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# Paleomagnetism and Detrital Zircon Geochronology of the Skeena Group, British Columbia

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# PALEOMAGNETISM AND DETRITAL ZIRCON GEOCHRONOLOGY OF THE SKEENA GROUP, BRITISH COLUMBIA

by

Christopher L. Ward

Accepted in Partial Completion
of the requirements for the Degree

Master of Science
Geology

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# PALEOMAGNETISM AND DETRITAL ZIRCON GEOCHRONOLOGY OF THE SKEENA GROUP, BRITISH COLUMBIA

A Thesis
Presented to the Faculty of
Western Washington University

In Partial Fufillment
of the Requirements for the Degree
Master of Science

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August 2008

## ABSTRACT

The mid-Cretaceous Skeena Group of British Columbia is a sedimentary continental margin deposit that overlies the lower Jurassic Hazelton Group of the Stikine Terrane. Nine paleomagnetic sites were collected in 2006 and 2007, demagnetized thermally in 50-15° C steps, and high temperature components fit using principal component analysis. A new $Ar^{40}/Ar^{39}$ age of 93.9 ± 0.6 Ma for a flow of the Rocky Ridge Formation was also collected.

Three volcanic sites of the Rocky Ridge Volcanics possess coherent magnetizations, but did not prove useful. Five of six sedimentary sites from the Rocher de Boule and Bulkley Canyon Formations appear more likely to retain a primary magnetization. Curie temperature analysis indicates the primary carrier of magnetic remanence is magnetite. Hysteresis and direct field demagnetization data indicate the magnetite is primarily multi-domain in the volcanic sites and possess a mix of single and multi-domain grains in the sedimentary rocks, which may account for the more likely primary remanence from the sedimentary formations

When subjected to a bootstrap fold test, the sedimentary sites have maximum grouping at 40% untilting, but the hypotheses that the magnetization was acquired either before or after tilting cannot be rejected at the 95% confidence level. An inclination-only paleolatitude analysis was used to estimate paleolatitude as different declinations between sites suggest rotation between sites. The resulting paleolatitude for the Skeena Group is ~57° ± 21°. This is equivalent to a location ~1150 ± 2000 km south of the expected latitude with respect to North America.

Uranium-lead ages of detrital zircons from a sample of the Rocher de Boule Formation were obtained using laser ablation inductively coupled mass spectrometry. These ages form several Mesozoic peaks indicating that the majority of zircons came from Stikine

terrane units and Mesozoic arc volcanism. A Mississippian peak with some Proterozoic aged grains suggests a source from the Yukon-Tanana terrane. No Archean-aged grains were found.

## ACKNOWLEDGMENTS

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# INTRODUCTION

The Cordillera of western North America is a complex jigsaw puzzle of terranes assembled by orogenic events spanning hundreds of million years (Coney, et al., 1980; Colpron, et al., 2007). Understanding the history of the Cordillera is important to comprehending the workings of the modern tectonic setting of western North America.

Numerous paleomagnetic studies of Cretaceous units of the Cordillera have suggested that the active margin was a dynamic and mobile belt of exotic terranes (Figure 1; Irving, et al., 1996; Cowan, et al., 1997). Volcanic, plutonic and sedimentary units of ages from the mid-Cretaceous to the Eocene (110-48 Ma) show a trend of anomalously shallow inclinations of primary paleomagnetic directions with respect to the continental North America geomagnetic poles of the same ages (Figure 2; Beck, 1989; Enkin, 2006). The implication of these results is that the terranes these units were deposited on were as much as 3000 km south of their present latitude, and moved northward at rapid plate velocities. This is contrary to structural evidence that these terranes were far less traveled (Price and Carmichael, 1986; Gabrielse, et al., 2006; Wyld, et al., 2006). Attempts to explain this contradiction (Butler, et al., 2001; Umhoefer, 2003) do not properly address the large amount of evidence of northward translation.

Recent studies suggest an even more complicated story. Enkin et al. (2003) and Haskin et al. (2003) present geological evidence that two major terrane domains, the Insular and Intermontane Superterranes (Monger, et al., 1982), were linked by the Dash-Churn overlap sequence in the Churn Creek area between the Yalakom and Fraser faults in southern British Columbia (Figure 1). Mid-Cretaceous sedimentary and volcanic units from both

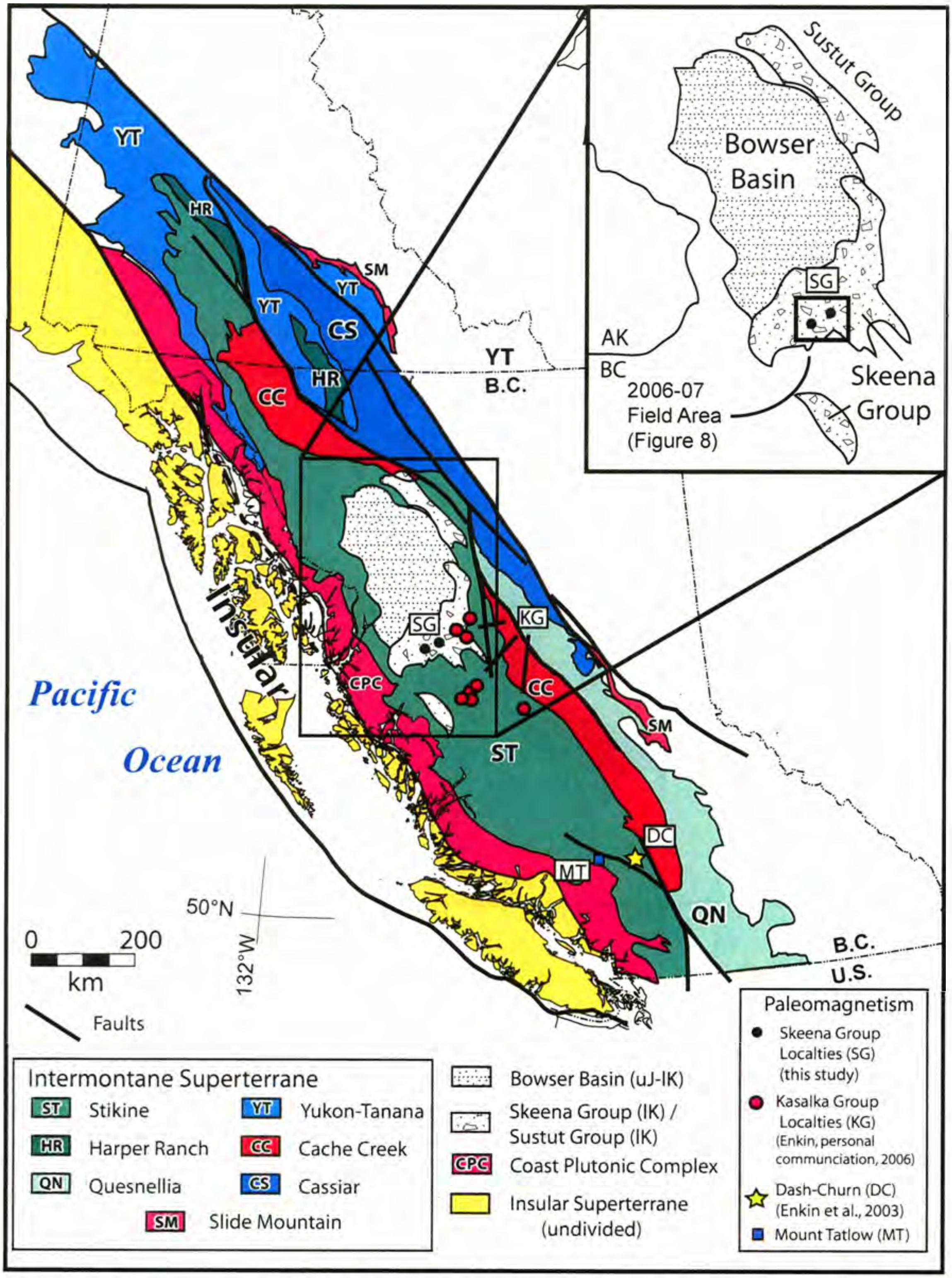



Figure 1: Terrane map of the Canadian Cordillera and the Skeena Group, associated sedimentary basins and relevant paleomagnetism studies.

Simplified from Colpron et al. (2007)

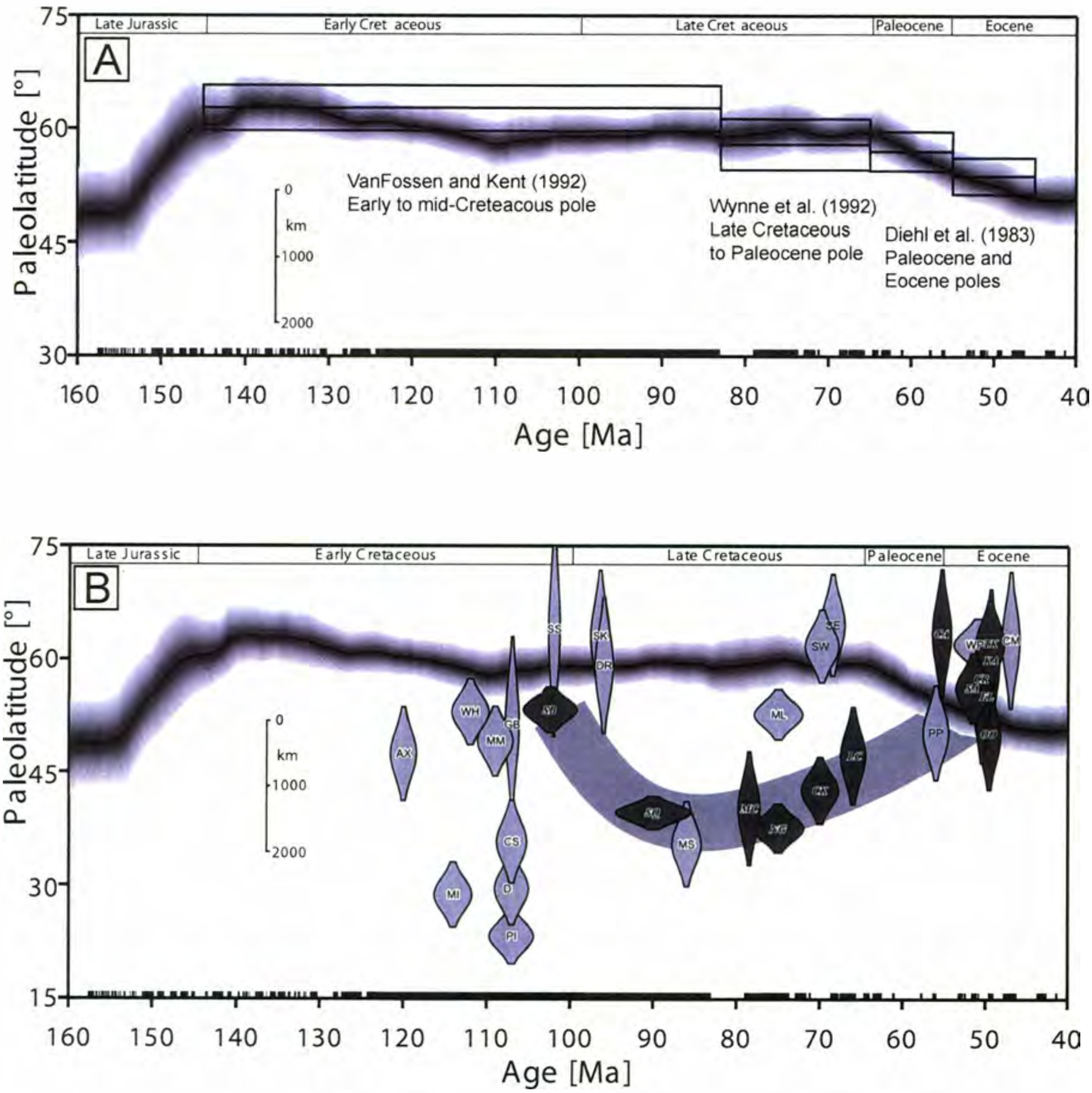



Figure 2: Paleomagnetic studies from late Cretaceous and Eocene units across the Cordillera have discordant paleolatitudes with respect to the North America pole. Geomagnetic polarity timescale included at bottom of each plot.

A) Expected paleolatitude at Mount Tatlow (MT, Figure 1; 51.3° N, 123.8° W) based on North America poles for the late Cretaceous and Eocene

B) Paleolatitudes from studies in the Cordillera (Enkin, 2006). Diamonds represent error margin for each study; dark grey diamonds are bedded rocks, lighter grey are intrusive units.

superterranes (Figure 3) are believed to be in stratigraphic contact (Haskin et al., 2003). This contradicts the classic "Baja British Columbia" model (Irving, 1985; Irving et al., 1996; Cowan, et al., 1997) that the superterranes were separate units during the late Cretaceous and Eocene and the northward displacement is partitioned between the two superterranes (Figure 4).

Paleolatitude estimates from the overlap sequence suggest a new model for terrane motion in the late Cretaceous. Paleomagnetic samples of the Albian-aged (112-97 Ma) Empire Valley volcanics, equivalent to the Spences Bridge Group (Irving, et al., 1995), have a paleolatitude of $53.2° \pm 2.8°$ (Haskin et al., 2003). Overlying the volcanics is the Churn Creek conglomerate, equivalent to the late Cretaceous Silverquick/Powell Creek Sequence (Schiarizza et al., 1997), which has a paleolatitude of $36.1° \pm 2.4°$ (Enkin et al., 2003). These results imply that instead of partitioned domains that moved northward separately, the superterranes were one large domain that was ~1000 km south of expected paleolatitudes at ~100 Ma, then moved south ~2000 km in ~10-15 Ma, then moved north to their present location by 48 Ma (Irving and Brandon, 1990).

As this model requires a rate of southward motion of $38 \pm 16$ cm/yr (Enkin et al., 2003), far quicker than estimated plate motions (5-10 cm/yr; Kelley, 1993) during this period, it is important to examine this model critically. The geologic evidence for the overlap sequence is complicated by thrust faults between the two units of the Churn Creek sequence. This suggests instead of a stratigraphic contact at ~95 Ma, it is a younger structural contact related to the Yalakom-Fraser strike-slip faults, with interleaving of units via flower-structure deformation (Figure 5). A paleomagnetic test of this model (termed the "yo-yo model" due to its prediction of rapid southward then northward motion for these rocks) is to determine a

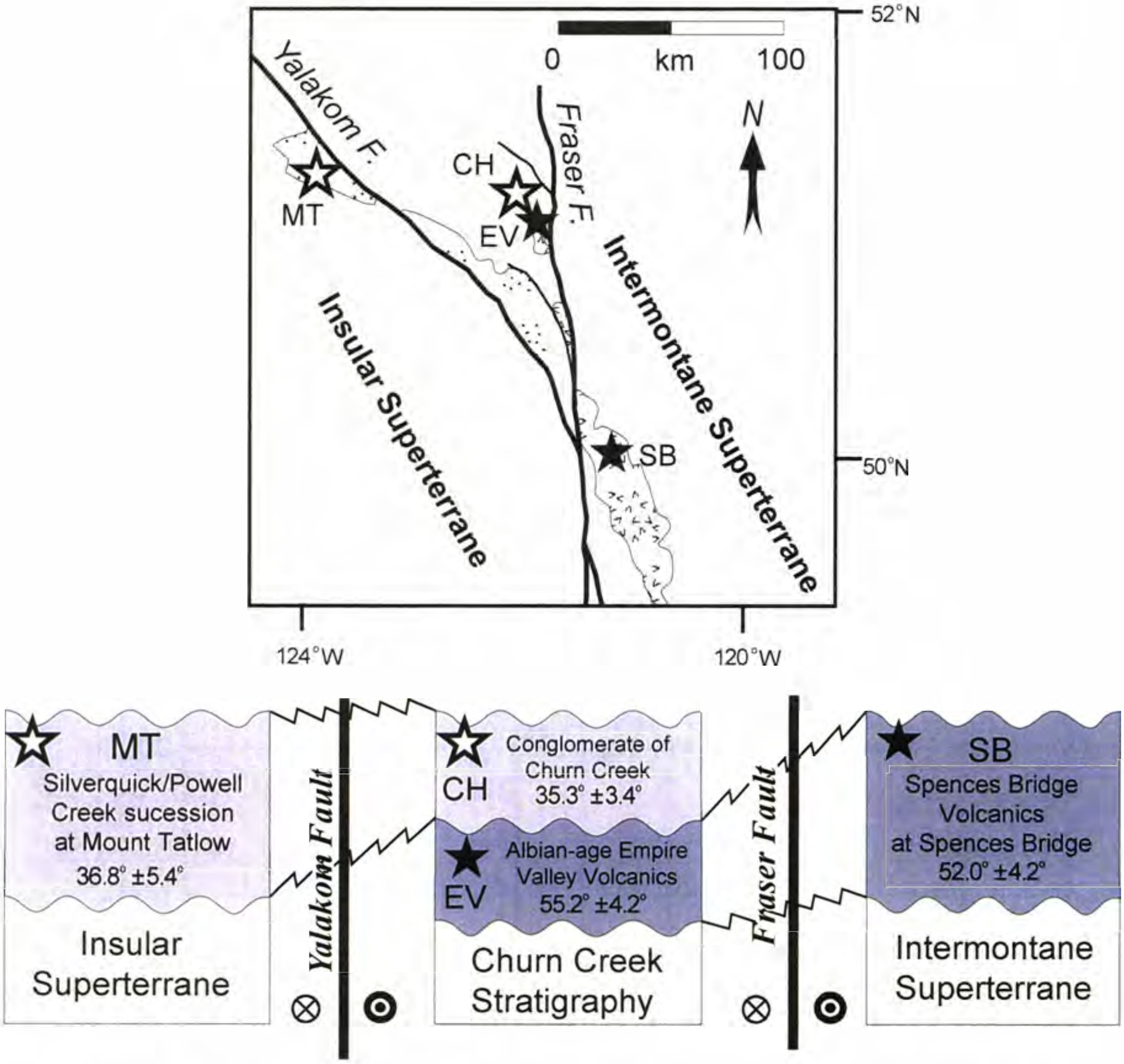



Figure 3: Paleolatitudes for units of the Dash-Churn overlap sequence (Enkin et al., 2003), south-central British Columbia. The conglomerate of Churn Creek (CH) is believed to stratigraphically overlie the Empire Valley Volcanics (EV) and laterally correlates with units on both superterranes. It is suggested that this is evidence that the superterranes were linked by 95 Ma.

Paleomagnetic results for Mount Tatlow and the Spences Bridge Volcanics from Enkin et al. (2006) and Irving et al. (1995). Adapted from Enkin (2006).

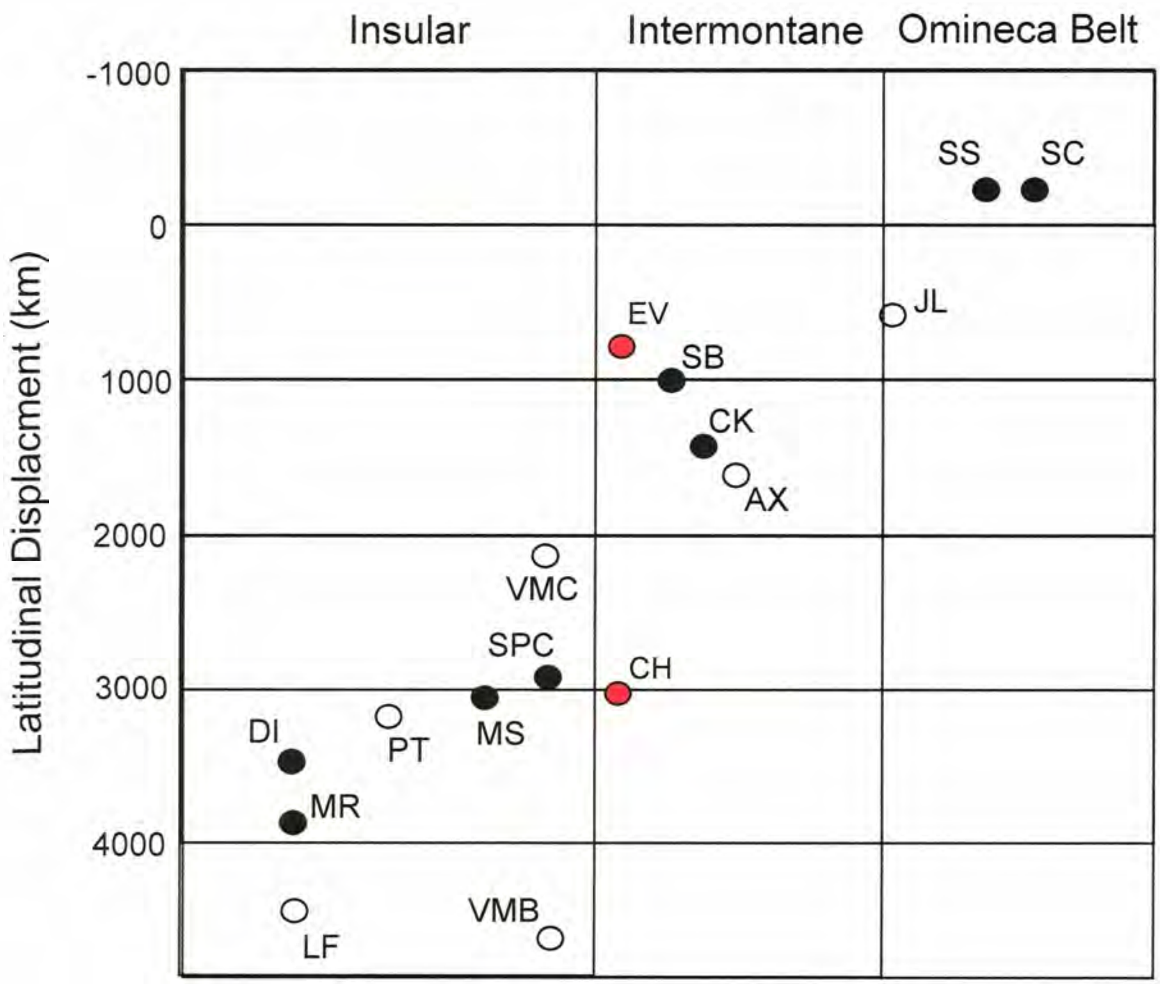



Figure 4: The classic "Baja British Columbia hypothesis" divides the late Cretaceous Cordillera into two seperate tectonic blocks, the Intermontane and Insular Superterranes. This allows partitioning of the strain of dextral translation. Closed circles are paleomagnetic studies with good tilt correction, open circles with uncertain tilt corrections. Studies from Irving et al., 1996.

Red circles are studies from Enkin et al., 2003 (CH: Churn Creek) and Haskin et al., 2003 (EV: Empire Valley Volcanics). They are believed to be in stratigraphic contact, therefore they are evidence that the two blocks were instead linked during the late Cretaceous.

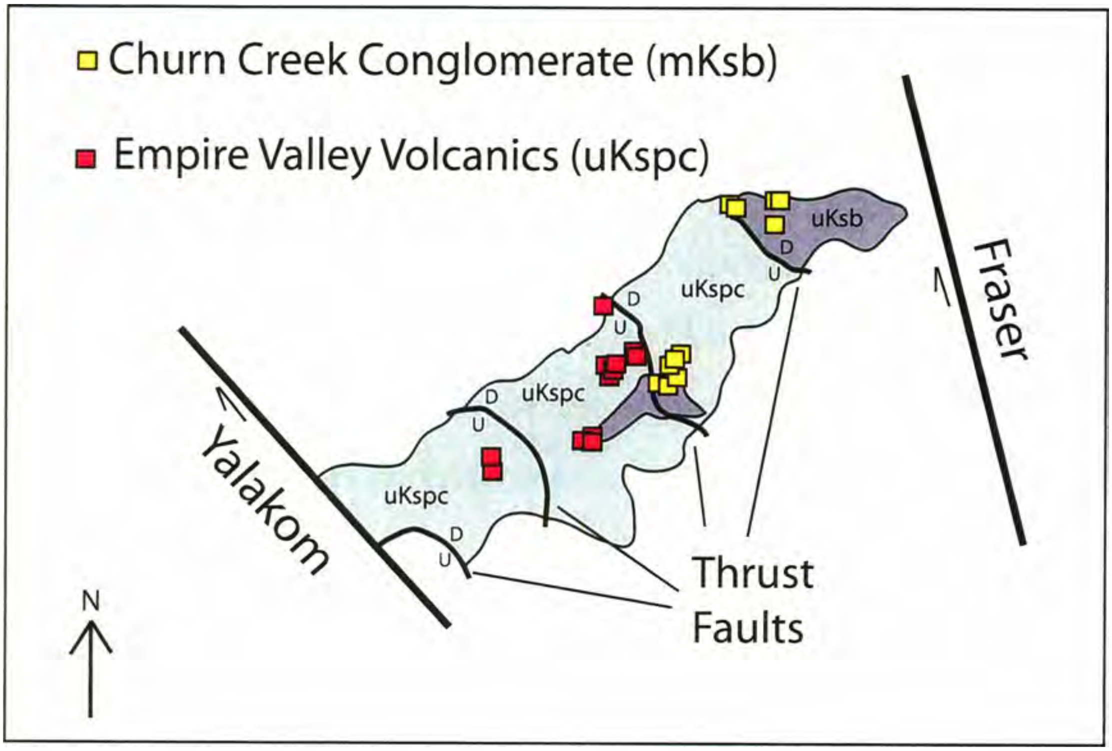



Figure 5: Thrust faults in the Dash-Churn overlap sequence possibly indicate that instead of being in stragraphic contact, the Churn Creek Conglomerate is overthrust onto the Empire Valley Volcanics as a part of a flower-structure system related to the Yalakom-Fraser fault zone. Modified from Enkin et al. (2003)

paleolatitude for younger units of the Intermontane Superterrane. If they provide a paleolatitude placing them further south than the Spences Bridge Group at ~105 Ma, then the overlap sequence is reasonable, supporting the yo-yo model.

The Skeena Group (described by Bassett and Kleinsphen, 1997) is an early to mid-Cretaceous fluvial-deltaic sedimentary sequence that unconformably overlies volcanic rocks belonging to the Stikine Terrane, a part of the Intermontane Superterrane (Figure 1). Radiometric ages of andesitic volcanics from the Skeena Group range from 104.8 ± 1.2 Ma to 95.1 ± 1.6 Ma (MacIntyre, et al., 2004; Bassett and Kleinsphen, 1996). Clastic sedimentary units have fossil and pollen ages from the Neocomian to the late Albian (Bassett, 1995). Therefore, paleolatitude results for the Skeena Group provide an opportunity to answer the problem raised by the yo-yo model. If the Skeena Group has a paleolatitude matching units of the Insular Superterrane, this would support the yo-yo model. If the results match a predicted "Baja BC" model displacement of less than ~1000 km, this would refute the yo-yo model.

A second way to examine the problem is to characterize the location of the younger Intermontane sediments through detrital zircon geochronology. If the Skeena Group were at the southern latitudes predicted by the yo-yo model, Archean-aged grains from the craton (Mahoney et al., 1999) should be found. If no Archean-aged grains are present, then the moderate displacement of ~1000 km is possible. Grain ages could also describe the relative location of inboard units of the Intermontane Superterrane.

PREVIOUS PALEOMAGNETIC STUDIES

Over the last three decades, several attempts have been made to collect paleomagnetic samples from volcanic rocks of late Cretaceous and Eocene age throughout central Stikinia (personal communication, Enkin, 2006). Quality paleomagnetic results from these units have been difficult to acquire due to several factors: the difficulty of access to outcrops, low outcrop quality of geomagnetic records due to lightning strike remagnetization, lack of adequately detailed geologic mapping, and few radiometric geochronology data.

Most of the accepted paleomagnetic data come from the upper Cretaceous Kasalka Group, an extensive intermediate volcanic arc that unconformably overlies the Skeena Group. Unpublished radiometric ages for the Kasalka Group range from 74 Ma (K/Ar) to 93.4 ± 4.7 Ma (K/Ar hornblende) (Enkin, personal communication, 2006). The few sites that appear to yield useful results were collected over a large geographic range (Figure 1; Table 1; provided by Enkin, personal communication, 2006). In these specimens, magnetization persisted up to 675° C; it is believed that both magnetite and hematite are primary magnetic remanence carriers in these samples.

In all, nineteen sites from eight localities were used to produce a Fisher mean direction corrected to paleohorizontal (Figure 6) with a declination (D) of 351.8° and an inclination (I) of 67.2°. Using the fold test of Enkin (2003), the optimum amount of untilting is 94.5% ± 6.0. A high percentage of untilting for optimum clustering of directions is an indication that this direction was recorded prior to deformation, and therefore is likely the primary magnetic remanence. If it is assumed that each locality is a separate block, then the Fisher mean inclination is 65.8° ± 4.8°. Assuming an axial dipole model for the geomagnetic field at magnetization, this provides a reasonable estimate of a paleolatitude ($\lambda$) of 48.05° ±

## Table 1. Paleomagnetic results for the Kasalka Group

| Site | N | $D_{geo}$ | $I_{geo}$ | $D_{strat}$ | $I_{strar}$ | k | $\alpha_{95}$ |
|---|---|---|---|---|---|---|---|
| Owen Lake (54.1°N, 126.8°W) - combined into one site (from Vandall, 1990) | | | | | | | |
| 7-14 | 36(7) | 29.6 | 73.5 | 303.3 | 70.8 | 734.3 | 2.2 |
| Nadina Lake (53.9°N, 127.0°W) - (from Vandall, 1990) | | | | | | | |
| 17 | 4 | 66 | 24 | 315 | 78 | 75 | 10.7 |
| 18 | 4 | 59 | 20 | 337 | 73 | 176 | 6.9 |
| 23 | 3 | 323 | 70 | 323 | 70 | 290 | 7.3 |
| 25 | 4 | 331 | 70 | 331 | 70 | 90 | 9.7 |
| Kenny Dam (53.7°N, 125.0°W) - from 1995 | | | | | | | |
| JNN12 | 10 | 169.2 | -59.9 | 167.3 | -67.9 | 141.9 | 4.1 |
| Newcombe Lake (54.0°N, 127.1°W) - from 1995 | | | | | | | |
| JNN13 | 8 | 259/0 | -82.3 | 116.6 | -81.3 | 154.6 | 4.5 |
| JNN15 | 4 | 70.6 | 68.2 | 29.8 | 79.1 | 689.7 | 3.5 |
| Mount Ney (53.9°N, 127.3°W) - from 1999 | | | | | | | |
| KSK04 | 3 | 133.1 | -61.3 | 149.1 | -67.2 | 34.2 | 21.4 |
| KSK05 | 10 | 149.2 | -64.6 | 170.2 | -67.8 | 214.7 | 3.3 |
| KSK06 | 11 | 144.6 | -65.5 | 166.2 | -69.4 | 179.8 | 3.4 |
| KSK07 | 5 | 259.7 | 28.1 | 339.2 | 60.4 | 48.0 | 11.2 |
| Morricetown (55.1°N, 127.4°W) - from 1999 | | | | | | | |
| KSK09 | 9 | 215.6 | 69.4 | 38.9 | 67.1 | 184.5 | 3.8 |
| Babine Lake (55.3°N, 126.7°N) - from 2000 | | | | | | | |
| KSS04 | 9 | 102.4 | 77.7 | 44.6 | 49.6 | 38.4 | 8.4 |
| KSS05 | 10 | 174.0 | 79.7 | 37.8 | 62.3 | 103.2 | 4.8 |
| Skeena Mountains (55.0°N, 127.0°N) - from 2000 | | | | | | | |
| KSS13 | 4 | 10.6 | 37.1 | 320.7 | 54.2 | 102.4 | 9.1 |
| KSS14 | 9 | 33.6 | 19.3 | 9.7 | 59.0 | 97.2 | 5.2 |
| KSS15 | 10 | 22.1 | 20.8 | 353.1 | 53.2 | 108.8 | 4.7 |
| KSS16 | 4 | 11.1 | 34.2 | 325.3 | 53.2 | 59.3 | 12.0 |

Unpublished paleomagnetic directions for 19 sites from the late Cretaceous Kasalka Volcanics of central British Columbia. Eleven sites at Owen Lake and Nadina Lake were collected by Tom Vandall for his Ph.D. Thesis (1990). The seven sites at Owen Lake are combined into one site here as they appear to not average out any polar secular variation. The remaining 14 sites were collected during several field seasons by Randy Enkin and others of the Geologic Survey of Canada.

All data and information courtesy of Randy Enkin (personal communication, 2006).

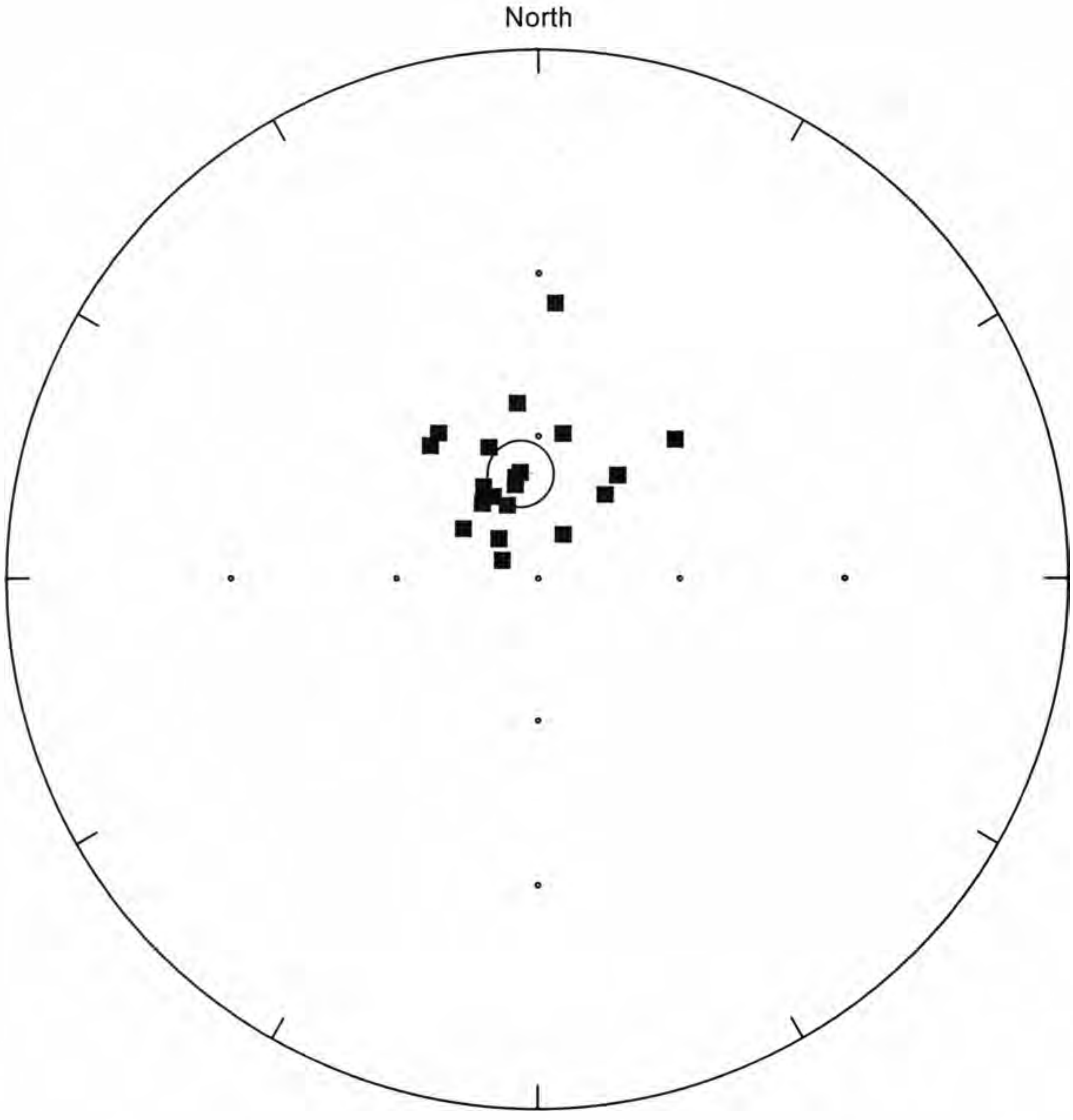



Figure 6: Tilt corrected and inverted to normal polarity means for paleomagnetic sites (n=19) from the late Cretaceous Kasalka Group (Enkin, 2006, personal communication).
Mean direction: D = 351.8°; I = 67.2 °; $\alpha_{95}$ = 6.9°.
Mean location: 54.35° N 126.9° W

6.8° for the late Cretaceous Kasalka volcanics. Using an appropriate pole for North America (Dickinson and Butler, 1998), the Kasalka volcanics are estimated to have formed 1300 ± 1000 km south of its expected latitude with respect to North America at ~80-75 Ma.

The main weaknesses in interpretations of these data are that the sites come from a large geographic region and the age of primary remanence is poorly constrained. Averaging these sites to one paleolatitude introduces further error in the amount of displacement. If the ages of these rocks truly span 20 Ma, this decreases the utility of the results to constrain the timing of terrane migration.

## GEOLOGIC SETTING

The early to mid-Cretaceous Skeena Group of central British Columbia (Figure 1) is a sequence of sedimentary and volcanic units that records transgression and regression in the southern margin of the marine Jura-Cretaceous Bowser Basin. This sequence sporadically crops out over a 32,000 $km^2$ region and uncomformably overlies several different units, including the late Jurassic Bowser Lake Group in the north and west and the early to middle Jurassic Hazelton Group in the south. Stratigraphically, the Skeena Group is overlain uncomformably by the late Cretaceous Kasalka Group (MacIntyre et al., 2004). The Skeena Group has since been broken up by post-Eocene block faulting (Richards, 1990). Three units of the Skeena Group were sampled during field work in 2006 and 2007: the Kitsuns Creek member of the Bulkley Canyon Formation, the Rocky Ridge Volcanics, and the Rocher Deboule Formation (Figure 7).

### *Kitsuns Creek Member of the Bulkley Canyon Formation*

The Kitsuns Creek member of the Bulkley Canyon Formation is described from exposures near the headwaters of Kitsuns Creek near Kitseguecla, British Columbia (Bassett, 1995). This name originally was applied to all micaeous sandstones and siltstones of Neocomian-Albian age (Richards, 1990). Bassett (1995) renamed the separated volcaniclastic sandstones and conglomerates found in association with volcanic centers of Rocky Ridge-type flows as a member of the newly named Bulkley Canyon Formation. The type section ("Sc" in Bassett, 1995) records coarsening sediment, with several episodes of volcanic clast-dominated conglomerate river channels with cross-bedded litharenites and mudstones. Small basalt flows, believed to be related to the Rocky Ridge Formation, are

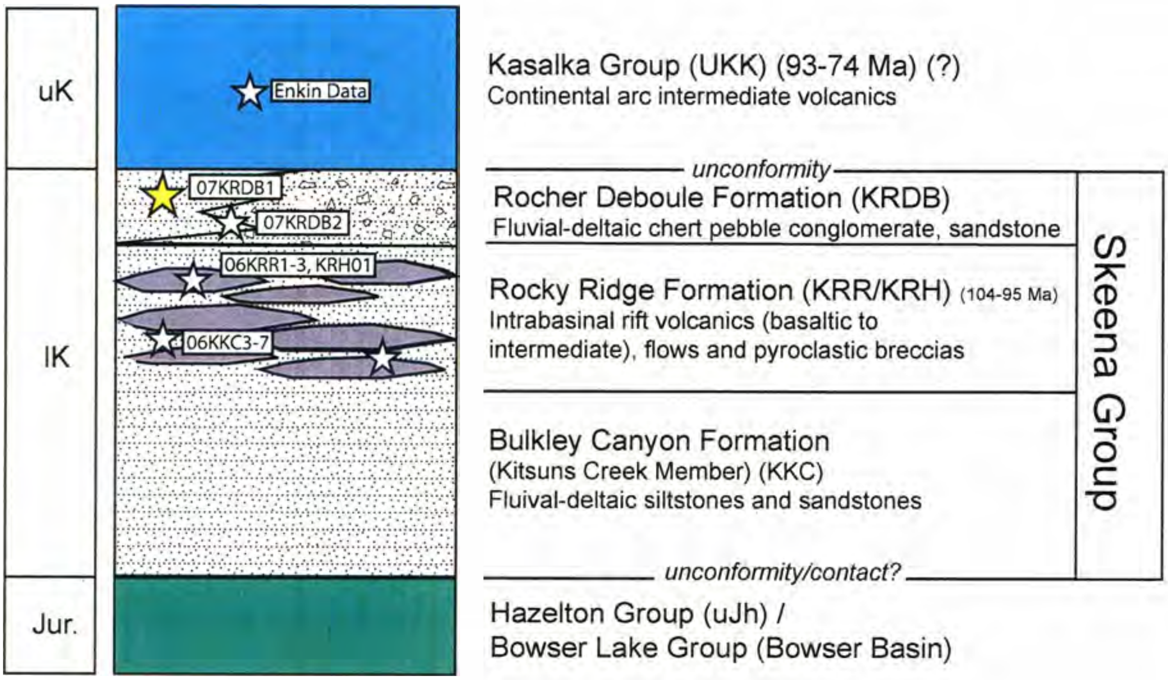



Figure 7: Simplified stratigraphic column for the Skeena Group near Smithers, British Columbia, with the locations of previous radiometric ages (Bassett and Kleinsphen, 1996; Macintyre et al., 2004), and sample sites from this study.

Adpated from MacIntyre et al. (2004).

interbedded in the sequence. Bassett (1995) describes observed northeastward paleocurrent directions, pointing from the Rocky Ridge volcanic vent. Pollen collected from the Kitsuns Creek Member indicates a Neocomian to early Cenomanian age (Bassett, 1995).

*Rocky Ridge Volcanics*

The term "Rocky Ridge Volcanics" was loosely applied to basalt-andesite volcanic flows found throughout the middle Skeena Group (Tipper, 1976). A more precise description has followed in more recent years (Richards, 1990; Bassett and Kleinsphen, 1997; Macintyre, et al., 2004). The type section includes the numerous flows, eruption breccias and tuffs of Rocky Ridge, north of Smithers, British Columbia. Sandstones similar to the Kitsuns Creek member are found interbedded with Rocky Ridge flows. Several volcanic outcrops of similar composition and age throughout the Skeena Group region have been described as individual vents of subaerial pryoclastic eruptions related to basin subsidence (Bassett and Kleinsphen, 1996). The flows are typically 10 to 20 meters thick and basaltic to basaltic-andesitic composition (Bassett and Kleinsphen, 1997). Large (4-10 mm) phenocrysts of hornblende are found in outcrops on Kitsuns Creek ridge (Sc in Bassett, 1995). Radiometric dates include a $^{40}Ar/^{39}Ar$ age of 95.1 ± 1.6 Ma (Bassett and Kleinsphen, 1996) and a U/Pb age of 104.8 ± 1.2 Ma (MacIntyre, et al., 2004) (Figure 7). For this study, a hornblende-rich flow on Ridge "Sc" (06KRH01; Figure 8) was sampled during the 2006 field season, and sent for $Ar^{40}/Ar^{39}$ age analysis at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia. The sample yielded a hornblende $Ar^{40}/Ar^{39}$ plateau age of 93.9 ± 0.6 Ma (Figure 9). Pollen assemblages indicate an early Albian to middle Cenomanian age (Bassett, 1995). Elongated vesicles indicate a northwestward flow direction, pointing

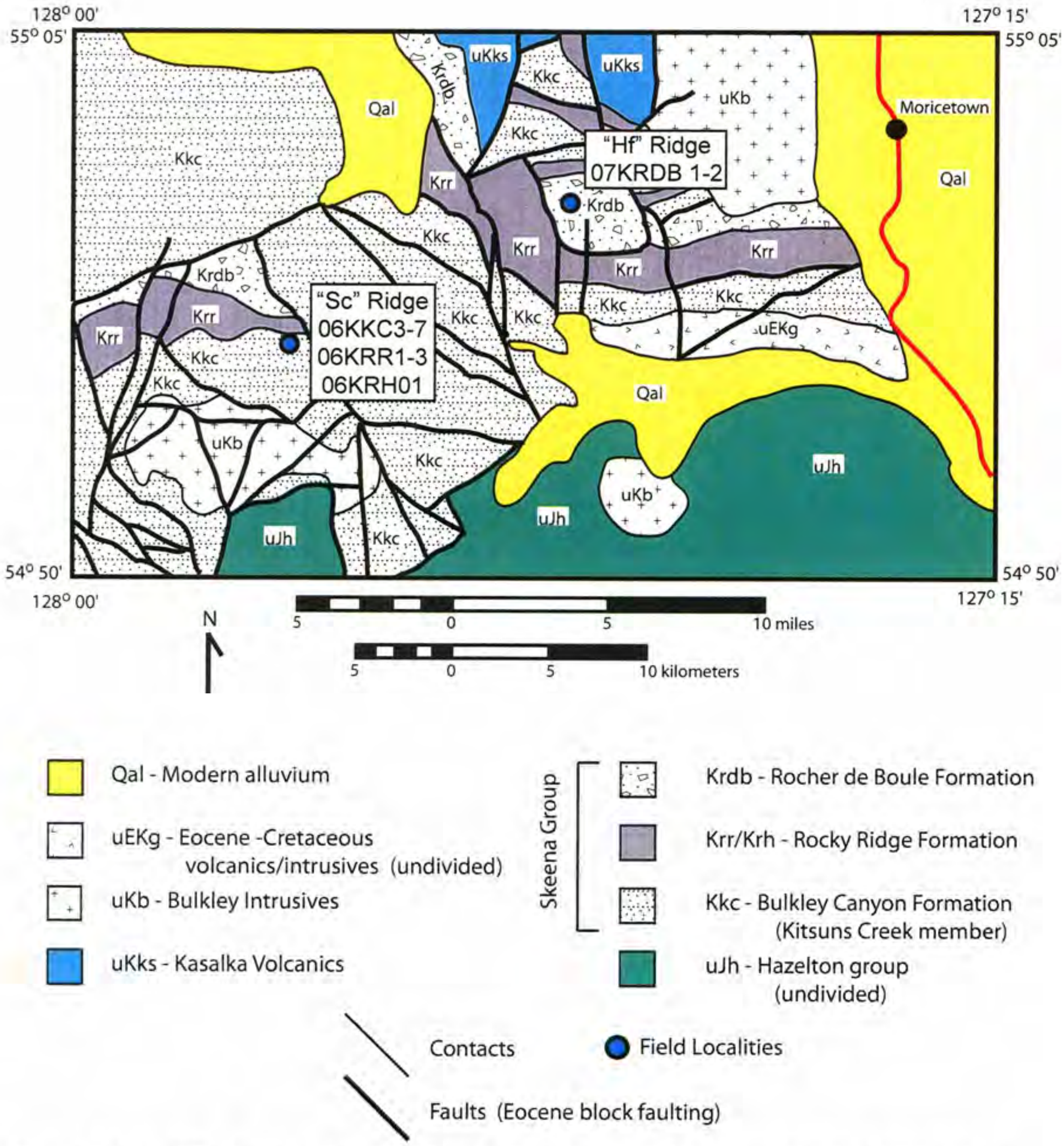



Figure 8: Simplified geologic map of region northwest of Smithers, British Columbia.

Adapted from the 1:125,000 geologic maps for Hazelton (Richards, 1990) and Smithers (Tipper and Richards, 1976).

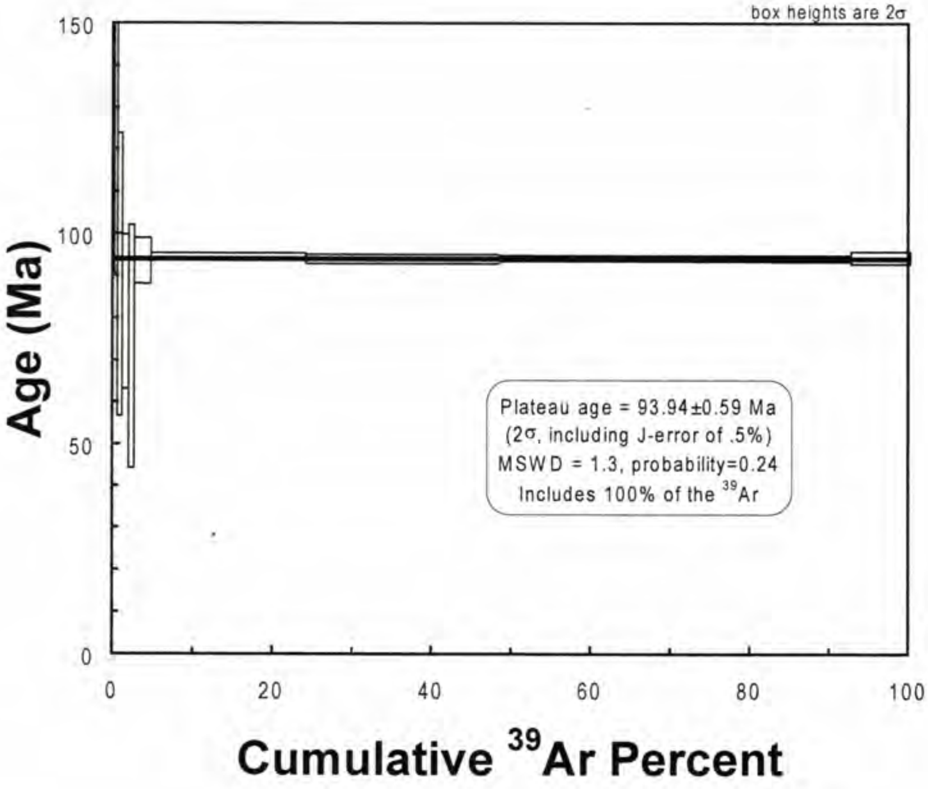



Figure 9: $^{39}Ar/^{40}Ar$ age plateau for hornblende from sample 06KRH01.

away from Rocky Ridge as the source vent, and internal structures indicate hot emplacement of the breccias as pyroclastic flows (Bassett and Kleinsphen, 1996).

*Rocher Deboule Formation*

The Rocher Deboule Formation (from Bassett and Kleinsphen, 1997) is the newest name for the chert-rich pebble conglomerates found stratigraphically above Rocky Ridge flows. These strata used to be grouped with sandstones and siltstones of the Red Rose Formation, which has been reclassified as belonging to the Jurassic Bowser Lake Group (Richards, 1990). The type section for the Rocher Deboule Formation spans a pair of ridges just north of Rocky Ridge (Sections Hf, Hg, Hh of Bassett, 1995) in the southern Hazelton Map (Richards, 1990). The Rocher Deboule Formation conformably overlies andesite-basalt flows correlated with the Rocky Ridge Volcanics. Outcrops are dominantly chert pebble conglomerate with interbedded micaeous sandstones and red siltstones, interpreted as being deposited in river channels and crevasses splays, but include debris flows (Bassett, 1995). The chert pebble clasts may share an affinity with the Tango Creek Formation of the nearby Sustut Basin deposits (Eisbacher, 1981).

Paleocurrent directions measured in sandstone units of the type section indicate a west to southwest direction of flow (Bassett, 1995). However, these results were quite varied, which is attributed to deposition in a meandering river channel. Paleocurrent directions measured near Smithers, British Columbia (map area of Tipper and Richards, 1976) indicate north and west-southwest directions of flow. To the north, near Terrace, British Columbia, (map area of Woodsworth, et al., 1985), units have a north-northwest paleocurrent direction

(Bassett, 1995). Pollen collected by Bassett, 1995 indicates a late Albian to early Cenomanian age.

# PALEOMAGNETISM

## SAMPLE COLLECTION AND PREPERATION

In the summers of 2006 and 2007, five to eight cores were collected from each of nine sites in the Skeena Group (Figure 8; Table 2). Three sites are of Rocky Ridge Volcanics (06KRR) from the Kitsuns Creek type section Sc (Bassett, 1995), five are of the Kitsuns Creek Member (06KKC) from the same section and one of a sandy member of the Rocher de Boule Formation (Bassett, 1995) type section Hf (07KRDB). Site selection was governed by accessibility and outcrop distribution, as the region has been subject to Holocene Cordilleran glaciation and erosion. Each of the two field areas is in a different tectonic block produced by Eocene faulting (Richards, 1990).

All sites were sampled using a standard 2.54 cm diameter diamond core drill. Care was taken to sample coherent and attitudinally measurable units as outcrop quality was generally poor. Also, outcrop location was taken into consideration to reduce the chance of lightning strike remagnetization.

Samples were oriented *in situ* using a sun compass and magnetic compass. Agreement of sun and magnetic compass bearings is interpreted to indicate lack of intense remagnetization at the outcrops. Three strike and dip measurements were taken at each outcrop, then averaged to minimize human error and attitude irregularity. The volcanic units (06KRR) lacked measurable structures; therefore their orientation was determined by sedimentary interbeds. Cores were cut into standard 2.25 cm length specimens using a non-magnetic diamond saw at the Pacific Northwest Paleomagnetism Laboratory at Western Washington University.

# Table 2. Paleomagnetic results for the Skeena Group

| Low-temperature Component 80-300° C | | | | | | Geographic | | | | Stratigraphic | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Latitude | Longitude | Dip Azimuth | Dip | n | D | I | *k* | $\alpha_{95}$ | D | I | *k* | $\alpha_{95}$ |
| 06KKC3 | 54.927 | 232.151 | 15 | 37 | 7 | 35.4 | 68.2 | 205.8 | 4.2 | 23.8 | 32.1 | 205.8 | 4.2 |
| 06KKC4 | 54.927 | 232.151 | 15 | 37 | 6 | 55.0 | 61.7 | 7.9 | 25.5 | 35.4 | 29.0 | 7.9 | 25.5 |
| 06KKC5 | 54.927 | 232.151 | 15 | 37 | 5 | 28.0 | 64.2 | 43.9 | 11.0 | 21.3 | 28.1 | 43.9 | 11.0 |
| 06KKC7 | 54.934 | 232.158 | 42 | 35 | 5 | 20.1 | 47.2 | 57.1 | 10.2 | 26.9 | 13.9 | 57.1 | 10.2 |
| 06KRR1 | 54.931 | 232.155 | 15 | 37 | 6 | 7.1 | 66.4 | 29.9 | 12.5 | 11.4 | 29.6 | 29.9 | 12.5 |
| 06KRR2 | 54.934 | 232.158 | 42 | 35 | 7 | 345.5 | 68.4 | 44.7 | 9.1 | 18.3 | 40.2 | 44.7 | 9.1 |
| 07KRDB2 | 55.016 | 232.398 | 178 | 70 | 7 | 174.2 | 82.5 | 194.7 | 4.3 | 177.5 | 12.5 | 194.7 | 4.3 |

| Medium-temperature Component 200-430° C | | | | | | Geographic | | | | Stratigraphic | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Latitude | Longitude | Dip Azimuth | Dip | n | D | I | *k* | $\alpha_{95}$ | D | I | *k* | $\alpha_{95}$ |
| 06KKC3 | 54.927 | 232.151 | 15 | 37 | 7 | 182.8 | 45.7 | 47.8 | 8.8 | 142.8 | 79.2 | 47.8 | 8.8 |
| 06KKC4 | 54.927 | 232.151 | 15 | 37 | 6 | 187.7 | 56.1 | 36.6 | 11.2 | 65.5 | 84.8 | 36.6 | 11.2 |
| 06KKC5 | 54.927 | 232.151 | 15 | 37 | 5 | 182.0 | 32.9 | 7.8 | 29.3 | 164.9 | 67.8 | 7.8 | 29.3 |
| 06KKC7 | 54.934 | 232.158 | 42 | 35 | 5 | 232.4 | 63.4 | 136.6 | 6.6 | 14.0 | 80.1 | 136.6 | 6.6 |
| 07KRDB2 | 55.016 | 232.398 | 178 | 70 | 7 | 36.1 | -10.8 | 2.6 | 47.3 | 52.0 | 41.5 | 2.6 | 47.3 |

| High-temperature Component 380-550° C Free Line Fit | | | | | | Geographic | | | | Stratigraphic | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Latitude | Longitude | Dip Azimuth | Dip | n | D | I | *k* | $\alpha_{95}$ | D | I | *k* | $\alpha_{95}$ |
| 06KKC3 | 54.927 | 232.151 | 15 | 37 | 6 | 236.8 | 66.5 | 29.9 | 12.4 | 334.8 | 65.7 | 29.9 | 12.4 |
| 06KKC4 | 54.927 | 232.151 | 15 | 37 | 6 | 223.9 | 64.2 | 18.8 | 15.9 | 333.5 | 71.5 | 18.8 | 15.9 |
| 06KKC5 | 54.927 | 232.151 | 15 | 37 | 7 | 212.8 | 51.4 | 5.3 | 29.0 | 283.5 | 79.0 | 5.3 | 29.0 |
| 06KKC7 | 54.934 | 232.158 | 42 | 35 | 5 | 244.9 | 66.8 | 6.8 | 31.7 | 8.3 | 74.0 | 6.8 | 31.7 |
| 06KRR1 | 54.931 | 232.155 | 15 | 37 | 3 | 16.0 | 51.0 | 6.8 | 51.7 | 15.6 | 14.0 | 6.8 | 51.7 |
| 06KRR2 | 54.934 | 232.158 | 42 | 35 | 5 | 17.3 | 58.9 | 11.8 | 23.2 | 28.2 | 25.6 | 11.8 | 23.2 |
| 07KRDB2 | 55.016 | 232.398 | 178 | 70 | 5 | 27.9 | 48.0 | 5.5 | 35.8 | 144.3 | 53.1 | 5.5 | 35.8 |

| High-temperature Component 380-550° C Anchored Line Fit | | | | | | Geographic | | | | Stratigraphic | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Latitude | Longitude | Dip Azimuth | Dip | n | D | I | *k* | $\alpha_{95}$ | D | I | *k* | $\alpha_{95}$ |
| 06KKC3 | 54.927 | 232.151 | 15 | 37 | 6 | 230.0 | 70.4 | 29.0 | 12.6 | 346.0 | 66.6 | 29.0 | 12.6 |
| 06KKC4 | 54.927 | 232.151 | 15 | 37 | 5 | 220.9 | 63.4 | 25.6 | 15.4 | 332.9 | 73.0 | 25.6 | 15.4 |
| 06KKC5 | 54.927 | 232.151 | 15 | 37 | 6 | 221.3 | 57.0 | 5.7 | 30.6 | 310.4 | 74.5 | 5.7 | 30.6 |
| 06KKC7 | 54.934 | 232.158 | 42 | 35 | 4 | 325.9 | 67.1 | 7.4 | 36.1 | 10.0 | 44.5 | 7.4 | 36.1 |
| 06KRR1 | 54.931 | 232.155 | 15 | 36 | 3 | 355.1 | 57.6 | 4.5 | 66.5 | 3.6 | 22.8 | 4.5 | 66.5 |
| 06KRR2 | 54.934 | 232.158 | 42 | 35 | 3 | 306.8 | 79.4 | 38.6 | 20.1 | 23.6 | 54.6 | 38.6 | 20.1 |
| 07KRDB2 | 55.016 | 232.398 | 178 | 70 | 3 | 29.8 | 66.3 | 30.0 | 22.9 | 162.1 | 39.4 | 30.0 | 22.9 |

| Remagnetized Sites | | | | | | Geographic | | | | Stratigraphic | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Latitude | Longitude | Dip Azimuth | Dip | n | D | I | k | $\alpha_{95}$ | D | I | k | $\alpha_{95}$ |
| 06KKC6 | 54.933 | 232.158 | 42 | 35 | 6 | 324.4 | 24.9 | 4.1 | 37.9 | 336.4 | 13.5 | 4.1 | 37.9 |
| 06KRR3 (Low-T) | 54.942 | 232.165 | 42 | 35 | 5 | 151.4 | 59.1 | 69.5 | 9.2 | 96.0 | 53.2 | 69.5 | 9.2 |
| 06KRR3 (High-T) | 54.942 | 232.165 | 42 | 35 | 5 | 166.6 | 28.8 | 39.1 | 12.4 | 142.3 | 42.8 | 39.1 | 12.4 |

Stratigraphic coordinates represent geographic coordinates corrected to paleohorizontal.
n = number of samples, D = Declination, I = Inclination, *k* = dispersion

MAGNETIC MINERALOGY

Magnetic properties of samples from the Skeena Group were measured using a Princeton MicroMag Model 3900 Vibrating Sample Magnetometer (VSM) to determine the magnetic remanence carriers. Work consisted of using small chip samples to determine the temperature dependence of saturation moment, hysteresis loops and direct current demagnetization (DCD) of remanence. The first test determined that Curie temperatures were consistent with only magnetite as the magnetic mineral. The other two tests collected values for the ratios of saturation remanence to saturation magnetization (Mrs/Ms), and remanent coercivity to ordinary coercivity (Hcr/Hc), to generate a Day plot (Day et. al, 1977). This plot portrays the magnetic domain status and inferred grain size of the magnetite present in the samples.

The decay of saturation moment with heating indicates that the Curie temperature (Tc) for the materials analyzed is near 570° C, consistent with magnetite being the primary magnetic mineral present (Figure 10). Problems with temperature calibration and procedure consistency prohibited precise determination of Tc, but Tc is probably slightly lower than that of pure magnetite. This is consistent with small amounts of titanium in the magnetite structure. All hysteresis loops were corrected for high field slope (response of non-ferromagnetic minerals) (Figure 11). Samples from the Kitsuns Creek Member and Rocher Deboule Formation plot on a modified Day Plot (Dunlop, 2002) near the single domain (SD) – multi-domain (MD) mixing line as 80-85% MD magnetite (Figure 12; Table 3). Most samples from the Rocky Ridge Volcanics plot in the multi-domain field. One site, 06KRR3, plots in the pseudo-single domain (PSD) field, but could be a mix of 90% MD and 10% SD

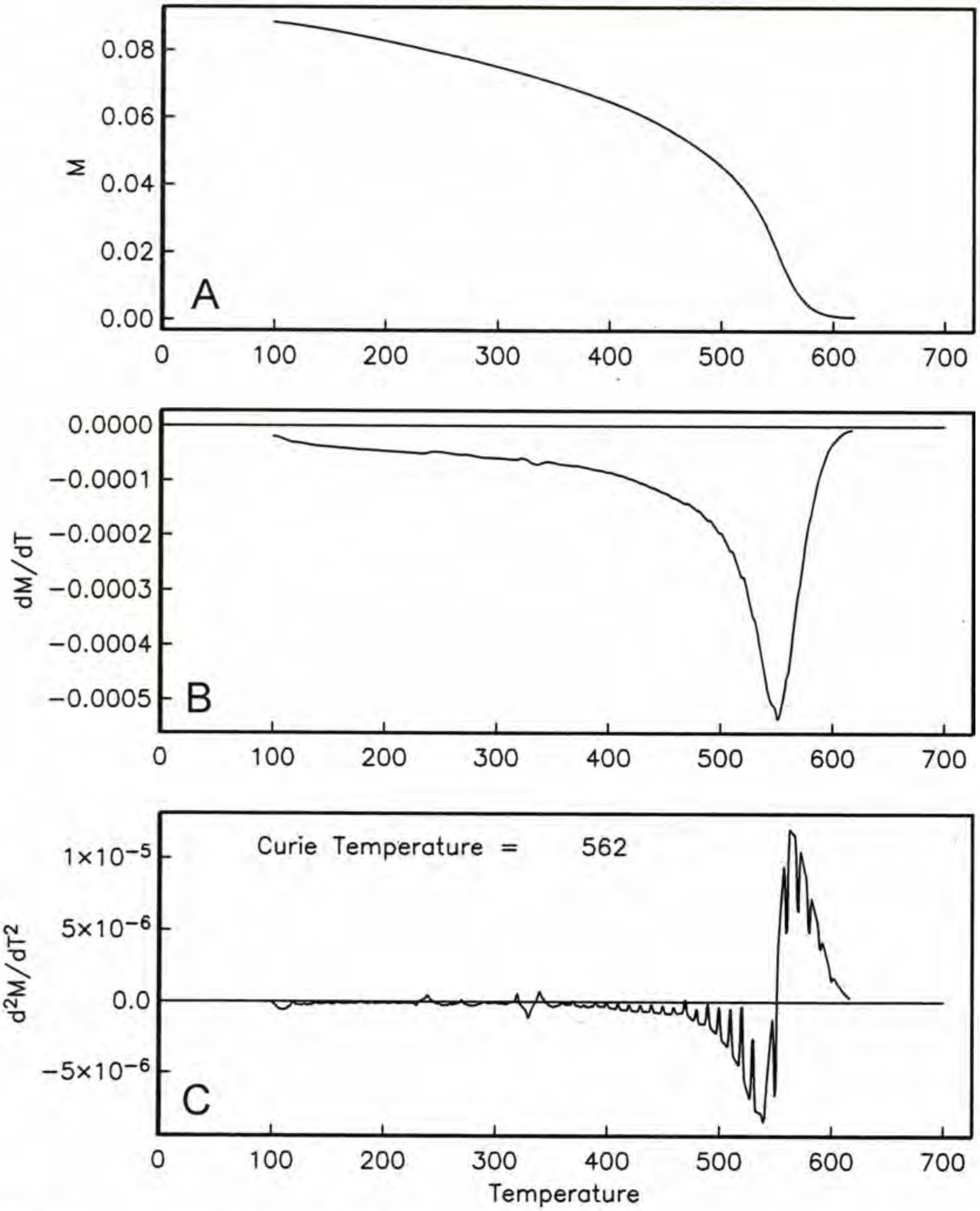



Figure 10: Decay of saturation moment with heating to determine the Curie temperature (Tc) for a sample of the Rocky Ridge Volcanics (06KRR2.2).

A) Saturation moment measured versus temperature.
B) & C) First and second derivative of intensity curve to determine inflection point (Tc) of curve A. Tc near 570 C indicates the presence of only magnetite.

This is a typical result for all samples from the Skeena Group.

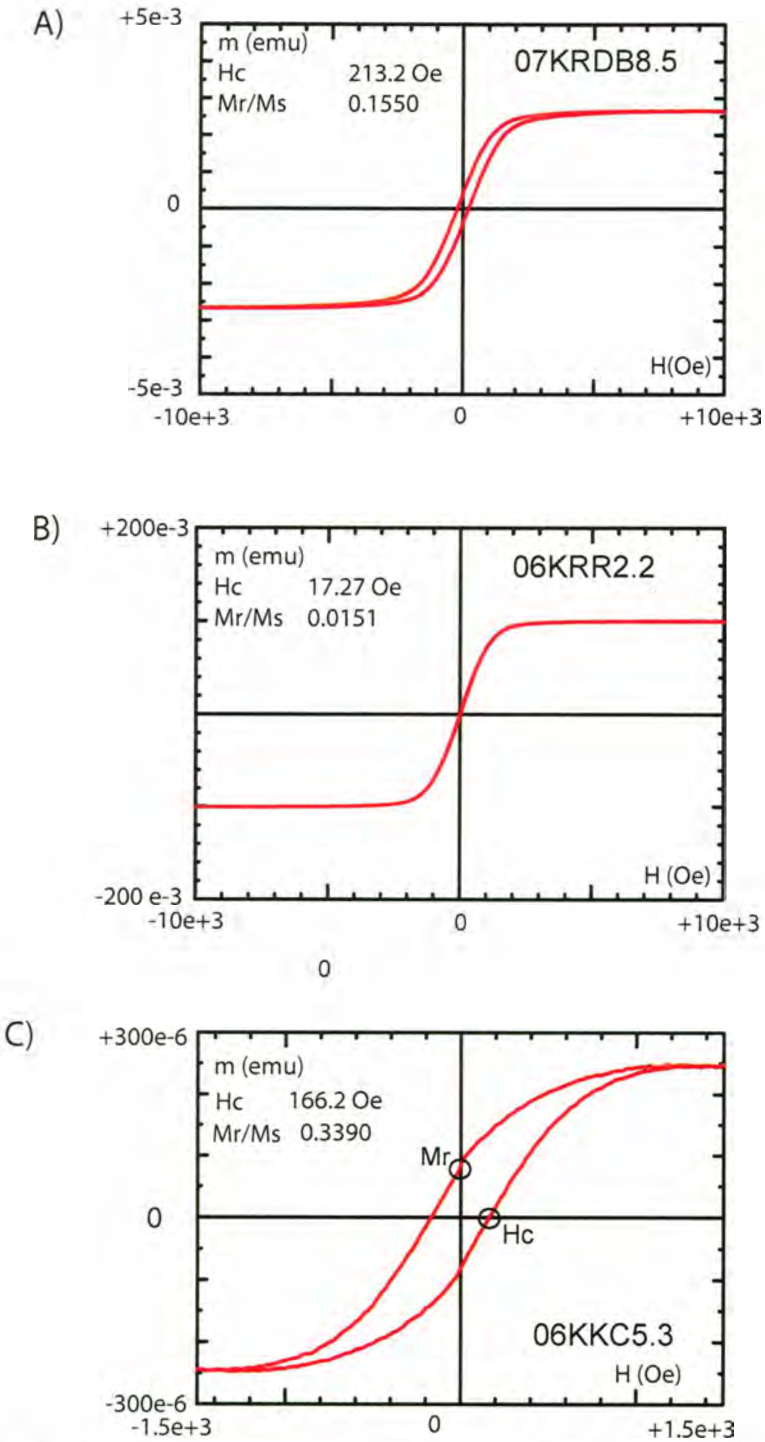



Figure 11: Hysteresis loops for samples from the Skeena Group.

a) Sandstone from the Rocher de Boule Formation

b) Andesite of Rocky Ridge Volcanics

c) Sandstone of Kitsuns Creek Member of the Bulkley Canyon Formation

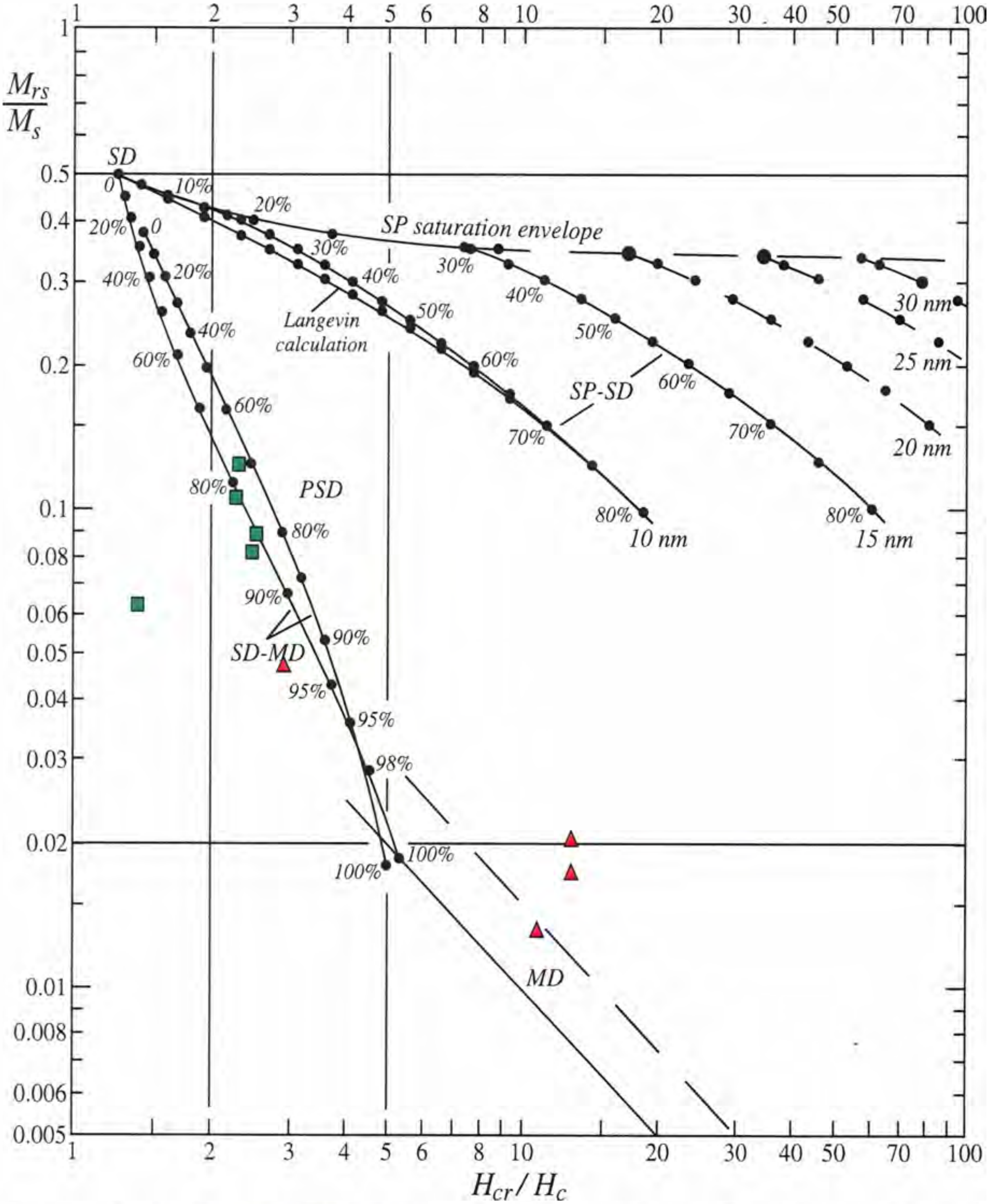



Figure 12: Modified Day Plot (Dunlop, 2002) for nine samples of the Skeena Group. The ratios of saturation remanence to saturation magnetization, Mrs/Ms, and remanent coercivity to ordinary coercivity, Hcr/Hc, are used to charcterize the magnetic domain state of magnetic grains.
MD = multi-domain, SD = single domain, SP = superparamagnetic,
PSD = psuedo-single domain

Table 3: Hysteresis loops results for the Skeena Group

| Sample | Ms (emu) | Hcr (Oe) | Hcr/Hc | Mrs/Ms |
|---|---|---|---|---|
| 06KKC3.10 | 3.25E-05 | 3.68E+02 | 2.50E+00 | 2.29E-01 |
| 06KKC4.4 | 2.00E-05 | 3.48E+02 | 2.55E+00 | 2.59E-01 |
| 06KKC5.3 | 8.50E-05 | 3.82E+02 | 2.30E+00 | 3.39E-01 |
| 06KKC6.7 | 1.74E-05 | 6.69E+02 | 2.32E+00 | 4.31E-01 |
| 06KKC7.8 | 2.34E-06 | 3.80E+02 | 4.14E+00 | 2.39E+00 |
| 06KRR1.3 | 1.98E-03 | 3.76E+02 | 1.30E+01 | 2.28E-02 |
| 06KRR1.8 | 4.64E-03 | 4.85E+02 | 1.30E+01 | 2.90E-02 |
| 06KRR2.2 | 1.52E-06 | 1.51E+04 | 8.73E+02 | 1.51E-02 |
| 06KRR3.7 | 1.02E-02 | 3.18E+02 | 2.93E+00 | 1.02E-01 |
| 07KRDB2.5 | 1.71E-04 | 2.96E+02 | 1.39E+00 | 1.55E-01 |

Ratios are unitless.

Ms = Saturation moment
Mrs = Saturation Remanence
Hc = Magnetic Coercivity
Hcr = Remanent Coercivity

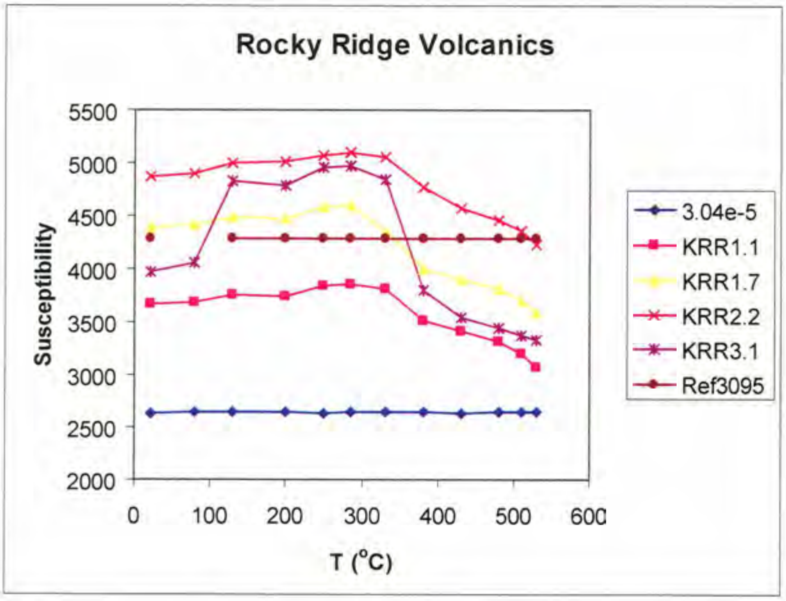
grains. This is probably a result of finer grain size, indicating a quicker cooling history than the other flows of Rocky Ridge Volcanics.

Using a Bartington Instruments MS-2 susceptibility meter, magnetic susceptibility of pilot samples was measured during thermal demagnetization to determine the stability of the magnetic carriers (Figure 13). Except for one sample (06KRR3), samples behaved according to lithology. After exposure to high temperatures, the susceptibilities of sedimentary samples increased where as the susceptibilities of the volcanic samples decreased. This is indicative of changes in the magnetite present; the larger grains in the volcanics breaking down, and smaller detrital magnetite or clay mineral grains of the sedimentary units oxidizing to increase bulk susceptibility. The result of this is an increase in noise in the natural remanence, making determination of any recorded components of the ancient geomagnetic field less precise.

Susceptibility was also compared to magnetic intensity of natural remnant magnetization (NRM) (Figure 14). The ratio of intensity to susceptibility times an applied field is the Koenigsberger ratio (Q) (Koenigsberger, 1938). Samples with extremely low or high Q values are of interest. Low Q values can indicate poor magnetic remanence and high Q values indicate possible lightning strike remagnetization (Hankard et al., 2005). Magnetic remanence acquired due to lightning strike currents have far higher intensity than remanence acquired in the Earth's ambient magnetic field.

## MEASURMENT AND ANALYSIS

Anisotropy of magnetic susceptibility (AMS) was measured on an Agico KLY-3 Kappabridge. The natural remnant magnetization (NRM) of each specimen was measured



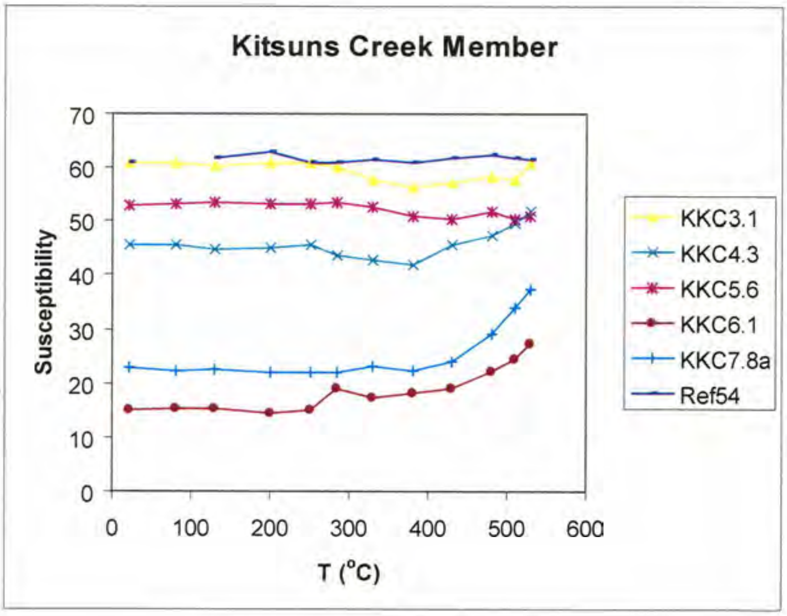
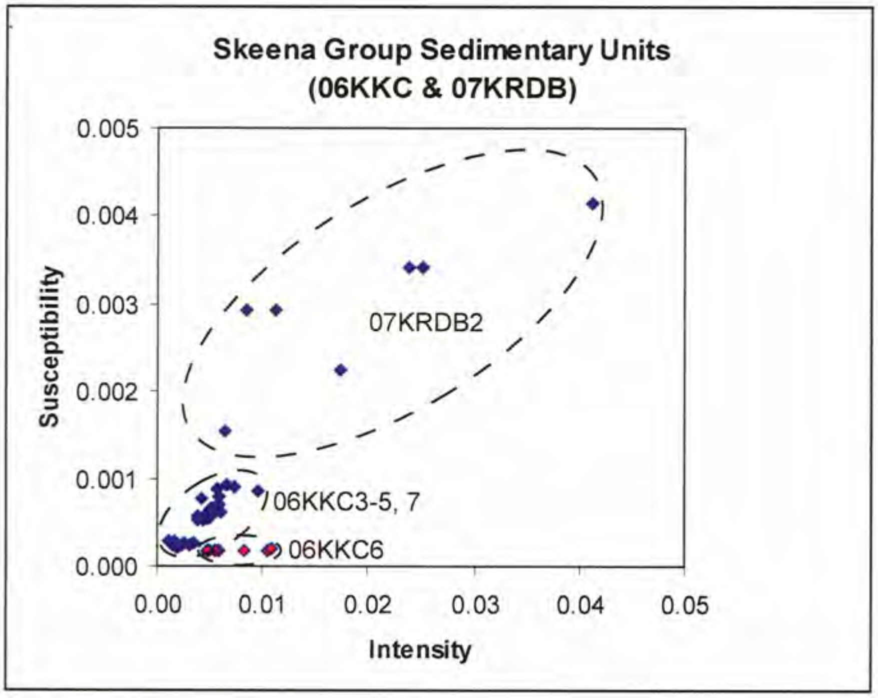




Figure 13: Susceptibility versus temperature for pilot samples of the Skeena Group. The level lines for repeat measurements of standards Ref54, Ref3095 and 3.04e-5 verify that changes in specimens are well outside of measurement error.



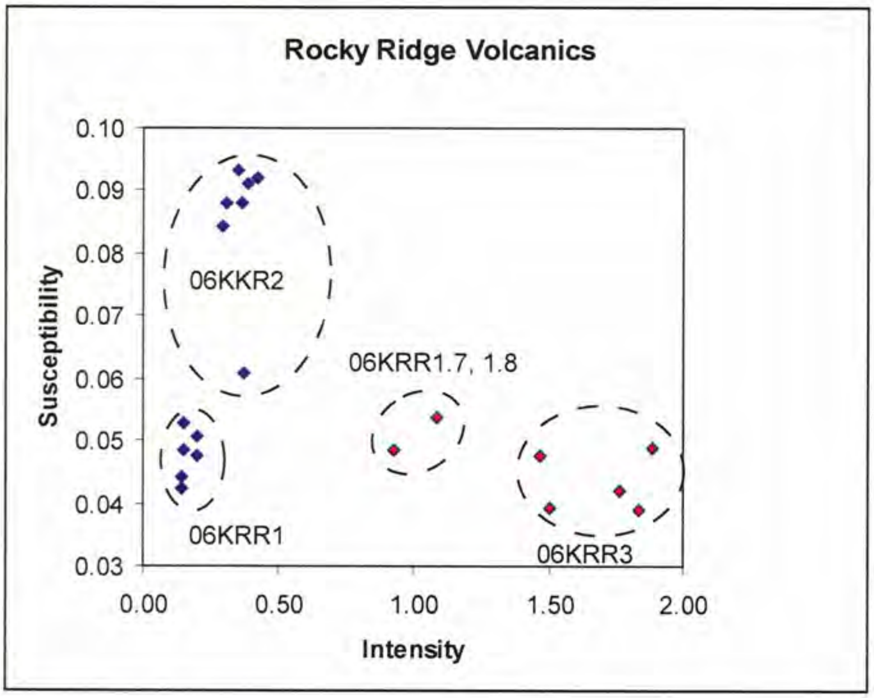




Figure 14: Susceptibility versus intensity for samples from the Skeena Group. Samples with high intensity and low suscpetibility possess errant directions, which are interpreted to be lightning remagnetizations.

using a 2-G Enterprises Model 755 cryogenic magnetometer in a magnetically shielded room with a 350 nT internal field. All nine sites have well-determined and coherent NRM directions. Susceptibility measurements from the KLY-3 and NRM intensity were combined to calculate Koenigsberger ratios (Q) (Koenigsberger, 1938). All samples were treated at least once with liquid nitrogen to cool them to 77K, allowing multi-domain (MD) magnetite grains to lose their soft MD magnetization during the Verwey transition (Verwey, 1939), cleaning up the magnetic signal (Dunlop and Argyle, 1997).

Pilot samples were thermally demagnetized in 15° to 50° C steps from 80° C to 600° C using an ASC Model TD-48 thermal demagnetizing oven (Figures 15, 16, and 17). Samples were oriented differently in the oven at each successive temperature step to eliminate possible magnetic bias introduced by the oven. Results were evaluated using orthogonal plots (Zijderveld, 1967), equal area plots of directions, and relative intensity plots. The remaining samples were then demagnetized using temperature steps selected to adequately quantify the direction of each magnetic component. Magnetic susceptibility was measured with a Bartington MS-2 susceptibility meter between heating steps to monitor changes to magnetic minerals. Directions of components were determined by principal component analysis (Kirschvink, 1980). The components were identified as linear trends of the demagnetization paths. Lines fit to just the measurements along these linear segments are termed free lines. The last-removed component defined by a path that appeared to go to the plot origin was fit with a line through the origin, called an anchored line, as well as a free line. Rough assessment of the quality of the lines is given by their Maximum Angular Deviation (MAD). Comparable components from all samples from each site were combined using the method of Fisher (1953) to calculate site means and statistics.

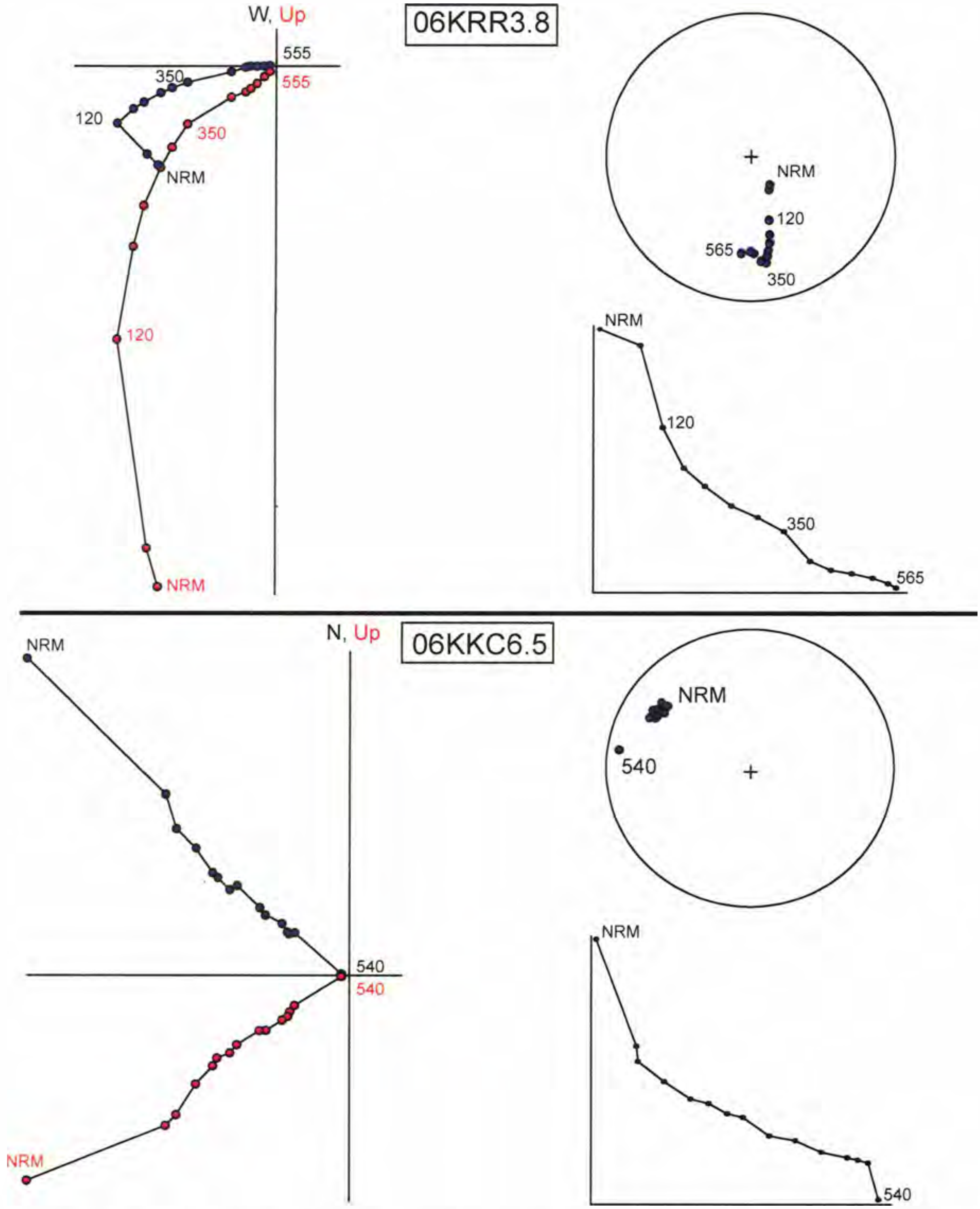



Figure 15: (Clockwise from left) Orthogonal vector, equal area and relative intensity plots for stepwise thermal demagnetization of samples 06KRR3.8 and 06KKC6.5. Black text - horizontal component, Red - vertical component.
Units in Celcius.

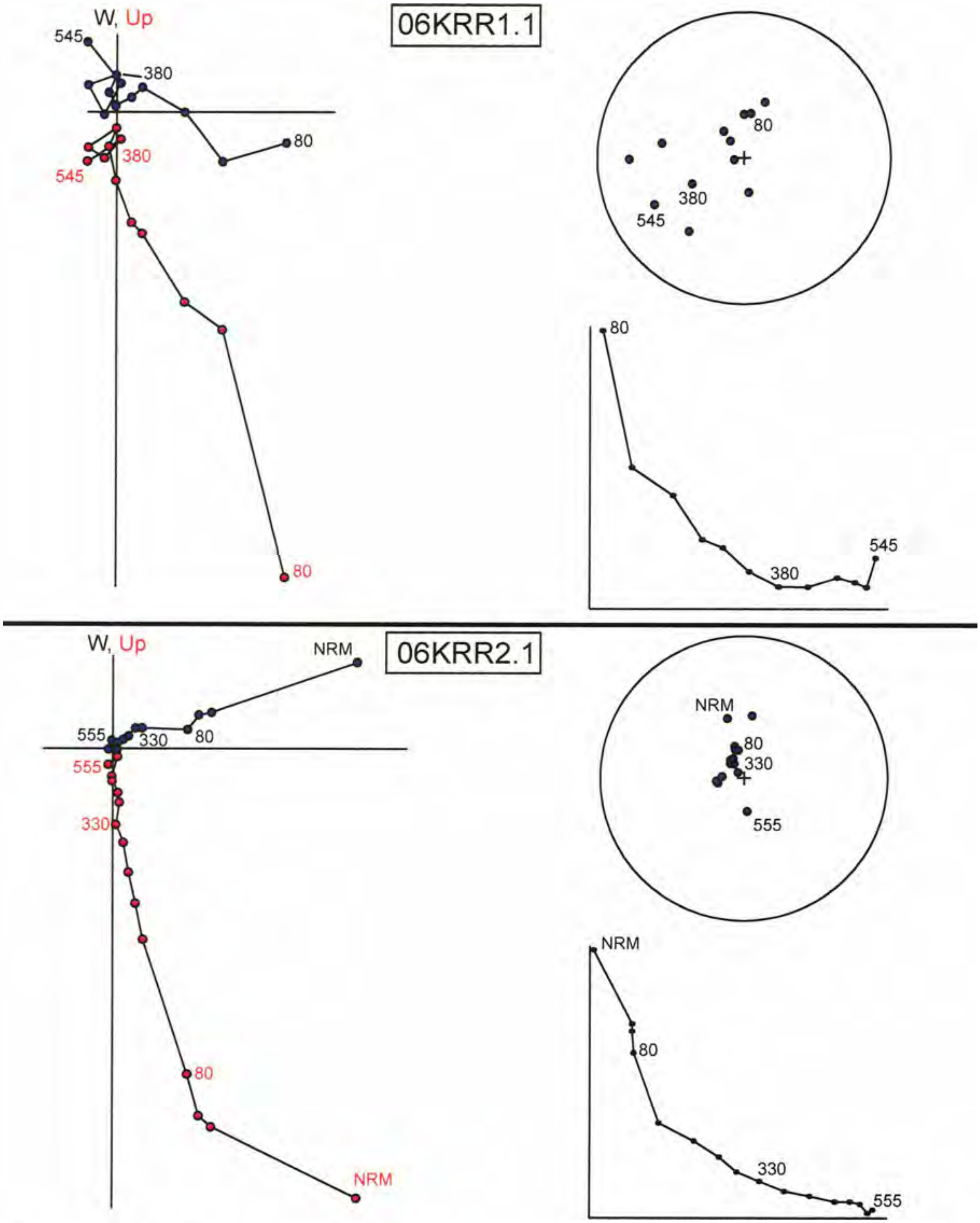



Figure 16: (Clockwise from left) Orthogonal vector, equal area and relative intensity plots for stepwise thermal demagnetization of samples 06KRR1.1 and 06KRR2.1. Samples have a poorly defined last-removed (high-temperature) component. Blue text - horizontal component, Red - vertical component. Units in Celcius.

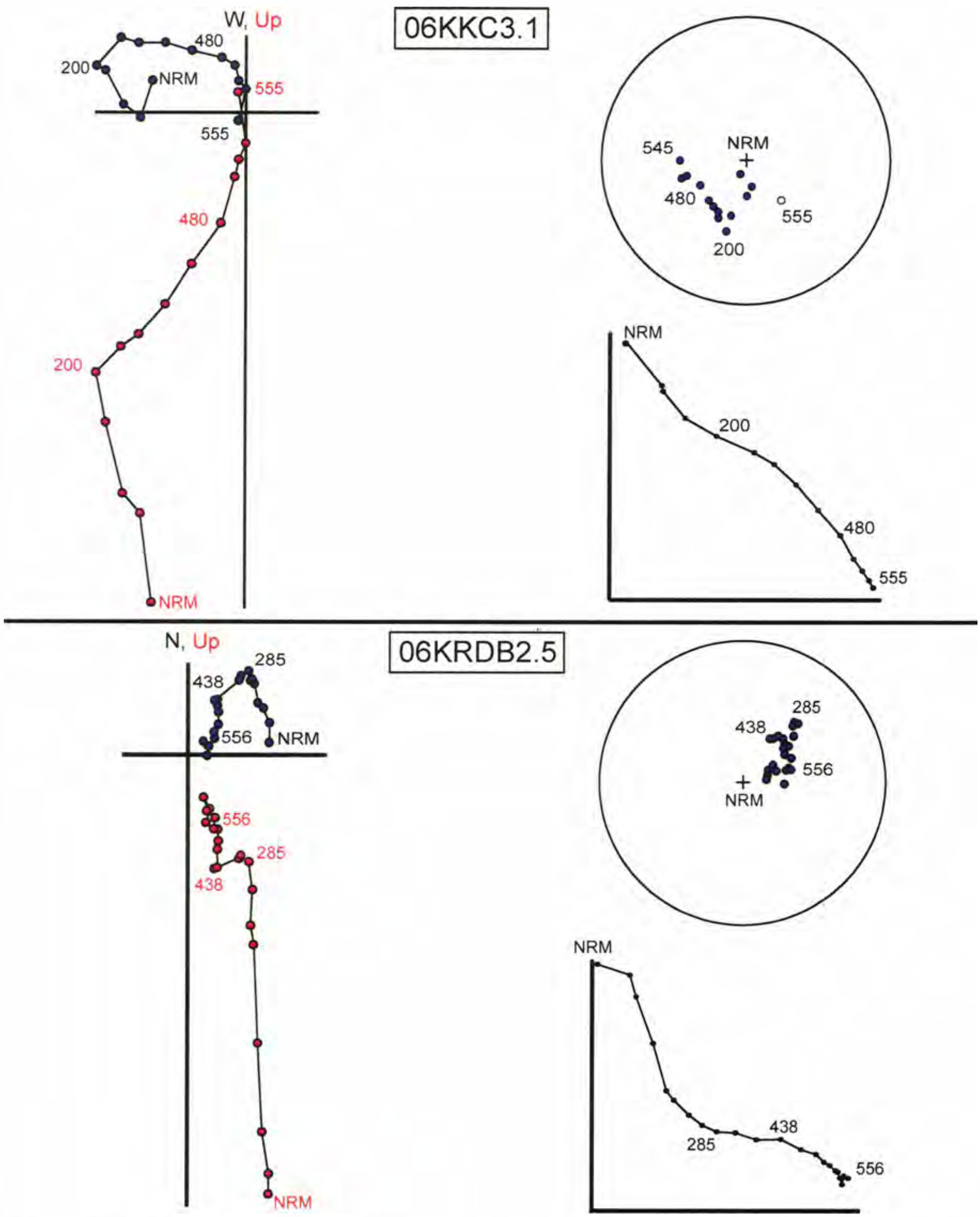



Figure 17: (Clockwise from left) Orthogonal vector, equal area and relative intensity plots for stepwise thermal demagnetization of samples 06KKC3.1 and 07KRDB2.5. Samples have a well defined first and last removed components (low- and high-temperature). Black text - horizontal component, Red - vertical component. Units in Celcius.

RESULTS

Of the nine sites, two had last-removed (highest temperature) components with significantly different declinations and inclinations than the other sites (Figure 15). Site 06KKC6 has a single component that trends to the origin of an orthogonal plot (in-situ Fisher mean: D = 324.4°, I =24.9°) and site 06KRR3 has an errant high-temperature component (mean: D = 166.6°, I = 28.8°). Combined with high Koenigsberger ratios (Q) (Koenigsberger, 1938) (Figure 14), this leads to the conclusion that these sites (and samples 06KRR1.7 and 1.8) have been remagnetized by lightning strikes (Hankard, et al. 2005).

The remaining seven sites have low- and high-temperature components (Figures 18 and 19; Table 2). The low-temperature component reaches unblocking temperatures around 200-300° C with the sedimentary sites (06KKC) unblocking at lower temperatures than the Rocky Ridge and Rocher de Boule sites. The sedimentary sites (06KKC and 07KRDB) also have a poorly defined intermediate temperature component (Figure 18; Table 2), which appears to contain little useable information.

The high-temperature component (380°-550° C) represents the presumed last-removed component of magnetization. By approximately 550° C, remanence in each sample was either too weak or too noisy to continue demagnetizing. Free and anchored line fits were made for each sample (Figure 19). For most sites, the free and anchored fits are similar, with the anchored lines having lower MAD values. The two Rocky Ridge sites (06KRR1 and 06KRR2) have different directions from the sedimentary sites from "Sc" ridge, which is unexpected on samples from the same tectonic block. Given the generally poor definition of the last component (Figure 17) and unusually low tilt corrected inclinations (Table 2), these sites have been excluded from further consideration. It is important to note that the directions

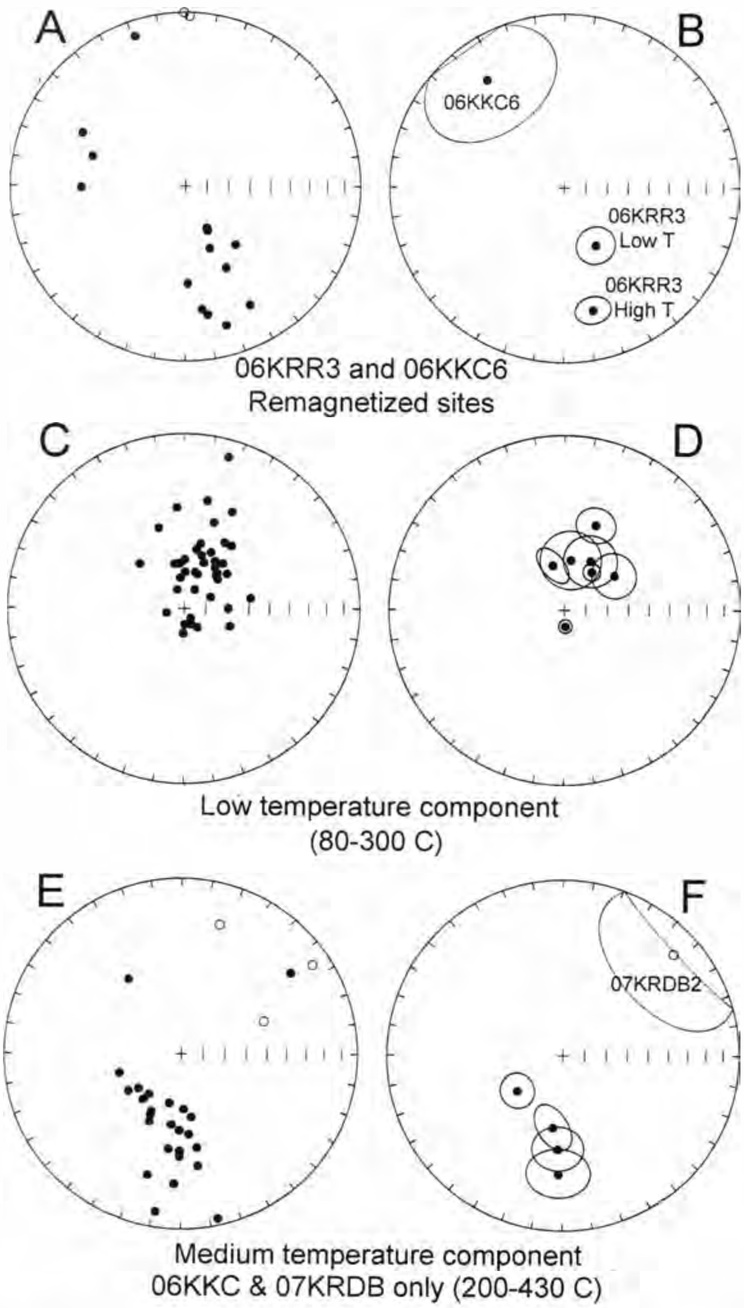



Figure 18: Equal area stereoplots of Principal Component Analysis free fits for remagnetized sites (A and B), low temperature components (C and D), and medium temperature components (E and F) for sample sites from the Skeena Group.

A, C, and E are in-situ (geographic) directions from individual samples.
B, D, and F are site mean directions and $\alpha_{95}$ envelopes of confidence.

Solid circle = Lower hemisphere (positive polarity), Open circle = Upper hemisphere.

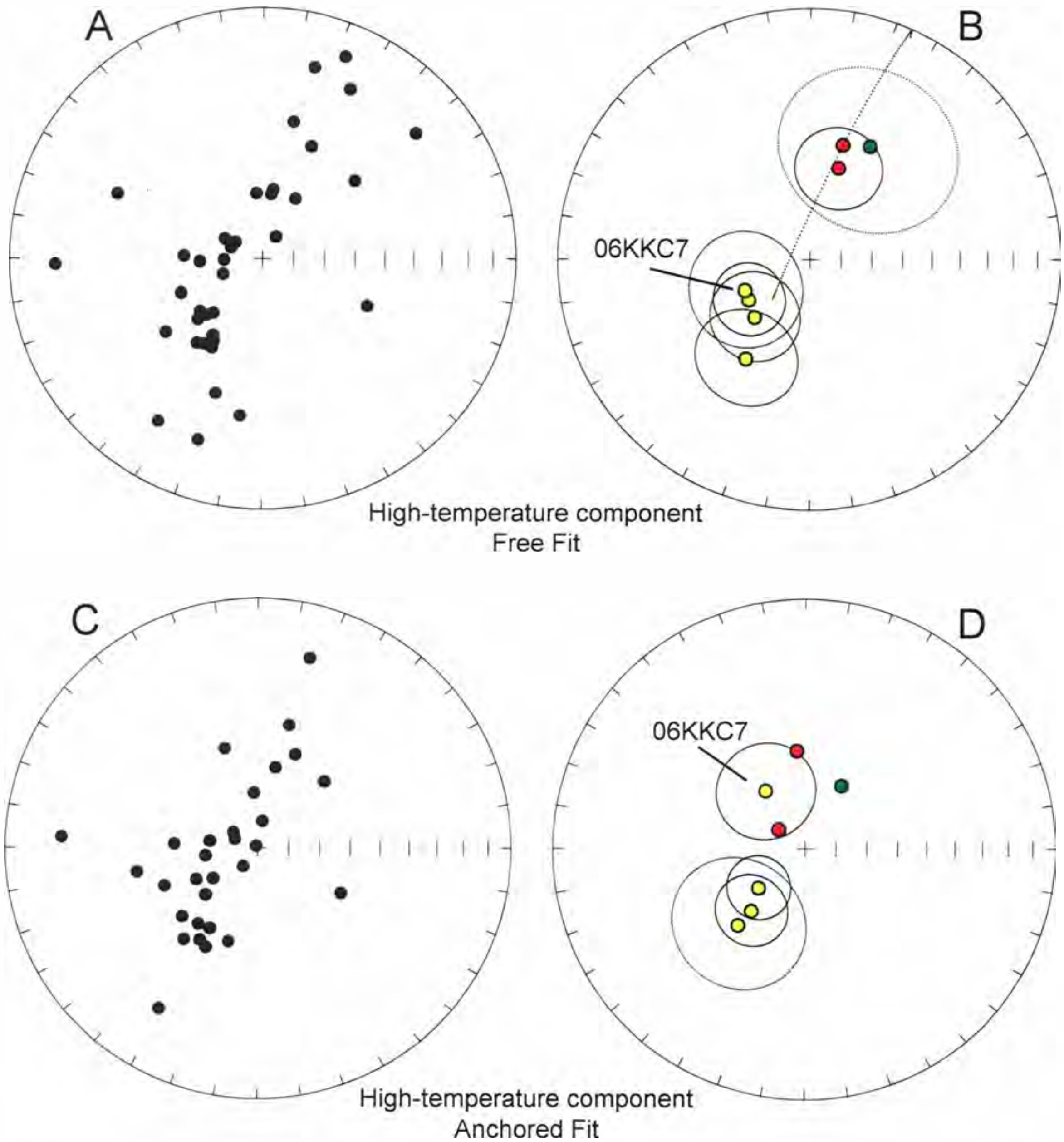



Figure 19: Equal area stereoplots of Principal Component Analysis free fits (A and B) and anchored fits (C and D) of the last-removed (high-temperature) component (380-550 C) for sites from the Skeena Group. Note differing anchored fit direction for 06KKC7.

Plots A and C are in-situ (geographic) directions from individual samples.
Plots B and D are site mean directions and $\alpha_{95}$ envelopes of confidence.

06KKC - yellow, 06KRR - red, 07KRDB - green
Solid circle = Lower hemisphere (positive polarity)

are not unreasonably inconsistent due to the problems of polar secular variation (PSV). As volcanic units average PSV over a shorter time period than sedimentary units, the difference in directions could be an effect of magnetic polar wander.

Because the anchored line fits have lower MADs, they were preferred in subsequent analysis. The one exception was 06KKC7 as the free line fit had a slightly lower MAD, but with a significantly different direction, neither could be preferred. The anchored line fit directions were tilt-corrected to see if dispersion would decrease as the sites were restored to paleohorizontal. Using the Fisher precision parameter $k$ as inverse of dispersion, if $k$ is highest at 100% untilting, then this is clear evidence that the remanence predates relative reorientation of the strata, and possibly was acquired early during lithification or cooling. Since there is a low number of sites, and little attitudinal diversity, the fold test was inconclusive (Figure 20). The minimum scatter is at approximately 40% untilting. However, since 100% untilting is within 95% confidence ($\alpha_{95}$), the hypothesis that the high temperature component is primary cannot be rejected. Other possible reasons for the intermediate peak in clustering includes between-site rotations and compound structures such as plunging folds, which cannot be ruled out due to the lack of good geologic mapping in the region.

INTERPRETATION

The first-removed (low-temperature) component would be expected to possess an observed present day geomagnetic field inclination of 73.4°. The in-situ Fisher mean has a lower than expected inclination of 68.8° ± 12.9° for the sample sites, but this is well within $\alpha_{95}$ confidence. Therefore, it is reasonable to describe the low-temperature component as a modern day magnetic field overprint.

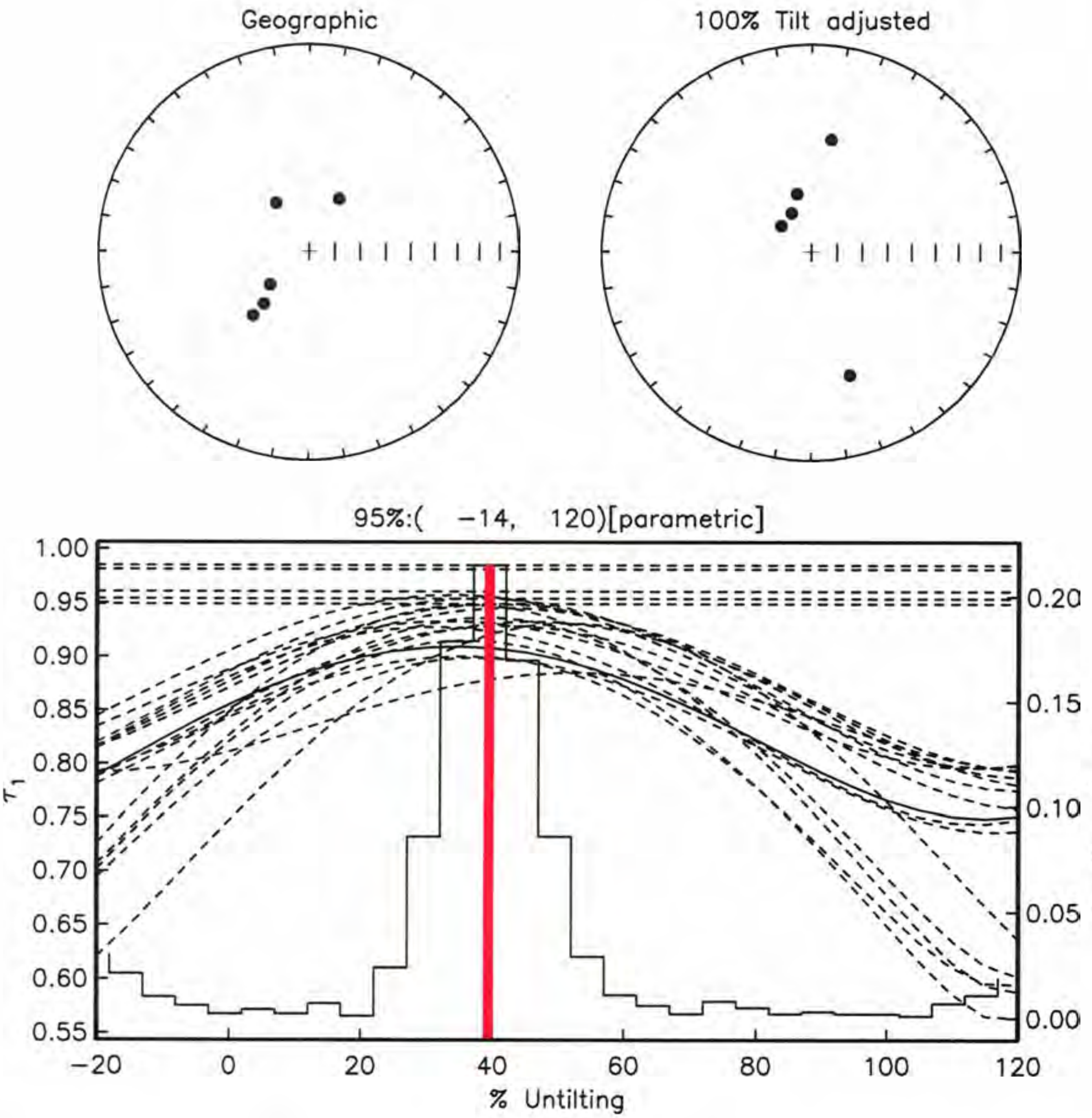



Figure 20: Parametric bootstrap fold test (Tauxe, 2002) of the sedimentary units of the Skeena Group (06KKC3 - 5, 06KKC7, and 07KRDB2). Volcanic units (06KRR1 and 2) were omitted.

Minimum scatter is at ~40% untilting but is not distinguishable from either 0% or 100% untilting within 95% confidence.

As sites from 2006 and 2007 are found on different tectonic blocks (Figure 8), it is appropriate to estimate the mean inclination and statistics using the inclinations only (McFadden and Reid, 1982) to calculate the overall inclination of the Skeena Group. The Rocher de Boule sample site, 07KRDB2, presents some challenges in this method of interpretation. While most tectonic blocks in the region, including the "Sc" ridge block, are tilted to the north, 07KRDB2 is tilted nearly vertical to the south. Two hypotheses for this discrepancy are large amounts of block rotation (up to 180 degrees!) or structural complexities yet unmapped. Field observations and the descriptions of Bassett (1995) do not suggest a structural answer for this problem. Tilt correction of the anchored line fit for 07KRDB2 block indicates that block rotation probably occurred before tilting, however, the relatively shallower inclination of 07KRDB2 may indicate some tilting occurred before block rotation. This reduces reliability of interpreting this site as it is impossible to assess the relationship between directions at this site, and the other sites, without uncertainty about the influence of block rotation.

With the uncertainties in the preferred data, the results of inclination-only analysis were varied (Table 4). The Gaussian mean inclination is a straight average of the inclination, assuming the declination for each site is zero. The Fisher mean inclination presumes a range of declination that would correspond to the observed range in inclination for a Fisher distribution. Therefore, the Fisher mean inclination is a more realistic calculation for the overall inclination of the Skeena Group.

## Table 4. Paleolatitude analysis of the Skeena Group

| Sites | Gaussian mean Inclination | Fisher mean Inclination | N | R | k | $\alpha_{95}$ | Paleolatitude (λ) | Error (degrees) | Displacement (km) |
|---|---|---|---|---|---|---|---|---|---|
| 06KKC3-5, 06KRDB2, 06KKC7 (Anchored) | 59.4 | 64.0 | 5 | 4.6 | 10.8 | 19 | 45.7 | 30.5 | 2300 |
| 06KKC3-5, 06KRDB2, 06KKC7 (Free) | 65.3 | 71.3 | 5 | 4.7 | 12.0 | 18 | 55.9 | 32.7 | 1200 |

| Sites | Fisher mean Declination | Fisher mean Inclination | N | R | k | $\alpha_{95}$ | Paleolatitude (λ) | Error (degrees) | Displacement (km) |
|---|---|---|---|---|---|---|---|---|---|
| 06KKC 3-5 and 7 (Free) | 340.2 | 73.0 | 4 | 3.97 | 107.7 | 6.75 | 58.5 | 11.6 | 900 |

| North American Pole | Pole Latitude | Pole Longitude | $\alpha_{95}$ | Age | Source |
|---|---|---|---|---|---|
| Housen et al., 2003 | 70.1 | 191.2 | 2.7 | 125-85 Ma | Various North American Sites |
| Dickinson and Butler, 1998 | 81.6 | 201.5 | 5.4 | 84-66 Ma | Elkhorn and Adel Mountains |

Results of paleolatitude analysis of the Skeena Group and North American paleopoles used in analysis.These poles are prefered as they only include North American sample sites, increasing paleopole accuracy.

Using the equation

$$\tan I = 2 \tan \lambda$$

where I is the inclination and λ is the latitude, the paleolatitude for the Skeena Group, including 07KRDB2, is 55.9° ± 32.7°. Without 07KRDB2, the paleolatitude is 58.5° ± 11.6°. Comparing these with an appropriate North American pole for the late Cretaceous (Housen et al., 2003), the Skeena Group formed either 1200 ± 3000 or 900 ± 1000 km south of its expected latitude with respect to North America at ~95 Ma. These distances are within error of each other; however, it is important to note that since the number of sites (n) is small, the error is inherently large.

# DETRITAL ZIRCON GEOCHRONOLOGY

U-Pb detrital zircon geochronology can provide insight into the development and provenance of sedimentary basins. For detrital zircon geochronology, the use of laser ablation inductively coupled plasma – mass spectrometry (LA ICP-MS) is ideal as it requires only few kilograms of sample material and allows quick sample preparation and analysis (Chang et al., 2006). Using this technique, the large number of single grain detrital zircon ages necessary (n = 117; Vermeesch, 2004) to statistically characterize the provenance of sedimentary units and their regional context is far less daunting (and less expensive) than using other U-Pb dating methods.

One sample from the Rocher Deboule Formation, the uppermost unit of the Skeena Group, was analyzed in late 2007. The results are used to characterize the sedimentary sources for the Skeena Group in the late Cretaceous and to discuss the implications of these sources on the paleogeographic provenance of Stikinia.

## MEASUREMENT AND ANALYSIS

### *Sampling*

One detrital zircon sample (07KRDB1) of medium- to fine-grained sublithic arenite from the Rocher Deboule Formation was collected in August of 2007 from a ridge designated in Bassett (1995) as "Hf" (Figure 8). The upper-most unit of the Skeena Group was chosen to characterize incoming sediment shed from inboard terranes, and, potentially, the continent, into the fluvial-marginal deposits of the Skeena Group. Pollen assemblages from this section (Bassett, 1995) indicate a Late Albian to Early Cenomanian age. This age is sensible as the

Rocher Deboule Formation conformably overlies the older Rocky Ridge Volcanics. Two hornblende-rich samples from the "Sc" ridge (Figure 8) have $^{40}Ar/^{39}Ar$ ages of 95.1 ± 1.6 and 94.9 Ma ± 0.6 Ma (Bassett, 1995; Sample 06KRH01).

*Analytical Procedure*

Sample preparation at the Mineral Separation Lab at the University of Idaho in October 2007 followed procedures from Chang et al. (2006). This included precautions to assure clean conditions to prevent contamination from stray detrital zircon grains. Fist sized (0.5-1.0 kg) samples were crushed first in a jaw crusher, then a disc mill. A Gemini water table removed light minerals and fine grains. Free fall and tilted Frantz Isodynamic magnetic separation removed magnetic minerals. Heavy liquid separation using Methylene Iodide (MEI) then isolated zircon grains from the remaining concentrate. From 6-8 kg of material, over 300 zircon grains with a typical size of 30-100 μm were extracted. To eliminate potential bias, no differentiation based on grain physical properties was made.

The detrital grains were mounted along with control zircons (Peixe, age=1099 Ma and FC1, age=564 Ma; Chang et al., 2006) at Washington State University, encased in a "puck" of epoxy, and then polished to expose the grains at their mean half thickness. The mounted grains were carbon coated, then imaged with an AMRAY 1830 Scanning Electron Microscope using scanning electron microscopy-cathodoluminescence (CL-SEM) at the Materials Characterization Laboratory at the University of Idaho to determine the grains' internal structures. All grains showed zoning, and few showed inherited cores (Figure 21).

From the sample, 140 zircon grains were analyzed at the Geoanalytical Laboratory at Washington State University using a Finnigan Element2 HR-ICP-MS (High Resolution-

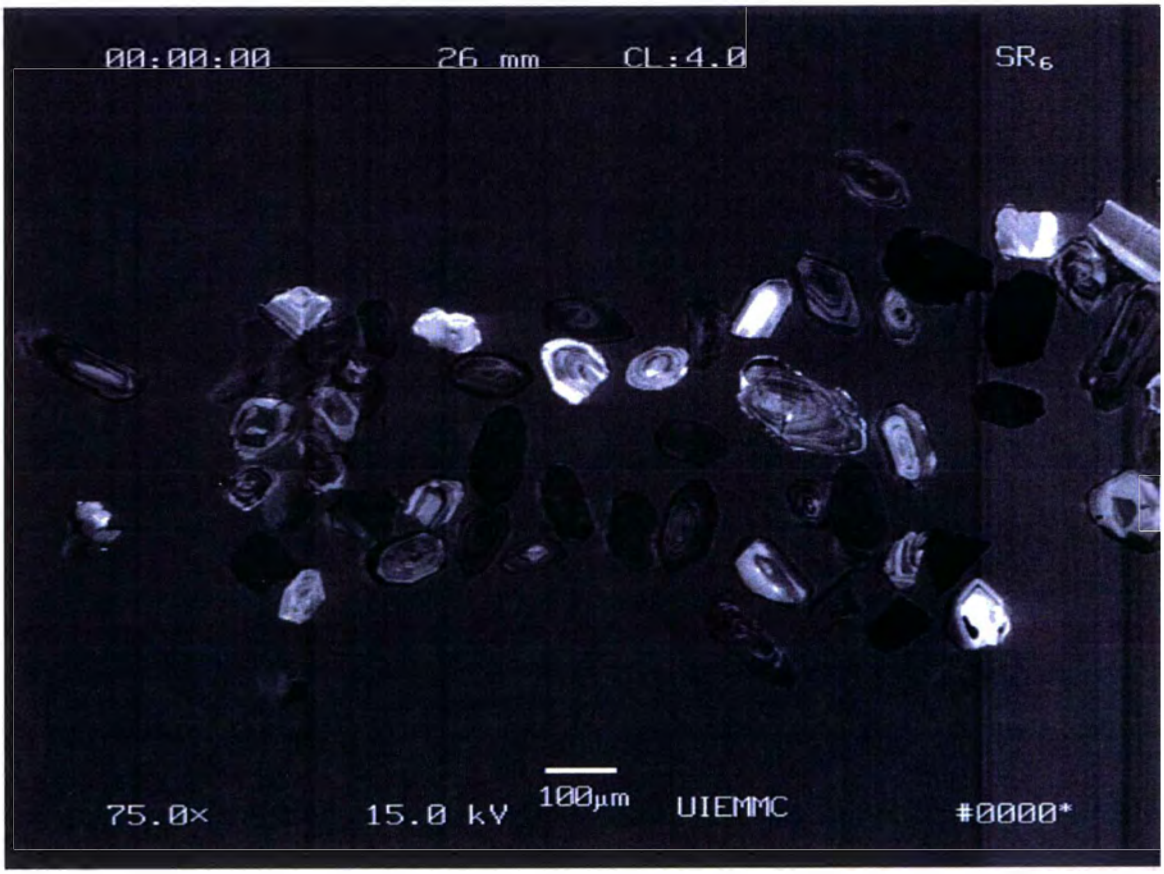



Figure 21: Scaning electron microscope cathodoluminescence (CL-SEM) image of detrital zircon grains from 07KRDB1. Most grains have clear zoning, euhedral to rounded/broken grain shape, and are ~50-100 µm long.

Inductively Coupled Plasma-Mass Spectrometer) combined with a New Wave UP-213 laser ablation (LA) system. Each grain was ablated using a 213 nm laser with a 30 μm spot for 35 seconds. Results for all grains were calibrated to the two control zircons FC1 and Peixe, which were analyzed multiple times after every fifth analysis of an unknown zircon grain. Results using both control zircons were similar; hence the data presented are based on the use of the Peixe control zircon. Each analysis was taken near the rim of the grain to avoid sampling an inherited core.

*Discordance*

Of 140 analyzed zircon grains, 16 were immediately rejected as having poor analyses due to the choice of location of the ablation spot or grain composition. The remaining 124 grains were then assessed for discordance from their "Concordia" ages (Ludwig, 1998). Ninety two grains were determined to be either concordant within an error of 2σ or within 30% of concordance on a Concordia plot (Figure 22). Thirty two grains failed the discordance test. However, it is not believed this is evidence of lead loss as many points are "pulled up" the Concordia diagram. Lead loss is usually indicated by lower than expected concordant values. Unless there has been a large amount of lead loss, the reasonable hypothesis is that common lead contamination is a likely cause for this shift. Also, the young ages of the grains means a small amount of contamination can create the appearance of considerable $^{207}Pb/^{206}Pb$ age discordance.

Using the methods of DeGraaff-Surpless et al. (2004), possible modern common lead contamination was assessed. This employs a mixing line on a Tera-Wasserburg diagram (Tera and Wasserburg, 1972) from a modern $^{207}Pb/^{206}Pb$ ratio of 0.86 for common lead

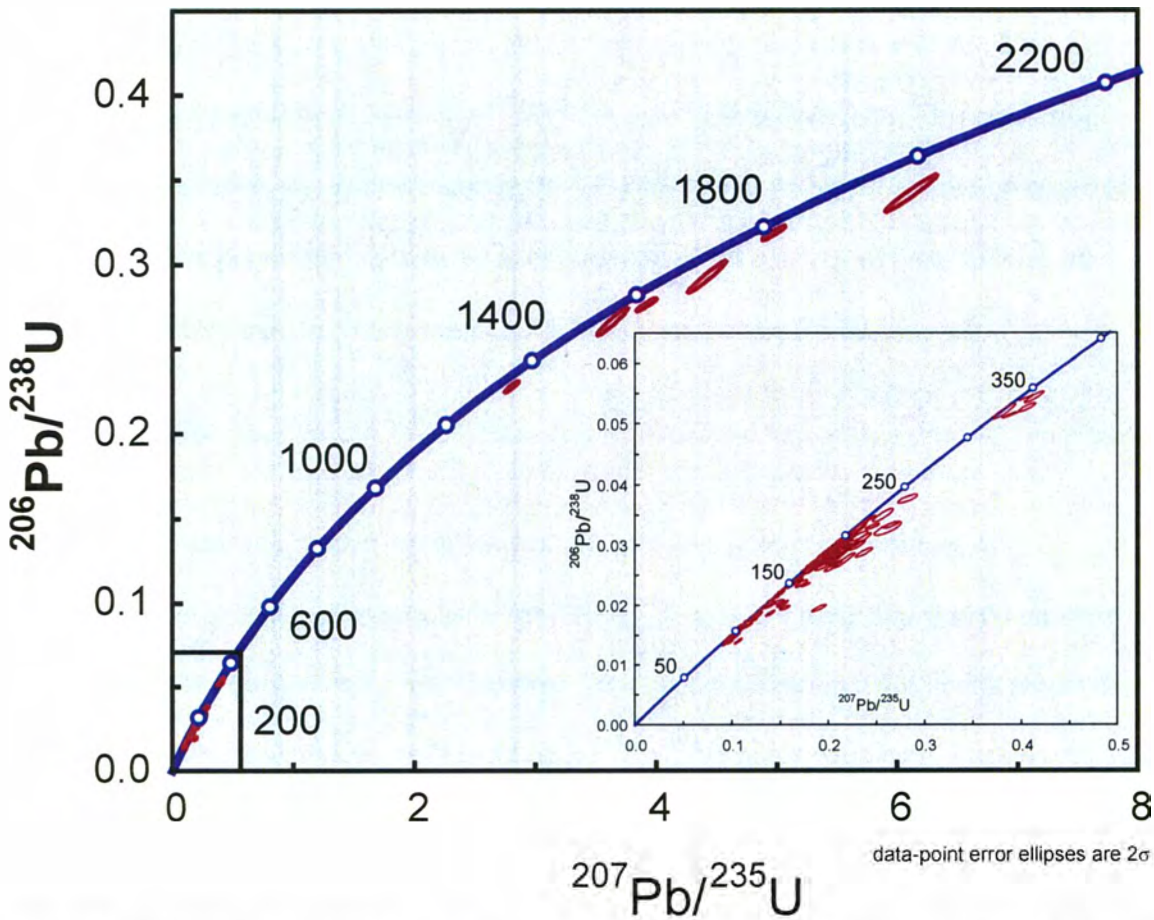



Figure 22: Concordia Plot of $^{206}Pb/^{238}U$ ratios versus $^{207}Pb/^{235}U$ ratios for 124 detrital zircon grains for sample 07KRDB1. Mesozoic grains (inset; n = 118) have elevated $^{207}Pb/^{206}Pb$ ratios, indicating common lead contamination.

Plot generated using Isoplot 3.0 (Ludwig, 2003)

(Cumming and Richards, 1975) to the age-corrected value on Concordia for each grain (Figure 23). Using this mixing line, all grains passed a level of 5% discordance at an error of $2\sigma$. Using a Tera-Wasserberg concordia diagram to plot the ratios of $^{207}Pb/^{206}Pb$ versus $^{238}U/^{206}Pb$ of individual discordant grains, the ages for these grains can be corrected by linearly regressing points back down the $^{207}Pb/^{206}Pb$ mixing line from 0.86. This correction changes the uncorrected age values minutely (0.1-0.2 Ma), well within all initial age errors of $2\sigma$. Therefore, it is proposed that these ages be accepted in the analysis of data. In total, all 124 unknown grains analyzed from sample 07KRDB1 were accepted for analysis.

*Statistical Analysis*

Small amounts of modern common lead can produce a large discordance of $^{207}Pb/^{206}Pb$ values in young detrital grains, the $^{206}Pb/^{238}U$ ratio is a more appropriate measure of age in all grains younger than 1 Ga. Common lead contamination in older grains produces less discordance, and therefore ages derived from $^{207}Pb/^{206}Pb$ ratios were used. Data were processed using Isoplot 3.0 (Ludwig, 2003) and all accepted grains were plotted on relative age probability diagram using a histogram bin width of 5 Ma (Figure 24). Using the Gaussian unmixing function in Isoplot (based on Sambridge and Compston, 1994) as a guide, rough mean ages for the main peaks were established (Table 5).

## RESULTS

The detrital zircon age distribution for the Rocher Deboule Formation is marked by six distinct peaks: two main peaks at ~100 and ~180 Ma, side peaks at ~140 Ma and ~215

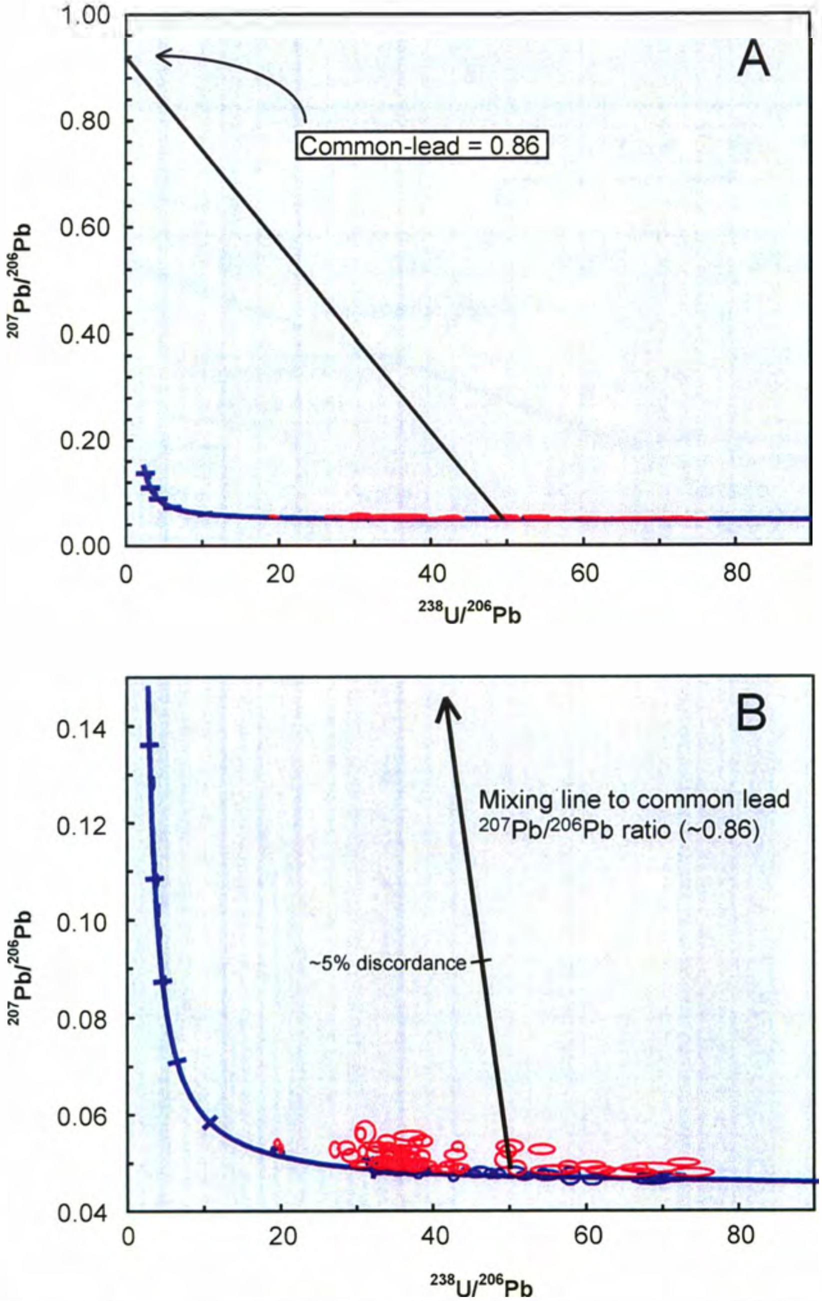



Figure 23: Tera-Wasserburg diagrams (Tera and Wasserburg, 1972) for $^{207}Pb/^{206}Pb$ ratios for 124 detrital zircon grains from sample 07KRDB1. Blue ellipses are concordant grains; red are discordant grains.

(A) Discordance of grains is estimated by using a mixing line from Concordia to a common lead $^{207}Pb/^{206}Pb$ ratio of 0.86 (Cummings and Richards, 1975).

(B) Using the 0.86 mixing line as a reference, all grains are less than 5% discordant from the Tera-Wasserburg Concordia due to modern common lead contamination. Method from Degraaf-Surpless et al., 2003. Plots generated by Isoplot 3.0 (Ludwig, 2003).

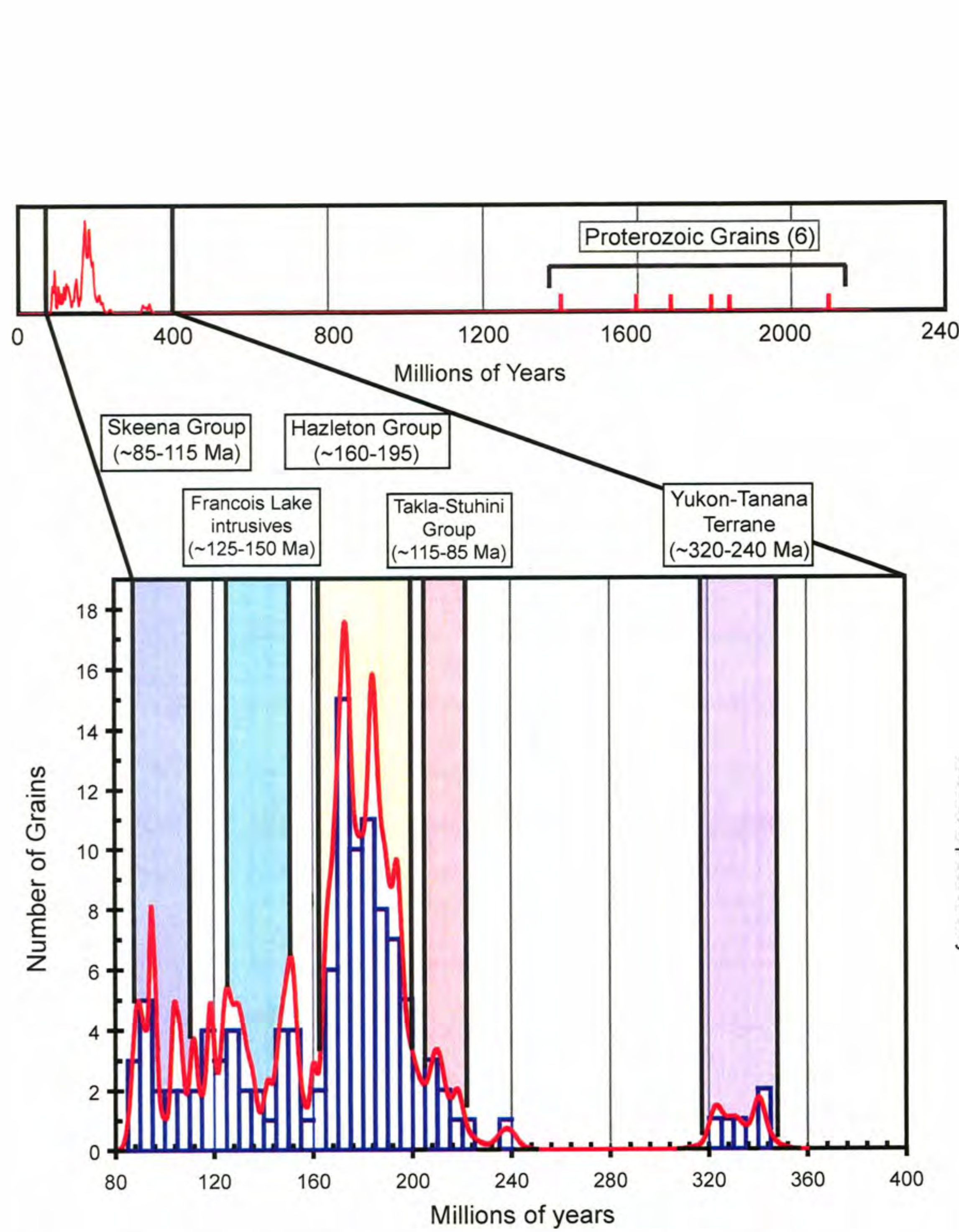



Figure 24: Relative probability plot of U-Pb ages for 124 detrital zircon grains from sample 07KRDB1. Histogram bins of 5 Ma.

Generated using Isoplot 3.0 (Ludwig, 2003).

Table 5. Detrital zircon peak ages

| Age (Ma) | 2σ error | Fraction | 2σ error |
|---|---|---|---|
| 100.94 | 0.66 | 0.17 | 0.08 |
| 141.84 | 0.79 | 0.19 | 0.08 |
| 180.06 | 0.65 | 0.52 | 0.13 |
| 214.5 | 2.5 | 0.08 | 0.05 |
| 332.6 | 2.8 | 0.04 | -- |

Peak age results of the Unmix Ages function in Isoplot 3.0 (Ludwig, 2003). Algorithm of Sambridge and Compston, 1994.

Ma, a small Mississippian peak, and several middle- to early-Proterozoic-aged grains. No Archean-aged grains were found during this analysis.

The mid-Cretaceous peak at ~100 Ma sets the upper bound on the age of the Rocher Deboule Formation, with the youngest grain at 87.3 ± 2.2 Ma (07KRDB1_53). This conforms to other radiometric ages for related units of the Skeena Group (95.1 ± 1.6 Ma for the Rocky Ridge Formation (Bassett and Kleinsphen, 1996)). This, however, contradicts pollen provenance ages of Late Albian-early Cenomanian (106-95 Ma) from the same study. Grains from this peak are believed to be derived from one main source: concurrent and older mid-Cretaceous intermediate volcanism of the Rocky Ridge Formation (Bassett and Kleinsphen, 1996). Rocky Ridge volcanism lasted from at least 107 Ma (MacIntyre, et al., 2004) to 95 Ma (Bassett and Kleinsphen, 1996). This peak records erosion of local volcanic exposures and transport of sediment into the Skeena basin.

The largest peak for 06KRDB1 is of middle to early Jurassic age grains (~180 Ma). The best possible source is the early- to middle-Jurassic Hazelton Group (Marsden and Thorkleson, 1992; Gordee, et al., 2004), a calc-alkaline island arc which is found extensively throughout Stikinia, and stratigraphically underlies the Skeena Group. Ages for the Hazelton Group range from 197 Ma (Marsden and Thorkleson, 1992) to 166 Ma (MacIntyre, et al., 2001). The ~180Ma peak thus likely records the uplift and erosion of the older Hazelton volcanics during the late Cretaceous.

Side peaks of the main peak include a late Jurassic peak at ~140 Ma and a late Triassic peak at ~215 Ma. Both peaks are poorly defined, a possible side effect of the size of the ~180 Ma peak; therefore the interpretations of these peaks are less precise. Suspected sources for these peaks are the late Jurassic Francois Lake intrusive suite (Schiarizza and MacIntyre, 1999) and the late Triassic Takla-Stuhini Group (Monger and Church, 1977). The Francois Lake intrusive suite is a group of granitoïd stocks and dikes with ages ranging from 148 to 138 Ma (MacIntyre, et al., 1997; Whalen, et al., 2001).The Takla Group (Monger and Church, 1977) is a late Triassic island arc assemblage with ages ranging from 218 to 193 Ma (MacIntyre, et al., 2001).

The two older peaks of Mississippian (~330 Ma) and Proterozoic (1.6-2.0 Ga) ages represent the oldest and perhaps most distant source material for the Rocher DeBoule Formation. The Cache Creek Terrane (Struik, et al., 2001), directly east of the Skeena Group and Stikinia, would be a likely source, because the chert pebbles of the Rocher Deboule Formation are consistent with input of sediment derived from the Cache Creek Terrane ocean floor sediments. However, no known volcanic units of Mississippian ages are found in the oldest local rocks of the Cache Creek Terrane (Struik, et al., 2001). Also, it is impossible to tell if the Proterozoic grains came directly from an original source (North American continent) or are reworked detrital grains from younger units. An alternative hypothesis is that these peaks represent detritus from the Yukon-Tanana Terrane (Colpron, et al., 2005). U-Pb zircon ages of ~320-340 Ma are found in volcanic units in the Yukon-Tanana Terrane (Nelson and Friedman, 2004). Ages of detrital grains in units of the Yukon-Tanana Terrane (Gehrels and Kapp, 1998; Ross et al., 2005; Bradley et al., 2007) also match the Proterozoic peak.

# DISCUSSION

The Skeena Group presents an excellent opportunity to test different reconstructions of late Cretaceous paleogeography. When found, units of the Skeena Group possess good paleomagnetic sampling qualities, and record the history of sedimentation with detrital zircons. Understanding how these different stories compliment each other is important to making a clear statement about the paleogeography of the Skeena Group.

The paleomagnetic results are inconclusive due to the low number of sample sites. As they are within error, no hypothesis can be ruled out. However, combined with the larger data set of the younger Kasalka Group (1300 ± 1000 km), it is clear that the Intermontane Superterrane was not ~3000 km south of its expected latitude with respect to North America between 95 and 75 Ma.

Several questions remain to be answered. The age of the Kasalka Group is uncertain, preventing their use in precisely describing plate rates during translation. Within error, it is impossible to rule out possible complications in terrane motion. The similarity in translation distance could indicate two possibilities: plate motion slowdown during the latest Cretaceous or a small southward motion. Further refinement of the sources of error could provide interesting insights into the details of the "Baja British Columbia" model.

There is no direct evidence in the detrital zircon data that directly suggests that Stikinia was ~1000 km south of its expected position at ~95 Ma. However, the data do not rule out this hypothesis, as no Archean-aged grains were found in 07KRDB1. Archean grains are derived from northern cratonic sources, and are used as evidence against southern latitude locations (Mahoney et al., 1999). Two explanations for this are a) the Roche Deboule river system was not sufficiently long enough to reach the craton, or b) Stikinia was at the moderate southern latitude suggested by the paleomagnetic evidence. Also of interest is the age distribution of Proterozoic grains in 07KRDB1. While most of the grains are of a common age range (1.6-2.0 Ga) for several regions of the craton, one grain is of an age (1.4 Ga) to be potentially from the Belt-Purcell Basin or more likely from its syn-depostional source (Anderson and Davis, 1995). While one grain is not conclusive proof, and could be far traveled or recycled multiple times, this is another potential line of evidence for a moderate location for the Intermontane Superterrane at 95 Ma. Future detrital zircon samples from lower sections of the Skeena Group could confirm the lack of Archean zircons, and the possibility of a Belt-Purcell source.

## FUTURE WORK

The Skeena Group has the potential to be a further source for clues about late Cretaceous Cordilleran paleogeography. However, improvements must be made in the general geologic knowledge of the Skeena Group. Current mapping (Tipper, 1976; Richards, 1990) is at a reconnaissance scale, and lacks important details about structure.

Future paleomagnetic sampling will be dictated by three factors: accessibility, exposure, and outcrop quality. The best exposures of the Skeena Group are in the high country of the Rocher de Boule Range. This introduces several complications: the expense and inflexibility of helicopter access, an increased chance of lightning strikes that reset the ancient geomagnetic records, and scarcity of water for cooling the sampling drill. Also, most ridges are representative of separate tectonic blocks with little structure, making collecting enough samples for an adequate fold test to assess primary magnetic remanence difficult.

Each formation has its own unique problems in sampling. The Kitsuns Creek Member produces the most reliable paleomagnetic results, has good exposures and clear sedimentary structures. The Rocky Ridge Volcanics are commonly brecciated, especially on Rocky Ridge (Tipper, 1976), so finding good flows is difficult. Also, some flows have been hydrothermally altered (Bassett, 1995), making the likelihood of good magnetic remanence low. The Rocher Deboule Formation is dominantly a chert pebble conglomerate, so only the few sandy members are reasonable for sampling.

From the results of this study, further sampling of the Kitsuns Creek Member would be ideal for expanding the results. The Kitsuns Creek member is more widely found and sampling from two to three more ridges would allow for a more definite fold test. Also, it would be ideal for further detrital zircon samples as detrital zircons are common in the Kitsuns Creek member (Figure 25). More samples from the Rocky Ridge Formation could help average out the possible effects of polar secular variation, and allow the reintroduction of the excluded 06KRR1 and 2 high-temperature directions. A potential new study area is the Sustut Basin, believed to be similar in age and source as the Skeena Group (Eisbacher, 1981). More radiometric dates would also provided better geochronological control of the Skeena Group. Undated igneous zircons were extracted from the sampled flows of the Rocky Ridge Volcanics on "Sc" ridge. The potential to date these and other flows could provide clarity to the paleomagnetic story of the Skeena Group

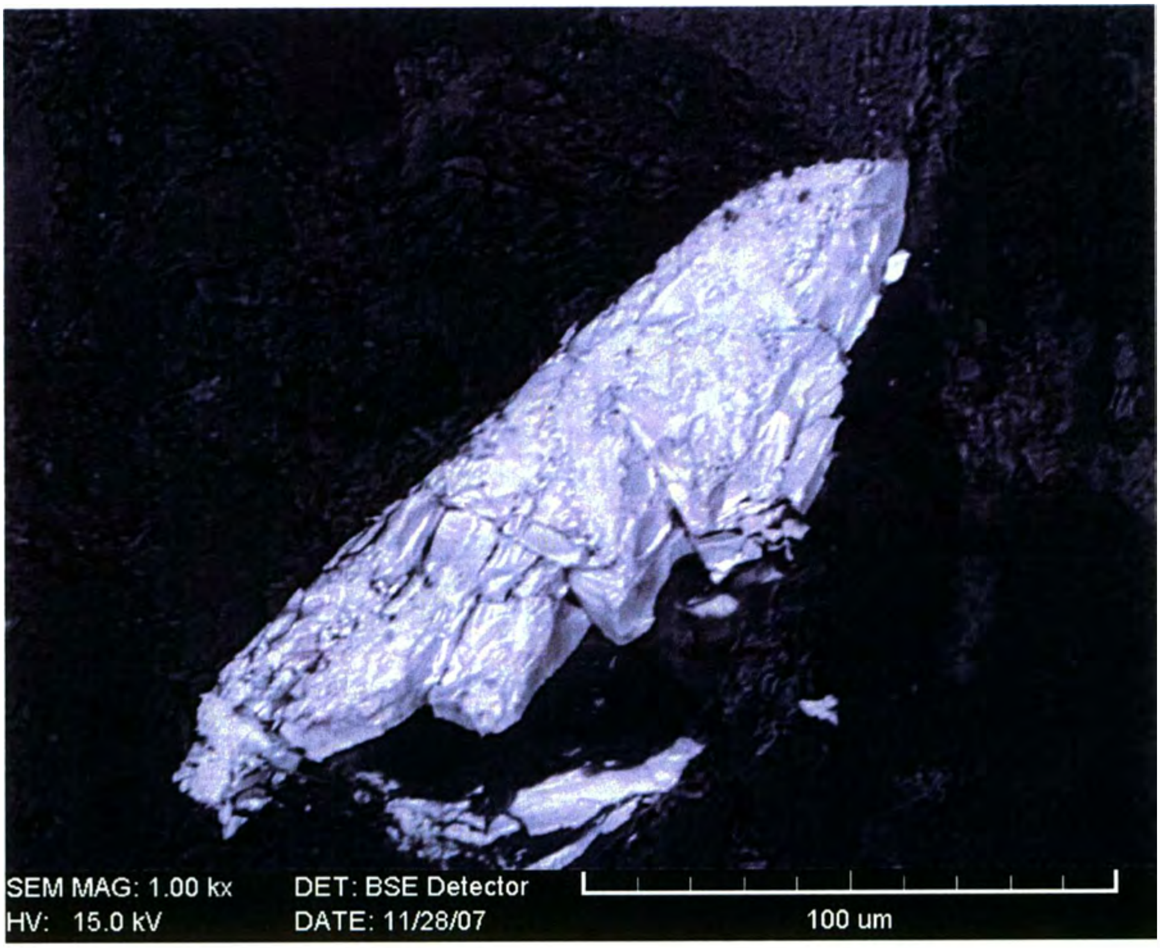



Figure 25: SEM image of ~100 um detrital zircon grain in sample from site 06KKC7.

## CONCLUSIONS

The Skeena Group of British Columbia preserves a story of late Cretaceous paleogeography for the Intermontane Superterrane. Paleomagnetic sampling from units of varying ages of the Skeena Group suggests that deposition occurred ~1000 miles south of its present day latitude. Further sampling is required to confirm this finding, but the chances of adding to the story are promising as some units are good carriers of paleomagnetic signals.

The ages of detrital zircon grains from a unit of the Skeena Group suggest that the Skeena Group received the bulk of its material from local units that were rifted and exposed during the intrabasinal volcanism that produced the Rocky Ridge Volcanics. Some grains came from units that are not directly inboard of Stikinia today, suggesting that relative positions of these terranes were different than they are today. The absence of Archean-age grains in a statistically significant sample of detrital zircons does not rule out different models for the paleogeography of the Skeena Group, but does support the paleomagnetic results.

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