with a combination of AF and thermal methods. Lower Ordovician carbonates of the Novi Mountain Formation pass the fold test and have a normal overprint that does not pass the fold test (probably Cretaceous). Plumley (1984) identified a ‘secondary normal component’ in Middle and Upper Ordovician carbonates of the Telsitna Formation, which we suspect might be a Cretaceous overprint. The ‘reversed characteristic component’ seems to be a robust result that cannot be explained by Cretaceous overprinting, and we suspect that primary normal polarities can also be found in this section;

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however, the pervasive Cretaceous normal overprint makes it difficult to distinguish this direction. Note that these carbonates are magnetically weak, so measuring any primary remanence (reversed directions) is evidence that these units did not experience significant metamorphism, consistent with regional conodont alteration indices (Dumoulin et al. 2002, 2018b, 2018a). Silurian-Devonian dolostones of the Whirlwind Creek Formation do not pass the fold test. Their overprint may be from a nearby Cretaceous pluton (Plumley 1984), but the measured direction is not an expected Cretaceous direction. One explanation is that there could be some unidentified local block rotations given that these sites are near the Iditarod-Nixon Fork fault zone (Patton Jr. et al. 1980). The Ordovician carbonates yield a paleolatitude of 30 ± 6°N, which is the expected paleolatitude of the nearest portions of northeastern Laurentia (Figure 4c; Müller et al. 2022), as well as very close to the projected paleolatitude of the Farewell terrane in various tectonic reconstructions that place it between Siberia, Baltica, and Laurentia in the early Paleozoic (Figure 4c; Dumoulin et al. 2002, 2018b, Colpron and Nelson 2009, McClelland et al. 2023).

**Location 6** – York succession, Seward Peninsula, Alaska, Arctic Alaska terrane, abstract – Ordovician-Silurian carbonates of the York succession in the northwestern corner of Seward Peninsula were extensively sampled by Plumley and Reusing (1984). They collected 384 samples in total, the results of which are only available in a conference abstract. Plumley and Reusing (1984) found a steep overprint (80° inclination, 'south' declination) that pervaded all the samples with no preserved primary remanence magnetization, despite the fact that these rocks record a low-temperature thermal history and are relatively well preserved (e.g. Dumoulin et al. 2014). Although the sampled sections experienced some post-Cretaceous deformation, Plumley and Reusing (1984) suggested that their overprint data precluded any Cenozoic rotation of the Seward Peninsula away from the Alaskan mainland.

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**Location 7** – Salmontrout Limestone and various unnamed Paleozoic carbonates, Porcupine River, Alaska, Porcupine fault system, publication – Plumley et al. (1989) focused on the paleomagnetism and structural history of various fault-bounded Paleozoic carbonates (Silurian–Permian?; see Section 3.4) in the Porcupine fault system along the Yukon-Alaska border region (Figure 1), which was previously considered part of the Porcupine terrane (Silberling et al.

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1994). The samples were measured on a spinner magnetometer and demagnetized with a combination of AF and thermal methods. Field tests (fold, conglomerate) from the Salmontrout Limestone and various unnamed carbonate rocks all failed. Plumley et al. (1989) speculated that their measured directions and overprints were imparted during Cretaceous reheating, and we agree. Site 86P038 (Devonian? carbonate) may have a primary remanence since it has an extra component with a shallower inclination. This would place this site at ~20°N latitude, which is the expected paleolatitude for the northwestern (present coordinates) Laurentian platform (~15°N) based on current reconstructions (Torsvik et al. 2012, Müller et al. 2022). All other measured directions seem to postdate any local deformation and/or rotation between sites because they are very similar across sites (steep inclinations, northeast declinations). Plumley et al. (1989) interpreted a clockwise rotation for this part of the Porcupine fault system (since the Cretaceous reheating event) based on a mismatch between the overprint directions and the Laurentian APW path. Our reanalysis of the data based on the most recent Laurentian APW paths (Beck and Housen 2003, Torsvik et al. 2012) confirms this and requires 58.0±17.7° of clockwise rotation since the terminal Cretaceous or early Paleogene (based on the methods of Demarest (1983); Figure 4d). It is unclear if this rotation is regional or local in scale, but given the scale and style of deformation in the Porcupine fault system (e.g. Faehnrich et al. 2021), a local block rotation seems more likely. These data strongly suggest that this portion of the Porcupine fault system remained active through much of the Cretaceous and early Paleogene and perhaps much later into the Cenozoic. More paleomagnetic data from this region is needed to confirm this hypothesis.

**Location 8** – Old Crow Batholith, Old Crow Range, Yukon, Arctic Alaska terrane and Porcupine fault system, publication – Paleomagnetic examination by Park (1990) on Upper Devonian granitoids of the Old Crow Batholith and nearby stocks in the Old Crow Range of Yukon was done by spinner magnetometer and demagnetization by AF and thermal methods. Notably, there were no constraints on tilting or original horizontality. The outlying stocks (Dave Lord (now Nothla Hill), Mt. Fitton, Mt. Sedgwick, Ammerman Mt.) yielded better paleomagnetic results, most likely due to more abundant magnetite in these magmas (Park 1990). Park (1990) found Cretaceous or Cenozoic directions in the Old Crow Batholith, which he interpreted as an overprint or possibly a record of the present-day field. Recent geochronological datasets display complex zircon U-Pb systematics in the Old Crow Batholith with crystallization ages ranging from ca. 367.5 to 375 Ma (Lane and Mortensen 2019, Ward et al. 2019). Our reanalysis of the data confirms that these data likely do not reflect a primary Late Devonian direction (Figure 4e), although the location of the Arctic Alaska terrane and/or complexly deformed rocks of the Porcupine fault system is still poorly understood. One possibility is these data reflect a Cretaceous overprint that underwent significant clockwise rotation and northward translation post acquisition, supporting the data from Plumley et al. (1989) from the Porcupine fault system described above. An unknown tilt has affected the data and cannot be corrected for without further examination.

**Location 9** – Kanayut Conglomerate, Phillip Smith Mountains, Alaska, Arctic Alaska terrane, publications – Paleomagnetic results from the Upper Devonian-Lower Mississippian Kanayut Conglomerate are reported in Hillhouse and Grommé (1980, 1983, 1988b). From 11 sites across the Phillip Smith Mountains, 384 cores were taken and subject to AF and thermal demagnetization. The type of magnetometer that was used was not specified. Hillhouse and Grommé (1988b) present some rock-magnetic data (IRM acquisition; Dunlop and Özdemir 1997) and conclude that a mixture of magnetite and hematite carry the magnetic signal. The Kanayut samples (siltstone and sandstone) conclusively failed a fold test, and all samples displayed a steep-downward direction that is characteristic of the Cretaceous overprint that pervades the Brooks Range. Hillhouse and Grommé (1980, 1983, 1988b) concluded that no primary remanence remains in the samples, and we agree. These authors also speculated on a potential regional heating event recorded in these rocks that never reached above 300°C but was long-lived enough to remagnetize them. This remains a reasonable interpretation based on subsequent work on Brookian regional metamorphic and thermochronological datasets (e.g. Hoiland et al. 2018, Craddock et al. 2018, and references therein). The remagnetization must have happened after most of the relative displacement had ceased, as the average of all sites across a wide swath of the Brooks Range has a low uncertainty ($A_{95}$ = 12°).

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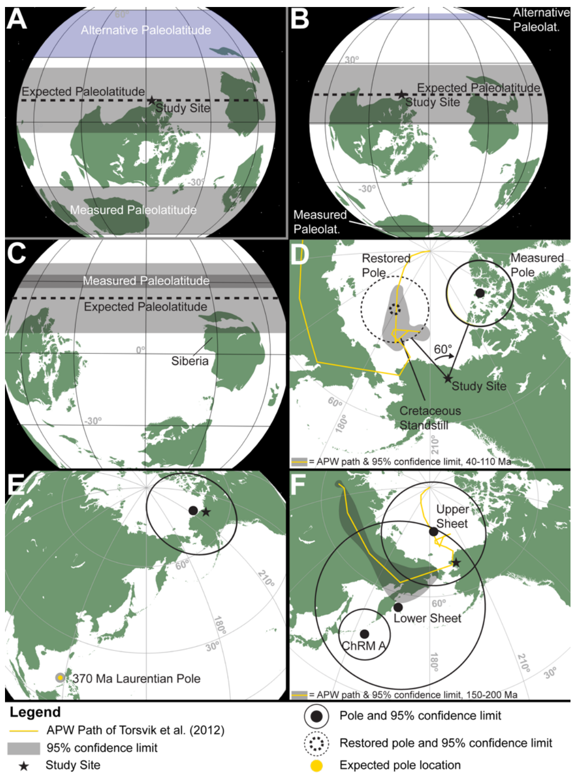


**Figure 4**. Results from Precambrian-Jurassic units (see text for further discussion). All reconstructions are from Merdith et al. *(2021)*, and all APW paths are from Torsvik et al. *(2012)*. A) Paleolatitude results from upper Ediacaran dolostones of the Risky Formation in the Wernecke Mountains (Location 3) with reconstruction at ca. 565 Ma. The expected paleolatitude uncertainty is 15º or less. B) Paleolatitude results from Cambrian sandstones of the Backbone Ranges Formation in the Wernecke Mountains (Location 3) with reconstruction at ca. 535 Ma. C) Paleolatitude results from Ordovician carbonates of the Farewell terrane in the Mystery Mountains of west-central Alaska (Location 5) with reconstruction at ca. 465 Ma. D) Cretaceous overprint pole from Devonian–Mississippian carbonates in the Porcupine fault system along the Yukon-Alaska border area (Location 7). A 60° rotation brings this pole in better alignment with the expected Cretaceous-Paleogene directions. E) Characteristic remanence (ChRM) pole from the Upper Devonian Old Crow Batholith north of Old Crow, Yukon (Location 8). F) 'ChRM A'

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from the Red Dog deposit (Location 12), and recalculated poles from the Asik massif, Angayucham terrane (Location 15).

**Location 10** – Miscellaneous sedimentary units, North Slope and Brooks Range, Alaska, Arctic Alaska, abstract – The extended conference abstract of Newman et al. (1977) focused on Upper Devonian, Mississippian, and Triassic sedimentary rocks throughout much of the Brooks Range foothills and North Slope. The abstract provides no information on measurement techniques, data evaluation, or field tests. They present a pole (graphically, no numbers are listed) from the Mississippian units that is located near the modern-day equator, and the authors suggest that 70º of counterclockwise rotation occurred post-deposition. A Triassic pole was also presented, also near the equator, but received no further comment. Hillhouse and Grommé (1983) were allowed to review the data and they concluded that all of the datasets failed the fold test (most likely due to Cretaceous overprinting). This conclusion contrasts with the pole presented by Newman et al. (1977), and without being able to evaluate the data ourselves, we are hesitant to make any conclusions about the reliability of these data.

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**Location 11** – Lisburne Group, Phillip Smith Mountains, Alaska, Arctic Alaska terrane, publications – Mississippian limestone of the Lisburne Group was also studied by Hillhouse and Grommé (1980, 1983, 1988b) at four sites and on 103 samples (see Location 9 for methods). Like data from the Kanayut Conglomerate, the Lisburne Group failed all field tests and was pervasively overprinted during Cretaceous regional deformation. This is not surprising given that carbonates are not as robust recorders of paleomagnetic directions as siliciclastic rocks (McNeill and Kirschvink 1993). The authors specifically avoided sampling chert beds and nodules within the carbonates. At the time, it was not known that the chert may have been more likely to preserve a primary remanence.

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**Location 12** – Kuna and Siksikpuk formations, Red Dog Zn-Pb Deposit, Alaska, Arctic Alaska terrane, publication – Lewchuk et al. (2004b) studied fine-grained siliciclastic rocks of the Carboniferous Kuna & Siksikpuk formations, the Red Dog Zn-Pb ore body, and surrounding host rocks (33 sites, 132 samples) in the western Brooks Range (Figure 1). Samples were collected underground in the active mine; therefore, some structural complexities were difficult

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to distinguish and correct for. Measurements were done on a cryogenic magnetometer and demagnetization was done with AF and thermal methods. Rock-magnetic measurements were also performed (IRM acquisition). The authors found two characteristic magnetization directions, as well as more recent overprints, including 'magnetization A' carried by magnetite and 'magnetization B' carried by pyrrhotite – this distinction was based on a decrease in sample strength above 350°C (the Curie temperature of pyrrhotite, Schwarz and Vaughan 1972). Magnetization A failed the fold test, while magnetization B produced inconclusive fold-test results. Lewchuk et al. (2004b) argued that magnetization A was acquired during Cretaceous metamorphism based on the steep inclinations, while magnetization B was considered significantly older and carried by pyrrhotite. The inclination is shallower than anything expected in the Mesozoic or Cenozoic (Beck and Housen 2003), and Red Dog mineralization (pyrrhotite) occurred shortly after deposition (Lewchuk et al. 2004b). Based on the direction of their magnetization A overprint, the authors concluded that a significant northward translation and counterclockwise rotation of the Arctic Alaska terrane was necessary to explain the data.

While we believe that the data themselves are reliable, we disagree with the interpretation of both magnetizations. For magnetization A, this direction lies significantly outside the expected Cretaceous overprint direction in the Brooks Range (Figure 4f). Instead of invoking a rotation/translation story, we believe it is simpler to hypothesize that some unknown amount of tilting has occurred in this area post-folding, especially considering the lack of field context. For example, an uncorrected tilt of ~10° to the northeast (perhaps in the Cenozoic) could have brought this direction far out-of-line with other Cretaceous overprints in the Brooks Range. Moreover, for the origin of magnetization B, it is not possible to completely reset magnetite (in magnetization A) without also resetting pyrrhotite – pyrrhotite is a less stable magnetic carrier in almost all conditions and has a lower Curie temperature (Dunlop et al. 2000); thus if the carrier is indeed pyrrhotite, then it must have precipitated after Brookian resetting. Alternate carriers for magnetization B, such as titanomagnetite, should also be considered, as they have similar unblocking temperatures to pyrrhotite (Dunlop and Özdemir 1997). The anomalously low inclination in magnetization B is interesting, but it could have also been imparted during a transitional polarity period or a geomagnetic excursion. The metamorphic and deformational history of the Red Dog deposit is complex (e.g. Moore et al. 1986, Ayuso et al. 2004, Slack et al. 2004), and the paleomagnetic data presented in Lewchuk et al. (2004b) need more detailed mineralogical and structural characterization before they can be interpreted in a regional tectonic context.

**Location 13** – Ivishak Formation, North Slope, Alaska, Arctic Alaska terrane, publications – The Ivishak Formation (sandstone, conglomerate) was also studied by Hillhouse and Grommé (1980, 1983, 1988b) in two wells near Utqiagvik (formerly Barrow). It is notoriously difficult to assess the reliability of oriented core from oil wells or other large-scale drilling campaigns. Inclination and polarity data tends to be reliable, but declination data commonly has errors of >20° (Nelson et al. 1987, Scott and Berry 2004, Ma et al. 2016). Loss of any coherent orientation data is also common and will depend on the coherency of the core, depth of the oriented section, and a variety of other drilling-based factors. In this study, one well intercepted the Triassic Ivishak Formation, where the samples yielded a very weak and inconsistent paleomagnetic signal. Hillhouse and Grommé (1980, 1983, 1988b) posited that these strata were remagnetized sometime post-deposition and we agree. A nearby well intercepted pre-Mississippian 'argillitic basement' of unknown early Paleozoic age (probably Ordovician or Silurian based on nearby collections of chitinozoans in similar strata; Carter and Laufeld 1975). Paleomagnetic directions from this pre-Mississippian unit were more coherent but also probably reset by either early Paleozoic orogenesis (Hillhouse and Grommé 1983) or Cretaceous Brookian deformation. Given the lack of context, no field tests were performed and so the true age of magnetization is difficult to constrain. Hillhouse and Grommé (1983) argued for Early Cretaceous counterclockwise rotation of Arctic Alaska based on these data, but we are hesitant to make any interpretation given the uncertain age and context of their magnetization.

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**Location 14** – Misheguk massif, Misheguk Mountain, Alaska, Angayucham terrane, abstract – The study by Harris et al. (1993) on mafic volcanic rocks of the ophiolitic Misheguk massif, a klippe of the Angayucham terrane in the western Brooks Range (Figure 1), is only available as an abstract. Few details are provided in the abstract, and the paleomagnetic data were mostly used to constrain structural deformation. No directions or poles were reported in the abstract.

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**Location 15** – Asik Mountain massif, Asik Mountain, Alaska, Angayucham terrane, publication – Lewchuk et al. (2004a) conducted a focused paleomagnetic study on mafic volcanic rocks at

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Asik Mountain in the western Brooks Range, another klippe of ophiolitic rocks of the Angayucham terrane (Figure 1). Measurements were done on a cryogenic magnetometer and demagnetization was done with AF and thermal methods. Magnetic susceptibility was also measured. A fold test was inconclusive, but the characteristic directions are different from both the steep Cretaceous overprint and modern-field directions. The authors argued that their characteristic magnetizations were most likely primary, and we agree. They average all their reliable sites together and argued for 50° of counterclockwise rotation or 11° of northward translation since ophiolite cooling (via crystallization or obduction).

While this was a reasonable interpretation at the time, we can improve upon it here. We now know that the Brooks Range ophiolite is composed of at least two major thrust sheets: the Misheguk Mountain allochthon (Jurassic) and the Copter Peak allochthon (Triassic-Devonian?; Harris 2004, Fredriksson and Pease 2019, 2022, Biasi et al. 2020). In addition to different ages, these thrust sheets have different tectonic histories and should not be lumped together when calculating an average direction. Sites 1-6 in Lewchuk et al. (2004a) are from the upper (Misheguk) thrust sheet, and sites 7-15 are from the lower (Copter Peak) thrust sheet. The new recalculated directions for both sheets are shown in Table 3 and Figure 4f. We performed a test of mean directions (Fisher et al. 1993) and found that directions from the upper and lower sheets have a 1.7% probability of being the same. Depending on the plate reconstruction that is used (Torsvik et al. 2012, Müller et al. 2022), the upper sheet direction may be consistent with a Late Jurassic age of magnetization; however, it is also consistent with a Cretaceous overprint (Fig. 4f). We suspect that the magnetization is Jurassic because several sites in the upper sheet gave anomalous directions that were not consistent with a regional Cretaceous overprint. The upper sheet, which has been interpreted as a forearc ophiolite (Harris 2004, Biasi et al. 2020), yields a paleolatitude of 80 ± 14 °N, . This is a higher paleolatitude than today (68°), but the uncertainty is too large to determine if this area was connected to Laurentia at the time (Müller et al. 2022). The lower sheet gives a direction that suggests its paleolatitude was 70 ± 23 °N. It is difficult to interpret the lower sheet direction without knowing its exact age. Since it is an orphaned piece of oceanic crust with large pole uncertainty (Harris 1998), it cannot be easily compared to any continental APW path.

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**No Location** – Upper Mississippian to Paleocene sedimentary units, North Slope and Brooks

Range, Alaska, Arctic Alaska terrane, abstracts – Two studies by Van Alstine (1986) and Van Alstine and Butterworth (1994) are available only in abstract form. Their samples are from throughout the North Slope and Brooks Range (Lisburne Peninsula to Sadlerochit Mountains), but no specific location data is provided. Despite this, they include enough data (596 samples) to merit discussion here. AF, thermal, and chemical demagnetization were performed along with IRM acquisition experiments. Interestingly, they find evidence for syn-folding magnetization in some unspecified units. They also claim that samples from Cape Lisburne to the central Brooks Range were normally remagnetized, while samples from the central Brooks Range to the Sadlerochit Mountains were reversely remagnetized. This contrasts with other studies (e.g. Hillhouse and Grommé 1983) that found only normal remagnetization in the Cretaceous overprint. The authors invoke large-scale and long-lived orogenic fluid migration to explain their results. We cannot assess the validity of these assertions without seeing more data than are currently available.

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**Table 3.** Directions that have been substantially recalculated in this review. Location column corresponds to Figure 1. Vandamme (1994) iterative cutoff method used for all studies.

| Location | Study | Pole | N | D (°) | I (°) | $R_1$ | k | a95 (°) | Pole Lat (°N) | Pole Lon (°E) | $R_2$ | K | A95 (°) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | Lewchuk et al. 2004a | Upper Sheet | 2 | 345 | 84.8 | 2.0 | 12323 | 7.1 | 77.1 | 185.8 | 2 | 322.4 | 14 |
| 15 | Lewchuk et al. 2004a | Lower Sheet | 9 | 248 | 80.1 | 8.5 | 16.54 | 13 | 56.3 | 165.2 | 7.5 | 5.5 | 24.2 |
| 19 | Harris 1985 | Kaltag Sites | 5 | 348 | 76.5 | 4.8 | 16.73 | 19.3 | 85.1 | 153.9 | 4.4 | 6.7 | 32 |
| 19 | Harris 1985 | Melozitna Sites | 4 | 352.3 | 80.3 | 4.0 | 446.7 | 4.1 | 83.3 | 183.4 | 4 | 131.5 | 8 |
| 28 | Thrupp 1987 | Blackburn Hills | >42 | - | - | - | - | - | 71.7 | 170.7 | - | - | 10.9 |
| 29 | Johnson et al. 2008 | Nunivak Island | 51 | 2.8 | 75.1 | 50.1 | 53.9 | 2.7 | 79.8 | 194.2 | 48.5 | 20.2 | 4.5 |
| 30 | Cox & Gordon 1984 | Pribilof Islands | 31 | 20.6 | 60.7 | 30.0 | 29.6 | 4.8 | 71.7 | 320.1 | 28.9 | 14.2 | 7.1 |

Note: N = number of sites; D = declination, I = inclination, $R_1$ = vector sum (direction), k = precision parameter, a95 = 95% confidence interval, $R_2$ = vector sum (pole), K = precision parameter (pole), A95 = 95% confidence interval (pole).

### 3.3 Cretaceous

**Location 16** – Yukon-Koyukuk volcanics, Isahultila Mountains, Alaska, Koyukuk arc, publications and thesis – Lower Cretaceous volcanics of the Koyukuk arc (Figure 1) were

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studied by Hillhouse and Grommé (1988a), Harris (1985), and Harris et al. (1985, 1987). The exact overlap between these studies is not clear, but we suspect that sites 1, 5, and 6 in Hillhouse and Grommé (1988a) correspond to sites 3, 6, and 7 in Harris (1985). This is the only paleomagnetic study of Koyukuk arc rocks that we know of. All other studies in the 'Koyukuk' region of Figure 1 are probably on Yukon-Koyukuk basin units.

Hillhouse and Grommé (1988a) used a cryogenic magnetometer in conjunction with AF and thermal demagnetization. They sampled a variety of volcanics, shallow intrusives, and siliciclastic turbidites. The turbidites were all demonstrably reset by later overprinting, but the igneous units yielded more reliable data. In these units, Hillhouse and Grommé (1988a) found several overlapping overprints, likely middle-late Cretaceous in age, and used best-fit planes to determine primary directions. Characteristic directions passed the fold test, but reversals in the units were not antiparallel as would be expected from a long-term field average (Cox and Doell 1960). This might be due to local rotations or interference from incompletely demagnetized overprints. The other studies (Harris 1985, Harris et al. 1985, 1987) used similar methods on the same units but came to different conclusions. Based on a series of failed fold tests, Harris et al. (1987) and Harris (1985) argued that most of the Cretaceous units in this area were reset in the Paleogene from nearby intrusive rocks. We have reexamined data from all studies and argue that the correct answer is probably somewhere in between. Several Cretaceous sites in Harris (1985) seem to pass the fold test, while some of the best-fit planes for the sites presented in Hillhouse and Grommé (1988a) are probably not meaningful. With the available data, we are unable to determine which sites from this area have not been overprinted, but it is likely that a future paleomagnetic study of this area could yield primary magnetization directions.

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**Location 17** – Biederman Argillite, Kandik River, Alaska, Kandik Basin, publication – The paleomagnetism of the Lower Cretaceous Biederman Argillite was studied by Howell et al. (1992), which mostly focused on the stratigraphy and structural geology of this area. Most details concerning their paleomagnetic study are not given, but AF demagnetization was performed on 12 samples (up to 100 mT) and natural remanent magnetization measurements were conducted on another ~90 samples, all of which were sandstones and argillites. Two stratigraphic sections at different orientations were sampled to generate a regional fold test, and the paleomagnetic results were similar between sections, thereby failing the fold test. The resultant direction is

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consistent with a Cretaceous overprint direction, but no error on this direction was provided.

**Location 18** – Kuparuk River Formation, North Slope, Alaska, Arctic Alaska terrane, publication – This important and well-cited work on the Lower Cretaceous Kuparuk River Formation was completed by Halgedahl and Jarrard (1987). The study provides the main paleomagnetic evidence for the counterclockwise rotation hypothesis of Arctic Alaska (see Section 4.2). Halgedahl and Jarrard (1987) examined siliciclastic rocks from three oriented drill cores in the Kuparuk River oil field. As discussed above, oriented drill cores are difficult to work with and can often provide misleading declination data; however, Halgedahl and Jarrard (1987) went to great lengths in this study to explain their drill-core orienting protocol. Measurements were made using a cryogenic magnetometer, and both AF and thermal demagnetization were used. Rock-magnetic experiments (IRM acquisition, susceptibility) were also performed. Conodont and vitrinite data suggest that these rocks did not experience elevated temperatures (Halgedahl and Jarrard 1987), and the Cretaceous overprint is not obviously present here. Field tests are difficult to assess in drill core, but reversals are preserved in the data. Overall, this study is remarkably thorough and well done for the time.

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The authors determined that their average paleomagnetic pole was ~2400 km south of the study site, at ~49°N latitude. To reconcile this pole with the expected pole for a Laurentian site of this age, the authors invoked a 70° counterclockwise rotation of the Arctic Alaska terrane (about a pole of rotation in the Mackenzie Delta) after ~130 Ma. This interpretation sparked a flurry of both support and skepticism (e.g. Embry 1990, Grantz et al. 1990, 1998, 2011, Lawver and Scotese 1990, Lane 1997, Lawver et al. 2002, Lane et al. 2016, Hutchinson et al. 2017, Ilhan and Coakley 2018, Mosher and Hutchinson 2019) towards the counterclockwise rotation hypothesis. In Section 4.2, we provide an in-depth reinterpretation of these data based on a better understanding of the position of Laurentia in the Cretaceous.

**Location 19** – Unnamed Cretaceous sedimentary units, Yukon and Melozitna rivers, Alaska, Yukon-Koyukuk basin, publication, thesis, and abstract – In addition to Location 16 above, Harris (1985), Harris et al. (1985), and Harris et al. (1987) sampled several other Cretaceous sites in the Yukon-Koyukuk basin. Similar methods were employed at all sites as described above, including a cluster of Cretaceous siliciclastic units near Ruby, Alaska. In this case, none

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of the sites passed any field tests. Harris (1985), Harris et al. (1985), and Harris et al. (1987) concluded that all sites were reset sometime in the Late Cretaceous based on steep inclinations. The sites near Ruby, Alaska yielded somewhat scattered overprint directions ($A_{95}$ = 32°; Figure 5a), probably due to local deformation associated with the Kaltag fault (Table 3) (Patton and Hoare 1968). The sites to the north (along the Melozitna river) yielded a more coherent overprint ($A_{95}$ = 8°; Table 3, Figure 5a).

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**Location 20** – Unnamed Lower Cretaceous mafic-intermediate tuffs, Ohogamiut, Alaska, Yukon-Koyukuk basin(?), publications – These ca. 128 Ma (Hauterivian) mafic-intermediate tuffs (Patton 2006) were sampled by Globerman et al. (1983) and later discussed by Coe et al. (1985) and Coe et al. (1989). One hundred and nine samples from 31 sites underwent AF and thermal demagnetization, but the type of magnetometer was not specified. The samples failed a fold test and were most likely reset in the Cretaceous, although remagnetization could have occurred syn-folding. A few samples still preserved a reversed component that is distinct from the normal overprint, so future paleomagnetic study of this area may be fruitful. The overprint gives a far-sided pole that barely overlaps with the expected Cretaceous pole (after correction for ~150 km of dextral displacement on the Kaltag fault, Figure 5b). Some amount of counterclockwise rotation post-dating emplacement (35.6 ± 26.3 °; Demarest 1983) would bring this pole into better alignment with the Laurentian APW path (Figure 5b).

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**Location 21** – Nanushuk and Torok formations, North Slope, Alaska, Arctic Alaska terrane, unpublished report – Paleomagnetic data reported in Stone and Witte (1983), which is cited in a review paper by Stone (1989), is from an unpublished industry report generated for ARCO-Alaska. We were unable to acquire a copy of this report, so we cannot comment on the data quality. The analyzed samples are from an unoriented well core in the National Petroleum Reserve, so only inclination data is reported. The sampled units include the Lower Cretaceous Nanushuk and Torok formations. A reversal was found, indicating that the magnetization is most likely primary. The inclinations imply a similar paleolatitude to that found by Witte et al. (1987), which is described below at Location 23.

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**Location 22** – Unnamed Middle Cretaceous volcanic and sedimentary rocks, Bettles, Alaska,

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Yukon-Koyukuk basin, publication and thesis and abstract – Harris (1985), Harris et al. (1985), and Harris et al. (1987) sampled unnamed Middle Cretaceous 'volcanic turbidites' and graywacke near Bettles, Alaska. See Location 16 for a methods description. These units passed fold and conglomerate tests (Figure 2), likely indicating that magnetization predates the Cretaceous overprinting event that reset many other sites in this region; however, the matrix (a coarse-grained sandstone) was determined to be a poor carrier of remanent magnetization by Harris and was not used in subsequent calculations. We largely agree with this assessment, but instead suggest that site 83-35 (graywacke) is a better recorder of paleomagnetic directions due to a low $\alpha_{95}$ (6.6°) and reasonable paleolatitude (63.6° N) of its pole. We use this site when calculating Yukon-Koyukuk average directions going forward.

**Location 23** – Nanushuk Formation, North Slope, Alaska, Arctic Alaska terrane, publication and thesis – The Albian Nanushuk Formation is the subject of an often-overlooked study by Witte (1982) and Witte et al. (1987). A total of 116 samples from 13 sites were measured on an unspecified magnetometer and demagnetized using thermal and AF techniques. The Nanushuk strata are gently dipping, and one site passed a broad fold test while another failed (Figure 2). Lewchuk et al. (2004a) reanalyzed these data and concluded that the magnetization was acquired syn-folding. They determined that the pole from these data should be 69°N, 182°E, $A_{95}$=11° (Figure 5c; the original pole from this study is at 73.7°N, 150°E, $A_{95}$=18°). We agree with Lewchuk et al. (2004a) and will use these recalculated data moving forward.

All samples from this study have normal polarity, as is expected for most of the Cretaceous (Yoshimura 2022). We assume a Middle to Late Cretaceous folding event, but the exact age of deformation is not well constrained (Mull et al. 1997, Moore et al. 2004, Houseknecht and Wartes 2013, Craddock et al. 2018). The paleolatitude of this site was 85.5 ± 8.1°N, which is the expected paleolatitude for this area of Arctic Alaska in the mid-late Cretaceous (Beck and Housen 2003, Kent and Irving 2010, Torsvik et al. 2012, Müller et al. 2022).

**Location 24** – Unnamed Cretaceous volcanic and sedimentary rocks, Nulato, Alaska, Yukon-Koyukuk basin, publication, thesis, and abstract – This cluster of samples includes sites 83-10 through 20 and 82-6 through 8 in Harris (1985), Harris et al. (1985), and Harris et al. (1987).

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Sites 10 to 12 were sampled from unnamed Middle Cretaceous volcanics; sites 82-6 to 8, 83-13, 83-14, and 83-20 were collected from unnamed Middle Cretaceous siliciclastic rocks (mostly siltstones and shales); and sites 83-15 to 19 were sampled from unnamed Upper Cretaceous siliciclastic units. All these sites are north of the Kaltag fault, and see Location 16 for a methods description. Harris (1985), Harris et al. (1985), and Harris et al. (1987) found that the Middle Cretaceous volcanics failed both fold and baked-contact tests (Figure 2) and were probably remagnetized later in the Cretaceous. The Middle to Upper Cretaceous sedimentary sites pass fold and reversal tests (Figure 2), indicating that the magnetization was most likely primary. Some of these sedimentary units may post-date regional metamorphism in the area, while some may have escaped significant heating due to the heterogeneity of deformation in the Yukon-Koyukuk basin (Harris et al. 1985). Poles from the Middle to Upper Cretaceous sedimentary units are significantly far-sided in comparison to the expected poles from a stable Laurentian site (Figure 5d; e.g. Torsvik et al. 2012). Harris (1985), Harris et al. (1985), and Harris et al. (1987) invoked ~15-20° of northward transport to explain this discrepancy. Using the latest Laurentian APW paths (e.g. Müller et al. 2022), we find that no degree of rotation can explain this far-sidedness. An inclination flattening factor of 0.4 (Section 2.1) could bring the pole into alignment with the Laurentian APW path, but these lithologies are not a good candidate for flattening (magnetite is the primary magnetic carrier). If no inclination flattening is invoked, then this portion of the Yukon-Koyukuk basin needed to travel ~1885±881 km northward (Demarest 1983) post-sedimentation (Figure 5d). See Location 27 for additional discussion.

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**Location 25** – Unnamed Upper Cretaceous sedimentary rocks, Kaltag, Alaska, Yukon-Koyukuk basin, publication, thesis, and abstract – This cluster of samples includes sites 83-21, 25, 28, 29, and 30 in Harris (1985), Harris et al. (1985), and Harris et al. (1987). All sites are from unnamed Upper Cretaceous siliciclastic rocks that are exposed south of the Kaltag fault. See Location 16 for a methods description. Sedimentary rocks in this region passed a conglomerate test according to Harris (1985) but insufficient data was reported to calculate an average direction for these sites (missing data from sites 83-21 and 25).

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**Location 26** – Deadman Pluton, Dawson, Yukon, Autochthonous Laurentia, publication – The ca. 91 Ma Deadman Pluton and surrounding host rock were studied by Symons et al. (2006).

From 23 sites, 237 samples were collected and measured using a cryogenic magnetometer. Thermal and AF demagnetization were employed, along with IRM rock-magnetic measurements. A baked contact test (Figure 2) was attempted, but all the wall-rock sites were reset by the pluton. Technically this is a failed baked-contact test, but it is possible that wall-rock at further distances from the pluton would yield different directions. The paleomagnetic results were consistent across all sites and yielded a different direction than expected from a stable Laurentian site (Figure 5e) or from the present-day field. The Deadman Pluton pole is far-sided from the expected Laurentian pole by 1282 ± 422 km (Demarest 1983), which is consistent with far-sided poles of the ca. 75 Ma Carmacks Group to the south of the Tintina fault system (e.g. Wynne et al. 1998). Symons et al. (2006) argued that the pluton was detached during north-vergent Cordilleran deformation and tilted to the southeast, ultimately generating the anomalous paleomagnetic direction. Regardless of the specific displacement mechanism, these results imply that deformation in this area was ongoing after 91 Ma (Hayward 2019), and we agree with this interpretation.

**Location 27** – Unnamed Cretaceous and Cenozoic volcanics, Saint Matthew Island, Bering Sea, Alaska, Koyukuk terrane(?), publication and thesis – Unnamed Upper Cretaceous (ca. 70–79 Ma) and Cenozoic igneous rocks presumably of the Koyukuk terrane were studied from this remote island by Wittbrodt (1985) and Wittbrodt et al. (1989). One hundred and twenty hand samples were collected from 18 sites and samples were thermal and AF demagnetized and measured using a cryogenic magnetometer. These data pass reversal and conglomerate tests (Figure 2), and the characteristic magnetization is almost certainly primary. Data from several intrusive rocks are presented, but it is unclear if the intrusions pre- or post-date tilting, so these data should not be used to calculate primary directions. The Cretaceous units give a low-error pole that requires 9.7±24.5° of clockwise rotation and 1462±1284 km of northward translation post-emplacement in order to align with the Laurentian APW path (Demarest 1983). Wittbrodt et al. (1989) argued that Saint Matthew Island is closely associated with the Yukon-Koyukuk basin, and the required ca. 1500 km northward displacement of the pole is in agreement with results from other parts of the Yukon-Koyukuk basin described above from Harris et al. (1987) (Location 24). Here, however, inclination flattening cannot be invoked to explain the far-sidedness of the pole since volcanic units were studied. The island also contains unnamed and

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poorly dated Cenozoic felsic tuffs and intrusive rocks, which yield a large-error pole that is in agreement with the Laurentian APW path for the early Paleogene.

**Location 5** – Jumbo Peak Pluton, Medfra, Alaska, Farewell terrane, thesis – The ca. 70 Ma Jumbo Peak pluton (Moll et al. 1980) was studied in Plumley's (1984) PhD thesis using similar methods described from Location 5 in Section 3.2. Here, 29 samples from four sites yielded a reversed direction; however, there are no constraints on original horizontality, so this direction could be due to an uncorrected tilt. Without any structural corrections, the data from this pluton cannot be fully interpreted.

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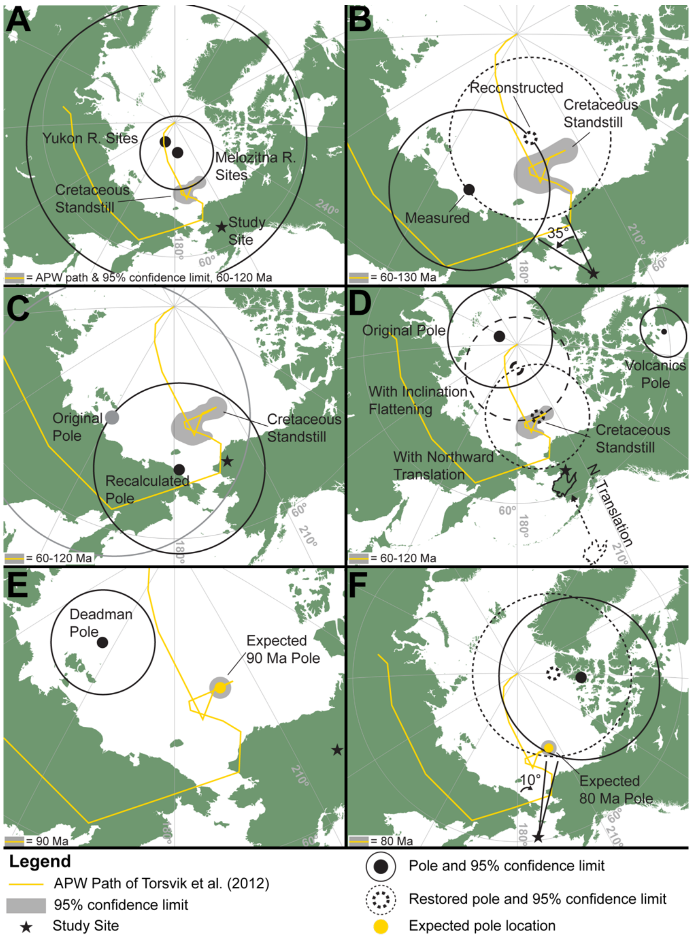


**Figure 5.** Paleomagnetic results from selected Cretaceous units (see text for further discussion). A) Cretaceous overprint poles from unnamed siliciclastic rocks near Ruby, Alaska (Location 19). B) Cretaceous overprint pole from mafic to intermediate tuffs in the Yukon-Koyukuk basin (Location 20). A 35° rotation brings this pole in better alignment with the expected Cretaceous direction. C) Cretaceous syn-folding poles from the Nanushuk Formation, Arctic Alaska terrane (Location 23). D) Middle-Late Cretaceous primary poles from unnamed siliciclastic rocks near Nulato, Alaska (Location 24). Reconstructed flattening and northward translation poles assume 0.7 flattening factor or 1885 km of northward translation, respectively. E) Pole from the Upper

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Cretaceous Deadman pluton in Yukon (Location 26). F) Late Cretaceous pole from volcanics on Saint Matthew Island, Alaska (Location 27). A 10° rotation brings this pole in better alignment with the expected 80 Ma pole.

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### 3.4 Paleogene-Neogene

**Location 5** – Nowitna Volcanics, Page Mountain, Alaska, Farewell/Innoko terrane, thesis – Upper Cretaceous-Lower Paleogene (~70 Ma) mafic to intermediate volcanics were erupted atop the Cretaceous Kuskokwim Group and lie between the Farewell and Innoko terranes. These volcanics were studied by Plumley (1984), and see Location 5 in Section 3.2 for methods. Forty-four samples were collected from seven flows and no field tests were performed on this unit. Despite this, the young age and low degree of regional metamorphism implies that the characteristic magnetization should be primary. Some of the cores were lightning-struck and never yielded a coherent magnetization. The average pole from the remaining samples is reversed and within error of the expected APW path for Laurentia at ca. 70 Ma, both before and after accounting for potential right-lateral displacement on the Kaltag fault (Patton and Hoare 1968). However, the low number of usable sites and high error on the resultant pole makes this conclusion uncertain. Future studies of these volcanics could produce useful paleomagnetic data.

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**Location 28** – Unnamed lower Paleogene mafic-intermediate volcanics, Blackburn Hills, Alaska, Yukon-Koyukuk basin, publication, thesis, and abstract – A suite of unnamed ca. 65 Ma mafic-intermediate volcanics were studied by Thrupp and Coe (1986), Thrupp (1987), and Coe et al. (1989). The main subject of these studies were samples from various southern Alaska terranes, so few details were provided about the Blackburn Hills samples. An unknown number of samples from at least 42 sites were demagnetized using AF and thermal methods. No details were provided about field tests, but the authors suggested the characteristic remanences to be primary. No table of directions was provided, but we were able to extract an average pole from Figure 5 in Thrupp's (1987) thesis (71.7°N, 170.7°E, $A_{95}$ = 10.9°). This pole is within error of the Laurentian APW path (Figure 6a).

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**Location 25** – Unnamed Eocene volcanics and intrusives, Kaltag, Alaska, Yukon-Koyukuk basin, publication, thesis, and abstract – This cluster of samples includes sites 22, 23, 24, 26, 27, 31, and 32 in Harris (1985), Harris et al. (1985), and Harris et al. (1987). All sites are composed

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of early Eocene (49-55 Ma) lavas, tuffs, and shallow intrusive rocks, and are all south of the Kaltag fault. See Location 16 in section 3.3 for a methods description. These units almost universally have poor horizontal controls, with unknown degrees of local tilt or rotation. No field tests were performed, but the different sites have significantly different directions, indicating that these units have escaped a regional remagnetization event. However, Harris (1985) found evidence for ongoing deformation in these units until ca. 50 Ma, so given the lack of horizontal control they cannot be used in tectonic reconstructions or further analysis.

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**Location 7** – Unnamed Miocene basalt and tuff, Porcupine fault system, Alaska, publications and abstract – Unnamed and reportedly undeformed Miocene volcanic units were studied by Plumley and Vance (1988), Plumley et al. (1989), and Kunk et al. (1994). See Location 7 in Section 3.2 for methods. The Miocene basalts were dated to ca. 14.4-15.7 Ma and yielded both normal and reversed polarity. A nearby 6.57 Ma tuff near Canyon Village was also reversed. The basalts were assigned to Chrons 5Br and 5Adn, which is still consistent with the updated polarity time scale of Ogg (2020). The tuff was assigned to Chron 3Ar, but the associated radiometric age now overlaps with a normal chron (C3An.2n). Chron 3Ar is still the closest reversed chron to the determined age (Ogg 2020). Kunk et al. (1994) did not provide any directional data or paleomagnetic results besides polarity. They cited an “in preparation” manuscript when discussing their paleomagnetic results, but no such manuscript was published. A conference abstract by Plumley and Vance (1988) provided a pole from the same basalts (Figure 6b; 86°N, 201°E, N=17, no error is given). This pole agrees with Kunk et al.’s (1994) assertions that the basalts give an expected Miocene direction for a stable Laurentian site. This suggests that they have not been rotated or displaced post-emplacement, which is consistent with the reported lack of deformation in these units.

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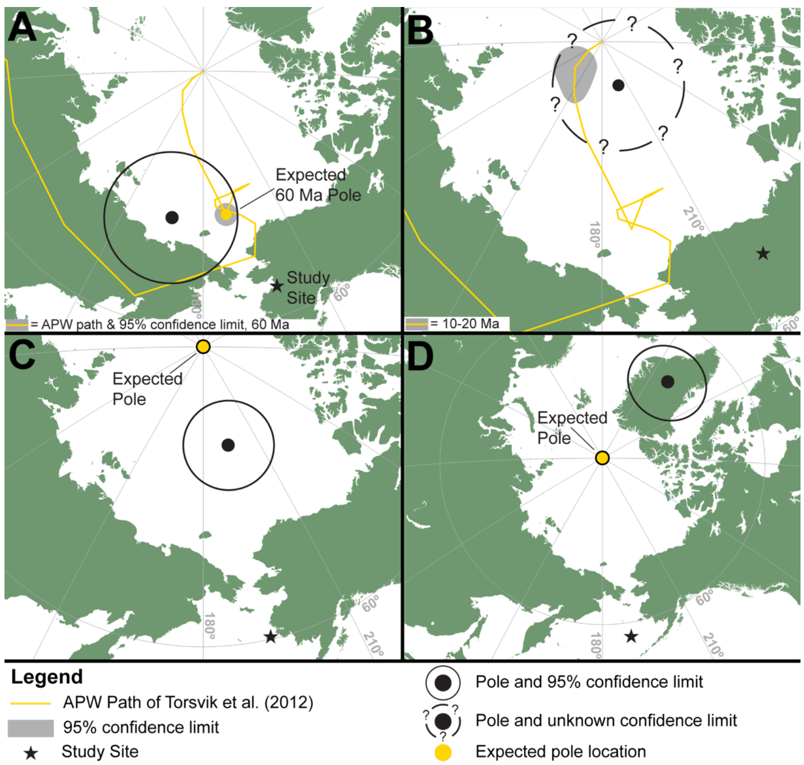


**Figure 6.** Results from Cenozoic units in the study area (see text for further discussion); all reconstructions and APW paths are from Müller et al. (2022). A) Early Paleogene pole from unnamed volcanics in the Blackburn Hills of the Yukon-Koyukuk basin (Location 28). B) Miocene (ca. 15 Ma) pole from unnamed basalts in the Porcupine fault system (Location 7). No error on the pole was given, so the error envelope is shown with question marks. C) Pole from Quaternary unnamed volcanics on Nunivak Island (outliers removed, Location 29), note the near-sidedness of the pole, which is too young to be explained by tectonic motion. D) Pole from Quaternary volcanics on the Pribilof islands (Location 30), which again are too young to be displaced by tectonic motion.

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### 3.5 Quaternary

**Location 29** – Unnamed mafic volcanics, Nunivak Island, Bering Sea, Alaska, publications and

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thesis – Data from unnamed mafic volcanics on Nunivak Island, Alaska, have been the subject of several studies (Cox and Dalrymple 1967, Hoare et al. 1968, Cox and Gordon 1984, Coe et al. 2000, Johnson et al. 2008) and are instrumental in global geomagnetic field models (e.g. Thébault et al. 2015, Cromwell et al. 2018, Alken et al. 2021). High-latitude volcanic sites from the last 5 Ma are rare outside of Iceland, which is why the original study of these volcanics by Cox and Dalrymple (1967) has received occasional revision and reanalysis (e.g. Johnson et al. 2008). The original measurements were completed with a spinner magnetometer and AF demagnetization (Cox and Dalrymple 1967, Hoare et al. 1968), while later measurements using a cryogenic magnetometer yielded similar results (Beck et al. 2001, Johnson et al. 2008). Several reversals or excursions were found in the volcanic stratigraphy, but no other field tests were done due to a lack of deformation and availability of conglomerates or baked contacts. Despite capturing a long-term average of the geomagnetic field, the average pole from all sites does not overlap with the geographic north pole (76.0°N, 191.9°E, $A_{95}$=5.6°, Table 3). After we remove any low-latitude poles that may be associated with excursions, we find that the resultant pole is still near-sided (79.8°N, 194.2°E, $A_{95}$=4.5°, Table 3) (Figure 6c). These volcanics are likely too young (<5 Ma; Johnson et al. 2008) for any tectonic rotation or translation to displace the pole to such a degree. A persistent low-inclination anomaly in the geomagnetic field is found today at high latitudes, but the longevity of such anomalies is controversial (Lawrence et al. 2009, Cromwell et al. 2018, de Oliveira et al. 2024). These results from Nunivak Island support a longer-lived inclination anomaly, at least covering the last ~5 Ma at high latitudes.

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**Location 30** – Unnamed mafic volcanics, Pribilof Islands, Bering Sea, Alaska, publications – Unnamed mafic volcanic rocks on these young volcanic islands (~2.2 Ma - present) were studied by Cox et al. (1966) and Cox and Gordon (1984). Measurements were made using a spinner magnetometer or fluxgate magnetometer in the field. AF demagnetization was rare, and only went up to 10 mT. Nevertheless, positive baked contact and reversals tests (Figure 2) indicate that the magnetization is primary. Cox et al. (1966) and Cox and Gordon (1984) found the Olduvai normal event (1.93 Ma; Ogg 2020) in their magnetostratigraphic sections, in addition to Brunhes- and Matuyama-age lavas. We have calculated the average direction of the data (Figure 6d, Table 3) and the resultant pole is too low latitude like the Nunivak Island results (see Location 29 for discussion). This pole is even farther (1518 ± 630 km; Demarest 1983) from the

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expected pole for North America, and we cannot easily explain why this is the case.

**Location 31** – Old Crow Tephra and associated sediments, Porcupine River, Yukon, publications and abstracts – This area has received extensive paleomagnetic study by multiple groups (Pearce et al. 1982, Westgate et al. 1983, 1985, 1995, 2013, Hedlin and Evans 1987, Evans et al. 1989, Gillen and Evans 1989, Evans and Wang 1994), and these studies employed a variety of paleomagnetic techniques (Table 1). The Old Crow Tephra is a common marker bed throughout the northern Cordillera, and the glaciolacustrine sediments often host extensive fossil assemblages (Westgate et al. 2013). A paleomagnetic anomaly/excursion is often found immediately below the Old Crow Tephra. Early researchers assigned this anomaly to the 114 Ka Blake event (Figure 7; Singer 2014), which was later shown to be an incorrect correlation. Later work by Jensen et al. (2013) in the Yukon-Koyukuk basin found the true Blake event (see Location 33). Recent dating of the Old Crow Tephra provides a revised age of 207 Ka (Burgess et al. 2019, 2021). This age is controversial because the previous age estimate was 155-163 Ka (Reyes et al. 2022). If the new 207 Ka age is correct, then the excursion below the Tephra is probably the 212 Ka Pringle Falls excursion. If the previous 159 Ka age is correct, then the 188 Ka Iceland Basin excursion is probably below the Old Crow Tephra (Ogg 2020).

**Location 32** – Old Crow Tephra, Allakaket, Alaska, publications – This exposure of the Old Crow Tephra was studied by Westgate et al. (1983) and Westgate et al. (1985). No paleomagnetic data was presented from this locality in these studies, except that the lacustrine beds have apparent normal polarity.

**Location 33** – Unnamed Quaternary sediments, The Palisades, Yukon River, Alaska, publication and abstract – This prominent exposure of Quaternary sediments along the Yukon River was studied by Opalka et al. (2004) and Jensen et al. (2013). Measurements were made using a cryogenic magnetometer and AF demagnetization, and all samples had normal polarity. Jensen et al. (2013) found an excursion above the Old Crow Tephra and argued that this was the Blake event (Figure 7). Earlier studies in Alaska and Yukon that claim to have found the Blake event underneath the Old Crow Tephra are most likely mistaken given recent geochronological data (see Location 31 for discussion).

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**Location 34** – Quaternary to Recent lacustrine sediments, Imuruk and Whitefish Lakes, Seward Peninsula, Alaska, publication and thesis– This study by Marino (1977) and Marino and Ellwood (1978) focused on recent geomagnetic excursions in ~150 Ka to present lake sediments. Measurements were made on a cryogenic magnetometer using AF demagnetization methods. One of the ‘excursions’ that was found was incorrectly attributed to the Blake Event (see Location 31 and 33 for discussion). The original Marino (1977) study was called into question by Marino and Ellwood (1978), who speculated that some of the ‘excursions’ that they measured could actually be due to slumping and other soft-sediment deformation. If an older excursion than the Blake Event was measured, their age model must be incorrect since all older excursions predate 150 Ka (Figure 7).

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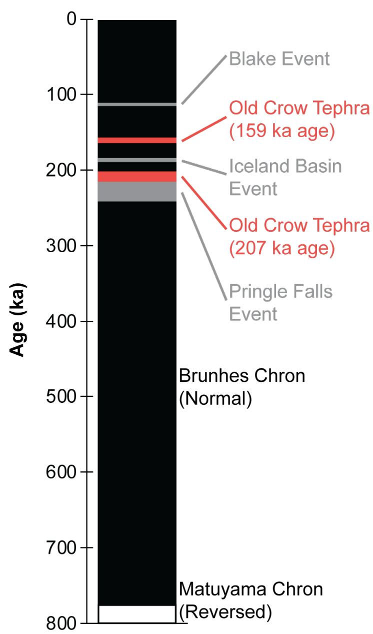


**Figure 7.** Geomagnetic polarity time scale for the last 800 kyr. Geomagnetic excursions (grey) or reversals are shown (Ogg 2020), along with proposed ages for the Old Crow tephra (red, see Location 31).

**Location 35** – Quaternary to Recent lacustrine sediments, Burial Lake, North Slope, Alaska,

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publication, thesis, and abstract – Burial Lake was the subject of a series of recent paleomagnetic studies (Dorfman et al. 2011, 2012, 2015, Dorfman 2013, Finkenbinder et al. 2014). These studies meet modern standards (Table 1), including extensive rock-magnetic characterization. Sediments from this lake cover the last ~37 Ka, and the studies were focused on determining various environmental conditions over this time.

**Location 36** – Quaternary to Recent lacustrine sediments, Cascade and Shainin Lakes, central Brooks Range, Alaska, thesis and abstract – The lacustrine sediments of Cascade Lake were studied by Steen et al. (2015) and Steen (2016). These studies meet modern standards (Table 1), including extensive rock-magnetic characterization. The sediments in Cascade Lake cover ~21 Ka to present, but the interpretation of the paleomagnetic results were complicated by the variety of sediment inputs into the lake; as a result, the correlations with local environmental conditions were not straightforward. Another lake ~150 km to the east – Shainin Lake – was also studied with similar methods. This lake yielded shallower inclinations than expected, which Steen et al. (2015) attribute to inclination flattening.

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## 4. Discussion

### 4.1 Overprints

As highlighted by previous researchers (e.g. Hillhouse and Grommé 1983, Coe et al. 1985, Stone 1989), the most common paleomagnetic signal in the study area is a prominent Mesozoic–Cenozoic overprint developed during Cordilleran deformation and metamorphism. This distinctly steep overprint is found from Yukon (Location 1, Mount Harper) to the Bering Sea (Location 6, Seward Peninsula). However, many sites that are Middle Cretaceous or older still retain some primary magnetization and were not completely reset during the Cordilleran Orogeny. For example, our oldest igneous sites are Neoproterozoic (Franklin LIP, Locations 1 and 2), and one of our oldest sedimentary sites is Cambrian (Location 5), all of which retain some primary remanent magnetization. Units farther to the north in the study area (e.g., Sadlerochit Mountains, North Slope, Arctic Alaska terrane) appear to have experienced less severe overprinting, but other portions of the Arctic Alaska terrane and Yukon-Koyukuk basin also evaded complete resetting during this event. This may be due to structural position within the Cordilleran orogen (e.g. Location 15, Asik Mountain) or more random ‘thermal windows’

(Harris et al. 1985) associated with less severe plutonism, fluid flow, or other tectonic processes (e.g. Location 24, Nulato sedimentary rocks). Thus, future paleomagnetic studies in this region, if carefully designed, could be highly informative for paleogeographic and tectonic reconstructions.

#### 4.1.1 Timing of Overprinting

The exact age of the overprint is difficult to determine and could be diachronous between different terranes (Figure 1). The steep-downward direction of the overprint precludes an overprinting age prior to the Middle Cretaceous, when expected overprint directions would have been more shallow (Beck and Housen 2003, Torsvik et al. 2012). Several Late Cretaceous to Cenozoic units discussed in this review (Locations 25, 27, 28, 5, and younger sites) retain primary magnetization, indicating that widespread overprinting was probably complete by the early Paleogene. Based on these constraints, the timing of overprinting was restricted to the Middle to Late Cretaceous.

Thermochronological data can provide additional constraints on the timing of overprinting. Most $^{40}Ar/^{39}Ar$ cooling ages from the Arctic Alaska and Ruby terranes range from ~120–100 Ma (e.g. Dillon et al. 1985, Roeske et al. 1995, Blythe et al. 1996, Vogl et al. 2002, Wildgoose 2013, O'Brien and Grove 2022), in agreement with metamorphic zircon overgrowth ages from the central Brooks Range (Hoiland et al. 2018). K-Ar cooling ages from the Yukon-Koyukuk basin typically yield ages of ca. 110–90 Ma (e.g. Harris 1985, Harris et al. 1987, Miller and Bundtzen 1994). Apatite and zircon fission track and (U-Th)/He ages range more widely in the Brooks Range and Seward Peninsula, from ca. 100–20 Ma with prominent cooling ages in the Cenozoic (Blythe et al. 1997, O'Sullivan et al. 1997, McDannell 2011, Craddock et al. 2018). Apatite and zircon fission track and (U-Th)/He ages from the Northern Richardson Mountains, Yukon yield similar age constraints of ca. 120–20 Ma (O'Sullivan and Lane 1997, McKay et al. 2021)

Given that the closure temperatures of these various thermochronological systems (~70°C to ~550°C; Reiners and Brandon 2006, Chew and Spikings 2015) overlaps with the temperatures that paleomagnetic directions are acquired (≥100 °C to ~600 °C; Pullaiah et al. 1975, Dunlop and Özdemir 1997), we can assume that the strong overprints in the study area likely occurred in the Middle to Late Cretaceous with some overprints potentially being acquired in the Paleogene. However, the field tests performed on Paleogene sites (Locations 25+) suggest that any resetting

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in the Cenozoic was probably highly localized and not regional in nature. This is supported by the preservation of Paleozoic and Precambrian remanence directions in the northeastern Brooks Range (Locations 2 and 4) despite also preserving Cenozoic Apatite and Zircon fission track ages (Craddock et al. 2018)

It is also important to note that there is probably some diachroneity in the timing of overprint acquisition in this region. 'The overprint' may consist of several temporally distinct overprints, imparted in different terranes at slightly different times, that have amalgamated in this region. However, we lack sufficient data to determine the timing, magnitude, or areal distribution of this diachroneity.

## 4.2 Overprint Interpretation

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Several older sites experienced complete paleomagnetic resetting despite never reaching temperatures above ~300°C, while the nominal temperature needed to fully reset magnetite is ~580°C (Dunlop and Özdemir 1997). The most likely explanation for this is protracted heating at moderate temperatures, which can reset paleomagnetic directions as effectively as short intervals at high temperatures (Pullaiah et al. 1975). We can use the long-lived nature of this overprinting to our advantage – because the overprints may have taken thousands or millions of years to impart, they could represent a long-term average of the geomagnetic field at the time. A compilation of the overprints is given in Figure 8a and Table 4. The average overprints from this region show some scatter, which is to be expected from an area with significant structural complexity between sites and terranes and with the added uncertainty of potential younger Paleogene resetting in some areas.

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It is also useful to compare the Middle to Late Cretaceous overprint directions to Cretaceous primary directions from the same terranes. In Arctic Alaska, there is only one Cretaceous study site that was not reset during the Brookian orogeny and that is the Kuparuk River Formation (Halgedahl and Jarrard 1987). The resultant pole from this study is contentious and the subject of its own section below (Section 4.2). In the Yukon-Koyukuk basin, three primary Cretaceous directions are available (Figure 8b). These primary directions show some disagreement with the average overprint direction from the Yukon-Koyukuk basin; all the primary poles have a consistent paleolatitude of ~59--62°N, which is slightly lower than the paleolatitude of the overprint pole at 65.6 ± 8.2°N (Table 4). In addition, the primary poles from

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Sites 24 and 27 seem to be rotated relative to the overprint pole (Figure 8b). This could be explained by tectonic deformation. It is not clear to what degree the shape of the Yukon-Koyukuk basin is original versus modified by oroclinal bending (e.g. Patton and Box 1989, Johnston 2001). The consistent paleolatitude, in combination with inconsistent degrees of rotation, suggests that oroclinal bending may have significantly rotated the paleomagnetic directions post-deposition. Alternatively, the results from Locations 24 and 27 may represent an incomplete record of the long-term average magnetic field. Further paleomagnetic study will be needed to resolve these issues. Regardless, a paleolatitude of ~60–65°N in the Middle to Late Cretaceous seems to be a consistent result from previous studies (Locations 16, 19, 20, 22) in the Yukon-Koyukuk basin (Table 4).

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**Table 4.** Cretaceous overprint directions. Location numbers correspond to Figure 1. See Table 3 for explanation of symbols. All averages calculated using the cutoff method of Vandamme (1994).

| Location | Study | Unit or Pole | N | D (°) | I (°) | R | k | a95 (°) | Pole Lat (°N) | Pole Lon (°E) | R | K | A95 (°) | Paleo-lat. (°N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1, Laurentia | Park 1992 | Mt. Harper Volcanics (HVc) | 8 | 1.3 | 79.1 | 7.5 | 15.1 | 14.7 | 83.5 | 223.4 | 6.8 | 5.7 | 25.3 | 69.0 |
| 1, Laurentia | Park 1992 | Mt. Harper Volcanics (HSc) | 4 | 334.0 | 80.5 | 4.0 | 383.6 | 4.7 | 78.3 | 177.0 | 4.0 | 106.8 | 8.9 | 71.5 |
| 1, Laurentia | Eyster et al. 2017 | Mt Harper Volcanics (MT) | 8 | 345.4 | 82.2 | 7.9 | 79.7 | 6.2 | 77.9 | 202.0 | 7.7 | 27.1 | 10.8 | 74.8 |
| 3, Laurentia | Park 1995 | Risky Fm. Component D | 7 | 347.6 | 75.0 | 7.0 | 161.8 | 4.8 | 83.9 | 117.6 | 6.9 | 53.6 | 8.3 | 61.7 |
| 7, Laurentia | Plumley et al. 1989 | Porcupine Carbonates | 26 | 28.8 | 81.2 | 25.7 | 82.7 | 3.1 | 78.7 | 260.6 | 25.0 | 25.4 | 5.7 | 72.9 |
| 17, Laurentia | Howell et al. 1992 | Argillite | 2 | 315.2 | 80.3 | 2.0 | 528.5 | 10.9 | 72.9 | 166.8 | 2.0 | 155.8 | 20.1 | 71.1 |
| 8, Laurentia | Park 1990 | Batholith & Stocks | 9 | 336.1 | 87.2 | 8.8 | 37.1 | 8.6 | 72.0 | 213.8 | 8.3 | 11.1 | 16.2 | 84.4 |
| 9, Arctic Alaska | Hillhouse & Grommé 1988b | Kanayut Conglomerate | 11 | 213.2 | 84.9 | 10.8 | 50.8 | 6.5 | 59.4 | 197.1 | 10.4 | 16.0 | 11.8 | 79.8 |
| 23, Arctic Alaska | Lewchuk 2004a | Nanushuk Fm. | 13 | 298.4 | 87.1 | 12.9 | 99.3 | 4.2 | 70.9 | 179.7 | 12.6 | 27.4 | 8.1 | 84.1 |
| 11, Arctic Alaska | Hillhouse & Grommé 1988b | Lisburne Group | 2 | 202.9 | 55.5 | 1.8 | 5.3 | 164.7 | 22.0 | 183.0 | 1.7 | 3.9 | 70.6 | 36.0 |
| 13, Arctic Alaska | Hillhouse & Grommé 1983 | Argillitic Basement | 1 | 263.3 | 77.0 | 1.0 | -- | -- | 57.4 | 154.7 | 1.0 | -- | -- | 65.2 |
| 16, Koyukuk | Hillhouse & Grommé 1988a | Volcanics near Hughes, AK | 30 | 24.3 | 74.5 | 19.6 | 2.8 | 19.5 | 86.3 | 237.6 | 14.3 | 1.8 | 28.3 | 61.0 |
| 16, Koyukuk | Harris 1985 | Volcanics near Hughes, AK | 3 | 313.8 | 82.3 | 2.9 | 16.3 | 31.6 | 72.6 | 166.3 | 2.6 | 5.1 | 61.1 | 74.8 |
| 19, Koyukuk | Harris 1985 | Seds. along Melozitna R. | 4 | 352.3 | 80.3 | 4.0 | 446.7 | 4.4 | 83.3 | 183.4 | 4.0 | 131.5 | 8.0 | 71.1 |
| 19, Koyukuk | Harris 1985 | Seds. near Ruby, AK | 5 | 348.0 | 76.5 | 4.8 | 16.7 | 19.3 | 85.1 | 153.9 | 4.4 | 6.7 | 32.0 | 64.3 |
| 20, Koyukuk | Globerman et al. 1983 | Tuffs near Ohogamiut, AK | 17 | 316.1 | 79.6 | 16.7 | 54.5 | 4.9 | 71.7 | 162.8 | 16.0 | 16.7 | 9.0 | 69.8 |
| 22, Koyukuk | Harris 1985 | Seds. near Wiseman, AK | 2 | 41.5 | 67.5 | 2.0 | 1435.8 | 6.6 | 63.6 | 317.8 | 2.0 | 749.9 | 9.1 | 50.4 |
| 5, Farewell | Plumley 1984 | Telsitna Fm. | 35 | 322.1 | 62.8 | 33.6 | 24.5 | 5.0 | 62.6 | 92.4 | 32.5 | 13.4 | 6.9 | 44.2 |
| 5, Farewell | Plumley 1984 | Whirlwind Creek Fm. | 39 | 35.9 | 47.2 | 38.3 | 53.6 | 3.2 | 48.5 | 333.9 | 38.1 | 41.7 | 3.6 | 28.4 |
| | *Average Laurentia* | | *56* | *9.8* | *80.5* | *55.0* | *53.9* | *2.6* | *82.6* | *239.2* | *53.1* | *18.7* | *4.5* | *71.4* |
| | *Average Arctic Alaska* | | *26* | *248.4* | *86.1* | *25.6* | *64.1* | *3.6* | *65.1* | *186.0* | *24.6* | *18.5* | *6.8* | *82.3* |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Average Koyukuk* | *54* | *282.6* | *77.2* | *50.5* | *15.2* | *5.1* | *61.0* | *153.1* | *45.8* | *6.5* | *8.2* | *65.6* |
| *Average Farewell* | *74* | *11.6* | *59.6* | *67.3* | *11.0* | *5.2* | *68.2* | *6.6* | *62.1* | *6.1* | *7.3* | *40.4* |

Regardless of the paleomagnetic reconstruction that is used (Figure 9; Beck and Housen 2003, Kent and Irving 2010, Torsvik et al. 2012, Merdith et al. 2021, Müller et al. 2022), the low paleolatitude for the Yukon-Koyukuk basin is at odds with the Laurentian pole in the Middle–Late Cretaceous. Based on the methods of Demarest (1983), up to 1032 ± 742 km of northward displacement and up to 58 ± 19.2° of counterclockwise rotation of the Yukon-Koyukuk basin is needed since the Late Cretaceous in order to bring this terrane into its current position relative to Laurentia. Reconstructions with greater translation require less rotation, and vice versa (Figure 9b). Regardless, it is clear from the overprint data that the Yukon-Koyukuk basin originated farther south (relative to Laurentia) than today. This lower paleolatitude permits a variety of reconstructions for the position of the Yukon-Koyukuk basin during Cordilleran orogenesis at ca. 90 to 120 Ma (Figure 9b).

The Arctic Alaska overprint pole shows a different history. This pole has a high paleolatitude of 82 ± 6.8°N, in slight disagreement with the expected paleolatitude of 75-80°N for Laurentia (Figure 9c; Beck and Housen 2003, Kent and Irving 2010, Torsvik et al. 2012, Müller et al. 2022). Based on our calculations, 46 ± 613 km of southward displacement or 60 ± 35º of counterclockwise rotation is needed to bring this overprint pole into alignment with the Laurentian APW path. We note here that the timing of overprint acquisition (Middle Cretaceous–Paleogene) postdates the proposed timing of counterclockwise rotation of the Arctic Alaska terrane (~130 Ma, see Section 4.2 and Location 18), and therefore the Arctic Alaska overprint pole does not support the original rotation hypothesis. A variety of reconstructions for Arctic Alaska are possible (Figure 9c), but based on geological evidence, we strongly favor a reconstruction that places it at the expected paleolatitude (75-80°N) or farther to the north (see Section 4.2; e.g. McClelland et al. 2021).

Although the Brookian orogeny began in the Middle to Late Jurassic with the collision of the Yukon-Koyukuk basin and Arctic Alaska terrane (e.g. Moore et al. 1994, Moore and Box 2016), the overprint data clearly shows that some relative motion between these terranes continued after the Early to Middle Cretaceous. The specific magnitude and mechanisms of northward transport of the Koyukuk terrane (and/or southward transport of the Arctic Alaska terrane) are not clear. The Yukon-Koyukuk is fault-bounded on all sides, so its displacement

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relative to Arctic Alaska since the Middle to Late Cretaceous isn't necessarily a surprising result. The total displacements on the Kaltag, Kobuk, Iditarod-Nixon Fork, and Kugruk fault zones are not well constrained, particularly if these are inherited or reactivated fault systems (Patton and Hoare 1968, Patton and Box 1989, Avé Lallemant et al. 1998, Miller et al. 2002, Till et al. 2007, Waldien et al. 2023, Drooff and Freymueller 2023). Debris from the Brooks Range contributed to Yukon-Koyukuk sedimentary deposits (e.g. Fredriksson and Pease 2019, 2022), but otherwise the magnitude of displacement on these faults (particularly prior to Cenozoic strike-slip tectonics) is poorly constrained.

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While the available data suggest an interesting paleogeographic history for these terranes, there is insufficient high-resolution and reliable data to make any definitive conclusions about oroclinal bending, rotations, or large-scale displacements, particularly for terranes with complex internal deformation. Arctic Alaska, for example, only has a few reliable directions or overprints for an area the size of California, and it is demonstrably a composite terrane with a polyphase accretion and deformation history (e.g. Strauss et al. 2013). Additional paleomagnetic studies will be needed to resolve the tectonic history of this region.

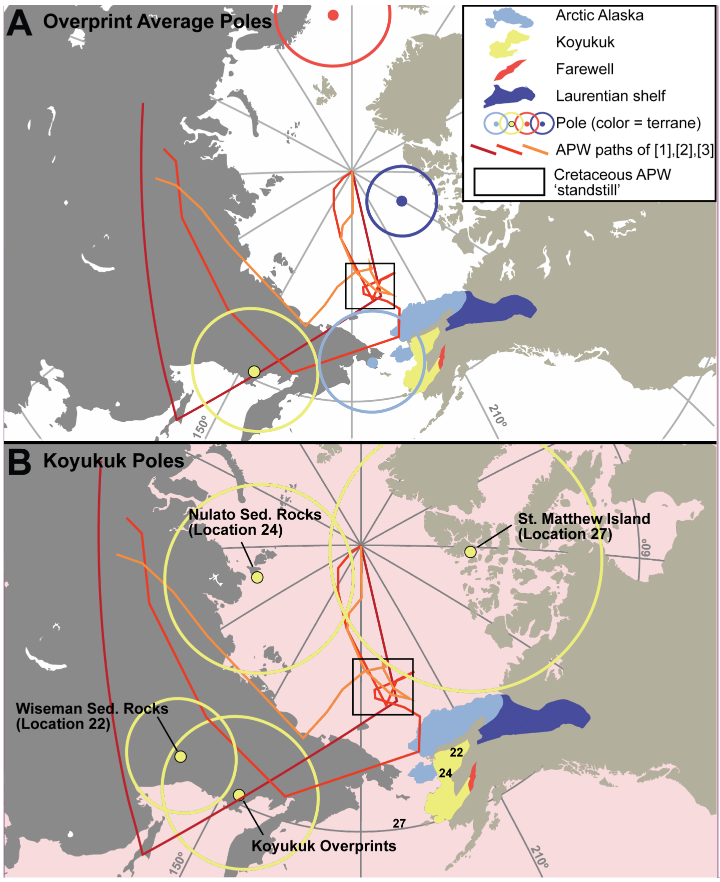


**Figure 8.** A) Compilation of average overprint poles for individual terranes. APW paths of [1] Beck & Housen (2003), [2] Torsvik et al. (2012), and [3] Müller et al. (2022) are shown for reference. Outlier poles were excluded from averages using the method of Vandamme (1994). B) Koyukuk average overprint pole shown with primary (non-overprinted) poles from Cretaceous units in the Yukon-Koyukuk basin and St. Matthew Island. The expected pole for a stable Laurentian site is within the 'APW standstill' box.



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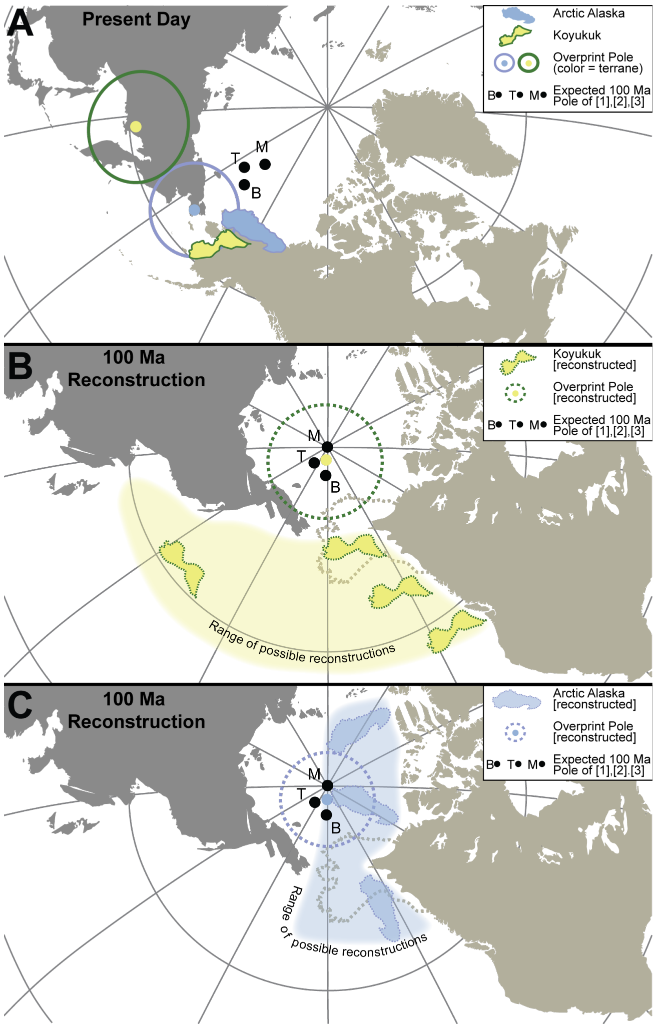


**Figure 9.** A) Early Late Cretaceous overprint poles from the Yukon-Koyukuk basin and Arctic Alaska terrane, which do not overlap the expected ca. 90-120 Ma poles of [1] Beck & Housen (2003), [2] Torsvik et al. (2012), and [3] Merdith et al. *(2021)* for a stable Laurentian site. Outlier data were excluded from averages using the method of Vandamme (1994). B) Possible Yukon-Koyukuk basin reconstructions at c. 90-120 Ma based on Cretaceous overprint data alone. C) Possible Arctic Alaska terrane reconstructions at c. 90-120 Ma based on Cretaceous overprint

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data alone (see also Figure 10 and Section 4.2).

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## 4.2 Arctic Alaska (non-)Rotation

Only one primary Cretaceous direction from the Arctic Alaska terrane has been published (Location 18; Halgedahl and Jarrard 1987). Since that time, however, our understanding of the position of Laurentia during the Early Cretaceous has improved significantly (e.g. Beck and Housen 2003, Müller et al. 2022). The expected pole position for a Hauterivian (ca. 130 Ma) site is now 1487 ± 515 km closer to the Kuparuk River Formation study site than previously estimated (Harrison and Lindh 1982, Demarest 1983). The Kuparuk River pole has a paleolatitude of 68.5 ± 5°N, while the expected paleolatitude for a stable North American site at this location is now ~84° (Beck and Housen 2003, Kent and Irving 2010, Torsvik et al. 2012, Müller et al. 2022). No amount of rotation can bring the Kuparuk River pole in alignment with the rest of Laurentia (Figure 10a), regardless of the reconstruction that is used.

The Kuparuk River pole could be moved much closer to the study site if inclination flattening is invoked, but this unit is not a good candidate for large degrees of flattening because hematite is not particularly abundant in the measured samples (Halgedahl and Jarrard 1987). Although some inclination flattening is still possible, it would likely not be profound enough to 'shorten' the pole to a degree necessary to support the counterclockwise rotation tectonic model. The Kuparuk pole could also be brought closer to the study site using geographic directions instead of the tilt-corrected directions. This would require an interpretation that the Kuparuk River locality was completely remagnetized post-folding; however, the reversals found in the examined core preclude any significant post-deformation remagnetization, as reversal stratigraphy is never created during regional metamorphism on this small of a scale. Alternatively, the regional tilt of the beds could have been accounted for incompletely; however, the Kuparuk River Formation is very gently folded at this distance from the Brookian deformation front, so any unaccounted-for dip correction would be quite minor.

Although the inclination data (and therefore paleolatitude + reversals) may be reliable in the Halgedahl and Jarrard (1987) dataset, declination issues are common during oriented drilling. For example, one can resolve the large-rotation disparity if we assume that during drilling, the cores became misoriented. The counterclockwise rotation hypothesis is dependent on accurate declination data, which is the most suspect portion of the paleomagnetic signal during oriented vertical drilling. However, Halgedahl and Jarrard (1987) went to great efforts to address this, including noting that the data from two separate wells were in agreement and noting that the likelihood that both cores were misoriented to the same degree during drilling (probably ~180°) is low. Thus, we conclude that the declination and inclination data are probably still reliable in this dataset.

Another possible explanation is that the Arctic Alaska terrane experienced significant translation instead of rotation during the opening of the Canada Basin. The implied paleolatitude of this terrane is 68.5 ± 5°N, and it could have traversed over the north pole into its current position (Figure 10b). Arctic Alaska continued to experience contraction until at least ca. 105 Ma (e.g. Till 2016), so when combined with the Hauterivian age of Kuparuk River Formation sedimentation, we calculate that the terrane would need to move 1925 ± 454 km in ~25 Myr, a rate of 77 ± 18 km/Myr or 7.7 ± 1.8 cm/yr (Demarest 1983). Such convergence rates are plausible (Kreemer et al. 2014), and so a 'polar traverse' model (Figure 10b) is consistent with the results of Halgedahl and Jarrard (1987). The timing of this event and the convergence directions are also in general agreement with southward convergence of Chukotka against other eastern Siberian terranes at this time (Figure 10b; e.g. Amato et al. 2014, 2015). This tectonic reorganization may explain how the provenance of detrital material entering the Colville basin changed from Chukotka-derived to Chukotka + Arctic Alaska-derived in the Albian (Moore et al. 2015).

In general, this model is also in agreement with the average overprint directions from the Arctic Alaska terrane and Yukon-Koyukuk basin (Figure 9). It is widely agreed upon that the Brookian orogeny was caused by the collision between Arctic Alaska and the Koyukuk arc starting in the Middle to Late Jurassic (e.g. Moore et al. 1994, 2015), so there must be some coherence among Cretaceous paleomagnetic directions in both terranes following the onset of this collision, even if the exact shortening/collisional history is still poorly constrained. Currently, most of the Cretaceous overprint poles are north of ~70°N, along with the syn-folding pole of Witte et al. (1987) (present coordinates; Figure 9), while the Kuparuk River Formation pole is located at ~50°N (Figure 10a); thus, based on these data, there is no geologically plausible way for both the counterclockwise rotation hypothesis and overprint data from all other sites to be in agreement. Note that small degrees of counterclockwise rotation (<30°) are still permissible under this model, but at the moment, we cannot build a more geologically definitive

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reconstruction without additional paleomagnetic data.

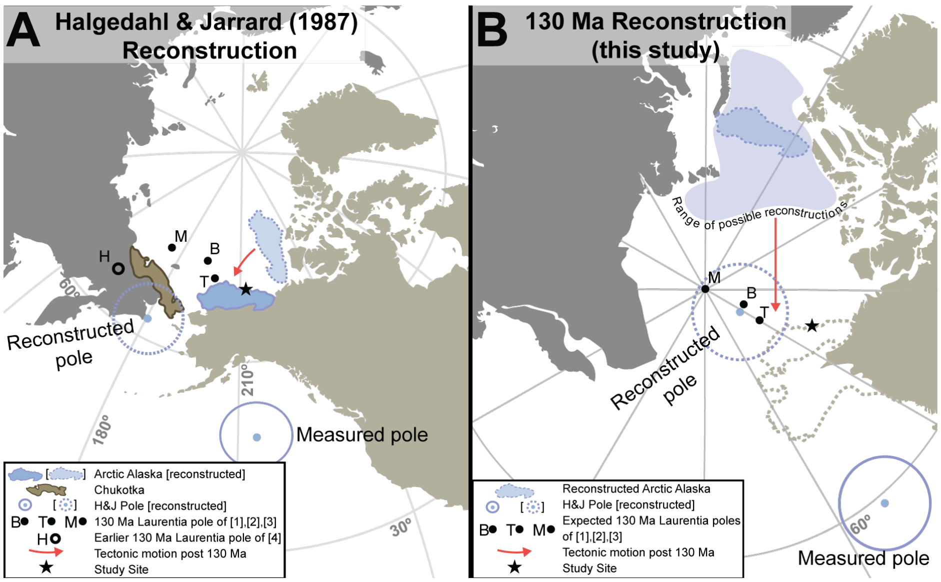


**Figure 10.** Reinterpretation of the Lower Cretaceous Kuparuk River Formation pole from Halgedahl and Jarrard (1987) (H&J). A) Original interpretation from 1987, which is no longer compatible with the APW paths of [1] Beck & Housen (2003) (B), [2] Torsvik et al. (2012) (T), or [3] Merdith et al. *(2021)* (M). [4] Earlier 130 Ma pole of Harrison & Lindh *(1982)*. B) A 'polar traverse' model for Arctic Alaska. Note the similarities between this reconstruction and the one shown in Figure 9c. The exact position of Chukotka at 130 Ma is not well constrained *(Merdith et al. 2021)*.

### 4.3 Other Tectonic and Paleobiogeographic Implications

Several other interesting tectonic observations result from this data compilation. First, it is clear that paleomagnetic data from Paleozoic carbonate rocks in the Porcupine fault system have an overprint that is significantly displaced from the Laurentian APW path (Plumley et al. 1989), which suggests 58.0 ± 17.7° of clockwise rotation since the Middle–Late Cretaceous (Figure 4d). This supports a model in which the fault system was active through the Cenozoic, perhaps even post-dating the current Miocene constraint if the assumption that these younger rocks are not deformed is incorrect (e.g., Kunk et al. 1994). Second, the paleolatitude of the Farewell terrane, as determined by primary data from Ordovician–Devonian carbonates (Plumley 1984), would suggest that it was most likely not part of the Laurentian passive margin. The calculated paleolatitude makes it a possible candidate for originating as part of or adjacent to the Siberian and Laurentian passive margins at this time (Figure 4c; Müller et al. 2022), a conclusion that is supported by the Siberian paleobiogeographic aspect of the Paleozoic faunas in these strata (e.g. Dumoulin et al. 2002, Blodgett et al. 2002, Bradley et al. 2003, Johnston 2008, Hudson et al. 2023). Third, calculated poles from several Paleozoic and Mesozoic sites in this review (e.g. Farewell terrane average overprint, Figure 8a) require various degrees of northward translation or (counter) clockwise rotation in order to align with the Laurentian APW path. For most of these studies, it is not clear how reliable the data truly are, or how well they capture a long-term average of the field, but more detailed study at any location that has already yielded primary magnetizations would be highly informative.

In addition to these tectonic implications, it is also worth noting that numerous Cretaceous units in northern Alaska contain dinosaur fossil or footprint sites (e.g. Brouwers et al. 1987, Druckenmiller et al. 2021). The discovery of these high-latitude dinosaurs sparked numerous subsequent studies, including abundant theories on dinosaur migration patterns and adaptations (Fiorillo and Parrish 2004, Brown and Druckenmiller 2011, Erickson and Druckenmiller 2011, Fiorillo et al. 2024). However, the high-latitude nature of these sites was often taken for granted, without any paleomagnetic confirmation of their primary paleolatitude. Although the various poles from Arctic Alaska often do not overlap, they do suggest a consistently high paleolatitude (~80°N) during the Cretaceous (Table 4). Regardless of any tectonic details that have yet to be resolved about the movement of Arctic Alaska, this consistently high paleolatitude places northern Alaska even farther to the north during the Cretaceous than it is today, thereby confirming that these dinosaurs were indeed 'polar', or nearly so.

**4.5 Future Work**

Perhaps the most intriguing finding of this compilation is the recognition that there is significant room for future improvement of paleomagnetic constraints on northern Cordilleran tectonics. Large portion of this region have limited to no paleomagnetic data, including St.

Lawrence Island, the eastern Brooks Range, the Farewell terrane, most of the Angayucham terrane and various smaller terranes surrounding the Tintina fault system, and the central North Slope. Highways that cut through this region (e.g., the Dalton and Dempster highways) also traverse through units with no paleomagnetic data, and these units could be sampled easily compared to most of this region. While some of these areas will be completely overprinted, our review has shown that many areas in the northern Cordillera are not reset and could yield useful data. Even additional work on characterizing the age and nature of the Cretaceous overprint would be highly informative. A focus on targeting volcanic lithologies would be key to avoiding complete resetting of primary directions. In this regard, volcanics of the Koyukuk arc and Angayucham terrane are probably the most promising units for future study. Sedimentary units can also yield non-overprinted data, but care must be taken to select fine-grained strata in the least-metamorphosed regions. The Sadlerochit and Shublik Mountains of the northeastern Brooks Range are the most promising in this regard, along with the identified thermal windows in the Yukon-Koyukuk basin (Harris et al. 1985). Finally, our review shows that better constraints on the paleolatitudes of Arctic Alaska, Koyukuk, and Angayucham terranes prior to the Middle–Late Cretaceous are feasible. Careful site selection and study design is key to future success in this region, but new paleomagnetic data would be a valuable contribution to refining our understanding of the paleogeographic and tectonic history of the northern Cordillera.

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## 5. Conclusions

Here, we have compiled and re-assessed the quality of all available paleomagnetic studies in northern Alaska and Yukon north of the Tintina fault system (Figure 1). Based on our assessment of these datasets, we conclude the following:

1. Primary remanence directions from Neoproterozoic igneous rocks (Locations 1 and 2) and Cambrian, Ordovician, Devonian, and Carboniferous sedimentary rocks (Location 5) can be found in this region despite previous assumptions that all pre-Cretaceous rocks were overprinted (Figure 1).
2. Many previous studies that found complete paleomagnetic resetting suffered from poor lithology selection – avoidance of carbonates and coarse-grained siliciclastics is key to any future paleomagnetic study design in this region.
3. Due to revisions in the Cretaceous poles for Laurentia, the counterclockwise rotation

hypothesis for Arctic Alaska is no longer supported by the paleomagnetic data presented by Halgedahl and Jarrard (1987). We instead favor hybrid translation of the Arctic Alaska terrane during the opening of the Canada basin with smaller degrees of counterclockwise rotation still being permissible.

4. Large-scale relative motion between the Arctic Alaska terrane and Yukon-Koyukuk basin and Laurentia was probably still incomplete by the Late Cretaceous. The precise mechanisms and timing of post-Albian deformation in this area are not yet clear.
5. The offset between Middle to Late Cretaceous overprint directions in Paleozoic carbonates in the Porcupine fault system and age-equivalent rocks in Laurentia suggests that this fault system was likely active through the Cenozoic.
6. ‘High-latitude’ dinosaur fossil sites in northern Alaska are confirmed; the paleolatitudes of some fossil-bearing strata were even more northerly than today.
7. Almost all paleomagnetic studies in this region do not meet modern paleomagnetic quality standards and merit revision of some kind. However, the few places where repeat studies were done (Location 1) indicate that some of the data and their interpretations will likely stand the test of time.

**Deleted:** terranes

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**Data Availability**

New data from the Kikiktat Volcanics are still being collected and will be made available in a later manuscript. All other data in this review are available in previously published studies (referenced below).

**References**

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