1991

Paleomagnetic Constraints On Allochthonous Canadian Cordilleran Displacement: Results From Stikinia, British Columbia

Thomas Andrew Vandall

Recommended Citation
Vandall, Thomas Andrew, "Paleomagnetic Constraints On Allochthonous Canadian Cordilleran Displacement: Results From Stikinia, British Columbia" (1991). *Digitized Theses*. 1944.
https://ir.lib.uwo.ca/digitizedtheses/1944

PALEOMAGNETIC CONSTRAINTS ON ALLOCHTHONOUS CANADIAN CORDILLERAN DISPLACEMENT: RESULTS FROM STIKINIA, BRITISH COLUMBIA

by

Thomas Andrew Vandall

Department of Geophysics

Submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Ontario
November 1990

ISBN 0-315-64250-5

ABSTRACT

Large scale tectonic displacements have been inferred from many previous paleomagnetic studies on rocks found within the allochthonous terranes in the Canadian Cordillera (CC). The first suggestion of large scale terrane displacement originated from the recognition of disjuncts in faunal distribution in rocks of Mesozoic age. In this study the quantitative displacements inferred from paleomagnetic results have been reevaluated by reviewing the existing paleomagnetic data base with the addition of new paleomagnetic results from mid–central Stikinia.

Detailed alternating field and thermal stepwise demagnetization were done on all studied specimens collected from the Early Jurassic Telkwa Formation, Cretaceous Kasalka Group and the Middle Eocene Ootsa Lake Group. The rocks sampled were stratified subaerial volcanic rocks comprised of lava flows and airfall tuffs. Thus it was possible to relate the directions of remanent magnetizations to the estimated paleohorizontal when their primary remanences were acquired.

Results from the Middle Eocene Ootsa Lake Group yield a pole position which is interpreted to be 50 Ma in age and is statistically indistinguishable from published 50 Ma reference poles for cratonic North America. This is consistent with paleomagnetic results from Stikinia, Quesnellia, southern Wrangellia, and the Coast Belt indicating that much of the allochthonous Cordillera had assembled and docked with cratonic North America by the Middle Eocene. Thus any large–scale northward displacement of the CC which may have taken place had ended by at least Middle Eocene time.

Paleomagnetic directions from the Early Jurassic Telkwa Formation from this study confirm, with improved precision, the paleomagnetic data obtained by

Monger and Irving (1980). The reevaluation of the Early Jurassic reference pole for North America combined with the reanalysis of the tectonic displacements indicated by the CC Early Jurassic paleomagnetic data base, including the results from the this study, indicates that Terrane I, from the Permian to Early Jurassic, was in its present latitudinal position relative to the craton. Similar latitudinal concordance of southern Wrangellia with Terrane I and North America is suggested by the reanalysis of the single Bonanza Group result from Vancouver Island. The paleomagnetic results from the Permian to Early Jurassic are consistently characterized by large and variable clockwise and anticlockwise rotations about vertical axes, especially near the margins of the Stikine Terrane, suggesting that amalgamation of the large composite Terranes I and II was not yet complete.

The latitudinally concordant data both before and after the Cretaceous constrains the timing of large–scale transcurrent displacements within this period. The significant implication which has not been considered by previous large–scale (≈ 2400 km) northward displacement models is that the pre–Cretaceous data requires first large–scale southward displacement of allochthonous CC after the Early Jurassic. The required timing and magnitude of displacement in these models are not compatible with major CC tectonic events including known major fault offsets. Thus, large–scale displacements are difficult to reconcile geologically, and as major fault offsets are a maximum of ≈ 900 km it seems unlikely that transcurrent displacements have been much in excess of this. It appears, therefore, that local tilting combined with moderate northward displacement best explains the discordant data from Coast Belt intrusions. Paleomagnetic constraints from rocks with reasonable paleohorizontal control were provided by the Kasalka Group of this study and several other recent studies which support moderate (≈ 1000 km) northward translation consistent with geologic estimates of strike–slip displacement along major CC transcurrent faults. Thus, the Cretaceous CC data is best explained by a CC displacement model in which moderate ($\approx$ 1000 km) northward translation has taken place, combined with local tilting of the Coast Belt intrusives and local block rotations principally in the Intermontane Belt. It follows, therefore, that the solution to the "tilt vs. translation" controversy is a combination of the two models. This model scenario is in agreement with paleomagnetic and geologic estimates of northward displacement. Further, it has the desirable attribute of not requiring data selectivity as a prerequisite to the model as all the CC Cretaceous paleomagnetic results can be accommodated by this model. In addition, it is consistent with moderate post mid–Cretaceous northward displacements originally proposed by Monger and Irving (1980) and later reconfirmed by Armstrong *et al.* (1985).

To Louise Michelle Beaudry–Vandall

ACKNOWLEDGEMENTS

I would first and foremost like to express my heart–felt gratitude to my loving wife, Louise Michelle Beaudry–Vandall, who provided constant support, patience, and understanding during my four years of study. She generously donated her expert assistance for three summers of fieldwork in British Columbia in addition to assistance in the laboratory with the final experiments for this research. *Merci ma chéri, tu me donnes toujours beaucoup.*

My sincere thanks and appreciation to H. Currie Palmer, my thesis supervisor, who provided me the freedom and independence to follow my own research initiatives while also providing the careful, enthusiastic guidance he knew I needed. Currie's co–authorship on two of my thesis publications and his proof reading of this thesis certainly added significantly to the quality of my writing and science.

I also wish to express my thanks and appreciation to the following:

Dave Symons, my M.Sc. supervisor, for his encouragement and support which brought me to the University of Western Ontario to work towards my Ph.D. Dave has continued to contribute his helpful guidance as a co–author and member of my Ph.D. advisory committee. As well Dave generously donated the use of his paleomagnetic laboratory for measuring some weakly magnetized specimens as well as the SIRM work. Larry Diakow, Don MacIntyre, Pat Dejardin and crews of the British Columbia Department of Energy, Mines and Petroleum Resources, for sharing their friendship, geologic expertise and logistical assistance during three summers of fieldwork. Glen Woodsworth of the Geological Survey of Canada and Dave Woodsworth who provided logistical and sampling assistance to Currie Palmer in the initial stage of this research. Ted Irving and Jane Wynne of the Geological Survey of Canada at the Pacific Geoscience Centre for their helpful discussions and

generous sharing of manuscript preprints. Jim Monger and Hubert Gabrielse at the Vancouver Laboratory of the Geological Survey of Canada for providing manuscript preprints and help concerning Cordilleran geology. Craig Leitch and co–workers at the University of British Columbia for their generous sharing of unpublished geologic mapping near Owen Lake. My colleagues and friends in the Department of Geophysics at the University of Western Ontario who all helped in various ways. Energy Mines and Resources Canada for a Research Agreement grant, National Science and Engineering Research Council of Canada for grants, and the Faculty of Science of the University of Western Ontario for research funds. Finally to my family for their encouragement and support, most of all to my brother Paul E. Vandall Jr.

I am truly indebted for awards that were a great honour and privilege that supported me through University: the Ontario Graduate Scholarship, Canadian Society of Exploration Geophysicists Scholarship, Canadian Geophysical Union Best Student Paper Award, and the University of Western Ontario – Summer Scholarships, – Graduate Research Award, and – Graduate Research Fellowship.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 – GENERAL REVIEW

1.1 Introduction

Early explorers in Western Canada could not help but notice the majestic beauty of the awe inspiring mountain ranges which rise up on the western margin of the foothills of the Interior Platform. Geoscientists observing the mountain ranges of the Canadian Cordillera (CC) for the first time, must have questioned themselves as to how this mountainous part of the continent developed, standing in stark contrast to the Interior Platform. This question remains as one of the ongoing scientific investigations in Canadian geoscience today. Certainly the recognition of the complex and diverse geologic setting of the Canadian Cordillera did little to simplify the answer to this question. With the relatively recent widespread acceptance of plate tectonics as a viable unifying theory to explain many of the Earth's geologic features, there was a process which earth scientists could invoke in a gross fashion to attempt to explain the development of the major features of the Canadian Cordillera. Although significant advances in our understanding of the evolution and development of the Canadian Cordillera have been made, many questions remain unanswered and new questions are being raised.

Paleomagnetism, the scientific study of the ancient geomagnetic field as preserved in rocks with fossil magnetization (natural remanent magnetization; NRM) is a relatively young discipline, the development of which was greatly accelerated by the plate tectonics revolution in Earth science. The imprint of the ancient geomagnetic field in rocks has numerous scientific applications pertinent to the study of the geomagnetic field itself, ocean seafloor spreading, stratigraphic correlation and age dating to name just a few. The most wide–spread application of paleomagnetism is concerned with tectonics. Its application as a very powerful tool used in continental tectonic reconstructions has been demonstrated over the last four decades. Positions of the major continental cratonic blocks since the break up of Pangea have been reconstructed with the use of continental apparent polar wander paths (APWPs). There are two fundamental assumptions which an individual paleomagnetic study must satisfy in a tectonic application.

The first of the these is an adequate averaging of paleosecular variation. As modern navigators are aware, the Earth's present north magnetic pole does not coincide with the geographic north pole which corresponds with the Earth's axis of rotation. The north geomagnetic pole at present is inclined at about 11.5° from the Earth's axis of rotation in the northern hemisphere. Historical study of the Earth's magnetic field indicates that the approximately antipodal magnetic north and south poles (dipole axis) change position with time, undergoing a so called "wobble" about the Earth's axis of rotation. This "wobble" is referred to as paleosecular variation, in which the magnetic poles can be as much as 20° or more from the Earth's axis of rotation at a given instant in the geologic past. This suggests that the use of paleomagnetism for positional studies on continental to subcontinental scales would not be very useful, since at any one instant in the geologic past, the position of the magnetic north pole changes. However for the recent past, when the direction of the north magnetic pole is time–averaged over 10^4 years or more, the geomagnetic field averages to that of a geocentric axial dipole (GAD), in which the Earth's axis of rotation corresponds to the averaged magnetic field dipole axis (Hospers 1955). Thus for a given paleomagnetic study to adequately average out paleosecular variation in rock samples obtained in the field, they must represent a representative cross–section of geologic time spanning at least 10^4 years.

The second assumption that must be satisfied is that the observed magnetization must record the geomagnetic field at an accurately dated time. Radiometric age dates on rocks are useful but are not direct recorders of the age of a magnetization. For example, U–Pb zircon ages date the time the U–Pb system in zircon closed upon cooling of the mineral through ≈ 800°C. Since this is well above the Curie temperatures of magnetic minerals, the temperature above which a magnetic mineral cannot retain a permanent magnetization, U–Pb age dates can only indicate an upper limit on the maximum possible age of a primary thermal remanent magnetization (TRM) isolated in these rocks. Subsequent reheating events whose peak temperatures exceed the Curie temperatures of the magnetic minerals present but do not exceed 800°C can reset a magnetization while leaving the U–Pb system unaltered since the time of original closure. In addition, below Curie temperature reheating events that persist for extended geologic periods can still reset a high blocking temperature primary magnetization (Pullaiah *et al.* 1975). Incorrect interpretation in these situations might unknowingly assign older ages to much younger magnetizations. By contrast, the K–Ar isotopic system has lower closure temperatures between ≈ 300–500°C, depending on the dated mineral, which correspond more readily with the blocking temperature ranges of magnetic minerals. Thus, because of its sensitivity to reheating, the K–Ar system can be a more precise recorder in establishing the actual age of a TRM. Biostratigraphic dating is also useful in unmetamorphosed rocks, as in the case of the Early Jurassic volcanic rocks studied herein. Dating of the rock by this method can be either very accurate or imprecise depending on the quality of the dated fossils, their stratigraphic range and ultimately on the accuracy of the portion of the geologic time scale used to correlate with an absolute age. A radiometric and/or biostratigraphic age of a studied rock is of fundamental importance to establishing the age of a magnetization preserved in the rock but alone they are not sufficient. Of equal importance are consistency tests, such as contact and conglomerate tests, reversals tests and tilt tests, all of which can help establish if a magnetization is primary, or at least constrain its upper or lower age limit (See Chapter 2).

Once the assumption is made that accurately dated paleomagnetic poles correspond to the geocentric axial dipole field, grids of paleolatitude can be developed for different periods in the geologic past. Paleolatitudes are simply derived directly from measured magnetic inclinations by the relation:

$$\tan(inclination) = 2\tan(paleolatitude).$$

Grids constructed from data derived from tectonically stable continental interiors are used in continental reconstructions. On a smaller geographic scale, paleolatitudes derived from orogenic belts, such as the Cordillera, can be compared with the stable continental paleolatitudes in order to detect possible latitudinal displacements between Cordilleran terranes and the North American craton. Unfortunately, paleolongitudes are indeterminate from paleomagnetic data, thus east–west displacements are not detectable, and therefore, paleomagnetic displacements yield only estimates of minimum terrane movements. Paleomagnetic declinations do however constrain the azimuthal orientation of cratons and smaller terranes, and therefore, are useful for detecting block rotations about vertical axes.

Thus paleomagnetism can provide a wealth of quantitative information concerning large scale transcurrent displacements and the deformation of plate margins, terrane boundaries and intracontinental rifts so that its application is well suited to tectonic investigations in the Canadian Cordillera.

1.2 Tectonic Framework of the Canadian Cordillera

Much of the following discussion has been taken from Gabrielse and Yorath (1989). They summarize aspects of the work of numerous authors in the not yet released Decade of North American Geology (DNAG), Volume G–2, entitled, *The Cordilleran Orogen: Canada.*

The Canadian Cordillera (CC) is characterized by five morphogeological belts (Fig. 1.2.1) which comprise the principal tectonic, structural and morphological elements. The boundaries are largely coincident with the major terrane boundaries, identified as faults. Each morphogeological belt is made up of terranes which share similar geologic features, which combined, express the discrete physiographic character in each belt of the CC. Herein terranes are recognized as parts of the Earth's crust which preserve a geologic record different from those of neighbouring terranes. The term "terrane" implies no genetic significance in accord with Dover (1990).

The following is a brief summary of the main elements involved in the tectonic evolution of the CC. It evolved through many complicated stages and processes. First was the development of a miogeoclinal succession along the rifted passive margin of western ancestral North America which began during the Middle Proterozoic (≈ 1600–900 Ma). Next an orogenic event in the Late Devonian (≈ 370 Ma) resulted in rifting, volcanism and plutonism in the outer margins of the miogeocline. Then during Mesozoic and Cenozoic time (245 Ma – Recent) the amalgamation and accretion of volcanic, island arc and oceanic terranes took place along with concurrent deformation, metamorphism, volcanism and plutonism. Finally, major displacements along dextral transcurrent faults characterized the Cretaceous and Cenozoic. The late stage of amalgamation and accretion of

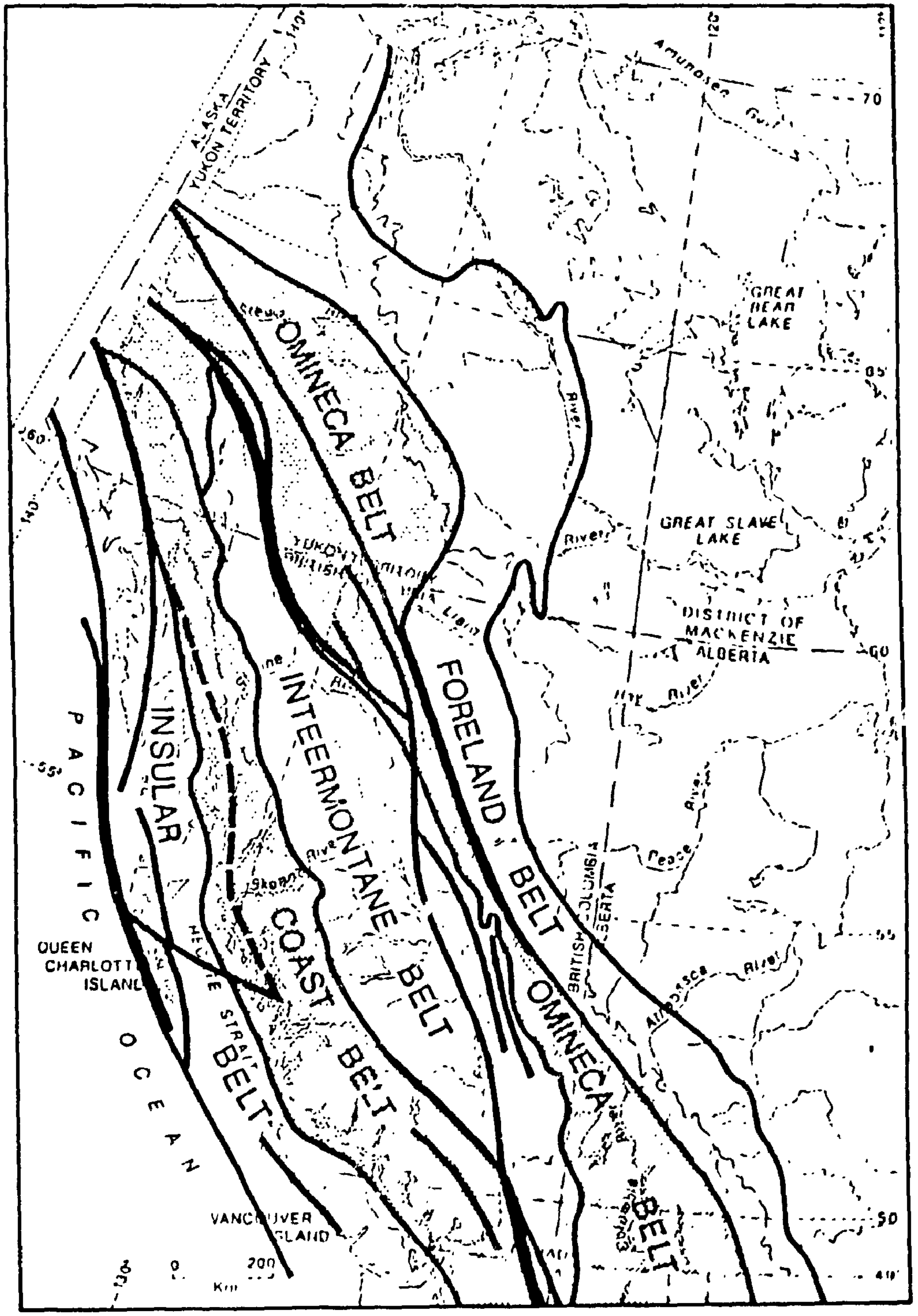

Figure 1.2.1 The morphogeological belts and regional strike—slip faults of the Canadian Cordillera from Gabrielse and Yorath (1989). Stippled areas are dominantly igneous and metamorphic rocks.

the volcanic, island arc, and oceanic terranes is under investigation in this study along with the major fault displacements during the Mesozoic and Cenozoic. The five morphogeological belts as they now occur were essentially developed during the late Mesozoic (Monger *et.al.* 1972).

Much of the following discussion of the linkages between the five morphogeological belts comes from Monger *et al.* (1972) and Gabrielse *et al.* (*in press*). The Foreland Belt is essentially the miogeocline which is a westward–expanding tapering wedge of supracrustal rocks in the Rocky Mountains which developed subsequent to mid–Proterozoic rifting which initiated the Cordillera. The miogeocline accumulated upon the westerly sloping Precambrian crystalline basement of ancestral North America which extends under the Rocky Mountains as far as its western boundary at the Rocky Mountain Trench. The basement may extend further westward to the south of 50°N under the Omineca Crystalline Belt, but in the CC there is no evidence of the Precambrian crystalline basement extending west of the Omineca Belt. By the Devonian, interaction between a coastal oceanic plate and the North American plate resulted in the shedding of clastic detritus eastward from oceanic crust into the miogeocline and ultimately resulted in local overthrusting of oceanic crust onto the miogeocline. West of the Omineca Belt all rocks appear to be allochthonous with respect to the craton. In the late Paleozoic, arc rocks represent the Omineca belt, oceanic crust the Intermontane Belt, arc rocks the Coast Belt, and a mixture of arc rocks and mid–Paleozoic continental crust the Insular Belt. The consolidation of the CC likely took place in the Mesozoic as suggested by the apparently physically continuous Upper Triassic rocks linking the Omineca, Intermontane, and Coast Belts in northern British Columbia. In southern British Columbia similar continuity is not recognized until the Cretaceous. Firm linkages between the Omineca, Intermontane, and Coast Belts with the Foreland Belt cannot be established until the Late Jurassic. Linkages between the outer Insular Belt and the Foreland Belt were not established until the Cretaceous. Throughout the Mesozoic the Canadian Cordillera evolved from a system of island arcs through an intermediate stage of increasingly restricted marine troughs fed in part by detritus from actively uplifted granitic and metamorphic rocks of the Omineca and Coast Belts, to a final stage in the late Cretaceous and Eocene of a firmly accreted CC. This evolution can possibly be related to the opening of the North Atlantic in Early Mesozoic time with consequent westward movement of the North American plate relative to the Pacific plate. Concomitantly there was northward transcurrent displacement within the Canadian Cordillera, possibly reflecting a strong northerly component of motion of the Pacific plate.

1.3 Geologic Evidence for Displacement

Prior to the late 1950's any hypothesis involving gross shifting of subcontinental areas would have been considered outrageous by most North American Earth scientists. However, as our understanding of major continental tectonic trends improved, there was a need to explain the divergences that were being recognized. One of the early advocates of intercontinental displacements as part of a system of global tectonics was Carey (1958). He suggested right–lateral displacement along a zone striking northwestward through the North American Cordillera as a possible system of distortion of younger tectonic trends. He assumed strike–slip movement had taken place on the Rocky Mountain Trench. Later, Wise (1963) advanced the concept of large scale right–lateral displacements in the North American Cordillera. He wanted to explain the diverging tectonic trends in the United States which give rise to several distinctive structural provinces. Wise (1963) proposed that right–lateral distortion of several hundred miles across a 300 mile wide zone from the Colorado Plateau to the Pacific Northwest from the Paleozoic through to modern times gave rise to the break in the linear tectonic trend of the Cordilleran belt in the western United States.

With a growing geologic data base in the CC, much of it obtained from geologic mapping carried out by federal and provincial surveys. the stratigraphic history of the relatively young Cordilleran belt was beginning to take shape. Tozer (1970), studying the distribution of Triassic faunas in the CC recognized distinct eastern and western regions. Within the western Cordillera, Triassic rocks were evidently deposited in warmer water than those of eastern Cordillera, suggesting that the present juxtaposition of these rocks might be the result of post–Triassic northward movement of the western Cordillera on the order of 400 km. Further, Monger and Ross (1971) described anomalous Upper Paleozoic faunal distributions in the Canadian Cordillera and suggested that their distribution might be due to major crustal movements which juxtaposed originally isolated biogeographic provinces. Alternatively, or in addition, this faunal diversity may be brought about by differing local environments (Monger and Ross 1971). Atwater (1970) suggested there was evidence of a slightly compressional strike–slip regime at the western edge of North America with a major change in plate motions in the Late Mesozoic. Atwater's (1970) analysis was based on the relative Pacific and North American plate motions from marine magnetic anomaly patterns in the northeast Pacific ocean. Around this time several discordant paleomagnetic results were obtained from rocks studied from the Cordillera (e.g. Cox 1957; Symons 1971a,b; Beck and Noson 1972; Irving and Yole 1972; Packer and Stone 1974). Thus, it was evident that many independent geologic sources of evidence were converging on the concept of large scale intracontinental displacement.

Monger *et al.* (1972) pointed out that the combined geologic evidence indicated that all pre–Mesozoic rocks west of the Omineca belt are allochthonous with respect to the North American craton and probably included oceanic crust, island arcs, and continental crust. Numerous later studies advanced and refined this plate tectonic model for the North American Cordillera to include the concept of a collage of suspect terranes and recognized allochthonous terranes (e.g. Monger 1977; Jones *et al.* 1977; Davis *et al.* 1978; Monger and Price 1979; Coney *et. al.* 1980). Models were developed based on the geologic and paleomagnetic data in support of large scale intracontinental displacement (e.g. Beck 1983, 1986; Chamberlain and Lambert 1985; Smith and Tipper 1986). Clearly there was a conflict between the inferred magnitudes of paleomagnetic displacement (e.g. Monger and Irving 1980; Yole and Irving 1980; Beck *et al.* 1981) and the magnitudes of displacement observable in the geologic record (e.g. Tozer 1970; Gabrielse and Dodds 1977; Tipper 1981). The controversy was further fueled by conflicting geologic (e.g. Gabrielse 1985; Price and Carmichael 1986) and paleomagnetic interpretations (e.g. Monger and Irving 1980; May and Butler 1986). Thus, it was evident at the time this research began that considerable controversy existed concerning the displacement history of the allochthonous Canadian Cordilleran terranes. Therefore, well–targeted paleomagnetic studies could certainly contribute to the resolution of the existing controversies in the Canadian Cordillera.

1.4 Canadian Cordilleran Paleomagnetic Data up to 1986

Given the rapidly accumulating geological and geophysical evidence, the CC has been increasingly recognized as a highly complex collage of terranes. This offers a difficult challenge to scientists attempting to understand the various stages of the Cordilleran tectonic development. Part of this understanding comes from paleomagnetic studies which are well suited to delineate large scale tectonic motions. To date, numerous paleomagnetic studies have been carried out on rock units from the CC, and these results have been used to establish a broad framework of collage development (e.g. Irving *et al.* 1980).

The first paleomagnetic study was conducted by Du Bois (1959) who studied Late Miocene volcanics from the Yukon Territory and northern British Columbia. He confirmed the geocentric axial dipole hypothesis (discussed in the introduction of this chapter) for the late Cenozoic in this region. Since then numerous paleomagnetic studies have followed, with data obtained from the many terranes in the CC, including data from each of the five morphogeologic belts (Fig. 1.2.1). By 1980 a paleomagnetic model for the evolutionary development of the Canadian Cordillera emerged (Irving *et al.* 1980).

Irving *et al.* (1980) recognized two major tectonic blocks of exotic origin that they named Wrangellia and Stikinia. Their boundaries probably do not refer strictly to the present boundaries of the two terranes as they are currently known. The outer western block, Wrangellia, is roughly equivalent to composite Terrane II of Monger *et al.* (1982) or to the Insular belt. The inner block, Stikinia, is part of Terrane I (Monger *et al.* 1982) and is roughly equivalent to the Intermontane Belt (Figs. 1.4.1 and 1.2.1). Both of these blocks are separated from one another by narrow remnants of former oceanic crust. The western oceanic remanents have a

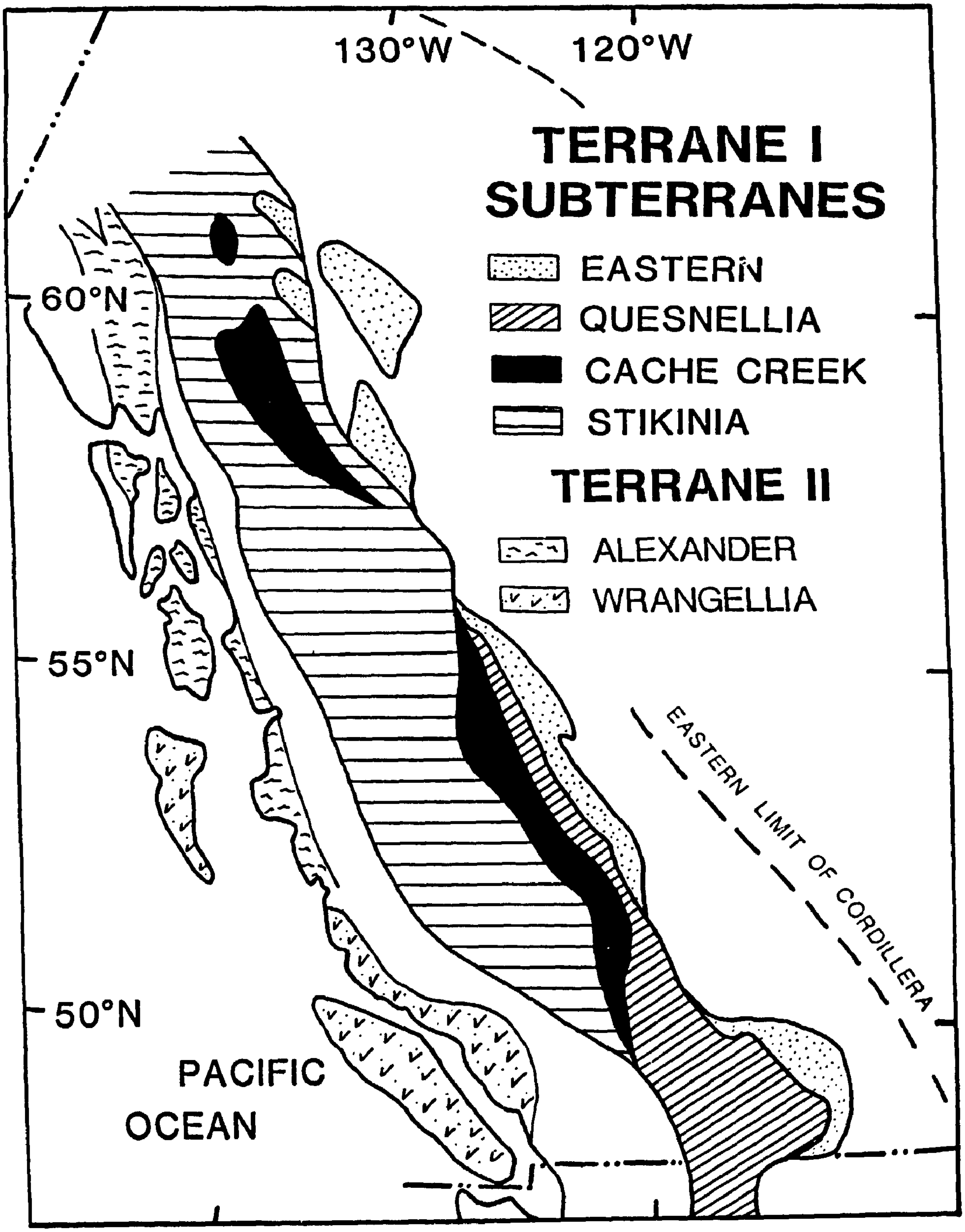

Figure 1.4.1 Major composite terranes I and II whose components amalgamated prior to accretion to the North American plate (modified from Monger *et al.* 1982).

minimum age of Middle Jurassic while the eastern oceanic remanants have a minimum age of Late Triassic. Paleomagnetic evidence was interpreted to suggest that the Stikine terrane was situated about 13° south of its present position and part of Wrangellia was situated over 20° south of its present position relative to the craton (Fig. 1.4.2). In this model Wrangellia moved northwards during the Jurassic and was sutured to the Stikine terrane in the Late Jurassic or Early Cretaceous with coincident emplacement of the plutons of the Coast Belt. Together the two tectonic blocks now including the Coast Plutonic Complex remained about 13° south of their present position until the Late Cretaceous or Early Tertiary when the now amalgamated terranes moved northward along major transcurrent faults to arrive at their present position relative to the North American craton (Fig. 1.4.2). Irving *et al.* (1980) also suggested that Wrangellia and Stikinia were formerly attached to oceanic plates, and that their northward motion reflects the general northward motion of the Pacific plate relative to North America since the Triassic. This model provided an interpretation of the available geologic and paleomagnetic data at the time. Certainly there were inconsistencies with respect to perceived latitudinally concordant Jurassic and Cretaceous paleomagnetic results (e.g. Symons 1971a; 1973*a*; 1973*b*; 1973c; Guichon Batholith, Howe Sound Intrusives, Topley Intrusives, and Copper Mountain Intrusives) which were in conflict with this model. In addition, there was no known fault system on which to accommodate the northward translation. However, this model's value was not in being correct or incorrect but rather in providing a model with which to test working hypotheses of Cordilleran displacement. A more recent tectonic interpretation, including new Cretaceous paleomagnetic results, by Irving *et al.* (1985) is broadly consistent with Irving *et al.* (1980) in terms of the inferred large

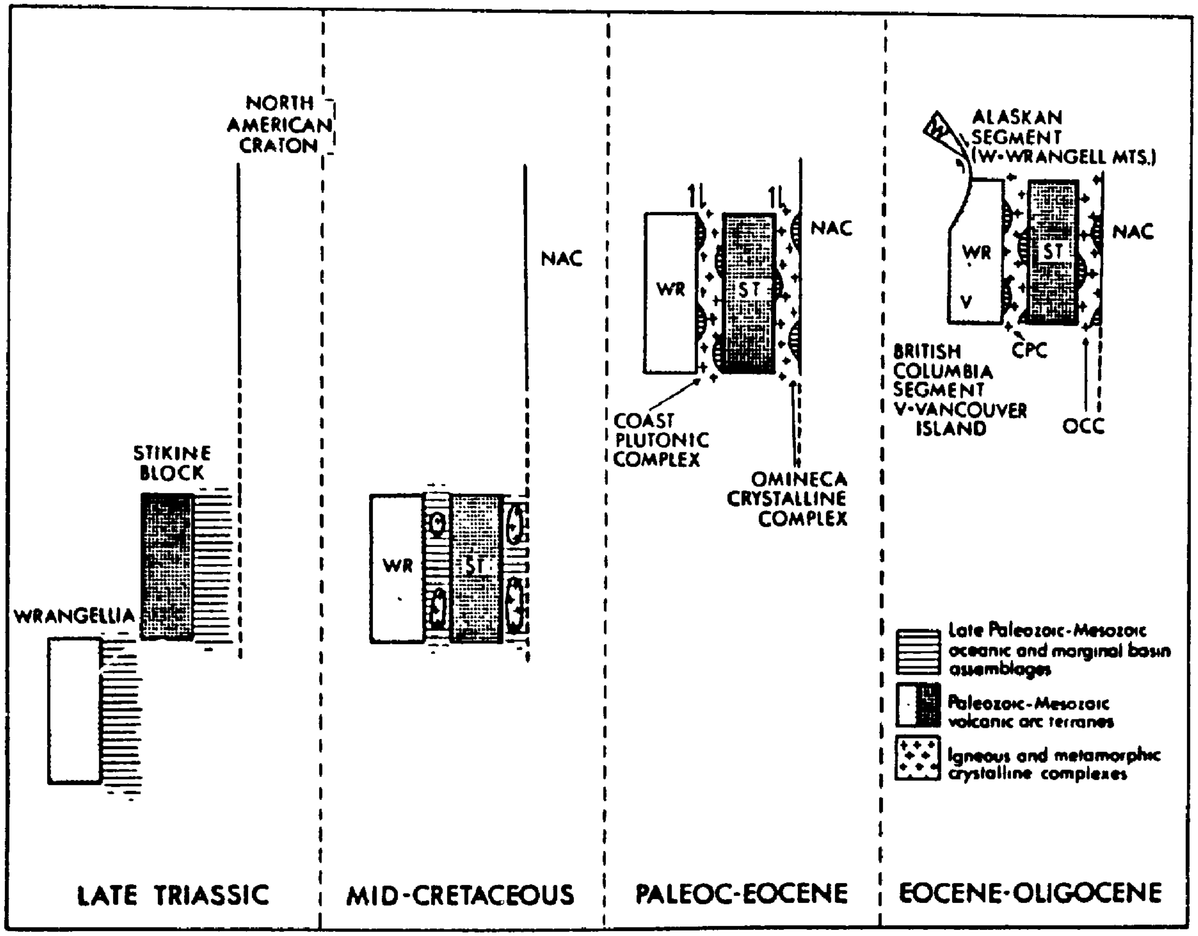

Figure 1.4.2 Model for the assembly of the major tectonic elements of the Canadian Cordillera from Irving *et al.* (1980).

scale northward displacement since the mid–Cretaceous. Again the locus of a system of transcurrent faults on which to take up this displacement remains elusive. Thus, the magnitude and timing of this displacement is very much uncertain which gives rise to the "tilt vs. translation" controversy (e.g. Symons 1973*a*, 1977a,b; Beck 1980a; Beck *et al.* 1981; Irving *et al.* 1985)

A review of the Canadian Cordilleran paleomagnetic data base reveals that many periods in the geologic record are unrepresented, and that many that are represented have conflicting interpretations of similar results (e.g. Symons 1973a; Irving *et al.* 1985). A large portion of the available data comes from studies on intrusive plutonic rocks rather than bedded volcanic or sedimentary sequences. Therefore, many of the aberrant pole determinations are ambiguous with respect to the probable cause of their discordancy giving rise to the "tilt vs. translation" controversy (e.g. Symons 1973*a*, 1977a,b; Beck 1980a; Beck *et al.* 1981; Irving *et al.* 1985). Results from the Cenozoic show that the major tectonic components of British Columbia were in place with respect to North America by the mid–Tertiary. In contrast paleomagnetic results from the Cretaceous are largely discordant and Irving *et al.* (1985) suggest that, although discordant, there is good agreement between Cretaceous paleopoles from the CC which indicates that the major terranes were assembled into a distinct mini–plate, called "Baja British Columbia", by this time. Its position relative to North America is displaced some distance to the south since these poles are all far–sided and do not agree with those calculated from cratonic North America for this time. Irving (1985) points out that the term "Baja British Columbia" originated with Stone (1977), the implication being that this region was formerly situated farther south and has since moved northward in a coastwise sense similar to the motion of Baja

California today. The magnitude of inferred displacement from the south is in question, but estimates range from ≈ 1300 – 2400 kms (e.g. Monger and Irving 1980; Irving *et al.* 1985). In several studies it has been suggested that the aberrant poles from "Baja British Columbia" can be explained by two possible models for post mid–Cretaceous tectonics. The translation model of Irving *et al.* (1985) involves a northward motion of ≈ 2400 km and uniform clockwise rotation of ≈ 66°. In contrast, tilt models involve either a uniform regional scale tilt about a sub–horizontal axis of ≈ 30° to the southwest (e.g. Irving *et al.* 1985), or local block fault tilts to the west and southwest (e.g. Symons 1973a; Symons 1977a,b) Although, Beck (1980a) and Irving *et al.* (1985) argue that the translation model is the most probable, they acknowledge that an underlying weakness of the model results from a lack of paleohorizontal estimates from the studied intrusive bodies. Significantly, the locus of a transcurrent fault system on which to take up the northward motion is also lacking. The most probable candidate on which to take up the northward motion is offered by the Northern Rocky Mountain and Tintina Trench fault system; however, cumulative displacements are only 750–900 km (Gabrielse 1985) and possibly less (Price and Carmichael 1986). In Early Jurassic and Late Triassic rocks, paleomagnetic determinations are quite variable indicating the likelihood that large independent rotations of smaller terrane blocks within the Canadian Cordillera took place. This suggests that the various terranes had not yet been assembled.

1.5 Objectives of this Research

Many geologic intervals in the paleomagnetic record of the Western Cordillera are poorly represented or altogether non–existent, thus the details of the CC development are far from clear. In Early Tertiary rocks, more definitive results are needed to provide an accurate determination of paleolatitude. In the Cretaceous many results are poorly dated and good age control is lacking. In addition, much of the available data are from plutonic rocks for which the paleohorizontal is indeterminate. As a consequence this leads to the "tilt vs. translation" ambiguity when attempting a tectonic reconstruction. In the Jurassic and Triassic, the quantity and quality of the paleomagnetic data is still insufficient to yield an understanding of the apparently extremely complex tectonic history of this time. In view of the conflicting geologic and paleomagnetic evidence for transcurrent displacement, many aspects of the CC evolution remain unresolved. Certain limitations do exist and any future paleomagnetic studies in the Western Cordillera will undoubtedly address some of these problems.

Certainly what is lacking is an integrated movement picture for a single terrane through time and this is one of the objectives of this reseach. It is hoped this can be done for the Mesozoic and Cenozoic elements of an areally restricted portion of the Stikine Terrane within the Terrace, Whitesail and Smithers map areas (Fig. 1.5.1). The paleomagnetic method is used as a tectonic tool in reconstructing the movement and assembly picture. Since many of the previous paleomagnetic studies have concentrated on massive plutonic rocks, this study has concentrated on volcanic sequences which usually enable the determination of paleohorizontal estimates essential to resolving the "tilt vs. translation" controversy.

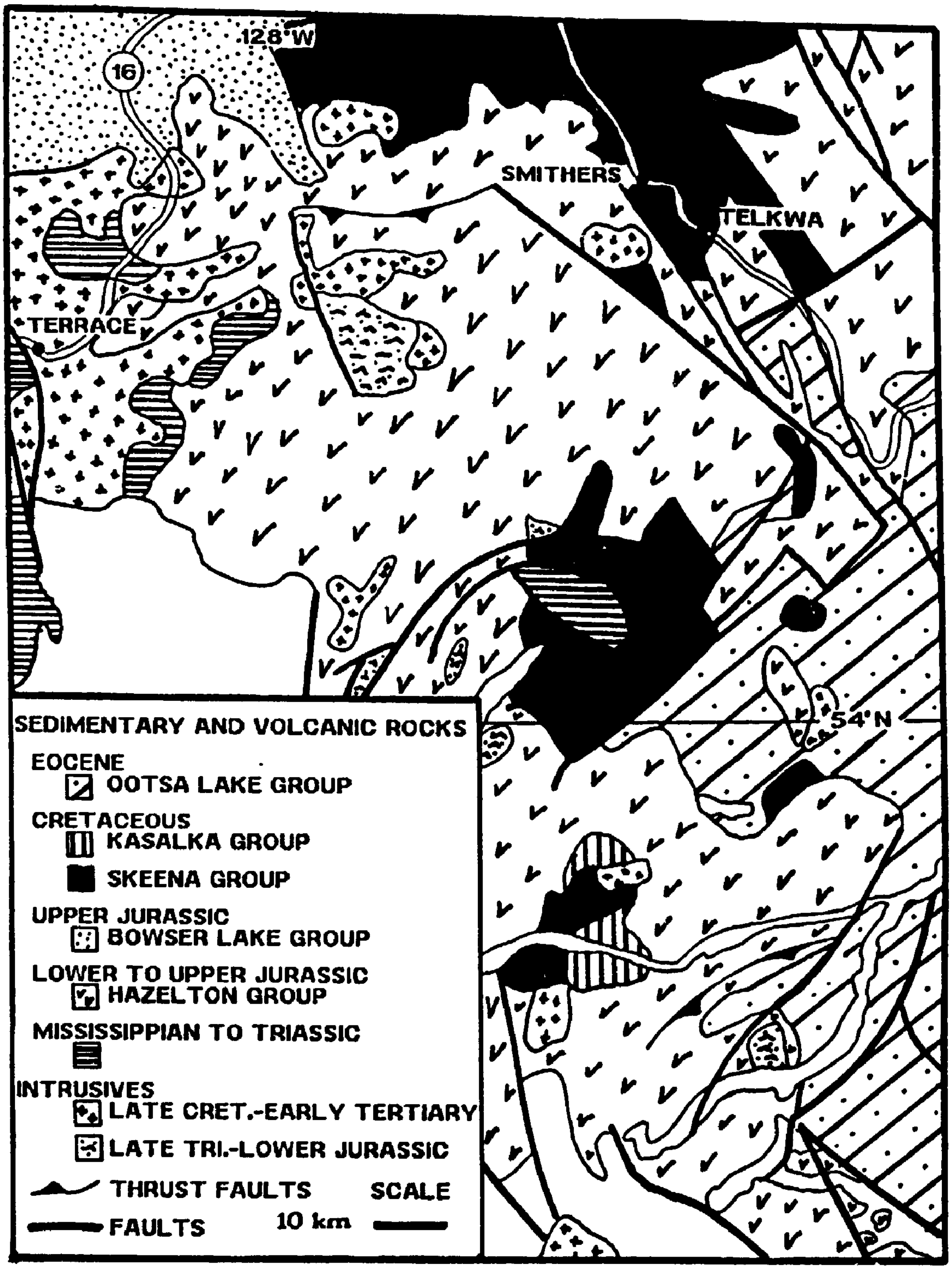

Figure 1.5.1 Regional geologic setting of the study area within the Stikine Terrane. Geology simplified from Tipper *et* al. 1981.

CHAPTER 2 – METHODS

2.1 Introduction

When this study began it was recognized that numerous paleomagnetic results from the Canadian Cordillera had been obtained from intrusive rocks for which original paleohorizontal is usually unknown. Therefore, the paleomagnetic sampling carried out in this study concentrated on stratified subaerial volcanic rocks comprised of lava flows and airfall tuffs. With bedded volcanic rocks, unlike intrusive rocks, it is possible to relate the directions of remanent magnetization to the measured paleohorizontal when the primary remanence is acquired. Thus, results from bedded volcanic rocks should help to resolve the "tilt vs. translation" controversy discussed in Chapter 1.

In the following discussion the writer assumes a working knowledge of the standard paleomagnetic techniques and the physical basis of rock magnetism. Since this knowledge is readily available in a number of standard paleomagnetic texts (e.g. Irving 1964, McElhinny 1973, Tarling 1983), no attempt is made here to reiterate this material.

2.2 Sampling and Experimental Work

Sampling was carried out in mid–central British Columbia in the Stikine Terrane where some of the best exposures of Mesozoic to Cenozoic volcanic rocks occur (Fig. 2.2.1). As outlined previously three periods in the geologic record of Stikinia were of particular interest for this study, namely, the Early Jurassic, Cretaceous, and Middle Eocene. Herein, data are presented from 80 paleomagnetic sampling sites. Usually at least five cores were drilled at each site using a portable

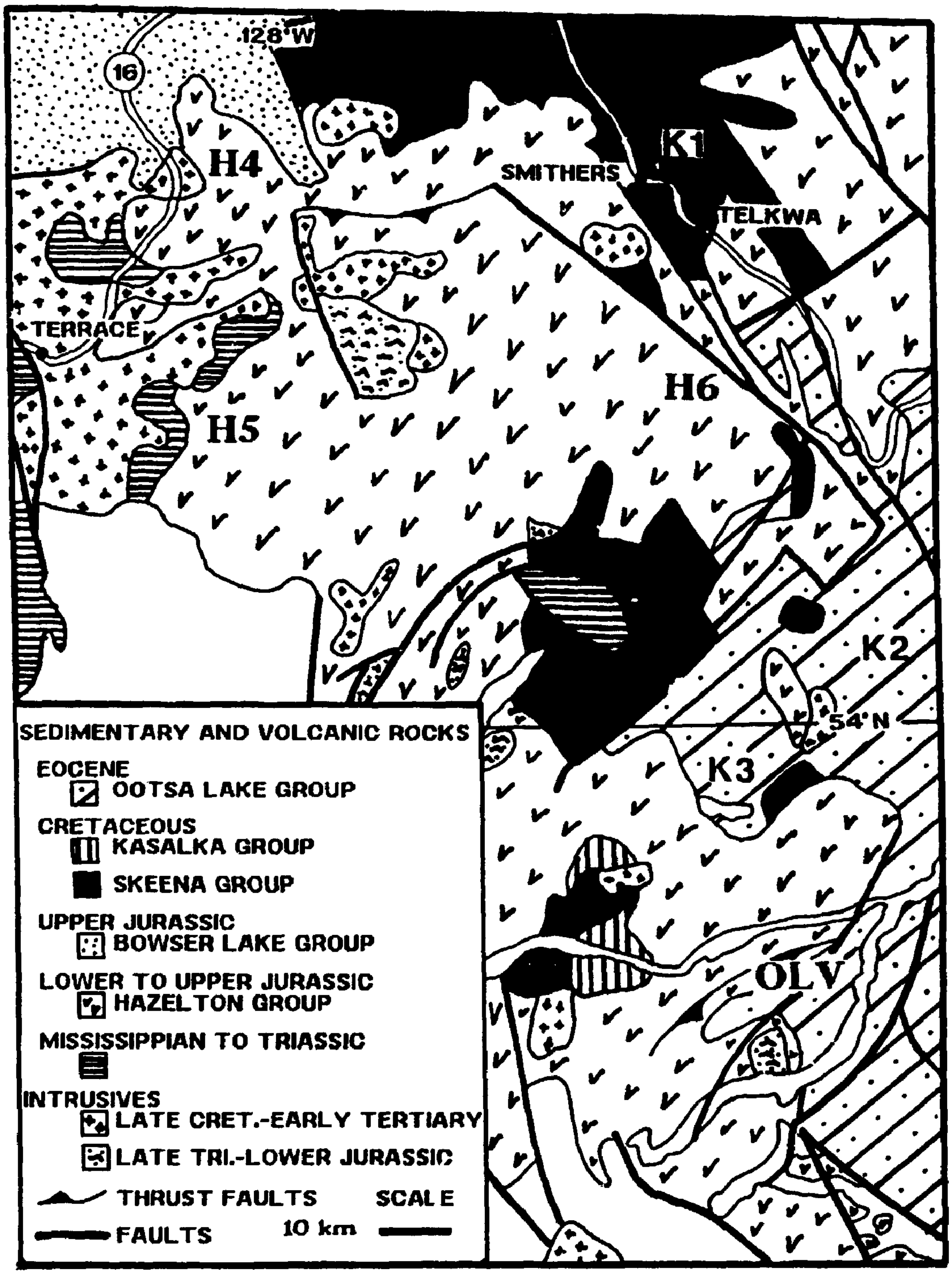

Figure 2.2.1 Sampling localities in Stikinia for Early Jurassic (H4, H5, H6), Cretaceous (K1, K2, K3) and Middle Eocene (OLV) volcanic rock units. Note the Cretaceous localities are within the Kasalka Group but the geologic mapping on this scale does not distinguish this. Geology simplified from Tipper *et al.* (1981).

water–cooled diamond–bit rock drill. The cores were oriented *in situ* using a solar and/or Brunton compass. Throughout the fieldwork checks were made for distortion of the local Earth's magnetic field because it can be perturbed by strongly magnetized rocks which should be avoided during sampling. A common cause of locally perturbed areas are zones of lightning induced remagnetization. Study localities are shown in Figure 2.2.1. The locations of individual sites for the Eocene and Early Jurassic rocks are in the two published manuscripts in the Appendix and for the Cretaceous rocks are in the discussion of the Cretaceous results in Chapter 4.

At the majority of sampling sites *in situ* bedding attitudes were measured and recorded. Where bedding attitudes could not be readily measured, bedding was inferred for a site location by interpolation from nearby outcrops and adjacent structural control from available geologic mapping. In the context of this study a paleomagnetic site is considered to be a volume of rock that has been magnetized at the same time, e.g. a single lava flow. One exception is the sampled airfall tuffs which were thinly bedded and cores drilled in different layers at these sites likely record magnetization at different times. This is demonstrated later by results from the Early Jurassic Telkwa Formation in which magnetic reversals were isolated within a single site in thinly bedded tuffs.

In the laboratory, one to three specimens were sliced from the 2.5 cm diameter cores into 2.4 cm lengths using a water–cooled diamond–blade cutoff saw. The number of specimens yielded by each core was controlled by the length of the core and the depth of the weathered surface at the top of the core. Many cores fractured during drilling in the field and these had to be glued together using a standard epoxy resin which is water resistant during core slicing with the cutoff saw. After slicing and drying the specimens, each core's scribe line was carefully transferred to the top of its respective specimens. The specimens were then labeled using white Pelikan ink that survives during thermal demagnetization.

Once the specimens were prepared, their virgin natural remanent magnetization (NRM) was measured. This was followed by a storage test of a minimum of two weeks duration, but in some cases up to several months duration, after which each specimen's NRM was remeasured. The storage test helped to identify specimens that readily acquired a strong viscous remanence magnetization (VRM) which in some cases proved to exhibit high coercivity upon subsequent alternating field (AF) demagnetization. The remanence directions from these specimens were rejected since the high coercivity VRMs are of no geological significance. Following remeasurement of each specimen's NRM for the storage test, each specimen was subjected to detailed progressive stepwise AF and/or thermal demagnetization. Since it has been shown by Doell and Cox (1963, 1965) that very little additional accuracy is gained by multiple sampling, not all companion specimens from each core were used. However, most companion specimens were used. Up to 14 demagnetization steps were carried out on some specimens depending on how rapid their direction and intensity changed between subsequent demagnetization steps. On average, due to the good remanence retention and high directional stability in these relatively young volcanic rocks, 8 to 10 steps were employed for the majority of specimens subjected to AF demagnetization. All magnetic measurements were done using a Schonstedt DSM–1 digital spinner magnetometer in the six spin measurement mode with the exception of a few weakly magnetized specimens which were measured using a cryogenic magnetometer. Since the specimens from fractured cores had to be glued together, they were only subjected to AF demagnetization. The AF and thermal step demagnetization were carried out using a Schonstedt GSD–5 tumbling AF demagnetizer and a Schonstedt TSD–1 thermal demagnetizer, respectively. AF demagnetization was done up to maximum fields of 100 mT, and thermal demagnetization was done up to peak temperatures of 700°C for specimens which exhibited high unblocking temperatures in the hematite range.

A number of very weakly magnetized specimens were analyzed at the paleomagnetic laboratory at the University of Windsor, directed by Dr. D.T.A. Symons. Here, magnetic measurements were carried out in a magnetically–shielded laboratory with an ambient field of less than 100 gammas or 1.0 X 10^{-4} mT (Huschilt 1983). The magnetically–shielded facility is particularly useful for demagnetization procedures with weak specimens because of the added protection from magnetic contamination by viscous remanence components (VRM). The magnetic measurements were done using a CTF Systems cryogenic magnetometer which has a usable sensitivity range down to at least 5 X 10^{-5} Am^{-1} which is an order of magnitude greater in sensitivity than the Schonstedt DSM–1 digital spinner magnetometer. Thermal demagnetization at the University of Windsor was also carried out with a Schonstedt TSD–1 thermal demagnetizer, while AF demagnetization was done using a Sapphire Instruments SI–4 AF demagnetizer capable of higher peak demagnetizing fields of 160 mT. Saturation isothermal remanence magnetization – demagnetization (SIRMD) experiments were also carried out at the University of Windsor. A Sapphire Instruments SI–6 pulse magnetizer was used to produce axial DC magnetic fields up to 900 mT for magnetic saturation experiments. The large magnitude SIRM intensities were measured using a Sapphire Instruments SI–5 spinner magnetometer. This was done to characterize the magnetic remanence carriers in the Cretaceous volcanic rocks studied which exhibited a variety of demagnetization behaviors.

2.3 Data Analysis and Tests

Following demagnetization, characteristic remanence directions were obtained for each specimen by a joint analysis of stereographic and orthogonal demagnetization diagrams and least–squares principal component analysis following the method of Kirschvink (1980). Remanence directions were accepted with a mean angular deviation (MAD) at least < 10° but usually < 5°. Directions where selected using a combination of criteria. They were quantitatively selected, using a minimum MAD criteria, and qualitatively based on a preferred anchored least squares line that was defined by a maximum number of demagnetization steps defining the primary straight line segment while maintaining a MAD close to the minimum value for that specimen. Visual analysis of the stereographic and orthogonal demagnetization diagrams in conjunction with the least squares data enabled the best possible selection of least squares lines defining the stable end point direction isolated in each specimen. Once the characteristic remanence direction in each specimen was obtained, site–mean remanence directions were calculated using conventional tiered statistics (Fisher 1953; Irving 1964).

Computer Programs

The Fortran program HSIFT (version 5) was used to compute the least squares principal component analysis. The program was originally developed by Kirschvink (1980) and modified at various stages by Henry Halls, Currie Palmer and the writer. A second modified version of HSIFT was also adapted for use by the writer on a IBM PC using the Microsoft Fortran compiler. Computation was carried out with both a Cyber mainframe at the University of Western Ontario, and with an 80286 IBM PC clone with a 16 MHz zero weight state clock speed. It was found the PC could carry out the computations accurately and with comparable speed to the mainframe, but because of the lengthy printed output from HSIFT, printing was best handled by the mainframe.

Vector diagrams were produced by a Calcomp plotter linked to a Cyber mainframe at the University of Western Ontario. Specimen demagnetization data files were created on the Cyber mainframe and used as input source files for DEGRAFF, a Fortran computer program which plotted the demagnetization directions given in polar co–ordinates (declination and inclination) for each specimen on an equal–angle stereographic projection. In addition, DEGRAFF plotted the orthogonal cartesian components of each specimen's demagnetization directions in the X, Y and Z planes following the method of As and Zijderveld (1958). DEGRAFF originally written by J. M. Degraff, Department of Geology at the University of Toronto, was also modified at different times by H.C. Halls and the writer. DEGRAFF also calculated difference vectors for each set of step demagnetization data from an individual specimen. However, due to the presence of relatively simple single component magnetizations isolated in the rocks from this study no meaningful secondary magnetization components were detected using the difference vectors.

Several utility programs were developed by the writer using Microsoft GW–Basic to carry out various standard and nonstandard paleomagnetic computations. The utility programs were produced as a complete user friendly, mutually compatible, menu driven program package designed for use on an IBM PC with a hard drive system. Available computation options include, paleomagnetic pole calculation, Fisher statistics, expected declination and inclination given a reference pole, tectonic displacement analysis (calculates relative rotations (RR) and relative paleolatitudinal displacements (RPD) and the error analysis of Demarest (1983)), tilt corrections, and a partial tilt test (calculates tilt corrected directions in percent increments of bedding tilt angles with a corresponding Fisherian statistics at each step). Data files can be entered and edited within the programs.

Tilt Tests

Since most sampling sites in this study have appreciable bedding dips, Graham's (1949) bedding tilt test was used to establish whether remanences were pre– or post–folding. If remanence directions in beds of different attitudes are widely scattered *in situ* but become clustered after correction for bedding attitudes, then the magnetizations were acquired prior to deformation. The variance–ratio test of Watson (1956) was used to established the confidence level for the tilt tests. A useful tabulation of this test is provided by McElhinny (1964) and the most oft cited minimum criteria for accepting a positive tilt test is the 95% confidence level. However, positive tilt tests in this study passed at the 99% confidence level. McFadden and Jones (1981) suggested that Watson's (1956) test is generally too rigorous and offer an alternative test, but for the purposes of this study their method was unnecessary.

A partial tilt test in which the estimate of Fisher's (1953) precision parameter (*k*) is maximized at a partial untilting of the bedding attitudes has received more attention in recent years as workers recognize more complex geologic situations involving primary dip and possible synfolding magnetizations (e.g. Granirer *et al.* 1986; Miller and Kent 1988; Bardeaux and Irving 1989; Hudson *et al.* 1989; Irving and Brandon 1990). Partial untilting involves the application of a progressive percentage of the bedding inclination, usually with respect to a horizontal strike axis, to form a structural correction of the *in situ* magnetization directions. This is done for each site in a study area until the dispersion between sites is minimized as indicated by the maximum (*k*) calculated from an overall unit mean. This is a useful procedure but some limitations do exist. As pointed out by Kodama (1988), a maximum value of Fisher's (1953) precision parameter (*k*) at partial unfolding is a necessary, but insufficient, condition to ensure that the magnetization is synfolding in age. Evidence independent of the fold test is needed to substantiate a synfolding age of magnetization. In addition, it is conceivable that a partial untilting could minimize dispersion beyond the levels of actual dispersion that existed over the period of time the magnetization was acquired. Given that a variable magnitude of dispersion is attributable to secular variation, the precise quantity of which is uncertain for various periods in the geologic past, it is almost impossible to detect and correct for these complications. Thus, reliance should be placed less on an individual paleomagnetic result from partial tilting than on the possible consistency among numerous determinations made over a region of concern. In this study partial tilt tests were routinely carried out for each rock unit studied but dispersions were essentially minimized by full tilt correction except for correction at one Cretaceous locality (K2). As part of the menu driven program package mentioned previously, a Microsoft GW–Basic computer program was developed by the writer to carry out a partial tilt test. The program progressively untilts the bedding in percentage increments of the measured bedding inclination about a horizontal strike axis for each site calculating Fisher's (1953) statistics at each increment.

Reversal Test

Another important test that was possible in this study is the reversal test. It is a measure of the directional consistency and primary nature of a magnetic remanence, since if secondary components are added to a bipolar distribution the resultants of opposed groups would no longer be antipodal, and the presence of an exact reversal indicates substantial secondary components are absent and secular variation has been adequately averaged. Also given that a reversal of the Earth's magnetic field takes a few thousand years (Hospers 1954; Hoffman 1988) the presence of reversals in the volcanic stratigraphy provides evidence that sampling has averaged secular variation.

Secular Variation Tests

Adequately averaging secular variation is a very important consideration for any paleomagnetic result intended to provide useful paleopole positions. The above reversal test in the writer's opinion is the most convincing measure of an individual study's averaging of secular variation, especially if several stratigraphically constrained antipodal reversals have been documented. However, the estimate of Fisher's (1953) precision parameter (*k*) can also be used to provide a test on the adequate averaging of secular variation in a given paleomagnetic study. By the method of Cox (1969) the 95% confidence limits on the accuracy of the calculated *k* values from the unit means in this study were determined. These were compared with the "expected *k*" values (McFadden and McElhinny 1984) for the geologic periods in question. It should be pointed out that the "expected *k*" values from McFadden and McElhinny (1984) are derived from modeling the Earth's secular variation in the geologic past by studying directional dispersions observed in hundreds of paleomagnetic studies thought to be attributed to secular variation. The inherent weakness is that the "expected *k*" values assume dispersion in a paleomagnetic study is due only to secular variation and this is more certainly the exception rather than the rule. The writer believes this test in itself cannot establish with confidence whether secular variation has been adequately averaged or not, but it certainly contributes helpful guidelines for the first order magnitude of secular variation that can be expected to have occurred during different periods in the geologic past.

2.4 Tectonic Analysis

In a tectonic analysis, an assumption which is critically important and often taken for granted is that the direction of the cratonic reference field in North America is well known. As suggested by Van der Voo (1989) it is no overstatement to claim that a detailed and reliable cratonic apparent polar wander path (APWP) is the first prerequisite for sound paleomagnetic interpretations of any sort. APWPs are the basic prerequisite for global paleoreconstructions. However, for investigations dealing with displaced terranes and structural analysis the reference poles for the APWPs are only useful as first order approximators of the reference field due to the manner in which they have been derived. See Vandall and Palmer (1990; Appendix) for a discussion of this. Unless a reference pole is accurately known within a very few degrees of error, the derived tectonic analysis will be similarly inaccurate. Latitude displacement errors can be of the order of hundreds to a thousand or more kilometers and rotation errors of many tens of degrees, both of which can be independent of the statistical precision of a pole determination. The best approach in calculating the reference poles for this type of tectonic study is by relying directly on the available up–to–date observations of the ancient magnetic field direction for the craton of interest. One simply selects from the current cratonic data base well–defined and dated cratonic paleomagnetic poles of relevant age, within the narrowest possible time–window (preferably < 5 Ma). These are then averaged (Fisher 1953), assigning unit weight to each pole, to establish a reference pole with its age centered within the averaging time–window. This approach has gained popularity in tectonic studies of the displaced terranes in the Canadian Cordillera including this study (e.g. Irving and Yole 1987; Marquis and Globerman 1988; Globerman and Irving 1988; Bardeaux and Irving 1989; Vandall and Palmer 1990a and 1990a; See Appendix) as it gives the best representative cratonic reference poles because it relies directly on observations of the ancient magnetic field direction. A more complete discussion of the different methods used for calculating cratonic reference poles is given by Vandall and Palmer (1990b) in the Appendix of this thesis.

Once a suitable reference pole has been established for the North American craton it can then be compared with the paleopole determined from within a terrane. The writer developed a computer program to carry out this analysis following the method of Yole and Irving (1980, 1981) who studied the displacement of Vancouver Island. A very helpful breakdown of the calculations involved is included in the Appendix of their paper along with a useful discussion of the tectonic analysis of paleomagnetic results from orogenic belts. (Note I caution interested readers to obtain both publications by Yole and Irving (1980, 1981) since the second publication contains important errata.) In addition, Demarest (1983) demonstrated how determinations of tectonic relative rotations (RRs) and relative paleolatitudinal displacements (RPDs) by this method have overestimated the size of the statistical confidence limits or error bars by about 25%. Thus the method employed in this study follows the calculations of Yole and Irving (1980) incorporating the error analysis of Demarest (1983).

It is important to point out that errors of geological significance always result in a paleomagnetic study to the extent that the underlying assumptions of the method have been violated. Further, these errors can often be larger than, and independent of, the calculated statistical errors. Thus although Demarest's (1983) analysis is statistically correct, in reality the error limits on RPDs and RRs include both the statistical error, and the often unrecognized error resulting from the violation, to a various extent, of the underlying paleomagnetic assumptions. As a result, the errors calculated by this widely used technique for determining RPDs and RRs, only reflects the statistical precision with which a pole and its reference pole are determined, and therefore are often minimum estimates.

CHAPTER 3 – EOCENE AND EARLY JURASSIC RESULTS

3.1 Introduction

In this chapter the writer has synthesized the main results from two published manuscripts which were initially published as abstracts (Vandall and Palmer 1988; Vandall *et al.* 1989) and presented at scientific meetings of the American Geophysical Union and the Canadian Geophysical Union. The writer encourages readers to refer to the two manuscripts in the Appendix of this thesis, entitled, "Upper limit of docking time for Stikinia and Terrane I: paleomagnetic evidence from the Eocene Ootsa Lake Group, British Columbia", published in the Canadian Journal of Earth Science and "Canadian Cordilleran Displacement: paleomagnetic results from the Early Jurassic Hazelton Group, Terrane I, British Columbia, Canada", published in the Geophysical Journal International. This research comprises a major part of the new paleomagnetic data presented in this thesis and it contributes significant new paleomagnetic constraints on the loosely understood allochthonous CC displacement.

In the following discussions the term "discordant" is used to describe paleomagnetic directions and their corresponding poles which are aberrant with respect to the correlative North American cratonic reference directions and poles, both in terms of inclination (relative paleolatitudes) and declination (relative rotations). The terms "latitudinally concordant" are used to describe paleomagnetic directions and their corresponding poles which exhibit concordant inclinations (paleolatitudes) but aberrant declinations (relative rotations) with respect to the correlative North American cratonic reference directions and poles.

3.2 Middle Eocene Ootsa Lake Group Results

At the time this research began there were essentially no paleomagnetic studies reported from mid–Tertiary bedded sequences in the CC. A single result was available from work by Fox and Beck (1985) on the Middle Eocene volcanic rocks just south of the Canadian – United States border from northeastern Washington State. Because numerous geoscientists studying CC tectonics have suggested that the inferred large scale northward displacement of the CC during the Cretaceous had been completed some time during the latest Cretaceous or Early Tertiary (e.g. Monger and Price 1979; Irving *et al.* 1980 Coney *et al.* 1980; Monger *et al.* 1982; Tipper 1984; Gabrielse 1985; Price and Carmichael 1986) it was important to test this by carrying out paleomagnetic studies. The results from Fox and Beck (1985), whose study area falls within the Quesnel Terrane which is part of composite Terrane I (Monger *et al.* 1982; Monger 1984), indicated that Quesnellia had reached its present latitudinal position relative to North America by the Middle Eocene. However, Fox and Beck (1985) did observe declinations to the north–northeast that suggested a 25° clockwise rotation of their study area. Therefore, their result is not concordant and indicates that significant block rotations occured in that region of Quesnellia after the Middle Eocene.

Further studies from different geographic and tectonic regions were needed to paleomagnetically constrain the final docking time of the CC and further confirm that most of the CC had assembled by the Cretaceous and subsequently had been displaced as a large coherent superterrane (e.g. Irving *et al.* 1980; Monger *et al.* 1982; Lambert and Chamberlain 1988; Thorkelson and Smith 1989). In order to do this, paleomagnetic results were sought from the central Stikine Terrane for which no Eocene paleomagnetic data was yet available. The Middle Eocene Ootsa Lake

Group was chosen for this study by virtue of its good stratigraphic exposure, age control and relatively fresh unaltered appearance.

The results from detailed demagnetization procedures on specimens from 18 sites demonstrated that the Ootsa Lake Group is characterized by a very stable, single component, prefolding magnetization spanning two polarity intervals within polarity Chron 21 (≈ 50Ma; Harland *et al.* (1982)). The mean paleomagnetic direction yields a paleopole which is statistically indistinguishable from the 50 Ma North American reference poles from either Irving and Irving (1982), Harrison and Lindh (1982) or Diehl *et al.* (1983). This demonstrates that this part of Stikinia has not undergone any paleomagnetically significant rotation and/or translation displacement since eruption and cooling of the Middle Eocene Ootsa Lake Group, implying final docking of Terrane I and much of the CC with North America. This work was presented at the 1988 Fall meeting of the American Geophysical Union (AGU) (Vandall and Palmer 1988) and shortly thereafter two paleomagnetic studies on Middle Eocene volcanic rocks from Quesnellia were published which also gave concordant paleopoles confirming this interpretation (Symons and Wellings 1989; Bardoux and Irving 1989).

The complete paleomagnetic results from the Ootsa Lake Group which appear in the publication in the Appendix (Vandall and Palmer 1990a) provide the detailed documentation of the work presented at the AGU meeting with the addition of three paleomagnetic sites which were sampled the following year. This research represents the first Middle Eocene paleomagnetic result from Stikinia. Studies on the younger Late Miocene Cariboo plateau lavas and Cariboo gabbro plugs that overlie and intrude the Stikine, Quesnel and Cache Creek terranes also yield concordant results (Symons, 1969a,b) and are therefore consistent with the result from this study. Further Middle Tertiary paleomagnetic data from intrusions of the Coast Plutonic Complex immediately west of Terrane I are also concordant with the exception of a low accuracy discordant result from the Mt. Barr Complex (Symons 1973d). These concordant results include: the Chilliwack batholith (Beck *et al.* 1982); the Hope Complex (Symons 1973d); the Grotto and Snoqualmie batholiths (Beske *et al.* 1973); the brown basalt dikes near Ocean Falls (Symons 1968); and the north–northwest–trending plutons of the Hawkesbury warp (Symons 1977b). Middle Tertiary studies from rocks farther west in the Coast Plutonic Complex and Wrangellia do show divergences (e.g. Symons 1973e; Hicken and Irving 1987). However, a recent result from the Eocene Flores volcanics of the Insular Belt of southwestern Vancouver Island yields a concordant pole (Irving and Brandon 1990) which suggests the Vancouver Island section of the Insular Belt was in its present position with respect to Stikinia and Quesnellia (Terrane I), and ancestral North America. Thus, in the main body of the Canadian Cordillera, paleopoles from volcanic rocks and intrusive rocks of mid–Tertiary age and younger are consistent with this result from the Ootsa Lake Group in central Stikinia. Table 3.2.1 is a summary of the useful CC Tertiary paleomagnetic results providing paleopoles including the results discussed above.

Given that these results indicate that southern Wrangellia, Stikinia and Quesnellia were in much the same latitudinal position relative to the North American craton during the Middle Eocene as they are at present, it is significant that the Ootsa Lake Group located in central Stikinia has not been rotated in contrast to some areas in Quesnellia (e.g. Fox and Beck 1985). The characteristics of the Middle Eocene paleomagnetic data fit quite well with the tectonic setting of each study. Accepting that most of the CC had assembled and stabilized by the Middle Eocene, the central location of the Ootsa Lake Group in Terrane I away from the terrane margins can be expected to have experienced greater stability.

Table 3.2.1

LIST OF CANADIAN CORDILLERAN TERTIARY PALEOMAGNETIC STUDIES AND THEIR POLES

Pole	Rock Unit	Age	Locality		N/R	N	Demagnetization	TC	Dec°	Inc°	R	*k*	α95°	PALEOPOLE		A95°		Ref.
			Lat°	Long°										Lat°	Long°	dp°	dm°	
FBV	Flat lying Basalts	Late Tertiary	60.5	-135.0 (4 areas)	11/35	46*s*	None	No	348.5	75.0	/	28	/					(1)
LMV	Level Mountain	1-6 Ma	58.5	-131.3	24/14	38*f*	1AF*p* 6*s*-80mT 2 Bulk steps	No	005.1	74.0	36.656	28	4.5	85	256	7.2		(2)
MEV	Mt. Edziza Complex	4 Ma	57.7	-130.6	27/57	84*f*	1AF*p* 8*s*-80mT 1 Bulk step	No	000.5	71.9	78.842	16	4.0	89	-328	6.2	7.0	(3)
MB	Mount Barr Complex	16-21 Ma	49.3	-121.5	4/1	5	1AF*p* -80mT 1-2 Bulk steps	No	022.0	75.0	/	62	8.0	72	- 86	13.3	14.6	(4)
GS	Batholiths Grotto & Snoqualmie	26/15 Ma	49.0	-122.0	4/3	7	2AF*p* -80mT Bulk (Stability problems)	No	365.5	68.5	6.98	360	3.2	86	209	4.5	5.4	(5)
CPV	Cariboo Plateau Lavas	10-14 Ma	51.5	-123.0 (Broad area)	22/26	48*f*	1AF*p* -80mT 1-2 Bulk Steps	No	356.4	72.3	46.939	44	3.0	84	-140	4.8	5.4	(6)
CG	Cariboo Gabbroic Plug	0-14 Ma	51.5	-121.2	M	17	1AF*p* -80mT 2 Bulk Steps	No	356.0	71.4	16.864	118	3.1	85	-147	4.8	5.5	(7)
BB	Brown Basalt Dikes	Upper Miocene-Pleistocene	52.5	-127.5	7/2	9	1 AF*p* -80mT 1 Bulk Step	No	004.5	74.0	8.675	/	9.4	82	-112	17.0	15.4	(8)
YP	Younger Plutons	Oligocene	53.1	-132.0	2/3	5	Bulk 30-40mT	No	338.0	80.0	/	138	4.0	70	-154	8.0		(9)
CB	Chilliwack Batholith	30-36 Ma	48.7	-122.3	R	34*s*	Th & AF *p*0? Bulk at 20 mT	No	182.8	-65.0	/	284	1.5	88	268	/		(10)
HC	Hope Complex	35-41 Ma	49.3	-121.5	3/2	5	1AF*p* -80mT 1 Bulk step	No	358.2	68.2	/	299	3.6	88	-152	5.1	6.1	(4)
ES	East Sooke Gabbro Stock	39 Ma	48.5	-123.7	M	29	1AF*p* -80mT 1 Bulk Step	No	329.9	64.2	28.281	39	4.2	70	151	5.3	6.7	(11)
EP	Eocene Plutons Hawksbury Warp NNW Limb	40-50 Ma	53.5	-129.0 (Broad Area)	9/2	11	1AF*p* -100mT 1-2 Bulk Steps	No	358.0	76.0	10.884	/	5.0	81	-134	8.0	8.0	(12)
NEV	Northeastern Washington Volcanics	50-48 Ma	48.4	-118.6 (Broad Area)	89/13	102	2AF*p* Steps? Bulk	Yes	015.6	68.9	/	/	3.7	79	- 56	5.3	6.3	(13)
KGV	Kamloops Group Volcanics	49 Ma	51.0	-120.4	17/7	24	2AF & 2Th*p* 3-4 Steps	Yes	355.0	73.4	10.884	20	6.9	81	-138	11.0	12.3	(14)
KCV	Kelowna & Castlegar Volcanics	52 Ma	49.9	-119.5	N	28	AF & Th *p*0? Bulk Full & Partial	Yes	352.0	69.0	/	21	6.0	85	197	10.0		(15)

Table 3.2.1 Continued

OLV	Ootsa Lake Volcanics	50 Ma	53.6	-126.7	6/7	13	All AF & Th All Stepwise PCA	Yes	002.2	69.2	/	32	7.4	88	- 5	10.7	12.6	(16)
FV	Flores Volcanics	50 Ma	48.8	-125.5	8/4	12	AF & Th #*p*? Bulk	Yes	349.8	69.6	/	41	7.0	81	188	9.9		(17)
MFV	Masset Formation Volcanics	62 Ma	53.7	-132.1	4/4	8	Bulk 30-40mT	No	026.0	78.0	/	81	6.0	72	-097	11.0		(9)
NVO	Nicola Volcanics Overprint	Eocene	50.0	-120.6	N	41	1AF & 1Th*p* Bulk	No	000.4	61.3	38.376	/	5.6	83	-303	6.6	8.6	(18)

Notes: Pole acronyms ending with "V" refers to volcanics, ending with "O" refers to overprint, all others are intrusives; Lat.- North Latitude, Long. - longitude (-ve is west); N/R - Normal to Reverse polarity site ratio, R - all sites reversed, N - all sites normal, M - mixed polarities of unknown ratio; N - Number of sites, *f* - number of flows, *s* - number of samples; Demagnetization - average demagnetization treatment/site, AF - alternating field, Th - thermal, *p* - pilot, #? - number not stated, PCA - principal component analysis; TC - bedding tilt correction; Dec - unit mean declination; Inc - unit mean inclination; R - resultant vector sum; *k* - precision parameter; α95 - radius about unit mean direction of 95% confidence; A95 - radius about mean virtual geomagnetic pole (VGP) direction of 95% confidence; dp - is the radius of the ellipse of 95% confidence about the pole along the site-pole great circle, dm - is the radius this ellipse perpendicular to the site-pole great circle; Ref.- reference for paleopole.

(1) Du Bois 1959; (2) Hamilton and Evans 1983; (3) Souther and Symons 1974; (4) Symons 1973d; (5) Beske *et al.* 1973; (6) Symons 1969a; (7) Symons 1969b; (8) Symons 1968; (9) Hicken and Irving 1977; (10) Beck *et al.* 1982; (11) Symons 1973e; (12) Symons 1974, 1977b; (13) Fox and Beck 1985; (14) Symons and Wellings 1989; (15) Bardoux and Irving 1989; (16) Vandall and Palmer 1990a; (17) Irving and Brandon 1990; (18) Symons 1985a. * Note many of the poles included here are based on very small quantities of data. Studies by Symons (1971b) and Irving *et al.* (1985) provide Tertiary poles but they are considered too speculative to include here (See text).

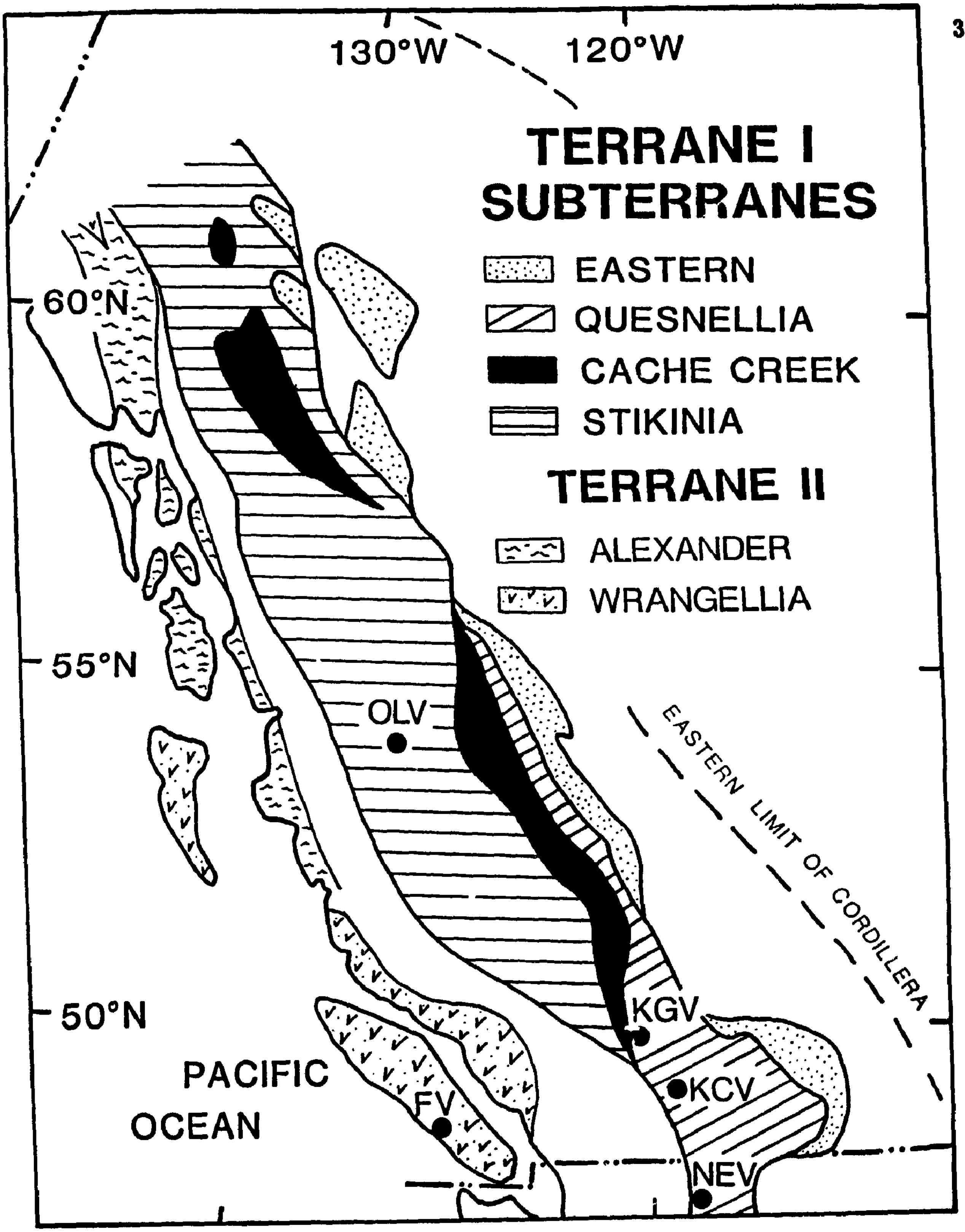

Figure 3.2.1 Study locations of the Middle Eocene paleomagnetic results relative to Terrane I and II after Monger *et al.* (1982). NEV – Northeastern Washington Volcanics, KGV – Kamloops Group Volcanics, KCV – Kelona and Castlegar Volcanics, OLV – Ootsa Lake Volcanics (this study), FV – Flores Volcanics (See Table 3.2.1 for references).

This is consistent with the discussions of kinematic models of large scale block rotation about vertical axes initiated at terrane boundaries by strike–slip faulting and oblique collision between terranes (e.g. Beck 1980b; Ron *et al.* 1984; Ron *et al.* 1986; Nur *et al.* 1986; Beck 1989a; Garfunkel 1989).

The combined, geographically distributed, Middle Eocene paleomagnetic results from the Cordillera by Fox and Beck (1985), Symons and Wellings (1989), Bardoux and Irving (1989), Vandall and Palmer (1990a), and Irving and Brandon (1990) (Fig. 3.2.1) provide significant geophysical evidence establishing the upper limit of docking time for much of Terranes I and II at 50 Ma.

3.3 Early Jurassic Telkwa Formation Results

Prior to this study discordant paleomagnetic results from the Hazelton Group had been published by Monger and Irving (1980). Since then a growing controversy has developed over the interpretation of discordant paleomagnetic data from the Early Jurassic (e.g. Monger and Irving 1980; Irving *et al.* 1980; Gordon *et al.* 1984; May and Butler 1986). It involved different perceptions of the geologic development of the Cordillera and differences in the analytical procedures used to calculate North American reference poles. The purpose of this work was to examine this controversy by a critical review of the data base with the addition of new paleomagnetic data from the Early Jurassic Telkwa Formation of the Hazelton Group sampled within a different region of the Stikine Terrane.

Previous paleomagnetic work on the volcanic rocks of the Hazelton Group by Monger and Irving (1980) was restricted to areas near the eastern margin of Stikinia (H1, H2, H3; See Fig. 1; Vandall and Palmer 1990b; Appendix). The results of

Monger and Irving (1980) suggested that Stikinia had been translated northward by ≈ 1300 km as well as rotated substantially about vertical axes since at least the time of magnetization of the Telkwa Formation between the Late Sinemurian and Early Pliensbachian. At that time absolute dating placed this stage boundary at ≈ 175 Ma based on the geologic time scale of Van Eysinga (1975). Monger and Irving's (1980) interpretation was based on the most up–to–date reference pole at that time (Irving 1979) which was calibrated using the geologic time scale of Van Eysinga (1975). Although the precision of their Hazelton Group result is somewhat low, their interpretation was supported by results from the Takla Group and Axelgold intrusion (Monger and Irving 1980). Conclusions about northward displacement and large scale variable rotations for parts of the CC from several later studies on Early Jurassic rocks (e.g. Symons 1983b; Symons and Litalien 1984; Symons 1985a; Irving and Yole 1987) were also consistent with Monger and Irving's (1980) result. However, these conclusions involved the use of different Early Jurassic North American reference poles. Thus, the proposed displacements and rotations were not calibrated with one another, and therefore, should not be compared. In addition, the North American Early Jurassic reference pole was imprecisely defined. This is demonstrated by numerous revisions over the last decade (e.g. Irving 1979; Irving and Irving 1982; Gordon *et al.* 1984; May and Butler 1986; Irving and Yole 1987; Hodych and Hayatsu 1988) with a very significant downward revision in age of the Triassic–Jurassic boundary (Late Sinemurian to Early Pliensbachian age is now ≈ 202 – 197 Ma; Harland *et al.* 1982 – very similar to that of Kent and Gradstein 1985 ≈ 200–196). Thus, in order to accurately evaluate the tectonic implications of these earlier paleomagnetic studies of Early Jurassic rocks, the tectonic displacements had to be recalculated using the same, current, more precisely defined, Early Jurassic reference pole. The review of the

Early Jurassic paleomagnetic data by May and Butler (1986) suggested that originally proposed large scale northward displacements of the CC were no longer supported by current cratonic reference poles. Thus, an evaluation of the "minimalist" hypothesis of Early Jurassic CC displacement should be provided by new paleomagnetic results from the Telkwa Formation and a reevaluation of the Early Jurassic North American reference pole.

The results from detailed demagnetization procedures on specimens from 35 sites, within three different geographic areas, demonstrate that the Early Jurassic Telkwa Formation of the Hazelton Group is characterized by a stable, two polarity, prefolding, primary remanence that was acquired upon cooling and deposition of volcanic lavas and tuffs. These data confirm the earlier data of Monger and Irving (1980) but provide improved precision. They also demonstrate that large block rotations about vertical axes have taken place on the eastern and western margins of the Stikine Terrane since the Early Jurassic. By contrast, central Stikinia, represented by the Telkwa Range result, has apparently undergone relatively little rotation suggested by the close agreement of its mean direction with the recalculated expected cratonic direction (H6V Table 5.1.1 and Fig. 5.1.1). Assuming that rotation has been in the smallest angle sense, then post Jurassic counterclockwise rotations have been observed on the west side of Stikinia in this study (H4V H5V H6V Fig. 5.1.1). In contrast, both counterclockwise and clockwise rotation have been observed on the east side of Stikinia by Monger and Irving (1980) (H1V H2V H3V Fig. 5.1.1). This pattern suggests these localized rotations did not affect Stikinia as a whole, but are confined to areas near the terrane margins where accretion tectonics on both sides of Stikinia could generate block rotations. Inasmuch as the data of this study substantiate the result of Monger and Irving (1980) but with greater precision, increased latitudinal resolution is now possible.

Three analytical procedures have been used to calculate reference poles for use in tectonic analyses. The earliest procedure involves a time–window moving average technique using intervals of equal time within which poles are averaged (e.g. Irving 1979; Harrison and Lindh 1982; Irving and Irving 1982). By another procedure, paleomagnetic Euler poles (PEP) (Gordon *et al.* 1984) are calculated from paleopoles that are fitted to small circles that are thought to represent a plate trajectory that remained constant over some 100 Ma. A third technique (e.g. Irving and Yole 1987; Hodych and Hayatsu 1988) is very simple, relying directly on observations of the ancient magnetic field direction. One simply selects from the current cratonic data base, in our case North America, well–defined and dated cratonic paleomagnetic poles of the relevant age within the narrowest possible time–window. These poles are then averaged giving each pole unit weight, to obtain a reference pole. This procedure is similar to the time–window moving average technique except that the size of the window is optimized (e.g. 5–10 Ma), centered about the mean age of the rock unit being studied.

The ages of the Early Jurassic magnetizations from Terrane I and Wrangellia (Monger and Irving 1980; Symons 1983b; Symons and Litalien 1984; Symons 1985a; Irving and Yole 1987; this study) are ≈ 200 Ma, using the geologic time scale of either Harland *et al.* (1982) or Kent and Gradstein (1985). Therefore, an Early Jurassic North American cratonic reference pole is required for a tectonic analysis of these paleomagnetic results. Irving and Yole (1987) recently calculated a Early Jurassic reference pole for their tectonic analysis of paleomagnetic data from the Bonanza Group in Wrangellia on Vancouver Island. However, it may not have sufficiently averaged secular variation (Prévot and McWilliams 1989; Vandall and Palmer 1990b).

It has been recognized by several workers that the Colorado Plateau has undergone clockwise rotation, suggested by both geologic (Hamilton 1981) and paleomagnetic evidence (Steiner 1984). Recent estimates on the amount of clockwise rotation of the Colorado Plateau include: 4° (Bryan and Gordon 1986), 11° (Steiner 1986) and 10° (Irving and Yole 1987). Although Irving and Yole (1987) dismiss data from the Colorado Plateau on several grounds, their strongest argument is the rotation complication. My approach is different. Much of the Early Jurassic Cordilleran data is characterized by large and variable declination differences so that the most useful information comes from the inclinations which are directly related to paleolatitudes. Correcting the data from the Colorado Plateau for clockwise rotation of either 4° or 11° has a small effect on the longitude of a combined Colorado–Newark Early Jurassic reference pole and a negligible effect on its latitude. Since inclusion of these data does not change the expected cratonic reference latitude but does help to average out secular variation, I argue that a combined Colorado–Newark North American reference pole best averages out secular variation, and therefore, is the most accurate for the needs of this analysis. In the final stages of editing this thesis Bryan and Gordon (1990) published a new 5° estimate of the Colorado Plateau rotation which does not effect this approach.

Recently Hodych and Hayatsu (1988) have reviewed the age dating and paleomagnetic work on the Newark Supergroup rocks that provide most of the Early Jurassic cratonic poles and have calculated an Early Jurassic reference pole. I used nine poles from the Newark Supergroup data combined with three poles from the Colorado Plateau corrected for 4° of clockwise rotation to calculate a Early Jurassic reference pole for North America (See Table 4 of Vandall and Palmer 1990b; Appendix). The Early Jurassic reference pole of Hodych and Hayatsu (1988) and a Combined Colorado–Newark reference pole calculated in this study (Table 4, Vandall and Palmer 1990b; Appendix) have been used in the following tectonic analysis the methodology of which is outlined in Chapter 2. The analysis indicates the Hazelton Group remanences are latitudinally concordant within statistical error with either the Combined Colorado–Newark reference pole (This study) or the Newark reference pole (Hodych and Hayatsu 1988). This result is consistent with a reevaluation of Triassic and Early Jurassic paleomagnetic results that previously supported the ≈ 1300 km northward displacement hypothesis. Table 5.1.1 lists the CC Permian to Jurassic data with corresponding RPDs and RRs. This result is also consistent with data from the Permian Asitka volcanic rocks from Stikinia that Irving and Monger (1987) interpreted as latitudinally concordant. Because of the downward revision of the geologic time scale and changes to the Early Jurassic reference pole for North America, Terrane I is no longer required to have been moved ≈ 1300 km from the south since the Early Jurassic and was, in fact, close to its present latitudinal position with respect to North America. The results from studies by Symons (1983b, 1985), Symons and Litalien (1984) and Irving and Yole (1987) are now interpreted to be latitudinally concordant with the expected Early Jurassic reference pole for North America.

This analysis indicates that Terrane I, from the Permian to Early Jurassic, was in its present latitudinal position relative to the craton, although it has undergone large and variable rotations especially near the margins of the Stikine Terrane. Similar latitudinal concordance of southern Wrangellia with Terrane I and North America is suggested by the single Bonanza Group result from Vancouver Island (See Table 5 of Vandall and Palmer 1990b; appendix). The paleomagnetic results from the Permian to Early Jurassic are consistently characterized by large and variable clockwise and anticlockwise rotations about vertical axes, indicating that amalgamation of the large composite Terranes I and II was not yet complete.

The data from the Karmutsen Formation (Symons 1971b; Irving and Yole 1972; Schwarz *et al.* 1980; Yole and Irving 1980), also on Vancouver Island, have not been included in this analysis as they exhibit a high degree of magnetic instability combined with variably directed magnetizations with elongate distributions. The reversed X component believed to be primary by Yole and Irving (1980) appears to be a hybrid component manifested by the marked east–west smearing of site–mean directions (See Fig. 4 of Yole and Irving 1980). Schwarz *et al.* (1980) recognized and documented this same smearing of the "X component" which they identify as the NW up and N up directions (Fig. 7 of Schwartz *et al.* 1980). Further, Symons (1971b) isolates markedly steeper reversed directions which are described as the "X component" (Yole and Irving 1980) and they also exhibit a similar east–west smearing. I attribute the smearing and variability of directions to incompletely resolved magnetization components. Thus, in my opinion the Karmutsen Formation results are not representative of a meaningful paleodirection.

This work was presented at the 1989 annual meeting of the Canadian Geophysical Union (CGU) (Vandall *et al.* 1989) and was published in the Geophysical Journal International. See Appendix.

3.4 Discussion

Terrane I, an allochthonous microplate, is thought to have been formed by the assembly of four subterranes in the Middle Triassic (Monger *et al.* 1982). The concordant paleolatitudes obtained from the Stikine and Quesnel subterranes in Terrane I are consistent with this hypothesis, although the large and variable internal rotations suggest that the assembly of Terrane I was not complete by the Early Jurassic. It is suggested that southern Wrangellia, part of the outboard

Insular belt, also characterized by large rotations and latitudinal concordance from data of the Bonanza Group (Irving and Yole 1987), was also close to its present position relative to Terrane I and North America. Since the paleomagnetic studies on Middle Eocene volcanics from Quesnellia, Stikinia, and southern Wrangellia (Fox and Beck 1985; Symons and Wellings 1989; Bardoux and Irving 1989; Vandall and Palmer 1990b, Irving and Brandon 1990) show that Terrane I and much of the CC had assembled and docked with North America by at least Middle Eocene, Terrane I must have been stabilized by at least the Middle Eocene because the main body of the CC paleopoles from younger rocks in the Cordillera are concordant as discussed earlier.

Cordilleran Cretaceous paleomagnetic data remain largely discordant (e.g. Beck and Noson 1972; Symons 1974; Beck *et al.* 1981; Irving *et al.* 1985; ; Butler *et al.* 1988; Marquis and Globerman 1988), and have been interpreted to indicate that much of the western CC was situated 2400 km south of its present position at that time. Geologic evidence suggests that the various terranes of the western CC were amalgamated by the mid–Cretaceous (Monger *et al.* 1982). It has been suggested (Irving *et al.* 1985) that this is supported by the Cretaceous paleomagnetic data. Although discordant, Irving *et al.* (1985) suggest that the vertical axis rotations observed in the Cretaceous paleomagnetic data are systematically ≈ 66° clockwise in contrast to the Permian to Early Jurassic results, which would indicate that the various terranes of the western CC had assembled as a unit by this time. The latitudinally concordant data both before and after the Cretaceous constrains the timing of large scale displacements within this period. Thus, displacement models based on the discordant Cretaceous data must accommodate large scale southward displacement of western parts of the Canadian Cordillera after the Early Jurassic, followed by northward displacement with possibly ≈ 66° of clockwise rotation with final stabilization of the CC by Middle Eocene. Certainly none of the CC assembly models, for example, Irving *et al.* (1980), Irving *et al.* (1985), Chamberlain and Lambert (1985), Umhoefer (1987) and Lambert and Chamberlain (1988) considered the possibility of latitudinally concordant Triassic and Jurassic data. Given that these data have been shown to be latitudinally concordant herein, the above models may have been conceptually prejudiced by the incorrect assumption, based on earlier interpretations (e.g. Monger and Irving 1980), that these data were similarly latitudinally discordant as the mid–Cretaceous results. Thus, these translation models have not considered how allochthonous CC terranes were first displaced to the south from their latitudinally concordant Permian to Early Jurassic paleolatitudes. Inasmuch as the northward displacement in these models was argued based on the general northward trend of the Pacific plate since the Triassic, this view must now be reassessed. It is reasonable to conclude that the viability of post Early Jurassic to mid–Cretaceous southward displacement is a prerequisite to the large–scale mid–Cretaceous northward translation models. As pointed out by Butler *et al.* (1989) the magnitude and timing of 2400 km of northward displacement is inconsistent with the currently perceived pre–mid–Cretaceous links between the North American miogeocline and parts of western Cordillera (Price and Carmichael 1986). Alternatively, Symons (1973a, 1974, 1977a, 1977b) consistently invoked differing local tilts to explain his discordant directions. While Beck *et al.* (1981) and Irving *et al.* (1985) also suggested that the Cretaceous paleomagnetic discordancy could also be explained by uniform regional tilting of 30° to the SSW, which is unlikely, it is important to point out that the tilting invoked by Symons involved differential tilting of smaller fault–bounded blocks. Recently Butler *et al.* (1989) have advanced the tilt hypothesis with stratigraphic, petrologic and isotopic data that indicate that parts of the Coast Plutonic Complex and the North Cascade Range have been tilted by ≈ 30° to the SSW. Certainly the regional tilt hypothesis appears more reconcilable in view of the latitudinal concordancy of the Permian to Early Jurassic and Middle Eocene to Recent data. However, this hypothesis cannot account for discordant Cretaceous data from bedded volcanic rocks in Terrane I (e.g. Marquis and Globerman 1988). It is therefore possible that Cretaceous Cordilleran tectonics were characterized by both regional tilting and moderate latitudinal displacement involving different terranes. It is this question which is addressed in the following Chapter by the evaluation of the Cretaceous CC paleomagnetic data base including new paleomagnetic results from the Cretaceous Kasalka Group within central Stikinia.

CHAPTER 4 – CRETACEOUS RESULTS

4.1 Introduction

In this chapter I review and discuss the existing CC Cretaceous paleomagnetic data base along with new Cretaceous paleomagnetic results from Stikinia which were initially presented and published as an abstract in the Canadian Geophysical Union 17th Annual General Meeting, Program with abstracts, Ottawa (Vandall and Palmer 1990c). The format of this chapter is similar to that of a stand alone manuscript. Therefore, in a few sections some material has been repeated, for example, the brief methods section of this chapter. It is intended that the new paleomagnetic data along with this review will be submitted for publication in a suitable scientific journal.

At the time this research began the controversy over the interpretation of discordant Cretaceous results from the CC was still very much unresolved (e.g. Beck 1980b; Irving *et al.* 1985). The available paleomagnetic data base up to 1986 included studies principally on massive plutonic rocks, most of which are part of the Coast Belt (Table 4.1.1). Thus, these results are subject to ambiguities because of the uncertainty of the structural attitudes of the intrusions, further compounded by the uncertainty of the paleomagnetic horizontal which may or may not be related to the current structural attitude of the intrusions (e.g. Monger and Irving 1980; Armstrong *et al.* 1985). Paleomagnetic data from accurately dated well bedded volcanic rocks can offer more definitive results and interpretations but as Irving *et al.* (1985) point out these are not always available and one is obliged to study intrusive bodies. In the CC the scarcity of accessible, well exposed, Cretaceous volcanic rocks suitable for paleomagnetic study is a major difficulty in providing definitive Cretaceous paleomagnetic results.

For the purpose of the following discussions the paleomagnetic results from northern Washington State including the Mount Stuart batholith (Beck *et al.* 1981), Winthrop and Midnight Peak Formations (Granirer *et al.* 1986) and the rocks of the Methow region (Bazard *et al.* 1990) will be considered part of the CC paleomagnetic data base. The reason being that the rocks investigated in these studies are considered to be part of the southern extentions of the major CC belts.

At a glance the first observation that is readily apparent from the CC Cretaceous data up to 1986 is that all the results are discordant with respect to the corresponding cratonic reference directions (Fig 4.2.1). The paleopoles are all far–sided and rotated clockwise from ≈ 0–60° with respect to their reference fields. The obvious question that comes to mind, is, what explanation can be given for these aberrant results? Two possibilities have been advanced in the literature involving either regional tilting in a southwesterly direction or large scale northward translation and clockwise rotation. These apparently conflicting tectonic models gave rise to what has been coined the "tilt vs. translation" controversy. To understand the development of these models and the controversy that surrounds them, it is appropriate to review the the Cretaceous paleomagnetic data up to the time this research began in 1986.

4.2 Review of Cretaceous Data

Intrusives

In terms of Cretaceous paleomagnetic data, the idea of large scale northward translation began with the first Cretaceous paleomagnetic result from the CC from the Mount Stuart batholith (Beck and Noson 1972). Beck and Noson (1972) sampled five sites and following AF demagnetization (principally at 20 mT or less) three sites retained a stable low coercivity magnetization that they

Table 4.1.1

LIST OF CANADIAN CORDILLERAN CRETACEOUS PALEOMAGNETIC STUDIES AND THEIR POLES

Pole	Rock Unit	Age	Locality Lat°	Locality Long°	N/R	N	Demagnetization	TC	Dec°	Inc°	R	k	α95°	PALEOPOLE Lat°	PALEOPOLE Long°	A95° dp°	A95° dm°	RPD°	RR°	Ref.
MS	Mount Stuart Batholith	Late Cretaceous	47.5	-121.0 (≈ 80 Ma)	N	17	2AFp -50-100 mT 1Bulk 10,15,20 mT	No	010.0	45.5	/	53	4.9	68	35	4.0	6.2	27±08	-26±12	(1)
HS	Howe Sound Plutons	≈ 95 Ma Cretaceous	49.5	-123.2	N	17	1AFp 8s-80mT 1Bulk 10,20,30 mT	No	350.8	65.2	16.127	18	7.9	83	129	10.4	12.9	14±10	-17±16	(2)
CS	Stephens Isle.	102 Ma	54.1	-130.7	N	7	[1AFp -100 mT	No	013.0	53.0	6.917	/	7.2	67	-339	7.0	10.0			(3)
	Captain Cove	109 Ma	53.2	-129.4	"	16	[1Bulk r10-55mT	"	021.0	61.0	15.478	/	7.1	72	-9	8.0	11.0			
	Gil Isle.	136 Ma	53.2	-129.3	"	9	[8Thp -650°C	"	029.0	50.0	8.190	/	17.0	59	-4	15.0	23.0			
	Combined Eastern Panel		53.5	-130.0	"	32		"	022.0	56.0	30.399	/	5.9	67	-360	6.0	9.0	30±07	-50±13	
	Banks Isle.	144 Ma	53.2	-129.8	"	8		"	345.0	70.0	7.028	/	22.0	81	-210	33.0	38.0			
EB	Ecstall & Butedale Plutons	≈ 70 Ma	53.3	-129.1	10/5	15	1AFp Bulk 1-2 AF Steps	No	026.0	67.0	14.584	/	7.0	74	-37	9.0	11.0	11±10	-43±18	(4)
AX	Axelgold	≈125 Ma	56.0	-126.0	N	13	AF & Th p#?	[Yes	025.0	69.0	/	70	5.0	76	-33	7.0	8.0	16±07	-57±14	(5)
AX'	Gabbro						Bulk r30-60 mT	[No	032.0	60.0	/	92	4.0	64	-12	5.0	7.0	27±06	-64±12	
TP	Topley Intrusions	≈ 140 Ma	54.0	-125.0	11/4 (2 sites M)	17	Th Bulk 3s -560°C	No	324.2	54.1	/	/	8.6	58	-238	8.3	11.8	31±09	05±14	(6)
TP'	(earlier study Bulk AF steps)					13	1AFp-80mT	No	332.5	63.3	12.338	18	9.1	70	129	11.4	14.4	-	-	(7)
SP	Spuzzum (S) & Porteau (P) Plutons	90-105 Ma	48.5 49.5	-121.5(S) -123.3(P)	N	8	AF & Th p#? Bulk AF & Th?	No	030.3	56.7	/	129	4.9	65	-15	6.2				(8)
SP*	- (alternative interpretation, this study)					12	(combined A1, B1, A3)		020.8	58.7	11.765	47	6.4	50	-122	7.1	9.5	22±08	-47±12	(13)
SC	Skelly Creek	94-99 Ma	49.4	-116.6	N	13	AF & Th p#?	No	349.0	74.0	/	53	6.0	78	-144	9.0	10.0	-1±09	-17±17	(9)
SS	Summit Stock	102 Ma	49.1	-117.0	N	9	Bulk AF & Th	No	048.0	72.0	/	290	3.0	61	-62	5.0	5.0	02±06	-76±11	
	(Tilt corrected SS for 24 W)				N	9	Some PCA	Yes	318.0	74.0	/	290	3.0	64	-166	5.0	6.0	-1±06	14±12	
CV	Crowsnest Fm. Volcanics	Albian 98-113 Ma	49.7	-114.5	N	35s	AF & Th All Stepwise	Yes	349.0	59.0	/	44	5.0	78	108	5.0	7.0	19±06	-18±10	(10)
CGV	Carmacks Group Volcanics	70 Ma	61.0	-135.0 (Broad Area)	2/16	18	AF & Th p#? Bulk AF & Th	Yes	166.7	-71.4	/	53	4.8	82	109	7.8		13±09	-08±21	(11)
SBV	Spences Bridge Group Volcanics	106 Ma	50.0	-122.0 (Broad Area)		17	AF & Th p#? Bulk AF & Th	Yes	038.7	63.9	/	44	5.4	64	321	7.5		16±07	-66±15	(12)
KV	Kasalka Group Volcanics	80 Ma	54.0	-126.9	N	13	AF & Th	Yes	319.5	74.5	/	259	~9	68	-182	13.5	15.1	00±13	22±33	(13)
							All Stepwise PCA	No	-	74.5	(*In situ* Inc from K2 + sites 23,24,25)							00±13	-	
SAO	Sylvester Allochthon Overprint (sediments)	≈ 105 Ma	59.4	-129.8	N	12	1AFp & 1Thp 4Ths-310°C PCA	No	328.3	76.6	11.89	102	4.3	76	172	8.5		07±08	-05±21	(14)

Table 4.1.1 - Continued

Notes: Pole acronyms ending with "V" refers to volcanics, ending with "O" refers to overprint, all others are intrusives; Lat.- North Latitude, Long. - longitude (-ve is west); N/R - Normal to Reverse polarity site ratio, R - all sites reversed, N - all sites normal, M - mixed polarities of unknown ratio; N - Number of sites, *f* - number of flows, *s* - number of samples; Demagnetization - average demagnetization treatment/site, AF - alternating field, Th - thermal, *p* - pilot, #? - number not stated, *s* - steps, *r* - range, PCA - principal component analysis ; TC - bedding tilt correction; Dec - unit mean declination; Inc - unit mean inclination; R - resultant vector sum; *k* - precision parameter; α95 - radius about unit mean direction of 95% confidence; A95 - radius about mean virtual geomagnetic pole (VGP) direction of 95% confidence; dp - is the radius of the ellipse of 95% confidence about the pole along the site-pole great circle, dm - is the radius this ellipse perpendicular to the site-pole great circle; RPD-relative paleolatitude displacement (+ve is North), RR-relative rotations (+ve is counterclockwise) (mid-Cretaceous reference pole 71N 196E α95=5 and Late Cretaceous reference pole 78N 186E α95=8, Globerman and Irving (1988) and Marquis and GLoberman (1988), respectively); Ref.- reference for study.

(1) Beck and Noson 1972, Beck *et al.* 1981; (2) Symons 1973a; (3) Symons 1977a; (4) Symons 1974, Symons 1977b; (5) Monger and Irving 1980, Armstrong *et al.*1985; (6) Symons 1983a; (7) Symons 1973b; (8) Irving *et al.* 1985; (9) Irving and Archibald 1990; (10) Irving *et al.* 1986.; (11) Marquis and Globerman 1988; (12) Irving and Thorkelson 1990 (Abstract Only); (13) This study; (14) Butler *et al.* 1988. Results by Rees *et al.* (1985), Granier *et al.* (1986) and Bazard *et al.* (1990) are not useful for tectonic analyses (See text). Concordant results are reported in abstract only by Globerman (1988) for the South Fork volcanics (SF Fig. 4.2.2).

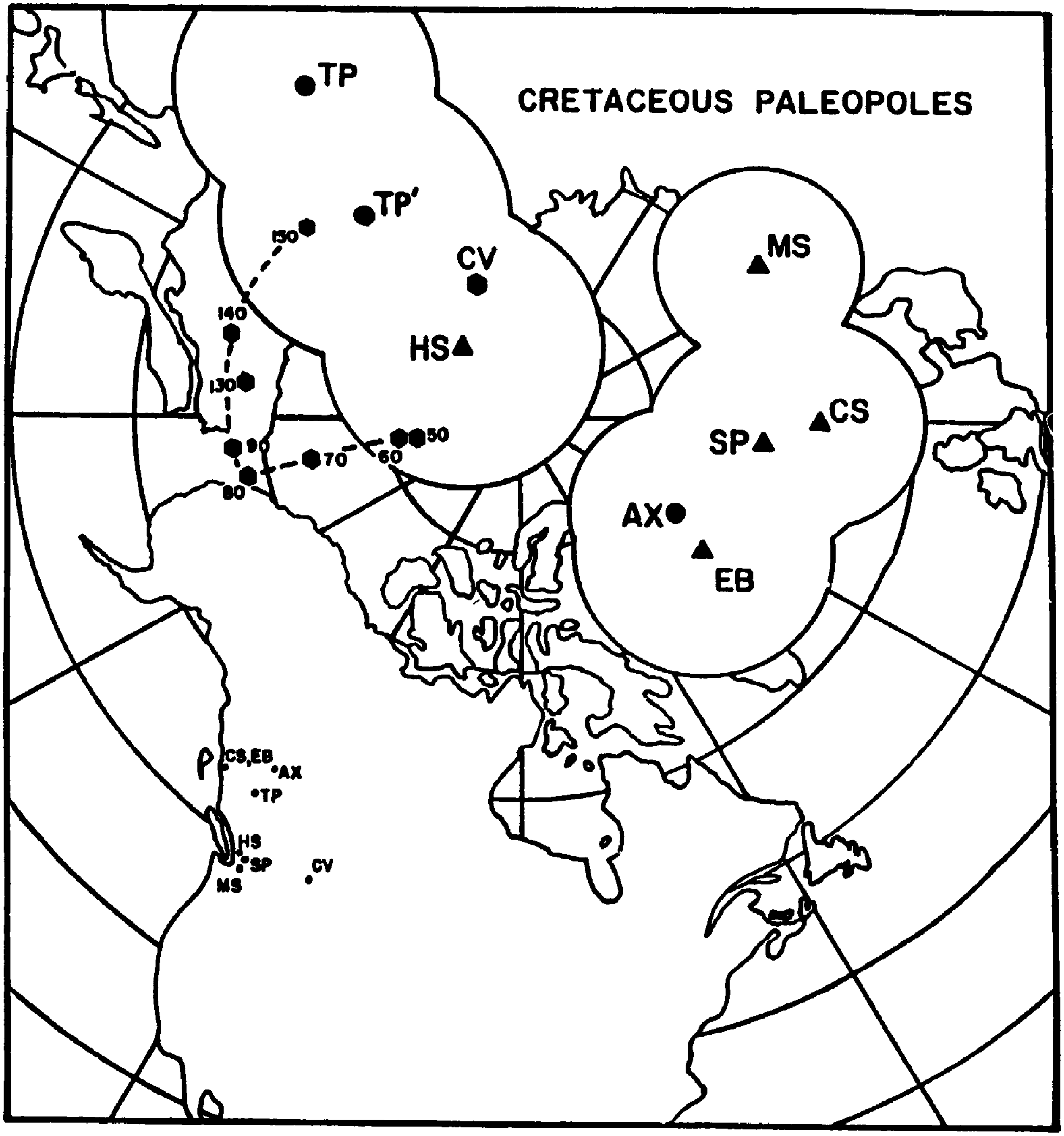

Figure 4.2.1 Cretaceous paleopoles from the CC up to 1986. Dashed line joins the Mesozoic reference poles from Irving and Irving (1982) (ages in Ma). Pole symbols are as follows, triangles – Coast belt, circles – Intermontane belt and hexagon – Foreland belt. See text and Table 4.1.1 for discussion.

interpreted as primary and Upper Cretaceous in age. Due to the large discordancy of the magnetization directions, Beck and Noson (1972) interpreted their results to indicate that the Mount Stuart batholith had originated roughly 25° farther from the Cretaceous reference field, implying that large northward translations had taken place since intrusion. In view of the fact that Beck and Noson's (1972) interpretation was based on an insufficient data base, even by the much more lenient paleomagnetic data standards of the day, their conclusion was extremely speculative. Beck himself (1989b) has stated, "Because so many things can go wrong with any paleomagnetic study, tectonic conclusions based on only a single pole, however well determined, have diminished credibility". Symons (1973a) shortly thereafter provided much more substantial Cretaceous data from 17 sites from the Howe Sound intrusives. AF demagnetization was done in 8 steps to 80 mT on a single specimen from each site followed by optimum AF bulk demagnetization at 10, 20, or 30 mT for the remainder of the specimens from each site. Symons (1973a) argued that the pole position for these sites is not significantly different from Cretaceous poles from the craton at that time and therefore does not support Beck and Noson's (1972) hypothesis of northward tectonic translation of the western Cordillera relative to the craton (HS Fig 4.2.1). However notwithstanding the large statistical errors, there was some disagreement between the Cretaceous reference pole and the Howe Sound pole position. Following a discussion of various alternatives a 15° southwest tilt of the Howe Sound area about a horizontal axis parallel to the Coast Belt was advanced as the most plausible alternative to explain the disagreement. Admittedly this was difficult to test since there is a lack of contemporaneous or younger sediments overlying the plutons (Symons 1973a) but the interpretation and results clearly did not support the conclusions of Beck and Noson (1972).

It is evident that the interpretations of paleomagnetic data from the Howe Sound intrusions (Symons 1973a) and the Mount Stuart batholith (Beck and Noson 1972) both of which are situated in the southern Coast Belt (HS and MS; Fig. 4.2.2) are in direct conflict. As Beck and Noson (1972) pointed out, their displacement model was compatible with one of the models explaining anomalous faunal distributions outlined by Monger and Ross (1971). Nevertheless Monger and Ross (1971) gave three models to explain fusulinacean distribution in CC Paleozoic rocks of which the simplest model involves paleoenvironmental factors only and not tectonic displacement. Thus, with insufficient data from the Mount Stuart batholith Beck and Noson's (1972) results and interpretations were highly speculative. Concurrently, Symons (1973b) reported concordant paleomagnetic results from the Topley intrusions (TP' Fig. 4.2.1) originally assigned a Late Jurassic age but which are now assigned to the Early Cretaceous based on more recent geologic time scales (e.g. Harland *et al.* 1982; Kent and Gradstien 1985). Similarly AF demagnetization was done in 8 steps to 80 mT on a single specimen from each of 13 Topley sites followed by optimum AF bulk demagnetization at 10, 20, or 30 mT for the remainder of the specimens from each site. As the Topley intrusions are situated in mid–central Stikinia in the Intermontane Belt (TP Fig. 4.2.2), these paleomagnetic results added further support to the result from the Howe Sound intrusions. This follows because the Stikine terrane is sutured to the Coast belt by intrusion, and it therefore most likely would have been affected similarly by any subsequent large scale displacement. However, as will be discussed, this result from the Topley intrusives was later superseded by subsequent thermal demagnetization work which updated the data with a significantly different interpretation (Symons 1983a).

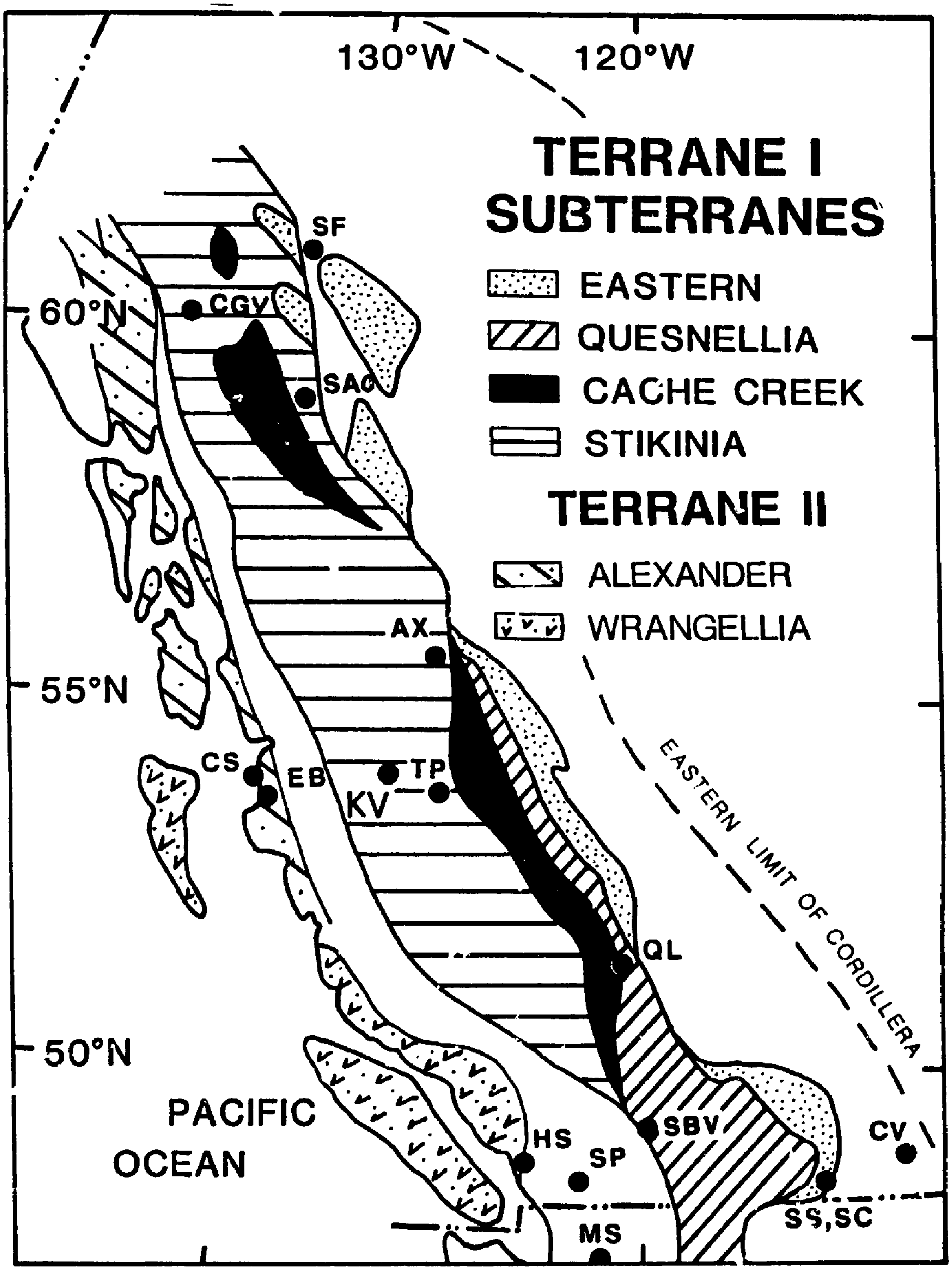

Figure 4.2.2 Cretaceous paleomagnetic study localities in the Canadian Cordillera. Composite Terranes I and II after Monger *et al.* 1982. See text and Table 4.1.1 for explanation and references.

Symons (1974) also studied the Upper Cretaceous Ecstall pluton situated in the central part of the Coast belt (EB Fig. 4.2.2) using similar demagnetization and analysis techniques as before (Table 4.1.1). Here he obtained a discordant paleopole removed from both the Mount Stuart virtual geomagnetic poles (VGP) (Beck and Noson 1972) and the Cretaceous reference direction. Recognizing evidence of tectonic tilting from the distribution of phases in the Ecstall pluton and from the contact and foliation plane attitudes, Symons (1974) concluded that the pluton's discordant pole was the result of postemplacement tilting to the west of ≈ 20°. Subsequently, Symons (1977b) updated the Ecstall pluton pole by combining similar discordant results from the Butedale pluton (EB Figs 4.2.1 and 4.2.2). Again a westward tilting of the plutons was invoked. In that same year Symons (1977a) obtained similar discordant paleomagnetic results from the nearby Captain Cove, Stephens Island, and Gil Island plutons which he combined, refering to them as the Eastern Panel, yielding a discordant mid–Cretaceous paleopole (CS Figs. 4.2.1 and 4.2.2). Both of the studies on the Butedale pluton and the Eastern panel plutons were carried out with similar demagnetization and analysis techniques (EB and CS, Table 4.1.1). Symons (1977a) interpreted that the tectonic panel including these plutons was tilted ≈ 30° to the southwest. This style of deformation was evidenced by the attitudes of contacts and foliations, plutonic trend directions, distribution of metamorphic grades, and consistent paleomagnetic data from the area to the east. In contrast, Symons (1977a) also obtained a concordant pole from the nearby Banks Island pluton to the west, although admittedly it was characterized by poor precision (Table 4.1.1). This intriguing result could be significant but further study is needed to substantiate any interpretation based on these preliminary data. In any event, Symons (1977a) further advanced the tilt hypothesis for all of the studied Cretaceous Coast Belt intrusives. It is important to point out that the tilting described by Symons (1973a, 1974, 1977a) was not regional on the tectonic scale implied later by Irving *et al.* (1985) who suggest uniform tilting of most of the allochthonous CC. Symons' tilting was on a smaller tectonic scale presumably involving small independent fault blocks.

By 1980 Monger and Irving (1980) provided Triassic, Jurassic and Cretaceous paleomagnetic data from the interior of the CC in the Intermontane Belt in support of the northward translation model. They studied the Triassic Takla Group, the Jurassic Hazelton Group and the Cretaceous Axelgold intrusion. As discussed in the preceding chapter the results from the Takla and Hazelton Group have now been shown to be latitudinally concordant. Therefore the evidence for ≈ 1,300 km of northward displacement, as originally outlined by Monger and Irving (1980), is greatly diminished and constrained within a much smaller time frame since only the results from the Axelgold intrusion remain latitudinally discordant (AX Figs. 4.2.1 and 4.2.2). AF demagnetization in the 30–60 mT range isolated a single normal polarity magnetization in the Axelgold intrusion that is consistent with a mid–Cretaceous age (Monger and Irving 1980) Since this age was somewhat uncertain, Armstrong *et al.* (1985) reviewed K–Ar and Rb–Sr dates ranging from 101 to 158 Ma for the Axelgold intrusive to establish that its probable age is 125 Ma with absolute minimum age limits of 115–119 Ma. Thus, the high unblocking temperature range of 500–600°C for the Axelgold intrusion indicates that the magnetization was almost certainly acquired between these limits (Armstrong *et al.* 1985). The outstanding problem is the interpretation of paleohorizontal for the intrusion. Paleohorizontal was estimated from the attitude of cm–scale layering defined by anorthosite and anorthositic gabbro assumed to have been produced by gravity–controlled magmatic currents. Unfortunately by applying a tilt correction to the magnetization a valid tilt test is not possible since layering attitudes are similar, dipping 10–15° to the southwest. Although unlikely, Monger and Irving (1980) suggest it is possible that the layering did not form horizontally, or alternatively the tilting occurred before the aquisition of remanence while the intrusion was still hot. Armstrong *et al.* (1985) reassessed the tilt ambiguity without resolution but did confirm the conclusions of Monger and Irving (1980) that part of the CC lying west of and including the Cache Creek Group, into which the Axelgold complex is intruded, was situated at least 1000 km south of its present position in the Early Cretaceous. This result is in direct conflict with Symons' (1973b) conclusions based on results from the Topley intrusives. In recognition of this conflict Monger and Irving (1980) offered an alternative interpretation of the single magnetic component recognized by Symons (1973b). In their reinterpretation of the paleomagnetic data they distinguish two magnetization components A and B, each in different Topley intrusions. The secondary B magnetization is characterized by only normal polarity within seven sites from three of the intrusions, with a lower mean stability index (Tarling and Symons 1967) (SI=4), and well grouped steep directions directed NW corresponding to a Paleocene cratonic reference direction. The A magnetization is characterized by a higher mean stability index (SI=20), eight sites in four different intrusions, two polarities, and a corresponding paleolatitude and declination scatter that is indistinguishable from discordant results Monger and Irving (1980) observed for the Hazelton. The implications are that the reinterpretation of results from the Topley intrusives indicates that they are in fact consistent with Monger and Irving's (1980) conclusions. As a result, Monger and Irving (1980) advanced the northward translation concept of Beck and Noson

(1972) to explain their discordant Cretaceous paleomagnetic result. Given that Monger and Irving (1980) acknowledged that the Intermontane Belt is attached to the Coast Belt because it is intruded by Coast Belt intrusions, it is curious that they did not challenge Symons' (1973a, 1974, 1977a, 1977b) alternative tilt interpretations. The most apparent reason may be that the ages of the magnetizations from Symons' (1973a, 1974, 1977a, 1977b) studies in the Coast Belt were recognized as being younger than the mid–Cretaceous magnetization age of the Axelgold intrusion and were therefore not in direct conflict with the Intermontane result. As was mentioned earlier and will be discussed below, Symons (1983a) later reinterpreted his original result from the Topley intrusives (Symons 1973b).

Subsequent work by Beck *et al.* (1981) provided much more substantial paleomagnetic data from the Mount Stuart batholith than was provided in the original study (Beck and Noson 1972). The new paleomagnetic results (Beck *et al.* 1981) were obtained by AF demagnetization in the 10 to 25 mT range from 14 reliable sites and combined with the 3 original sites from Beck and Noson (1972) (MS Table 4.1.1). This provided the necessary paleomagnetic data to give credibility to the paleomagnetic results from the Mount Stuart batholith. The new data from the Mount Stuart batholith, not substantially different from the original result, were also markedly far–sided and rotated clockwise from the expected Cretaceous cratonic direction (MS Fig. 4.2.1). Beck *et al.* (1981) considered both tilt and translation models to explain the discordance. However, they favored northward translation and clockwise rotation suggesting that the local geology did not support tilt in the required direction and it probably is not possible for a panel of rock the size of the Mount Stuart batholith to tilt through the necessary angle (35°). As will be discussed, these arguments against tilting of the Mount Stuart batholith are not widely accepted and this gives rise to considerable controversy (e.g. Beck 1980a; Butler *et al.* 1989; Umhoefer and Magloughlin 1990; Butler *et al.* 1990). In any event, an interesting observation is that Beck *et al.* (1981) also did not consider the interpretations of Symons (1973a, 1974, 1977a, 1977b) based on intrusive results from the Coast Belt where evidence of variable tectonic tilts was cited and consistently invoked rather than northward displacement.

Thus the only two discordant Cretaceous paleomagnetic results that have been interpreted in support of northward translation and clockwise rotation at this time were results from the Axelgold intrusion (Monger and Irving 1980) and the Mount Stuart batholith (Beck and Noson 1972; Beck *et al.* 1981). Undoubtedly the understanding at that time of latitudinally displaced Triassic and Jurassic rocks discussed in Chapter 3 obviously had a significant impact on the interpretation of discordant Cretaceous paleomagnetic results.

By 1981 the "tilt vs. translation" controversy was firmly entrenched in the paleomagnetic literature (e.g. Symons 1977a; Monger and Irving 1980; Beck 1980a; Beck *et al.* 1981). Subsequent paleomagnetic studies by Irving *et al.* (1985) and Rees *et al.* (1985) provided further paleomagnetic data directed at resolving the controversy. Irving *et al.* (1985) studied the mid–Cretaceous Spuzzum and Porteau plutons of the Coast Belt (SP Fig. 4.2.2) and following both thermal and AF demagnetization treatment two magnetic components were identified. The A component which is characterized by high coercivities and unblocking temperatures (550–675°C) at eight sites is considered to have been acquired within the age range 105–90 Ma based on U/Pb and K/Ar dating constraints. The B component, which is characterized by high coercivities and a mixture of high (1 site) and low (3 sites) unblocking temperatures, is considered to be a later overprint magnetization caused by regional heating and low grade metasomatism.

One of the sites (4) has been used in both unit means as it has been interpreted to exhibit both A and B components.

There are several reasons why I believe component B was acquired at the same time as A and that it is in fact the same magnetization. The first is that there is a very subtle directional difference between the A and B components. The mid–Cretaceous A direction reported by Irving *et al.* (1985) is directed at (D = 030°, I = 57°, $\alpha95$ = 4.9°, k = 129) which exhibits the highest kappa (129) of all the Cretaceous results thus far discussed (average kappa is $\approx$ 40). This suggests that secular variation may not have been adequately averaged out in the eight sites. If all the magnetizations are grouped together the unit mean from the 11 stable sites (remember site 4 contributes both A and B components) changes very little (D = 021°, I = 58°, $\alpha95$ = 6.4°, k = 47) (Table 4.1.1) but the kappa is reduced and perhaps better averages secular variation. Looking at Table 1 of Irving *et al.* (1985), a comparison of A and B component directions from sites 01 and 09 or 21 and 11 respectively, demonstrates little inclination difference with a subtle declination difference. Site 25 has a relatively steep direction but conversely site 22 and/or 29 has a relatively shallow direction. Also the A and B components in site 4, where the B component is reversed, are almost antipodal as Figure 11 of Irving *et al.* (1985) shows. Thus, the directional distinction between these sites appears indistinguishable if you look at the site means together.

Another distinction drawn between the A and B components (Irving *et al.* (1985) is the low unblocking temperatures of the B component in all specimens from sites 9 and 11, and specimens from 3 reversed cores from site 4. Site 25 which also displays the B component does have high unblocking temperatures, but it is considered anomalous. Although not stated, presumably the 3 reversed and 3 normal cores from site 4 are from different cores (Table 1; Irving *et al.* 1985).

Thus out of the 4 B component sites, only two are uniquely characterized by only low unblocking temperatures and these two sites are within argillites from the Late Jurassic to Early Cretaceous Gambier Group into which the Porteau pluton intruded. Therefore, the lower unblocking temperatures in the argillites could be the consequence of the lower contact temperature in these country rocks as a function of their distance from the contact. Alternatively the contact metamorphism may have produced new minerals, the composition of which resulted in low Curie temperature material. Consequently the lower unblocking temperatures observed in the argillites do not require that the B component was acquired substantially later in time than the A component. Thus, the unblocking temperature distinction between the A and B components in my view is not significant.

Further, if later regional heating was sufficient to completely remagnetize sites in both the Spuzzum and Porteau plutons at the same time, yielding the B magnetization component, this event should have at least partially remagnetized some of the A component sites which are adjacent to B component sites (e.g. Sites 25 and 23, Fig. 2, Irving *et al.* 1985). This does not seem to be the case as was stated (Irving *et al.* 1985) both AF and thermal demagnetization of the A component sites show only simple univectorial magnetizations, and therefore no sign of a later thermal event is present. It is for these reasons that I believe there is no significant distinction between the A and B components and that they are in fact the same magnetization. The slightly different Cretaceous Spuzzum–Porteau direction and pole provided by this reinterpretation is given in Table 4.1.1.

The significance of this reinterpretation is on the direct evidence of a mid–Tertiary remagnetization that could account for Symons (1973a) more nearly concordant result from the Howe Sound intrusives which are adjacent to the north of the Porteau pluton. The Howe Sound result appears to be in direct conflict with the Spuzzum–Porteau result (HS and SP Fig. 4.2.1), and although I question the existence of a later Spuzzum–Porteau Tertiary B component magnetization, I concur in part with Irving *et al.*'s (1985) assessment of the difference between their results. It is possible that a B type component exists but more substantial data in support of its existence are required to demonstrate this, especially in view of the fact that the directional distinction between them may be inherently small. The difference between Irving *et al.*'s (1985) results and Symons' (1973a) results may reflect two different ages of magnetizations and/or differential tilts. Alternatively, it may be due to the more detailed AF and thermal demagnetization techniques used by Irving *et al.* (1985) which more effectively isolated stable end components. It is also possible that the granitic rocks of the Howe Sound intrusives possibly preserve the ancient magnetic field much less faithfully than the mafic and intermediate composition rocks of the Spuzzum and Porteau plutons. As the two results are in direct conflict, the true test of their disagreement would be to resample the Howe Sound intrusives and carry out detailed AF and thermal step demagnetization. By implication this assessment reveals potential ambiguities with regards to other CC paleomagnetic studies in which less than detailed AF and thermal step demagnetization procedures have been followed.

The question remains – how is the discordant Spuzzum and Porteau plutons pole explained? Irving *et al.* (1985) concluded that a composite block made up of Wrangellia, the Coast Plutonic Complex, the Cascade Terrane, Stikinia and perhaps Quesnellia (essentially the Insular, Coast and Intermontane Belts) probably underwent northerly translation of 2400 km and 40–60° of clockwise rotation relative to North America after the mid–Cretaceous and before mid–Teriary time. This interpretation was based on the interpreted regional consistency of paleomagnetic data which argues against regional tilt because it would require uniform tilting of most of the allochthonous CC. However, recall that the tilting described by Symons did not invoke uniform regional tilting. In addition, the regional consistency of paleomagnetic data as suggested by Irving *et al.* (1985) depended on data selection and rejection critieria and is therefore not straightforward. Thus as Irving *et al.* (1985) concluded, the "tilt vs. translation" problem had not been resolved and further paleomagnetic observations are necessary to study the regional consistency of magnetizations.

In Rees *et al.*'s (1985) study they hoped to isolate a primary magnetization in Triassic–Jurassic volcaniclastic rocks in the Quesnel terrane but unfortunately the high stability magnetizations (> 600°C, >50 mT) showed no general coherence over the rock unit as a whole. In contrast, they found that their removed magnetizations of intermediate unblocking temperatures (200–500°C) and coercivities (30–50 mT) are systematically directed northeast and downward. They concluded that this result provides a secondary overprint magnetization that was aquired as a result of mid–Cretaceous plutonism during the Cretaceous normal superchron. However, these removed directions are only marginally different from the present Earth's field. Furthermore they are only recorded in 22 of the 93 studied specimens. Also we are not told about the directional nature of the removed components from the remaining 71 specimens. This could be an important result but much more data would have to be obtained before interpretations based on them would have credibility.

Reinterpreted Results and Their Implications

As was mentioned earlier, in view of the conflict between the results and interpretations from the Axelgold intrusion and the Topley intrusives, Symons (1983a) reinterpreted his original result (Symons 1973b) from the Topley intrusives. The original result was based primarly on relatively low field AF demagnetization treatments (Table 4.1.1) therefore Symons (1983a) carried out subsequent thermal bulk demagnetization on the same specimen collection at 200, 450 and 560°C. Symons' (1983a) reanalysis provided a significantly different unit mean direction characterized by high unblocking temperatures, presumably having removed the secondary B type Paleocene magnetization Monger and Irving (1980) had suggested was present in the original results. The updated unit mean provides a far–sided discordant 142 Ma paleomagnetic pole (TP Fig. 4.2.1) which now supports Monger and Irving's (1980) earlier interpretation for northward translation although no rotation is suggested. However, Figure 2e of Symons (1983a) depicts a stereoplot of contoured specimen directions (demagnetized at 560°C) which shows a marked streaking or elongate distribution of directions from which the new Topley unit mean was calculated. Unfortunately as pointed out by Beck (1989b), elongate distribution of directions can signify many potential problems. A couple of common problems involved may include sampling of too much time thereby catching polar wander at work, or the magnetic cleaning was not sufficent to isolate the components. It is possible this result is a reasonable representation of the Early Cretaceous field but this observation argues against that. The true test of this result will come from internal consistency of directions from independent studies of other Early Cretaceous rocks. Unfortunately this consistency does not yet exist in the Cretaceous CC paleomagnetic data base, and therefore the interpretations based on these results remain problematical. What this reanalysis does provide however, is unequivocal evidence that the original AF demagnetization treatments and analysis techniques were not successful in isolating the primary magnetization direction. Similar reanalysis of paleomagnetic results from the Jurassic Guichon batholith (Symons 1983b) and Copper Mountain intrusives (Symons and Litalien 1984) provides further evidence of unsuccessfully isolated primary magnetizations.

Inasmuch as the demagnetization and analysis techniques employed by scientists working in the Cordillera were widely used and accepted by most workers in paleomagnetism of the day, it is unlikely that this problem with incompletely isolated magnetization components was expected. Notwithstanding, the instrumentation limitations at that time made routine detailed step demagnetization impractical. Thus, this series of reanalyzed paleomagnetic results serve well to illustrate the limitations of widely used demagnetization and analysis techniques in the 1960's, and 70's. Explicitly the method in question employs a representative test specimen (often described as a pilot specimen) for establishing either AF or thermal demagnetization character for the whole site by the use of detailed step demagnetization procedures. Initially a pilot specimen is selected because it is representative of the overall site NRM direction and intensity. However, by association some workers have also implied that a pilot specimen is also representative of the demagnetization character for all the specimens in a site. I submit that the term "representative" may be misleading since one has no step demagnetization data to begin with, and to then decide which specimen in the site is "representative" of the demagnetization character of the remaining specimens seems presumptuous. Nevertheless, following step demagnetization of a "representative" specimen one establishes "optimum" bulk demagnetization treatments for the remainder of specimens from a site. This procedure will work with magnetically homogeneous sites, but does break down in lithologically inhomogeneous sites and/or sites with multicomponent magnetizations and/or noisy demagnetization behaviours. Following the "optimum" bulk demagnetization, individual specimen directions are used to calculate site means

(Fisher 1953). In some cases where more than one bulk demagnetization step has been done, site means are calculated from specimen directions for each demagnetization step. Following this, the demagnetization treatment providing minimum site mean dispersion is selected to represent the magnetic direction for that site in a subsequent unit mean calculation.

In a study where the rocks exhibit a single magnetic component with high magnetic stability that responds well to demagnetization, this type of treatment and analysis is likely to be faster and just as effective as the more modern approach taken in this study (step demagnetization of each specimen combined with least squares principle component analysis (PCA)). The obvious problem in my experience is that the most ideal looking rocks can often be riddled with unforseen magnetic complications which can go unrecognized without detailed step demagnetization and PCA of each specimen. The consequence of not following this procedure can lead to incompletely resolved magnetization components which give rise to hybrid magnetic directions which are tectonically meaningless. Even in an apparently straightforward study if one does not employ detailed step demagnetization for each specimen, preferably combined with PCA analysis techniques, the results are open to question by the "what if" scenario. "What if" the rocks had been treated by detailed step demagnetization for each specimen combined with PCA analysis techniques, would the results be appreciably different? Appropriately the burden of proof is always on the shoulders of the investigator. Thus, rather than make assumptions on the stability and demagnetization character of specimens within a site, based on the detailed demagnetization of one or two companion specimens, while carrying out a method which already relies heavily on several fundamental assumptions, it is more scientifically prudent to carry out detailed step demagnetization on each specimen studied. As Hillhouse (1989) points out, detailed demagnetization with PCA techniques reveals the components that make up the total magnetization and ensure that a stable magnetic direction has been isolated in each rock specimen. Obviously this was logistically impractical with earlier instrumentation limitations but advances in instrumentation and computer technology have been made which significantly simplify and speed up the measuring-demagnetization processes. This of course assumes one has access to more modern equipment. Thus, this changes the once impractical routine detailed demagnetization into the practical.

The reanalyses by Symons (1983b, 1983a) on the Topley intrusives and the Guichon Batholith, and Symons and Litalien (1984) on the Copper Mountain intrusives demonstrates that their original results provided hybrid magnetizations which reflect the incompletely resolved primary magnetization components. The arguments by Rees *et al.* (1985) and others, that the original results from the Guichon batholith and the Copper Mountain intrusives represent Cretaceous remagnetization directions, do not consider the hybrid nature of these unresolved magnetizations which makes them tectonically meaningless. Therefore, the original results from these intrusives cannot be included as representations of any meaningful paleomagnetic field. In addition, suggestions that both the updated results from the Guichon Batholith (Symons 1983b) and the Copper Mountain intrusives (Symons and Litalien 1984) exhibit mid–Cretaceous paleomagnetic directions seem to be unsupported since both are characterized by K/Ar dates of ≈ 200 Ma, and both preserve normal and reverse polarities inconsistent with magnetization during the mid–Cretaceous normal superchron.

Bedded Volcanic Rocks

So far this review of the CC Cretaceous paleomagnetic data has not included results from bedded rocks. By 1986 no studies had been reported from

Cretaceous bedded sedimentary rocks and only two studies had been carried out on Cretaceous bedded volcanic rocks. One from the Crowsnest Formation (Irving *et al.* 1986), situated on the deformed cratonic Foreland Belt (CV Fig. 4.1.2), and the second from the Winthrop and Midnight Peak Formations (Granirer *et al.* 1986), situated in the southern Intermontane Belt. Given that the Crowsnest Formation lies within the thrust sheets of the Foreland Belt situated east of the allochthonous CC terranes, concordant or nearly concordant paleomagnetic results were expected from this study since the generally accepted geologic development (e.g. Norris 1964, Price 1981) suggests that the thrust sheets moved a maximum of only 200 km from the southwest or west. It was with some surprise that the results from the Crowsnest Formation were in fact quite discordant (CV Table 4.1.1 and Fig. 4.2.1). Several explanations were offered that might account for the discordancy but Irving *et al.*'s (1986) preferred interpretation was that the Crowsnest Formation had formed close to its present position relative to the craton but was deposited so quickly that the paleosecular variation was not adequately sampled, and the result is an aberrant "spot" reading of the paleofield. The second paleomagnetic study on bedded volcanics of the Winthrop and Midnight Peak Formations (Granirer *et al.* 1986), situated in the southern Intermontane Belt much of which is thought to be allochthonous, provided another discordant paleopole. Given the allochthonous nature of the sampling region which has yielded previously reported discordant paleomagnetic results from intrusives, a discordant result was not entirely unexpected. Unfortunately the magnetization may have been acquired during folding because restoring the beds by only one half of the apparent tilt brings the unit mean (k) to a maximum. Thus the upper age limit of magnetization is uncertain, and as outlined by Bazard *et al.* (1990) who provided a much more thorough analysis of the paleomagnetism of the

Methow–Pasayten belt, the remagnetizations and structural complications in the Methow region prevent straightforward interpretation and therefore the results from the region must be viewed with extreme caution. Inasmuch as the results from the Crowsnest Formation and the Methow–Pasayten belt may raise more questions than they answer, they do contribute important observations that serve as excellent examples of the kind of complications which arise in studying the paleomagnetism of complicated orogenic terranes. It is quite possible that complications like these may affect other CC paleomagnetic results and as of yet have been unrecognized.

Review Summary

The most readily apparent problem with the CC Cretaceous paleomagnetic data base up to 1986 is that not one of the studies provides a simple, straightforward and unequivocal interpretation. The consistency of paleomagnetic poles from the CC that can reasonably be considered representative of the Cretaceous is arguably poor, and several unresolved conflicting results exist. The reanalyses by Symons (1983b, 1983a) on the Topley intrusives and the Guichon Batholith, and Symons and Litalien (1984) on the Copper Mountain intrusives demonstrates that the original results on these intrusives provided hybrid magnetizations which reflect the incompletely resolved primary magnetization components. Indeed as discussed by Hillhouse (1989), a serious problem in determining paleomagnetic poles from orogenic belts is the removal of secondary magnetic components that mask the primary magnetization. Clearly the above reanalyses testify to the fact that without detailed AF and/or thermal step demagnetization on each specimen, preferably combined with PCA techniques, primary and secondary magnetization components may not be resolved with sufficient precision to adequately define poles useful for intracontinental tectonic studies. Thus many of the results herein discussed are open to question by the "what if" scenario. "What if" the rocks had been treated by detailed AF and thermal step demagnetization for each specimen combined with PCA techniques, would the results be appreciably different?

With the relatively poor consistency and apparent conflict among results from the Cretaceous data base, some interpretations based on these data may require revision. This is not surprising given the complicated and difficult geologic setting with which workers have had to contend, in addition to the changing northward displacement model with respect to the Permian to Early Jurassic data. Nevertheless two distinctly different interpretations of the data have emerged which appear to be in conflict. Symons consistently invoked local tilting to explain his discordant directions from the Coast belt intrusive rocks. A variation there of suggests that tilting was regionally uniform for a large part of the western CC, which could explain similar discordant results from the Intermontane belt (e.g. Irving *et al.* 1985). However, such extensive uniform tilting seems geologically implausible. Thus, alternatively Irving *et al.* (1985) and others prefer large–scale post mid–Cretaceous northward displacement combined with systematic clockwise rotation to explain the discordant results. Decidedly there are complexities which preclude straightforward interpretation of the Cretaceous data base. As Irving *et al.* (1986) discovered, even the most fundamental assumption of adequately averaging of secular variation can be a significant problem. It is clear that in order to contribute useful paleomagnetic data any new result and interpretation must be as unequivocal as possible. With the lack of definitive well dated paleomagnetic data from bedded volcanic rocks in the CC, this is an obvious target for study which under the right conditions can offer the greatest potential for resolving the "tilt vs. displacement" controversy. For this reason the Upper Cretaceous Kasalka Group was selected for study by virtue of its volcanic affinity, good age control and location in mid–central Stikinia.

4.3 Geology and Sampling

The paleomagnetic sampling for this study has been carried out at three localities, all of which are situated in mid–central Stikinia within the Intermontane belt. The rock units studied are part of the Upper Cretaceous Kasalka Group that was originally defined by MacIntyre (1976) in the Tahtsa Lake District. MacIntyre (1976, 1985) describes the Group as a continental volcanic succession that is comprised of predominantly porphyritic andesite and associated volcaniclastic rocks. The Kasalka Group overlies with angular unconformity the Skeena and Hazelton Groups (MacIntyre 1985) and is cut by Late Cretaceous intrusions. The Kasalka Group is therefore younger than Albian or Early Cretaceous and K/Ar isotopic ages reported by MacIntyre (1985) and L. J. Diakow (Personal Communication 1990; British Columbia Ministry of Energy, Mines and Petroleum Resources, unpublished Kasalka K/Ar dates) indicate that the Kasalka Group spans the Late Cretaceous. Although volcanic rocks of similar age and lithology are not widespread in mid–central Stikinia, MacIntyre (1985) points out that possible correlatives to the Kasalka Group are the Tip Top Hill volcanics near Owen Lake (Church 1970, 1972) and the Brian Boru Formation of the Telkwa Range (Sutherland Brown 1960). In addition, subsequent detailed mapping in the Babine and Telkwa Ranges (MacIntyre *et al.* 1987; MacIntyre and Desjardins 1988; MacIntyre *et al.* 1989), and in the Whitesail Lake area to the south (Diakow and Koyanagi 1988; Diakow and Mihalynuk 1987; Diakow and Drobe 1989) have outlined volcanic rocks of similar age and lithology which have been mapped as the Kasalka Group. Since outcrop of the Kasalka Group is somewhat less than ideal and access to exposures is logistically difficult, the sampling for this study was designed as a reconnaissance project to sample the volcanic rocks at three test localities: the Mount Cronin area (K1), the Owen Lake area (K2) and the Nadina Lake area (K3) (Fig. 4.3.1). Note the Kasalka Group exposures are small in a regional sense and were not distinguished by the regional mapping compilation by Tipper *et al.* (1981), and therefore these localities appear to be within the Ootsa Lake Group and the Skeena Group. The sites were collected in the three areas to characterize the remanence stability and to establish if rocks in these areas retain a stable primary remanence. Future sampling was, and is, planned to increase the quantity and quality of the Kasalka Group paleomagnetic data.

The Mount Cronin area (K1), approximately 12 km northeast of Smithers (Fig. 4.3.1), is part of the Babine Range which is a northwest–trending horst of folded and faulted Jurassic and Cretaceous rocks. The Cretaceous and Tertiary volcanic rocks have been affected by a very young compressional tectonic event which appears to be unique to the Babine Range (MacIntyre and Desjardins 1988). This event may be related to transpressional tectonics where opposing transcurrent movement on bounding faults may have occurred. This is not the ideal geologic setting for obtaining primary magnetic directions with good structural control. However, since an ideal Kasalka Group stratigraphic section suitable for paleomagnetic study has yet to be discovered one is obliged to work in less than ideal settings. Six sites were collected in this area in maroon and grey crystal tuffs and porphyritic andesite flows. Samples for each site were drilled from isolated outcrops since no accessible stratigraphic sections were available. Thus, stratigraphic relationships between some of the sites are uncertain. Moderate bedding dips were measured at or near three of the sites with bedding attitudes

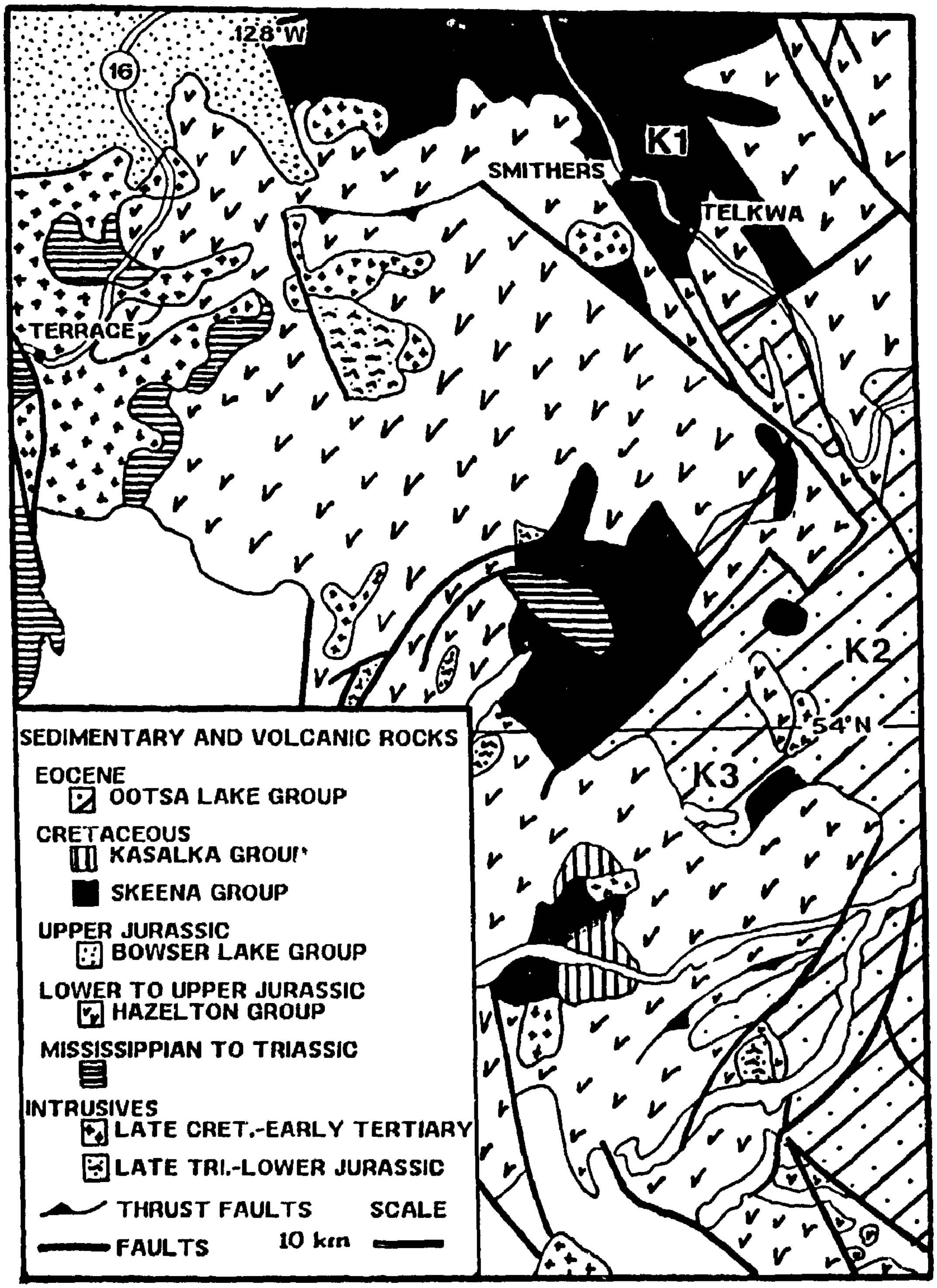

Figure 4.3.1 Regional geologic setting of the Kasalka Group localities. K1–Mount Cronin, K2–Owen Lake and K3–Nadina Lake areas. Note the geologic mapping on this scale does not distinguish the Kasalka Group at these localities. Geology simplified from Tipper *et al.* (1981).

interpolated for the remaining three sites. Fresh rock exposures in the area are rare because much of the area is covered by talus.

The Owen Lake area (K2) (Fig. 4.3.1) is well to the south in the Whitesail Lake map area. In this area Church (1970, 1972) originally mapped the Upper Cretaceous Tip Top Hill volcanic rocks which are a continental assemblage of volcanic rocks and contemporaneous intrusions. As mentioned previously, MacIntyre (1985) indicated the Tip Top Hill volcanic rocks were possible correlatives to the Kasalka Group. C. Leitch and co–workers (Personal communication 1989; Unpublished data, University of British Columbia, Department of Geology) who have conducted more recent mapping have adopted the correlation with the Kasalka Group. The Tip Top Hill rocks include porphyritic andesite, dacite, and rhyolite flows which have yielded a K/Ar date of 77 Ma (Carter 1981). Eight sites were collected from a small ≈ 100 m stratigraphic homoclinal succession composed of intercalated bladed–feldspar porphyry andesite flows characterized by a moderately shallow westward dip. The succession is part of an erosional remanent with intermittent vegetative cover which stands as a topographic knoll 100 m above the adjacent lower lying area. In hand sample, the feldspars in the andesites are fresh in appearance, and since outcrops are free from substantial weathering these rocks are likely to be good magnetic recorders. Unfortunately exposure in the accessible area is limited and no other suitable sampling sites were located.

The third sample area at Nadina Lake (K3) (Fig. 4.3.1) is located still further south southwest of the Owen Lake area. Recently Diakow and Drobe (1989) mapped this area (1:50000 scale) as part of the Newcombe Lake map sheet which is immediately north of the Tahtsa Lake District where MacIntyre (1985) first described the Kasalka Group volcanic rocks. Eleven sites were collected along the shoreline of Nadina lake at isolated outcrops of varying strike and dip. In common with the Mount Cronin area stratigraphic relationships among many sites are uncertain. All sites were drilled in gray to green andesite flows bearing platy plagioclase phenocrysts except at site 19 where a rhyolite flow was sampled. Unlike the fresh feldspar porphyry Tip Top flows, many of these andesites appeared more deeply weathered.

4.4 Methods

The Kasalka Formation was sampled at three study localities as discussed above. the Mount Cronin area, the Owen Lake area and the Nadina Lake area. In total, 25 paleomagnetic sites were collected in subhorizontal to moderately steep dipping flows using a portable drill. At least five cores were drilled and oriented by magnetic and/or solar compass at each site. Bedding attitudes were measured at or near each site where possible, and interpolated between sites and known structure from available mapping in the absence of nearby attitudes. In the laboratory two specimens were cut from each core. The specimens were analyzed using a Schonstedt DSM–1 spinner magnetometer, Schonstedt GSD–5 tumbling alternating field demagnetizer and a Schonstedt TSD–1 thermal demagnetizer. After measuring the natural remanent magnetization (NRM), each specimen was subjected to detailed alternating field (AF) and/or thermal stepwise demagnetization in up to 14 steps. The number of AF demagnetized specimens relative to thermal demagnetized specimens was in the approximate ratio of five to one. Alternating field demagnetization was done up to maximum fields of 100 mT and thermal demagnetization was done up to peak temperatures of 700°C. Characteristic remanence directions in each specimen were obtained by a joint analysis of stereographic and orthogonal demagnetization diagrams and least squares principal component analysis following the method of Kirschvink (1980). Directions of remanence were accepted with a mean angular deviation (MAD) < 10° most of which were < 5°. The site mean remanence directions were calculated using conventional tiered statistics (Fisher 1953; Irving 1964).

***SIRM* Experiments**

Specimens representative of the variety of lithologies and different magnetic characters from each of the three sample localities, including specimens exhibiting different degrees of weathering, were subjected to saturation isothermal remanent magnetization (SIRM) and demagnetization experiments. The specimens chosen had previously been subjected to stepwise AF demagnetization to 100 mT significantly reducing their NRM. The experiments were carried out at the Univesity of Windsor where each specimen was remagnetized along the *z* axis in a pulse DC field at steps of 10, 20, 40, 80, 160, 250, 350, 500 and 900 mT, progressively building up a strong IRM using a Sapphire Instruments SI–6 pulse magnetizer. Following each remagnetization step the large magnitude SIRM intensities were measured using a Sapphire Instruments SI–5 spinner magnetometer. The acquired SIRM was then AF demagnetized using a Sapphire Instruments SI–4 AF demagnetizer at 10, 20, 30, 40 and 50 mT.

4.5 Results

Orthogonal vector decay and stereographic plots were produced for each specimen and the data from most specimens were of very good quality exhibiting stable linear vector decay towards the origin. A few specimens exhibited removal of low coercivity and low unblocking temperature viscous components. The data from five sites had to be abandoned, either because of extreme within site dispersion due to stable but varied within site directions (site 3), or extremely weak NRM intensities of the order of 0.1 mAm$-^{1}$ (sites 15, 16, 19 and 21). Between–locality demagnetization characteristics varied.

Specimens from the Mount Cronin area, within sites 1, 2, 4, 5 and 6, displayed very stable directions upon both AF and thermal demagnetization. Changes in direction and intensity were small for each specimen during step demagnetization except near the high unblocking temperatures (625–675° C) in thermally demagnetized specimens where directions changed and intensities decayed substantially (Fig. 4.5.1 and 4.5.2). The intensity decay curves illustrate the characteristic hard magnetization which exhibits coercivities in excess of 100 mT (Fig. 4.5.1) and high unblocking temperatures in excess of 625° C (Fig. 4.5.2), typical of hematite. These *in situ* directions are all normal polarity components which systematically exhibit steep inclinations with varied declinations.

In contrast, the behavior of specimens from the Owen Lake area, sites 7 to 14, displayed substantial and linear decay towards the origin after the removal, in some specimens, of initial low coercivity and low unblocking temperature viscous components (Fig. 4.5.3). The AF demagnetized specimen from site 13 (Fig. 4.5.3 a and b) isolates the characteristic stable component but shows the initial removal of a large upward directed viscous magnetization aquired during storage while the specimen was inverted. Alternating fields of 100 mT in most specimens removed at least 80 to 90 percent of the original NRM and the characteristic magnetization direction was unblocked by temperatures in the 550–580° C range, typical of magnetite. Figures 4.5.3 f and g show a companion specimen from site 13 in which the characteristic stable direction was retained just above 600° C suggesting that some hematite is present. The characteristic *in situ* normal polarity directions are very well grouped, consistently dipping steeply to the north–northeast (Fig. 4.5.3).

The demagnetization behavior from specimens within the Nadina Lake area, sites 17, 18, 20, 22, 23, 24 and 25, are intermediate relative to those from the Mount Cronin and Owen Lake areas. Many specimens display linear but moderate decay towards the origin after the removal, in some specimens, of initial low coercivity and low unblocking temperature viscous components (Fig. 4.5.4). Alternating fields of 100 mT in these specimens removed between 50 to 90 percent of the original NRM and thermal unblocking temperatures were in the 550–625°C range typical of magnetite and hematite (Fig. 4.5.4). Unlike the the Mount Cronin and Owen Lake areas which exhibit tighter grouping of their *in situ* directions, this area exhibits scattered *in situ* directions as show in Figure 4.5.4 b, c, e, f and h.

The site means and unit means calculated separately for each sample area are shown in Tables 4.5.1 and 4.5.2. Only downward directed stable remanence directions were isolated in the 20 sites providing quality data. The *in situ* site mean directions from the rocks in the Mount Cronin area dip steeply and are loosely grouped about the vertical displaying varied declinations (Fig. 4.5.5). In contrast, the *in situ* site means from the Owen Lake area are very tightly grouped dipping steeply to the north northeast (Fig.4.5.6 a). Although the within–area *in situ* site means are at least reasonably grouped in the Mount Cronin and Owen Lake areas, between areas, their unit mean directions and corresponding site mean dispersions are significantly different (Table 4.5.2). In the Nadina Lake area, *in situ* site mean directions are poorly grouped (Fig. 4.5.6 b). Sites 23, 24 and 25 as a group appear to exhibit a steep northwest direction very close to that expected for a concordant Late Cretaceous magnetization. In contrast, sites 17 and 18 are directed east northeast and shallow, and sites 22 and 20 are directed north and south of east, respectively, with moderate inclinations. The three *in situ* site mean groups K1, K2, and K3 appear quite different exhibiting a variety of magnetic directions.

The bedding attitudes for each site are given in Table 4.5.1 with a three tiered qualitative reliability ranking. The tilt corrected site means shown in Table 4.5.1 have been determined by applying full bedding attitude corrections in each case. In the Mount Cronin Area (K1), the before and after tilt correction unit means are quite different (Table 4.5.2). There is a significant increase in site mean dispersion as an increasing percentage of the tilt is applied reaching maximum dispersion at full tilt correction (Fig. 4.5.5). The kappa from the uncorrected unit mean is 23 which progressively drops to a minimum at 3 following full tilt correction. This indicates a negative tilt test at the 95% confidence level (McElhinny 1964; McFadden and Jones 1981) demonstrating that the magnetization isolated in the five sites from the Mount Cronin area is post–folding, and therefore a secondary magnetization component. Given the characteristically high coercivity of this magnetization (>>100mT), combined with its high unblocking temperatures, this magnetization is likely to have been aquired chemically by the alteration of the original magnetic mineralogy by subsequent reheating and hydrothermal fluids. The AF and thermal demagnetization characteristics (Figs. 4.5.1 and 4.5.2), as well as the results from the SIRM experiments (Fig. 4.5.7 a) from the Mount Cronin Area indicate that magnetite, which was probably part of the original mineralogy, is no longer present. The alteration was probably a consequence of the Tertiary compressional tectonic event which is unique to the area (MacIntyre and Desjardins 1988). Thus, one would expect a Tertiary overprint direction to be steeply dipping to the north. Although the Mount Cronin remanence direction dips very steeply, it is not directed in the expected north Tertiary direction (Fig. 4.5.5). This suggests that the area containing the sampling sites, which is known to be part of a horst block (MacIntyre and Desjardins 1988), has been tilted ≈ 20° to the north northwest. Alternatively, since there are only five sites, secular variation may not have been averaged out. In any event it is improbable that this magnetization records the Late Cretaceous magnetic field.

In the Owen Lake Area (K2), the before and after tilt correction unit mean dispersions are low and unchanged because all eight sites are part of the same homoclinal succesion (Table 4.5.1 and Fig. 4.5.6 a). Unfortunately the tilt test in this case cannot distinguish if the magnetization is pre– or post–folding. However, the relatively fresh appearance of feldspars in these andesites strongly suggests the rocks have not undergone substantial alteration, and therefore the magnetization in these rocks is primary and close to the K/Ar Late Cretaceous rock age. The presence of abundant fine grained opaques (too small to identify) in polished section which magnetically behave like magnetite and titanomagnetite (Figs. 4.5.3 and 4.5.7 b) supports this conclusion. Thus, the primary magnetization in these lava flows was most likely acquired before the westward tilting of 25° took place. Its improbable that the 25° westward dip reflects a primary flow attitude in these intermediate composition rocks that would have been moderately fluid magmas. However, some portion of their present attitude may be a primary feature.

In the Nadina Lake Area (K3), the *in situ* site means exhibit several different directions that are widely dispersed (Fig. 4.5.6 b). This feature in itself argues against the presence of a post–folding secondary overprint unlike the rocks from the Mount Cronin area. After applying full tilt correction to each site, two distinct magnetic directions appear (Fig. 4.5.6 b) (Refered to as *A* and *B* in Table 4.5.1). For the sake of facilitating discussion sites 20 and 22 are considered to be a distinct magnetization *B*, however in reality they are only distinctly different from

A. Herein the steeper component is refered to as *A* and the shallower component is refered to as *B*. Magnetically the *A* and *B* components appear similar because representative specimens of both directions exhibit similar high coercivity (>100mT) AF step demagnetization characteristics (e.g. Figs. 4.5.4 **a** and **e**). In contrast sites 23, 24 and 25 representative of the *A* component, do respond better to AF demagnetization with specimens commonly losing 90% of their NRM by 100 mT. No specimens exhibiting component *B* show this behavior. This suggests that both magnetite and hematite may carry the *A* component and this is supported by thermal demagnetization data (Fig. 4.5.4 **b** and **c**). In contrast, only hematite may carry the *B* component. However, single domain magnetite has high coercivities in the ranges exhibited by both *A* and *B*. The critical test that could be provided for component *B*, by thermal demagnetization, is lacking since sufficient unglued cores are not available from sites 20 and 22. Also it was hoped comparisons could be made between specimens from the *A* and *B* component sites with the SIRM experiments but the critical specimens were unsuccessfully measured during the SIRM build up due to instrumentation problems. Thus the available AF step demagnetization data can only tentatively be distinguish between the *A* and *B* components as many more sites are needed to conclusively establish if the *B* component does represent magnetization at a different time than *A*. One explanation that may account, in part, for the different *B* component direction that cannot be ruled out is incorrectly assigned bedding attitudes. As indicated the bedding attitudes have only a fair reliability rating for almost all the sites in the Nadina Lake Area. This problem could be significant but without further fieldwork it cannot be assessed. Another potential problem is secular variation since so few sites are represented and unit mean dispersions are very low (Table 4.5.2). In any event the *A* component unit mean dispersion improves dramatically to a maximum after full tilt correction from a kappa of 5 to 146 (Table 4.5.2). This indicates a positive tilt test well above the 95% confidence level (McElhinny 1964; McFadden and Jones 1981) demonstrating that the *A* component isolated in the five sites from the Nadina Lake area is pre–folding, and therefore likely to be a primary magnetization of Late Cretaceous age. The example SIRM acquisition and demagnetization curves for specimens preserving component *A* exhibit pseudosingle to single domain magnetite behavior (Fig. 4.5.7 c, d and e) which demonstrates the ability of these rocks to preserve a stable primary magnetic direction.

4.6 Discussion

Unlike the controversy with the Early Jurassic reference pole, the positions of the mid– and Late Cretaceous North American reference poles have been recently updated (e.g. Globerman and Irving 1988; Marquis and Globerman 1988) using the preferred technique discussed in Chapter 3. As the pole positions have changed little, further discussion of the Cretaceous reference field is beyond the needs of this study.

In the earlier review of the CC Cretaceous paleomagnetic data the point was made that all the results obtained thus far were discordant, most greatly so, with respect the the North American reference frame. The sites in the Cretaceous Kasalka Group rocks were selected with the intention of obtaining reconnaissance studies on the magnetic stability and character of three test localities, with the intention of doing more comprehensive future sampling in the area(s) that exhibit probable primary magnetizations. With this in mind, these results were quite successful in demonstrating that very stable, high coercivity and high unblocking temperature probable primary magnetizations have been preserved in the Kasalka

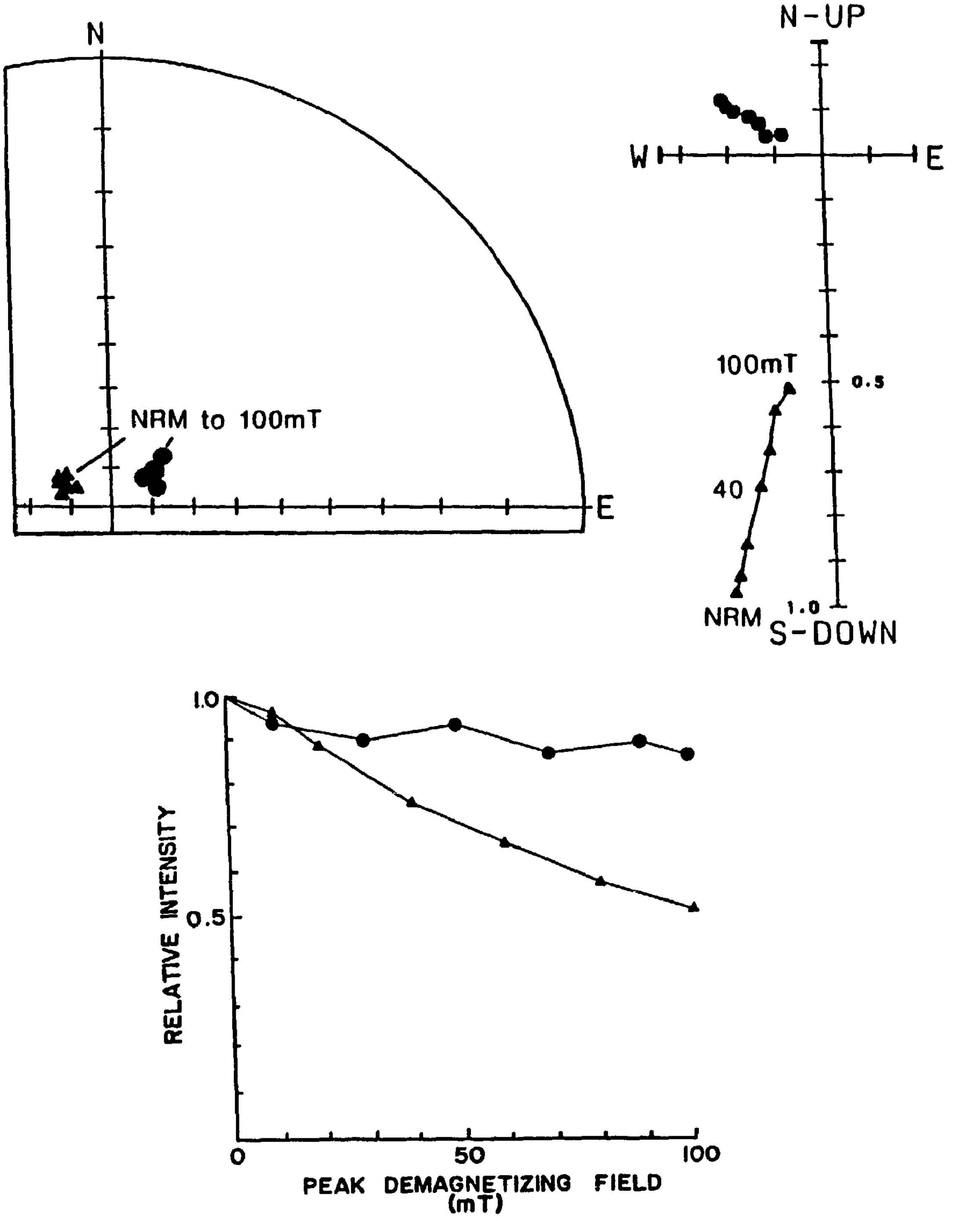

Figure 4.5.1 *In situ* direction changes, orthogonal plot and intensity decay curves from example AF demagnetized specimens from the Mount Cronin area. Circles–specimen from site 2, Triangles–specimen from site 4. Circles and triangles on orthogonal plot represent vector projections on the horizontal and vertical planes respectively for specimen from site 4.

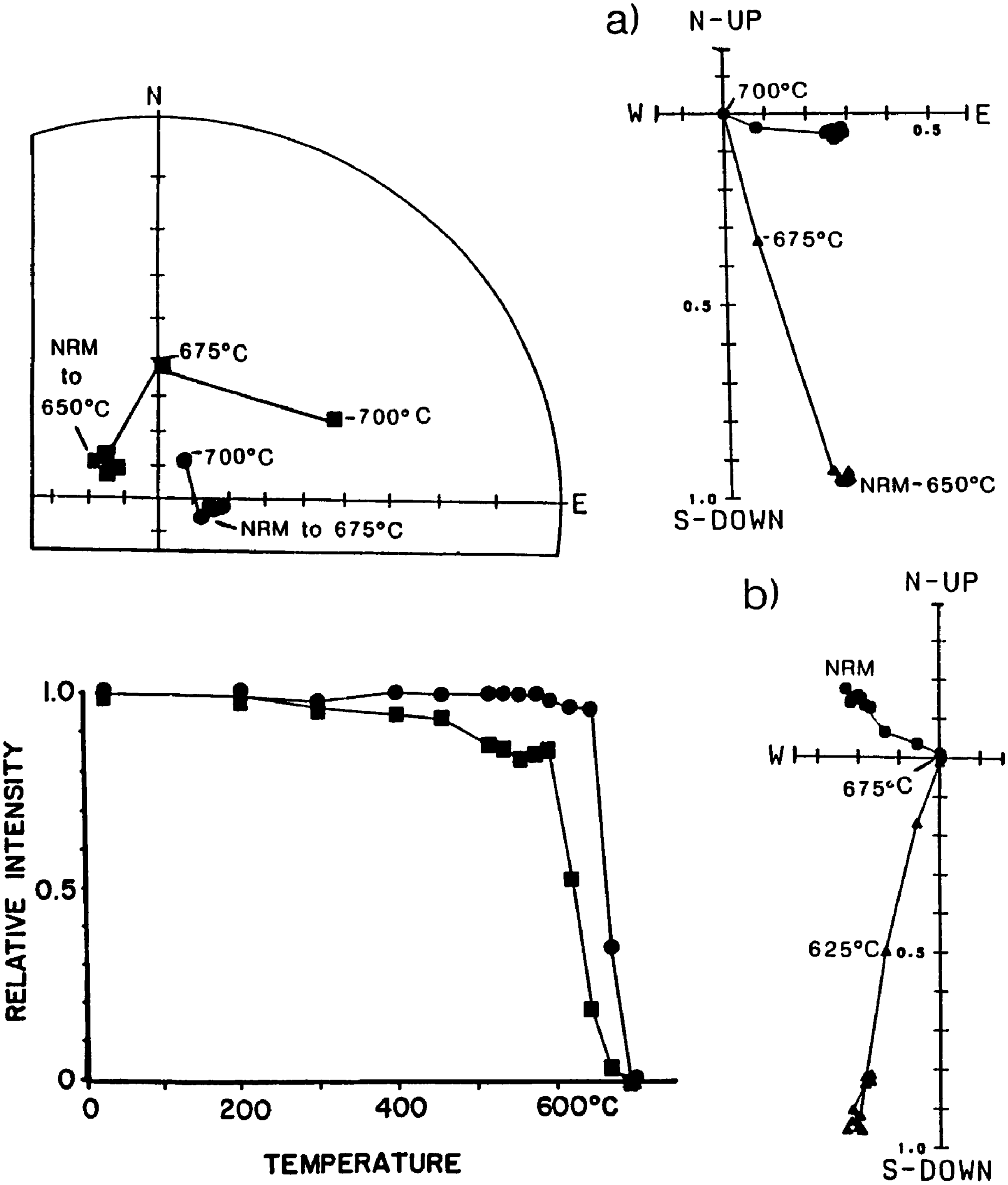

Figure 4.5.2 *In situ* direction changes, orthogonal plots and intensity decay curves from two example thermal demagnetized specimens from the Mount Cronin area. Circles—specimen from site 5, Squares—specimen from site 4. Orthogonal plots as before (Fig. 4.4.1), (a) site 5 and (b) site 4.

Figure 4.5.3 Example demagnetization data from Owen Lake area. (a)–*In situ* direction changes for plot (b). Orthogonal plots as before (Fig. 4.4.1); AF plots for specimens from sites 13 (b), 10 (c), 7 (d), and thermal plots for specimens from sites 7 (e) and 13 (f). (g)–Intensity decay curves, squares correspond to (e) 7, and circles correspond to (f) 13.

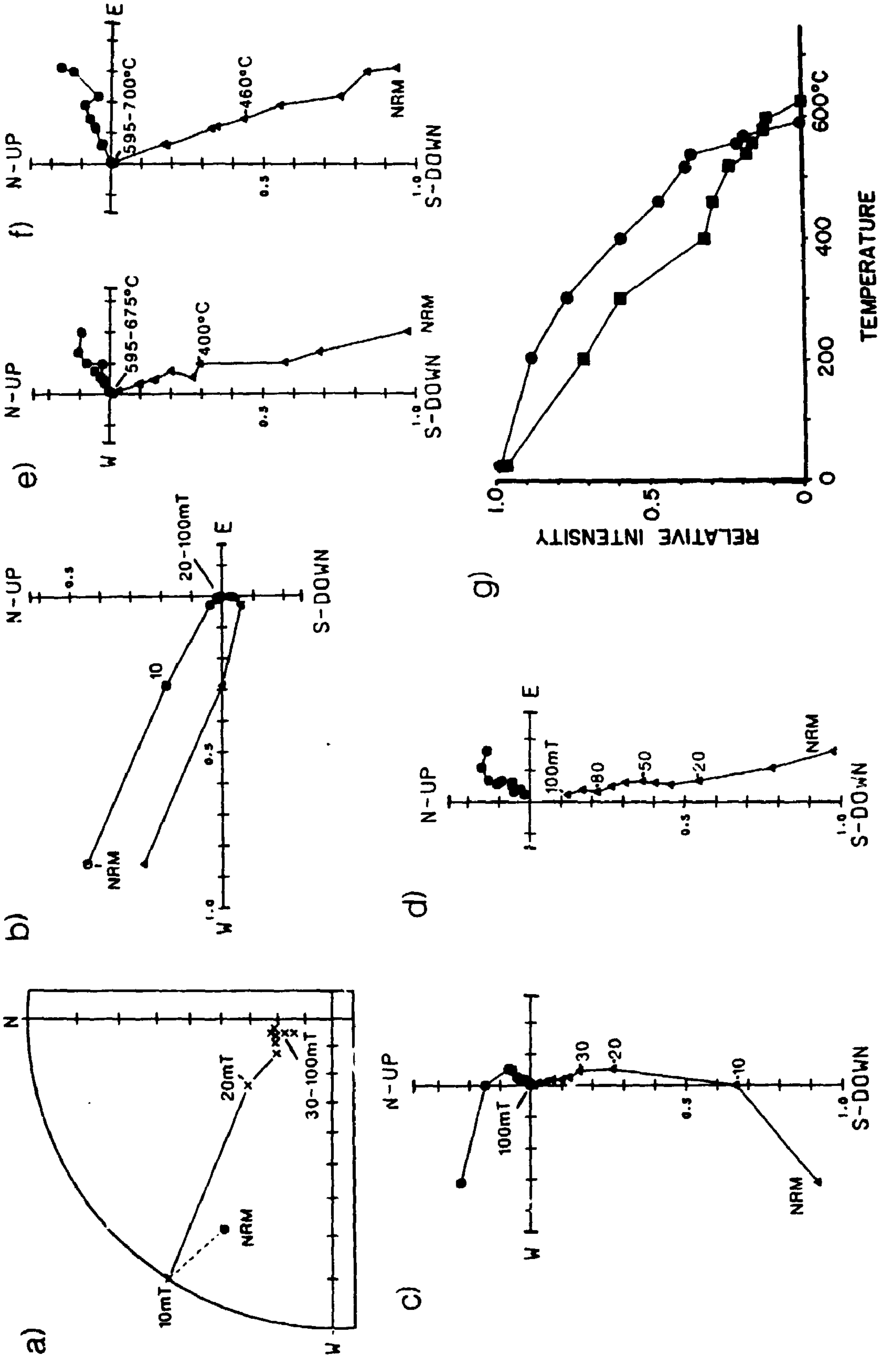
a)
N
W
10mT
20mT
30-100mT
NRM
b)
N-UP
S-DOWN
E
W
0.5
1.0
10
20-100mT
NRM
c)
N-UP
S-DOWN
W
100mT
30
20
10
0.5
1.0
NRM
d)
N-UP
S-DOWN
E
100mT
80
50
20
0.5
1.0
NRM
e)
N-UP
S-DOWN
W
595-675°C
400°C
0.5
1.0
NRM
f)
N-UP
S-DOWN
E
595-700°C
460°C
0.5
1.0
NRM
g)
RELATIVE INTENSITY
1.0
0.5
0
TEMPERATURE
200
400
600°C

Figure 4.5.4 Example demagnetization data from the Nadina Lake area. Orthogonal plots as before (Fig. 4.4.1); AF plots from sites 17 (a), 20 (e), 22 (f), 25 (g), and thermal plots from sites 18 (b) and 24(c). (d)–Intensity decay curves, circles correspond to plot (b) 18, and triangles correspond to (c) 24. (h)–*In situ* direction changes for plot (b)–circles, (c)–triangles, (e)–squares, (f)–hexagons.

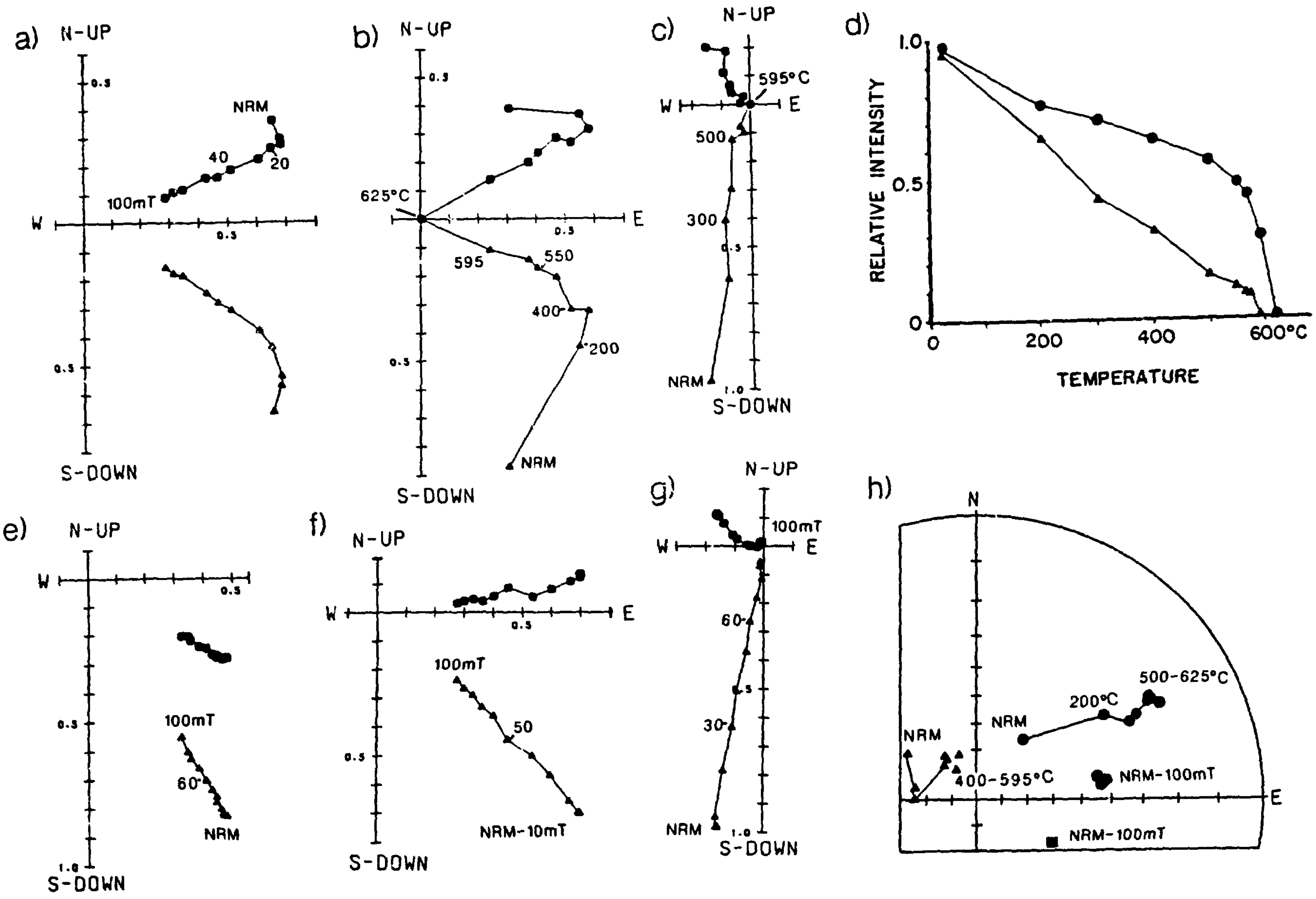
a)
N-UP
0.5
NRM
40
20
100mT
W
0.5
0.5
S-DOWN
b)
N-UP
0.5
625°C
E
0.5
595
550
400
200
0.5
NRM
S-DOWN
c)
N-UP
595°C
W
E
500
300
0.5
NRM
1.0
S-DOWN
d)
RELATIVE INTENSITY
1.0
0.5
0
0
200
400
600°C
TEMPERATURE
e)
N-UP
W
0.5
0.5
100mT
60
NRM
1.0
S-DOWN
f)
N-UP
W
E
0.5
100mT
50
0.5
NRM-10mT
S-DOWN
g)
N-UP
100mT
W
E
60
0.5
30
NRM
1.0
S-DOWN
h)
N
NRM
NRM
200°C
500-625°C
400-595°C
NRM-100mT
E
NRM-100mT

Table 4.5.1 Kasalka Group Site Mean Remanence Data

Site	Area	N	D°	I°	ϕ°	ψ°	CD°	CI°	R	k	α95°
1	K1	5	088	63	210	53_a	176	47	4.650	11	23.8
2	"	4	057	84	210	53_a	206	42	3.917	36	15.4
3	"	–	–	–	018	50_c	–	–	–	–	– *
4	"	4	289	76	340	45_b	327	35	3.987	247	5.9
5	"	6	105	81	340	45_b	351	50	5.867	38	10.9
6	"	6	208	76	180	49_b	187	28	5.462	10	23.2
7	K2	4	038	74	261	25_a	303	73	3.979	141	7.8
8	"	4	039	71	261	25_a	312	73	3.994	504	4.1
9	"	5	028	73	261	25_a	305	70	4.981	214	5.2
10	"	5	032	72	261	25_a	306	72	4.961	103	7.6
11	"	5	010	76	261	25_a	295	66	4.919	49	10.9
12	"	5	027	74	261	25_a	301	70	4.994	624	3.1
13	"	3	022	75	261	25_a	297	69	2.949	40	19.8
14	"	5	029	73	261	25_a	304	71	4.985	271	4.7
15	K3	–	–	–	257	72_b	–	–	–	–	– *
16	"	–	–	–	257	72_b	–	–	–	–	– *
17	"*A*	4	066	24	257	72_b	315	78	3.960	75	10.7
18	"*A*	4	059	20	257	72_b	337	73	3.983	176	6.9
19	"	–	–	–	201	80_a	–	–	–	–	– *
20	"*B*	5	119	56	025	56_b	065	30	4.962	104	7.5
21	"	–	–	–	025	56_b	–	–	–	–	– *
22	"*B*	5	078	56	000	0_b	078	56	4.855	28	14.8
23	"*A*	3	323	70	000	0_b	323	70	2.993	290	7.3
24	"*A*	5	355	84	000	0_b	355	84	4.767	17	19.0
25	"*A*	4	331	70	000	0_b	331	70	3.967	90	9.7

Notes: K1 – Mount Cronin Area, K2 – Owen Lake Area, K3 – Nadina Lake Area. N is the number of cores; D and I are the mean remanence vector's declination and inclination, respectively, in degrees, relative to present horizontal; ϕ is the down dip azimuth of bedding and ψ is the dip angle from horizontal, letters indicate relative reliability of bedding attitudes, $_a$ –good, $_b$ –fair, $_c$–poor; CD and CI are the same as D and I but are after full tilt correction relative to bedding; R is the resultant vector for the summation; k and α95 are the precision parameter and radius of the circle of 95% confidence (Fisher 1953). In Area K3, two tilt corrected remanence directions are denoted by *A* and *B*. * – abandoned sites with extreme dispersion and/or very weak intensities.

Table 4.5.2 Uncorrected and Corrected Kasalka Group Unit Means and Poles.

Area	U/%	N	D°	I°	k	α95°	Dp°	Dm°	Long° W	Lat° N
K1	U	5	106.4	85.4	23	16.4	32.3	32.6	112.8	51.5
	100%	5	225.0	68.0	3	59.7	–	–	–	– *
K2	U	8	028.7	73.8	718	2.1	3.4	3.7	68.5	73.5
	20%	8	012.4	76.3	718	2.1	3.5	3.8	99.1	78.3
	40%	8	351.4	77.2	718	2.1	3.6	3.9	143.6	77.7
	60%	8	330.3	76.3	718	2.1	3.5	3.8	171.3	72.0
	80%	8	313.7	73.9	718	2.1	3.4	3.7	184.4	64.7
	100%	8	302.3	70.5	718	2.1	3.1	3.6	191.7	57.4
K3$_1$	U	5	039.4	61.3	5	40.1	–	–	–	– *
	100%	5	329.6	75.2	146	6.4	10.6	11.6	177.4	72.1
K2+K3$_1$	60%$_a$	13	330.0	75.9	318	2.3	4.0	4.3	173.7	72.1
	80%$_a$	13	319.5	74.5	259	2.6	4.3	4.7	182.3	67.5
	100%$_a$	13	311.0	72.7	156	3.3	5.3	5.9	188.3	62.9

Notes: K1 – Mount Cronin Area, K2 – Owen Lake Area, K3$_1$ – Nadina Lake Area remanence direction *A*, K2+K3$_1$ – Areas K2 and K3$_1$ combined; U is an uncorrected unit mean, 20% to 100% refers to percentage of tilt applied to determine tilt corrected unit mean, subscript $_a$ refers to percentage tilt applied to site means from Area K2 only – 100% tilt was applied to Area K3$_1$; N is the number of site means; D, I, k, α95 are same as Table 4.5.1; Dp is the radius of the ellipse of 95% confidence at the pole along the site–pole great circle and Dm is the radius of this ellipse perpendicular to the site–pole great circle; Long° W and Lat° N are the west longitude and north latitude of each pole, respectively; * – extreme dispersion no pole calculated.

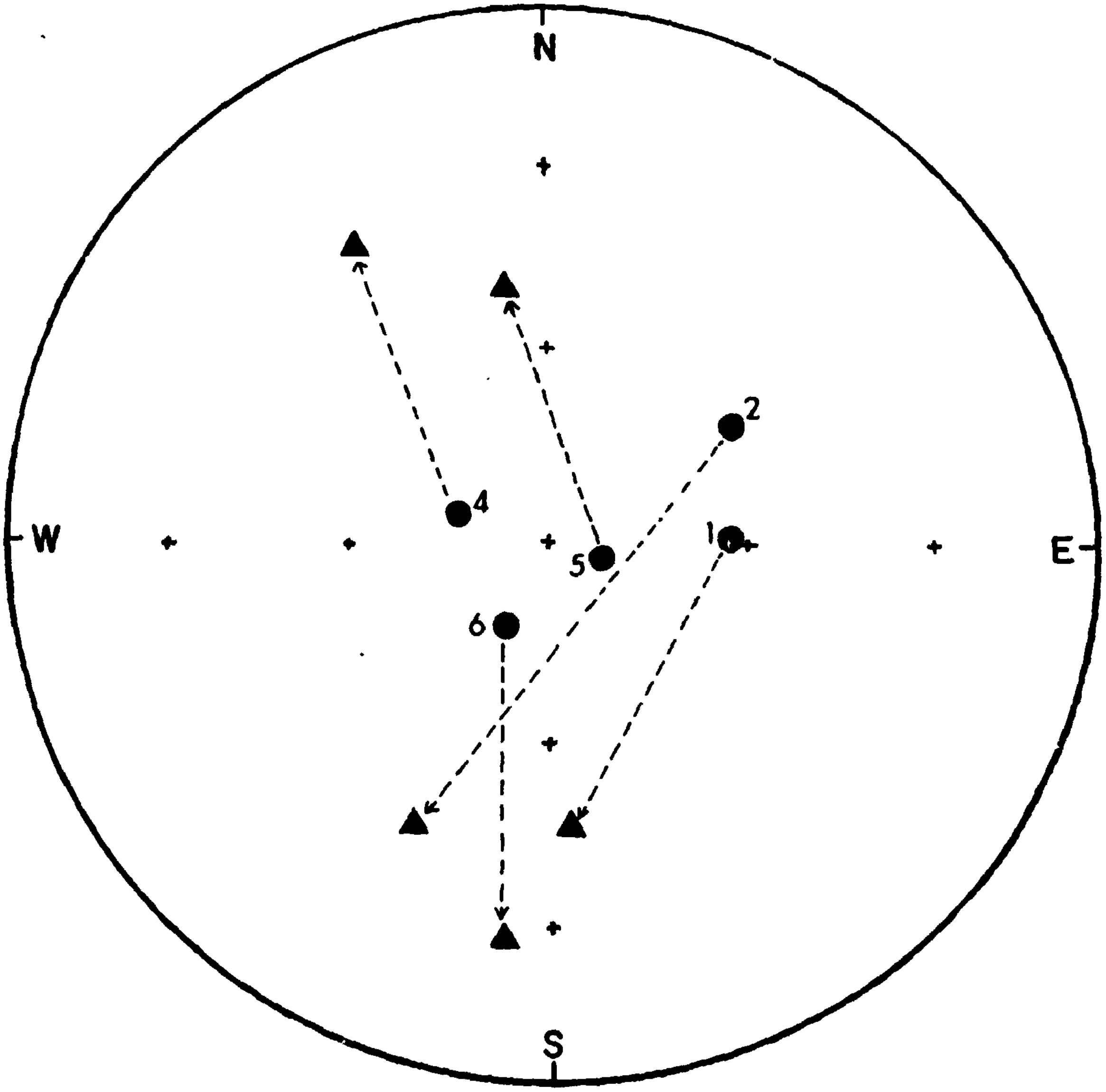

Figure 4.5.5 Equal–area stereographic projection showing the *in situ* (circles) and tilt corrected (triangles) site mean Kasalka Group directions from the Mount Cronin Area (K1). All directions are normal plotted on the lower hemisphere. Data from Table 4.5.1.

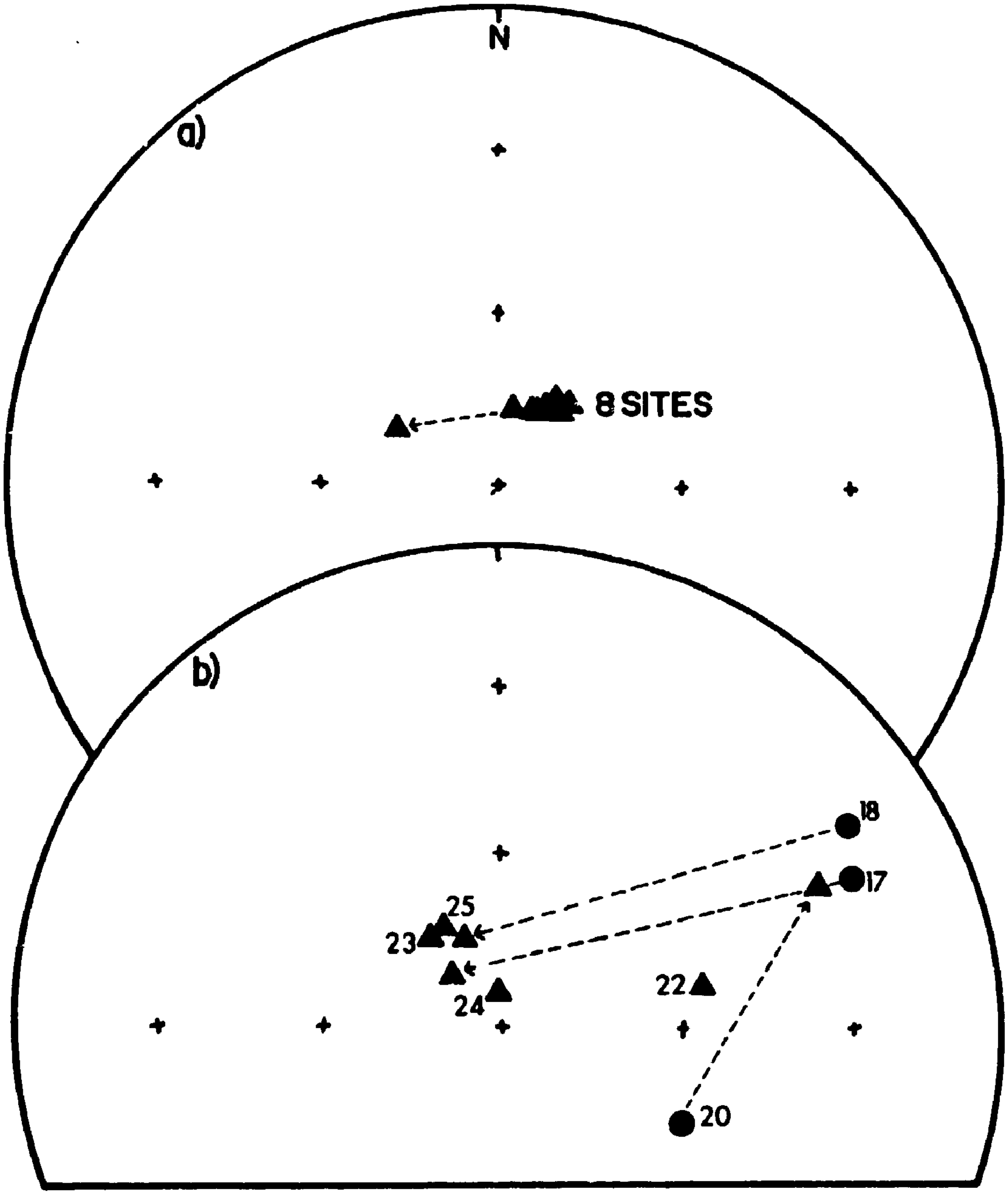

Figure 4.5.6 Equal–area stereographic projection showing the *in situ* and tilt corrected site mean Kasalka Group directions from: (a) the Owen Lake Area (K2) (Isolated triangle is the tilt corrected unit mean) and (b) the Nadina Lake Area (K3). Dashed arrows are directed at corrected site mean where applicable. All directions are normal plotted on the lower hemisphere. Data from Table 4.5.1.

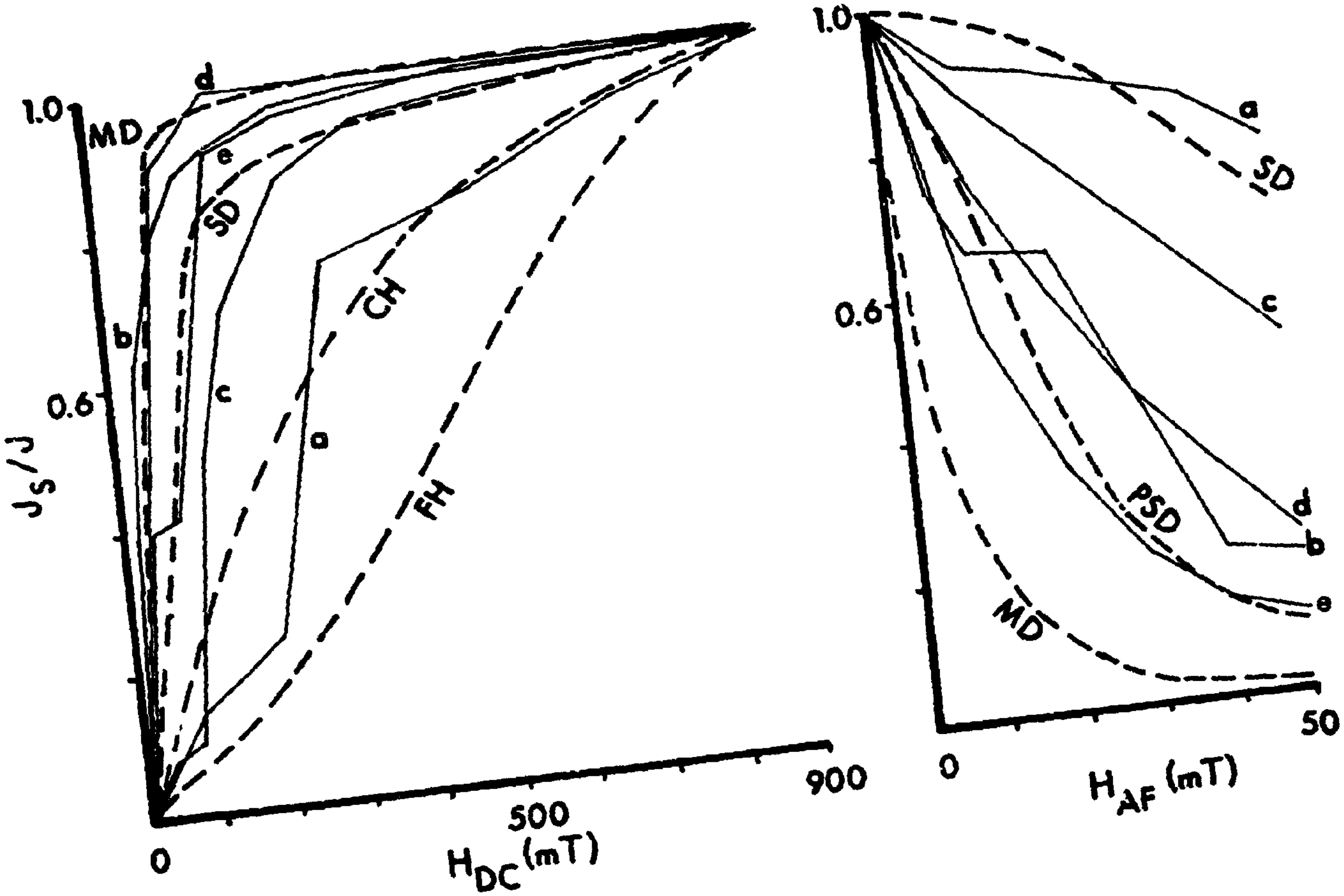

Figure 4.5.7

SIRM acqusition and demagnetization curves for example specimens from sites 1 (a), 8 (b), 18 (c), 23 (d) and 24 (e). The type curves for single, pseudosingle, and Multidomain magnetite (SD, PSD, MD) and for fine and couse hematite (FH, CH) are from Dunlop (1971, 1972, 1973, 1981).

Group rocks in the Owen Lake and Nadina Lake areas.

Table 4.5.2 shows the combined Kasalka Group unit means (K2+K3) incorporating all eight sites from the Owen Lake area and five sites exhibiting component *A* from the Nadina Lake area. By combining the results from the Owen Lake and Nadina Lake areas (Component *A*) the pre–folding nature of the K2 component is demonstrated. Maximum unit mean precision is obtained after combining the fully tilt corrected K3 component *A* site means with the 60% tilt corrected K2 site means (K2+K3 60%, Table 4.5.2), which may reflect a 10° primary dip of the K2 locality within the flow–foliation plane. Geologically this is a reasonable estimate since it is valid to assume that primary dip, if present in andesitic lava flows, would have been much less than the measured *in situ* flow dip of 25°. This interpretation of a paleoslope is not conclusive since additional determinations of the Late Cretaceous magnetic field in Kasalka Group rocks are needed. In addition partial untilting of the K2 site means is not a prerequisite for good agreement between the K2 and K3 component *A* directions. Thus regardless of the possibility of a primary dip, the tilt corrected directions from the Owen Lake area and component *A* from the Nadina Lake area are in excellent agreement and close to the expected Late Cretaceous cratonic direction. This is a very significant discovery given that the earlier review of paleomagnetic studies, principally on Cretaceous intrusive rocks, from the CC yielded largely discordant directions. A single exception is the direction from the Howe Sound plutons (Symons 1973a). One could reasonably argue that the results from the Owen Lake area which exhibit very low dispersion (k= 718) combined with low dispersion results from the *A* component (k=146) at Nadina Lake do not average secular variation. Nevertheless, the good agreement between the maximum (k) combined tilt corrected Kasalka unit mean of Dec = 330, Inc = 76, k = 318, $a95$ = 2.3, N =

13 sites (K2+K3 60%, Table 4.5.2) and the expected cratonic direction (≈ *Dec* = 335 , *Inc* = 75 , See Table 4.1.1 for ref. pole) suggests that an appeal to coincidence may be beyond that which can be considered reasonable. Even if full tilt correction is applied to the K2 sites the combined Kasalka unit mean of *Dec* = 311, *Inc* = 73, *k* = 156, *a*95 = 3.3, N = 13 sites (K2+K3 100%, Table 4.5.2) is still close to the expected direction. The critical test of this intriguing result will be provided by obtaining additional data from other stratigraphic sections with attitudes different from those already studied. In the interim, given the absence of any direct evidence to the contrary, it is reasonable to conclude that the true tilt corrected Kasalka Group unit mean is best represented by the intermediate tilt corrected K2+K3 80% unit mean directed at *Dec* = 320, *Inc* = 75, *k* = 259, *a*95 = 2.6, N = 13 sites (Table 4.5.2 and 4.1.1). This is a classical example of a situation in which the statistical precision with which a unit mean is determined, is geologically non–representative of the true error, a point which in all probability affects other CC results, although not generally acknowledged (e.g. See discussions by Butler (1990) and Marquis *et al.* (1990)). Due to the uncertainty of the existence of primary dip and possible secular variation effects the true error about this mean is probably better represented by a much larger *a*95 of 8–10°. Most importantly, this acknowledgement of the possibility of larger error does not preclude the fact that the combined Kasalka unit mean directions (Table 4.5.2) with paleohorizontal control, argues against systematic ≈ 66° clockwise rotation and ≈ 2400 km of northward translation of "Baja British Columbia".

Tectonic Implications

The following assessment of the CC Cretaceous paleomagnetic data is a "minimalist" approach predicated by the prejudice from classical physics in which the *principle of the conservation of energy* and *Newton's first law of motion* are invoked. Recall that Newton's first law is the *law of inertia* by which a body at rest tends to remain at rest. This philosophical approach may seem abstract, nevertheless in my view it applies to any consideration of plate tectonics. Based on this premise, accepting that the pre– and post–Cretaceous CC paleomagnetic data are latitudinally concordant, while acknowledging that the errors inherent in the paleomagnetic method permit but do not require latitudinal displacements of ≈ 500 km, it is reasonable to presuppose that the Cretaceous data is similarly latitudinally concordant. It follows therefore, that the assertion of the burden of proof in the first instance is directed at tectonic models of contrary opinion to this presupposition. Inasmuch as previous models of CC displacement were based on the prior premise that CC Triassic and Jurassic data were also discordant and in accord with northward displacement (Hillhouse and McWilliams 1987), the above assertion at that time was reversed to favor similar discordance of Cretaceous data. Thus the conclusions discussed in Chapter 3 regarding latitudinally concordant pre–Cretaceous data have significant implications for CC displacement models.

To evaluate the tectonic implication of this Kasalka Group result it is necessary to include a discussion of several recent paleomagnetic studies on Cretaceous rocks from the CC that have been carried out by others subsequent to the time this study began in 1986. These include studies on bedded volcanic and sedimentary rocks (Marquis and Globerman 1988; Butler *et al.* 1988; Globerman 1988; Bazard *et al.* 1990; Irving and Thorkelson 1990), and intrusives (Irving and Archibald 1990).

Intrusives studied by Irving and Archibald (1990) include the Skelly Creek batholith and the Summit stock, both of which are interpreted to yield concordant results from the western edge of the deformed cratonic margin (SC and SS Fig.

4.2.2 and Fig. 4.6.1). The Skelly Creek batholith is believed to have not been appreciably tilted since emplacement because bathozonal data indicates that tilting in any direction is unlikely to have exceeded a few degrees (Irving and Archibald 1990). The Summit stock however, is believed to have been tilted to the west by ≈ 24° also evidenced by bathozonal data. An interesting observation is that the uncorrected Summit stock direction is similarly rotated clockwise like many of the discordant directions from previous Cretaceous studies, including the aberrant result from the Crowsnest Formation to the east in the Foreland belt. In both cases Irving and Archibald (1990) indicate their tilt estimates are somewhat crude, but assuming their interpretations are correct, these results are important since they extend the concordant Cretaceous North American western margin into the southern Omineca belt. In addition, this corroborates the interpretation of Irving *et al.* (1986) that the Crowsnest Formation volcanics have not undergone any significant displacement since their formation, and that the aberrant direction they preserve is best explained by incomplete averaging of secular variation.

With respect to the results from bedded rocks by Granirer *et al.* (1986), Bazard *et al.* (1990) provided a much more thorough analysis of the paleomagnetism of the Methow–Pasayten belt and concluded that complications in the region prevent straightforward interpretation. Thus unfortunately, studies by both Granirer *et al.* (1986) and Bazard *et al.* (1990) are unable to provide paleomagnetic results that are useful for tectonic analyses. In contrast, the paleomagnetic results from studies by Butler *et al.* (1988) and Marquis and Globerman (1988) do provide results that are important for CC tectonic analyses. Significantly, they provide the first Cretaceous paleomagnetic studies that are based on bedded rocks with paleohorizontal control.

MS – Mount Stuart Batholith
HS – Howe Sound Plutons
CS – Combined Eastern Panel
EB – Ecstall and Butedale Plutons
AX – Axelgold Gabbro
TP – Topley Intrusions
SP – Spuzzum Porteau Plutons
SC – Skelly Creek Batholith
SS – Summit Stock
CV – Crowsnest Formation Volcanics
CGV – Carmacks Group Volcanics
SBV – Spencers Bridge Volcanics
KV – Kasalka Group Volcanics
SAO – Sylvester Allochthon Overprint

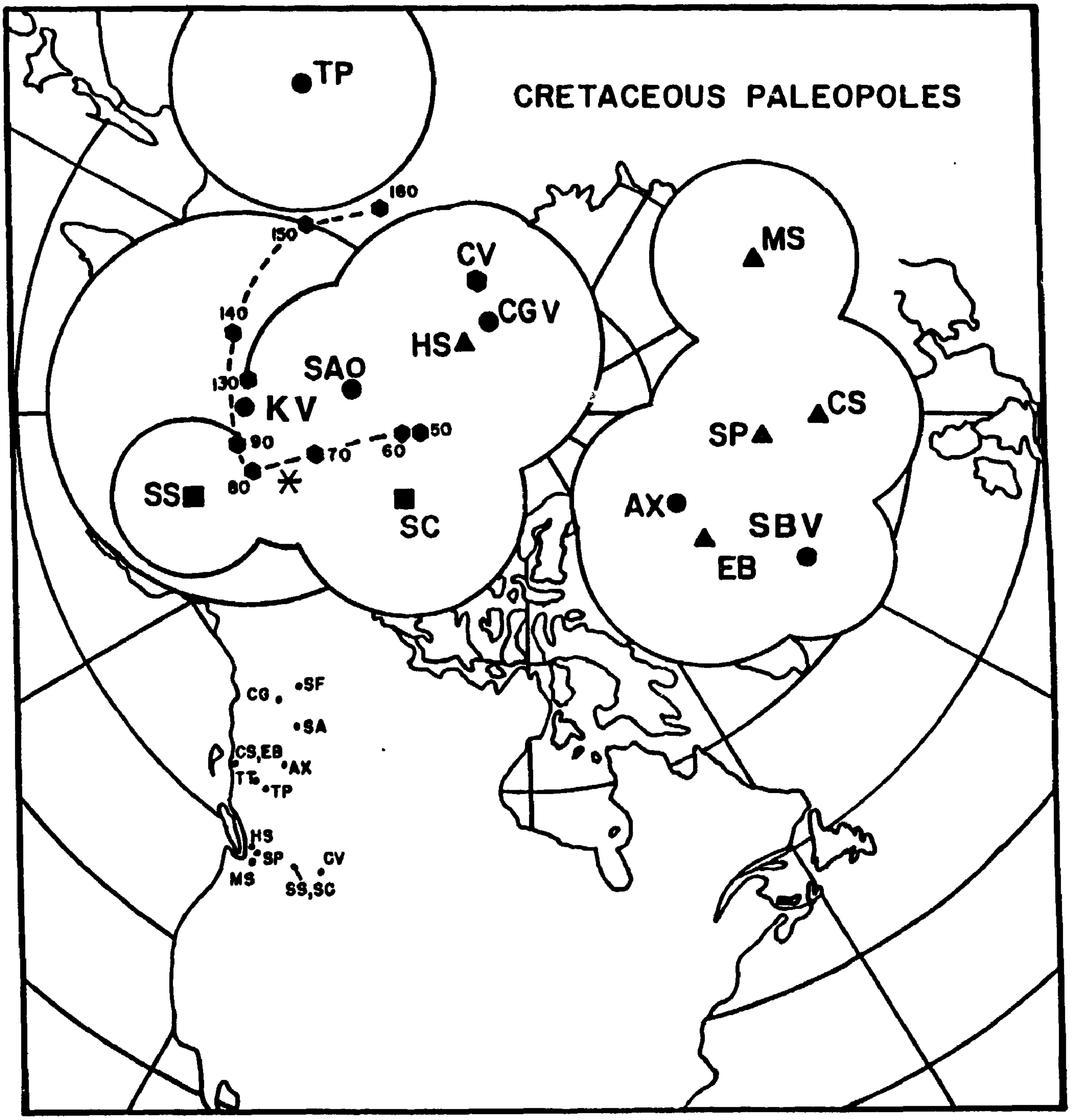

Figure 4.6.1 Study locations and Cretaceous paleopoles from the CC. Star represents mid–Cretaceous reference pole from Globerman and Irving (1988). Dashed line represents Mesozoic APWP from Irving and Irving (1982). Pole symbols are as follows, triangles – Coast belt, circles – Intermontane belt, squares – Omineca belt and hexagon – Foreland belt. Note: SAO is west of NRMTF near Omineca–Intermontane boundary. See text and Table 4.1.1 for explanation.

Butler *et al.* (1988) sampled the Cassiar batholith and an adjacent Permian limestone which is part of the Sylvester Allochthon, situated in northern British Columbia (SAO Fig 4.2.2). The allochthon is relatively small and lies within the Omineca belt immediately east of the Cassiar batholith which borders the Intermontane belt to the west. Samples from the batholith exhibited very low stability and no successful ancient magnetizations could be isolated. However, 12 sites within the limestones provided a stable high coercivity low unblocking temperature (320°C) magnetization thought to be carried by pyrrhotite. Directions were obtained by PCA techniques fitting four thermal demagnetization steps between 150 and 310°C (Butler *et al.* 1988). The *in situ* site mean directions are tightly grouped close to the expected mid–Cretaceous cratonic direction, and since untilting dramatically increases dispersion, this magnetization has been interpreted as a secondary overprint related to emplacement of the Cassiar Batholith which yields K–Ar ages between 100–110 Ma. A tectonic analysis of the resulting Sylvester Allochthon paleopole indicates the relative paleolatitudinal displacement (RPD) to the north of 7±8° and the clockwise relative rotation (RR) of 5±21° are not significant at 95% confidence limits. (Note: this RPD and RR is slightly different from those reported by Butler *et al.* (1988) because a slightly different reference pole was used (See Table 4.1.1), however this does not affect their interpretation.) Thus, rotation of the sampling area is insignificant, but although the northward translation suggested by the Sylvester Allochthon pole is not statistically significant, the pole is biased by shallow inclinations which are consistent with moderate northward translation. As Gabrielse (1985) documented, mid–Cretaceous to Eocene northward displacement along the dextral Northern Rocky Mountain Trench Fault (NRMTF) system at ≈ 700–900 km, this is the first Cretaceous paleomagnetic result which is in good agreement with a geologic estimate of northward coast–wise translation. Although the Sylvester Allochthon is situated within the Omineca belt, part of which has been shown to be concordant to the south (Irving and Archibald 1990), it is situated near its western margin west of the NRMTF along which the inferred ≈ 2400 km of post mid–Cretaceous northward translation is to have taken place. Thus, this result is in conflict with the magnitude of northward translation inferred by Beck (1981) and Irving *et al.* (1985) which is based only on data from intrusives which includes results by Symons (1977a, 1977b) that were interpreted as latitudinally concordant. Of course this requires that dextral northward displacements along the major faults west of the NRMTF like the Finlay fault system have been small, and this indeed seems to be the case (≈ 300 km) (Gabrielse 1985). Further, geologic displacement models for example by Chamberlain and Lambert (1985) and Lambert and Chamberlain (1988), based primarily on the paleomagnetic interpretation by Irving *et al.* (1985), recognized that large scale northward displacement cannot be accommodated by known transcurrent fault systems, and therefore, argued that most of the displacement took place prior to collision of the allochthonous terranes with the craton. This does not appear to be possible given that geologic evidence indicates that Terrane I had already collided with the North American craton during the Middle Jurassic (Monger *et al.* 1982) and all inboard CC sutures, most importantly the Omineca Belt, had been closed before the Middle Cretaceous (Armstrong 1988).

The tectonic implication of this result from the Sylvester Allochthon is in reasonably good agreement with the Kasalka Group result from this study (SAO and KV Table 4.1.1, Fig 4.6.1, Fig. 4.6.3). Certainly the very thorough detailed step demagnetization procedures combined with PCA analysis techniques ensure that the principal magnetic components have been isolated in these two studies.

Given the different tectonic and geographic positions of the two studies (SAO and KV Fig. 4.2.2), combined they offer significant evidence arguing against post mid–Cretaceous northward displacement much in excess of the geologic estimates cited by Gabrielse (1985) and Price and Carmichael (1986) which range between 500–900 km. Thus these results are more consistent with the moderate post mid–Cretaceous northward "translation" as originally suggested by Monger and Irving (1980) and outlined in more detail by Irving *et al.*'s (1980) displacement model (Fig. 1.4.2). This evidence also supports the consistently invoked local "tilt" interpretations of Symons based on his discordant results from several Coast belt intrusives, although moderate translation has also been involved. Although opinions differ (e.g. Umhoefer and Magloughlin 1990; Butler *et al.* 1990), this follows since Butler *et al.* (1989) have advanced the "tilt" hypothesis to also explain the discordant data from the Mount Stuart batholith and the Spuzzum pluton on the grounds of geological and paleobarometric evidence. Further, Butler *et al.* (1990) have demonstrated that moderate northward displacement only marginally affects the original estimates of tilt that were invoked by Symons. Considering the evidence for local tilting of Coast belt intrusives (e.g. Symons 1977a, 1977b; Butler *et al.* 1989), geologic and paleomagnetic evidence of moderate displacement (e.g. Gabrielse 1985; Butler *et al.* 1988; This study), and the concordant pre– and post–Cretaceous CC paleomagnetic data, local tilting of the Coast belt intrusives combined with moderate northward translation of allochthonous CC seems to be the most reasonable explanation of the current data. Interestingly, previous speculations by Umhoefer and Magloughlin (1989) included a similar scenario in their critical discussion of Butler *et al.*'s (1989) appraisal of the discordant Cretaceous paleomagnetic data.

A recent result not yet considered is from the Upper Cretaceous Carmacks

Group which was sampled in three areas, one in northern British Columbia and two in the Yukon (CGV Fig. 4.2.2) (Marquis and Globerman 1988). Following bulk AF and thermal demagnetization principally at 40 mT and 550°C, 18 sites provided well grouped tilt corrected magnetizations which were interpreted to be Upper Cretaceous in age. The corresponding pole position (CGV) is not far removed from Symons' (1973a) Howe Sound plutons pole (CGV and HS Fig. 4.6.1). Thus, the data with paleohorizontal control (KV, CGV, SAO Fig. 4.6.1) do not support earlier suggestions that Cretaceous poles were systematically rotated ≈ 66° clockwise. Figure 4.6.2 (a) shows the calculated RRs for the CC Cretaceous results (Table 4.1.1) which are in fact characterized by a range of rotations between 22° counterclockwise to 66° clockwise. Most significantly, the indicated northward displacement of the Carmacks Group is also moderate (1500±950 km), which considering the error, is consistent with other paleomagnetic results and geologic estimates of moderate displacement. Indeed Butler (1990) suggests that the indicated displacement of this result is smaller (1200±1150 km), invoking arguments concerning the poor precision with which the Late Cretaceous reference pole is known, and the possible multiple sampling of non time–independent adjacent flows. However, in rebuttal Marquis *et al.* (1990) appropriately point out that paleosecular variation has a somewhat stochastic nature in which the paleofield, may for certain, periods undergo little change. Although this is a reasonable assumption, stillstands of secular variation are likely the exceptions rather than the rule. Nevertheless, the tectonic implications of either point of view are not significantly different as Marquis *et al.* (1990) point out. The most salient point discussed by Butler (1990) is the poor precision with which the Late Cretaceous reference pole may be known, the position of which if significantly changed by subsequent studies will affect all Late Cretaceous results.

In the CC these include the Mount Stuart batholith, the Ecstall and Butedale plutons, the Carmacks Group volcanic rocks and the Kasalka Group volcanic rocks of this study (Table 4.1.1). Until such time as that happens one must rely on the current best estimate of the Late Cretaceous reference pole.

Additional CC results by Globerman (1988) on the South Fork volcanic rocks and by Irving and Thorkelson (1990) on the Spences Bridge volcanic rocks were available in abstract only at the time of completing this thesis, therefore an evaluation of their results was not possible. Globerman (1988) indicated that the South Fork volcanic rocks from the Foreland belt (SF Fig. 4.2.2) provide a concordant mid–Cretaceous pole which would be expected from this location east of the allochthonous CC terranes. In contrast, Irving and Thorkelson (1990) obtained a discordant mid–Cretaceous pole from the Spences Bridge group in the Intermontane belt. Importantly this result is consistent with a moderate northward displacement. Although the data from these studies cannot be assessed the conclusions based on them seem to be in accord with the "tilt" and moderate displacement interpretation of this study.

Model Assessment

In the following discussions the "tilt" and moderate displacement model of this study is referred to as the TMD model. Invoking moderate post mid–Cretaceous northward translation of the Coast, Intermontane and part of the Omineca belt combined with tilting of the Coast belt intrusives does not preclude clockwise rotations from also having taken place. As Figure 4.6.2 shows, variable but largely clockwise rotations are implied by the Cretaceous data. Given that the TMD model invokes broadly similar west to southwest local tilts, the RRs exhibited by the Coast belt intrusives should all be clockwise, and this is indeed the case (Fig. 4.6.2 b). Thus, it is suggested that these apparent vertical axis rotations are principally a result of rotation about horizontal axes striking ≈ NW. The rotations observed from results in the Intermontane and Omineca belts (Figs. 4.6.2 c and d) are variable indicating rotations due to local effects, presumably block rotations about vertical axes similar to the Permian–Early Jurassic results. Notwithstanding, given the associated errors several of the smaller rotations (Figs. 4.6.2 c and d) may not be geologically significant. Consistent with this interpretation, the Axelgold Gabbro from the Intermontane belt exhibits compositional layering, which taken as a record of paleohorizontal argues against tilting being invoked to entirely account for its discordant result. Thus in all probability local clockwise block rotations, which have been shown to characterize this region in Stikinia (Monger and Irving 1980), are also responsible for part of the discordancy. Although Armstrong *et al.* (1985) recognize uncertainties regarding the Axelgold result, their conclusion based on the tilt–corrected Axelgold unit mean suggests that 1000 km of northward translation took place since the mid–Cretaceous. This interpretation is in good agreement with the TMD model and other paleomagnetic results from rocks with paleohorizontal control.

Figure 4.6.3 is a summary of the Cretaceous relative paleolatitudinal displacements (RPDs) and their associated errors from Table 4.1.1. which demonstrate how the paleomagnetic data supports moderate displacement and tilting. The best paleomagnetic results constrained by paleohorizontal control (Fig. 4.6.3) are situated in the Intermontane belt and the western Omineca belt where they exhibit a systematic error overlap in the 900–1300 km range. In contrast the RPD errors from results in the Coast belt do not completely overlap. Where most of them do, at ≈ 2200 km, is well in excess of the 900–1300 km range from results with paleohorizontal control. Taken at face value, the implication of

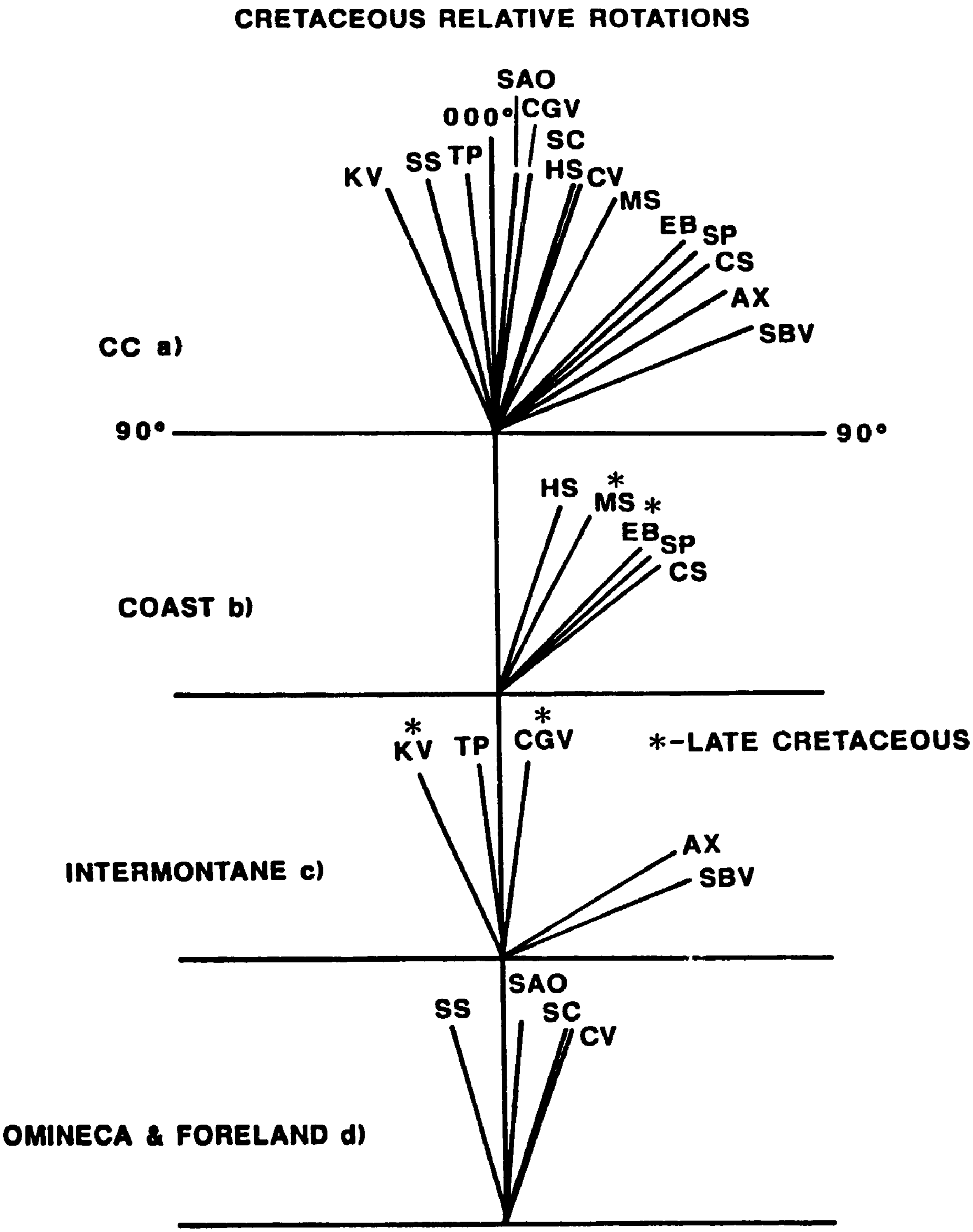

Figure 4.6.2 Relative rotations (RRs) from CC Cretaceous paleopoles. 000 is the expected cratonic reference. Asterisks – Late Cretaceous result. a) Combined RRs, b) RRs from the Coast belt, c) RRs from the Intermontane belt and d) RRs from the Omineca belt. See text and Table 4.1.1 for explanation.

≈ 1000 km of differential post mid–Cretaceous northward translation between the Intermontane Belt and the Coast Belt seems geologically implausible. Recall that the mid–Cretaceous Coast belt intrusives physically intrude the rocks of the Intermontane belt and no known major fault system west of the NRMTF exists which could possibly accommodate this displacement. It is highly unlikely that a major CC strike–slip structure along which 1000 km of translation has taken place could go unrecognized. Thus, these additional arguments based on the summary of paleomagnetic data are in my view strongly in support of local tilting contributing significantly to the discordancy of Coast Belt intrusive results. As discussed in the review of this Chapter other complications may also be partly responsible for these discordant results from the Coast Belt intrusives. Nevertheless, systematic clockwise rotation combined with ≈ 2400 km of northward translation (Irving *et al.* 1985) since the mid–Cretaceous are not supported by this tectonic assessment. Instead, the earlier post mid–Cretaceous moderate displacements proposed by Irving *et al.* (1980) (Fig. 1.4.2) and reassessed by Armstrong *et al.* (1985) appear to be more consistent with the TMD model described in this study.

The convergence of the Cretaceous data towards a CC displacement model in which moderate (≈ 1000 km) northward translation has taken place combined with local tilting of the Coast belt intrusives and local block rotations principally in the Intermontane belt, is in my view the best explanation of the Cretaceous CC paleomagnetic data. This model is reasonably consistent with recognized geologic structures and the evidence of known dextral offsets along the Tintina and NRMTF systems. It also has the desirable attribute of not requiring data selectivity as a prerequisite to the model as all the CC Cretaceous paleomagnetic results can be accommodated by this model with the possible exception of the Topley intrusives result, which for reasons already discussed is problematical.

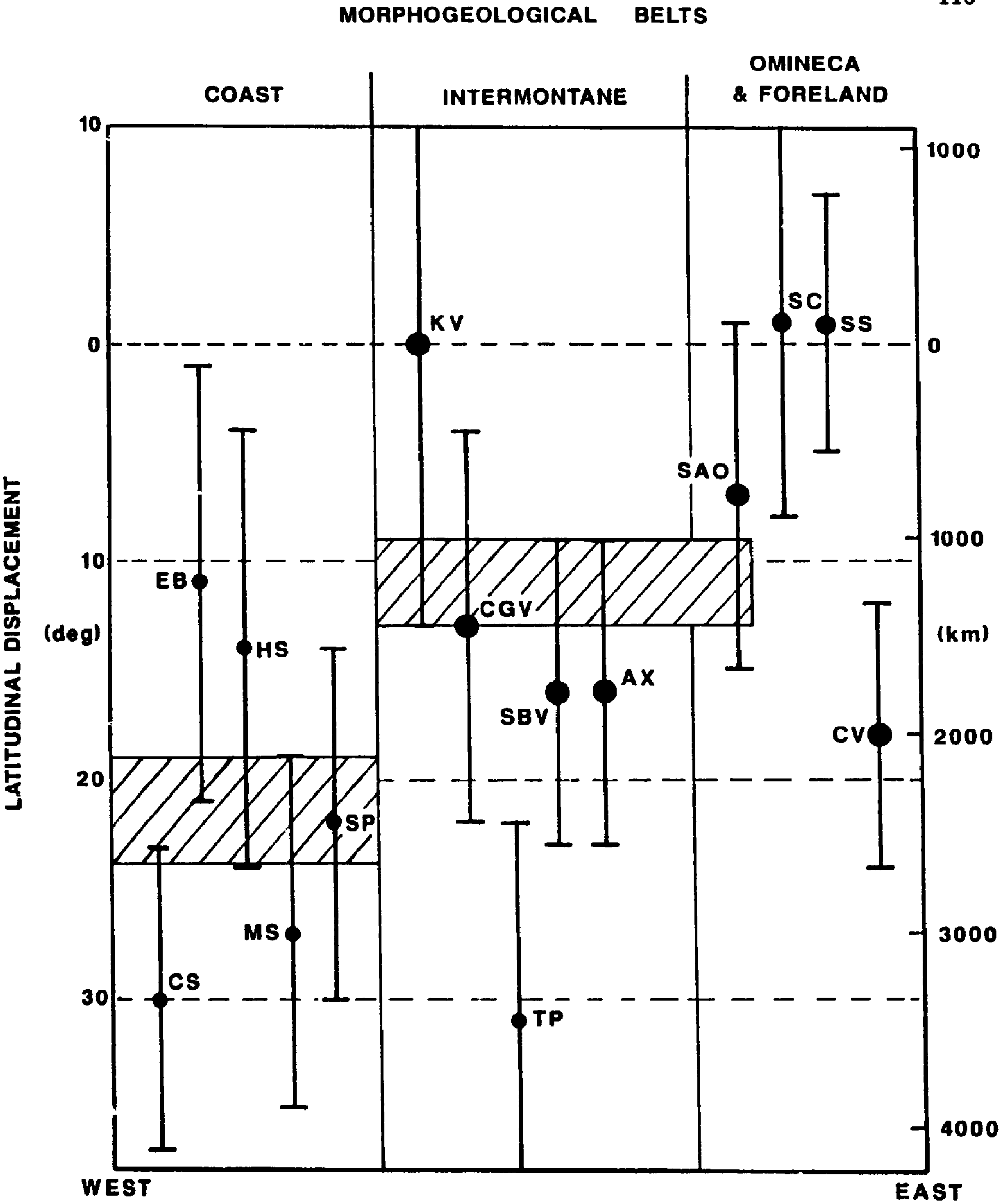

Figure 4.6.3 Relative paleolatitudinal displacements (RPDs) from CC Cretaceous paleopoles with respect to east–west position in morphogeologic belts. Larger symbols indicate RPD with good paleohorizontal control. See text and Table 4.1.1 for explanation.

Some of the Cretaceous results may be subject to revision due to the less than detailed AF and thermal step demagnetization procedures used in many of the Cretaceous paleomagnetic studies. However, this will remain to be seen until such time as new studies are provided. It is acknowledged that the magnitude of post–mid–Cretaceous northward translation can be more precisely constrained by further paleomagnetic studies. Notwithstanding, in view of the Late Cretaceous results from the Carmacks Group and the Kasalka Group it seems most of the ≈ 1000 km of northward translation took place between 70 and 50 Ma, although this is difficult to assess without improving the precision of the Kasalka Group result. In addition, the difference in displacement suggested by a comparison of the results from the mid–Cretaceous Sylvester Allochthon and the Late Cretaceous Carmacks Group cannot be adequately assessed until the results from further studies are made available. If this assessment of CC Cretaceous displacement stands up to close scrutiny, and only time will tell, it appears proponents of both the "tilt" and "translation" models will be vindicated. This assessment favorably acknowledges many of the valid and well founded observations contributed by proponents of both "tilt" and "translation" which prior to this study appeared to be in conflict.

CHAPTER 5 – SUMMARY AND CONCLUSIONS

5.1 SUMMARY

In the preceding chapters I have presented new paleomagnetic data and made an attempt at a reasonably comprehensive review of the CC paleomagnetic data base. It is hoped that this research has made a significant contribution towards a better understanding of the current CC paleomagnetic data base and its constraints on allochthonous CC displacement. The division of the discussion into the Tertiary, Cretaceous, and Permian to Early Jurassic geologic periods seemed a logical one based on the unique implications of the data within each period. A conspicuous void in the data base exists within the Middle Jurassic to Early Cretaceous period. Data from this period are extremely important since they would provide a critical test of interpretations based on Permian to Early Jurassic data and mid– to Late Cretaceous data. Certainly the Middle Jurassic to Early Cretaceous period needs to be targeted for future paleomagnetic study.

Considering the interpretation herein of the Late Triassic and Early Jurassic data, the weakest links are the cratonic reference fields which are subject to revision because of the different opinions with regards to cratonic data selection and analytical procedures. As noted, down shifting of the geologic time scale in this time frame has had a significant impact on the tectonic implications for the data. This demonstrates how sensitive tectonic implications are to small errors and/or changes in the reference field. Even under the best circumstances the paleomagnetism has not proven to be capable of distinguishing tectonic displacements of < 500 km. Recall the discussion earlier in which it is pointed out that RPD and RR errors are, more often than not, minimum estimates.

A conspicuous feature of the CC paleomagnetic data base that has not been given enough attention in this study are the large and variable rotations particularly in the Permian to Early Jurassic data. The question arises – Are these rotations the result of tectonic block rotations about vertical axes or have they been artificially manufactured by incorrectly assuming untilting about horizontal axes. Figure 5.1.1 is a plot of the Permian to Early Jurassic rotations from data summarized in Table 5.1.1. In the first instance the feature that most stands out is an apparent lack of systematic rotations which may suggest that untilting about horizontal axes in some cases may not be valid. However, closer observation reveals that the results from southern Quesnellia (GB Guichon batholith, NV Nicola Volcanics, CM Copper Mountain Intrusives) are all similarly rotated clockwise ≈ 45°. Indeed, Irving *et al.* (1985) and Rees *et al.* (1985) recognized this and suggested that it was a result of mid–Cretaceous overprinting based on the premise that these directions closely resemble the mid–Cretaceous directions in Coast Belt intrusions. An inconsistency in this opinion is that the mid–Cretaceous directions from the Intermontane belt, in which Quesnellia is situated, have now been shown to be significantly different from the Coast Belt intrusive directions. Of course two of these studies are characterized by bipolar directions which precludes their association with remagnetization in the Cretaceous normal superchron. Therefore, assuming an Early Jurassic age for these magnetizations to be correct, one can speculate that a ≈ 45° clockwise rotation of a large block of southern Quesnellia has taken place since the Early Jurassic. Just what significance this may have had on the assembly of Terrane I is uncertain but this observation suggests additional future studies may lead to future important discoveries regarding the development of the CC. Further discussion of this is beyond the scope of this thesis; however this does serve as a useful example of the way in which these large rotations may be tectonically

Table 5.1.1 LIST OF CANADIAN CORDILLERAN PERMIAN TO JURASSIC PALEOMAGNETIC STUDIES AND THEIR POLES

Pole	Rock Unit	Age	Locality Lat°	Locality Long°	N/R	N	Demagnetization	TC	Dec°	Inc°	R	k	α95°	PALEOPOLE Lat°	PALEOPOLE Long°	A95° dp°	A95° dm°	RPD°	RR°	Ref.
GB	Guichon Batholith	≈ 198 Ma	50.5	-121.0	10/3	13	3Th Bulk Steps 200, 450, 560°C	No	028.3	36.3	/	/	7.3	52	-347	4.9	8.5	05±08	-41±08	(1)
CM	Copper Mtn. Intrusives	≈ 198 Ma	49.3	-120.5	9/2	11	1Thp 13s-680°C Bulk 540/560°C	No	025.9	41.2	10.937	160	3.6	57	12	2.7	4.4	00±06	-38±07	(2)
SV	Stuhinni Group Volcanics (Formerly Takla Group)	≈ 220 Ma	56.6	-126.4	N	14	AF & Th p#? Bulk 60 mT, 500-550°C	Yes	290.0 (combined two areas)	41.4	/	/	≈7.0	31	141	≈15.0	10.0	05±11	43±12	(3)
NV	Nicola Volcanics	≈ 205 Ma	49.9	-120.5	N	26 (33s)	1AF & 1Thp 3Bulk 30mT, 565, 650°C	Yes	040.7	47.4	25.078	/	5.5	53	-11	4.7	7.2	-04±07	-53±08	(4)
BV	Bonanza Group Volcanics	≈ 200 Ma	50.7	-128.0	N	13	AF & Th p#? Some Bulk	Yes	276.0	42.0	/	50	6.0	22	154	6.0	9.0	02±08	68±09	(5)
ATV	Asitka Volcanics (Early Permian)	≈ 260 Ma	56.7	-126.6	N	5s	AF & Th p#?	Yes	354.0	40.0	Tuff	41	8.0	56	63	6.0	9.0	04±07	-45±07	(6)
ARV					R	5s	Bulk & Stepwise	Yes	85.0	-38.0	Rhyolite	209	3.0	15	159	2.0	4.0	05±04	44±04	
ABV					R	15s		Yes	129.0	-40.0	Basalt	20	8.0	40	123	5.0	9.0	04±06	00±07	
H1V	Hazelton Group Volcanics	≈ 198 Ma	56.5	-126.8	R	4	AF & Th p#?	Yes	114.0	-52.0	/	14	25.0	40	144	35.0	24.0	-	50±29	(3)
H2V			55.8	-126.6	N	4	Bulk & Stepwise	Yes	242.0	56.0	/	29	18.0	17	-175	25.0	18.0	-	102±23	
H3V			55.6	-126.4	5/2	7		Yes	359.0	55.0	/	15	16.0	70	57	22.0	16.0	-	-15±20	
									Mean Inc 54									-3±19		
H4V	Hazelton Group Volcanics		54.8	-126.1	8/1	9	AF & Th	Yes	265.0	56.0	/	24	10.7	27	169	11.0	15.0	-	78±15	(7)
H5V			54.4	-128.2	6/4	10	All stepwise	Yes	227.0	50.0	/	38	8.0	5	13	7.0	11.0	-	116±11	
H6V			54.5	-127.1	N	8	PCA	No	328.0	50.0	/	51	7.9	56	112	7.0	11.0	-	16±11	
									Mean Inc 52									-2±10		

Notes: Lat.- North Latitude, Long. - longitude (-ve is west); N/R - Normal to Reverse polarity site ratio, R - all sites reversed, N - all sites normal; N - Number of sites, s - number of samples, s - number of specimens; Demagnetization - average demagnetization treatment/site, AF - alternating field, Th - thermal, p - pilot, #? - number not stated, PCA - principal component analysis ; TC - bedding tilt correction; Dec - unit mean declination; Inc - unit mean inclination; R - resultant vector sum; k - precision parameter; α95 - radius about unit mean direction of 95% confidence; A95 - radius about mean virtual geomagnetic pole (VGP) direction of 95% confidence; dp - is the radius of the ellipse of 95% confidence about the pole along the site-pole great circle, dm - is the radius this ellipse perpendicular to the site-pole great circle; RPD -relative paleolatitude displacement (+ve is North), RR-relative rotations (+ve is counterclockwise) (Early Permian 43N 126E α95=4 and Late Triassic 56N 100E α95=5 from Irving and Irving (1982), Early Jurassic 63N 85E α95=7.0 from Vandall and Palmer 1990c (This study); Ref.- reference for study.

(1) Symons 1983b, Supersedes Symons 1971a; (2) Symons and Litalien 1984, Supersedes Symons 1973c; (3) Monger and Irving (1980); (4) Symons 1985 (5) Irving and Yole 1987; (6) Irving and Monger 1987; (7) Vandall and Palmer 1990b (This study). Results from the Karmutsen Formation by Symons (1971b), Irving and Yole (1972), Schwarz et al. (1980) and Yole and Irving (1980) demonstrate they possess significant unstable and hybrid remanence components of uncertain age. Also results from the Jurassic Westcoast Complex by Symons (1985b) are not primary and their age is uncertain. Thus, these results are too problematical to include here.

PERMIAN–EARLY JURASSIC RELATIVE ROTATIONS

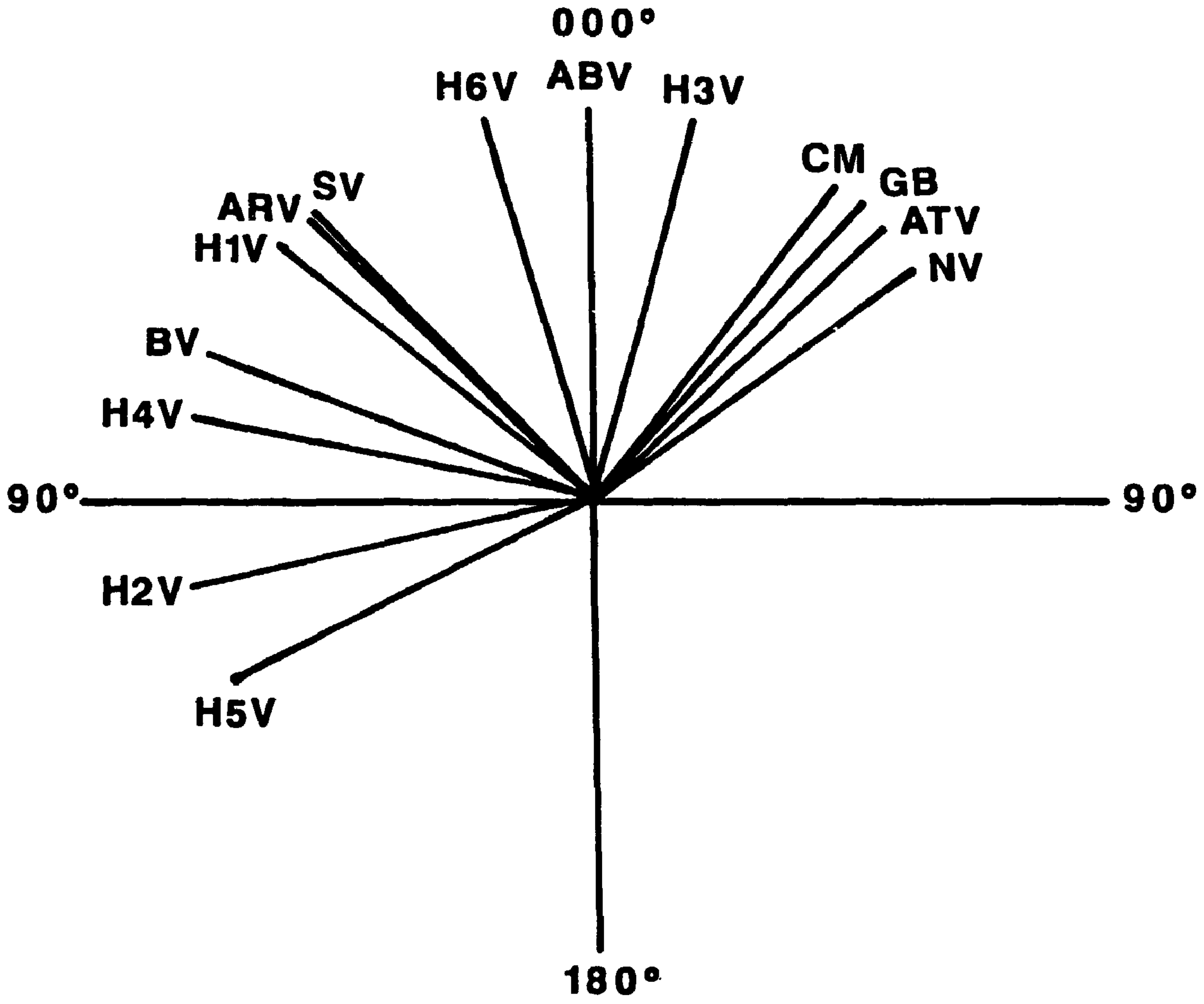

Figure 5.1.1 Relative rotations (RRs) from CC Permian to Early Jurassic paleopoles. 000 is the expected cratonic reference. See text and Table 5.1.1 for explanation.

significant and can help to further understand CC development.

In the final stage of editing this thesis I was made aware of a most recent publication by Irving and Wynne (1990) which also is a review of the CC paleomagnetic data base. The paper is particularly well written, presenting a very eloquent analysis of the data with opinions both complimentary and contrary to my own. As time does not permit a discussion of the pros and cons of our different opinions I at least refer interested readers to consider its contents.

This study could not have been carried out had it not been for the very substantial contributions made to the CC data base by D. T. A. Symons, E. Irving and their co–workers. Over the last two decades their efforts have produced the majority of CC data on which this study has relied. The thought provoking ideas expressed in numerous discussions in their publications have laid the foundation on which subsequent discussions have been based. Particularly useful have been the various syntheses by E. Irving and co–workers which have put CC paleomagnetism into a manageable framework. Thus, while recognizing these significant contributions have strongly influenced my research, I cannot take full credit for the ideas developed and expressed in this thesis.

5.2 CONCLUSIONS

The Ootsa Lake Group volcanic rocks studied herein have provided the only Middle Eocene paleomagnetic result from the Stikine terrane. This result along with other recent studies provide concordant 50 Ma paleopoles which not only constrain the upper limit of CC northward displacement, but also due too their concordancy, contribute to the North American cratonic paleomagnetic data base. Due to the presence of several consistency tests, excellent geochronologic control and the use of detailed AF and thermal step demagnetization combined with PCA techniques it is unlikely that this result and interpretation will be subject to revision in the future.

The results from the Early Jurassic Hazelton Group substantiate previous results by Monger and Irving (1980) with improved precision. Because of the downward revision of the geologic time–scale and changes to the Early Jurassic cratonic reference pole the data no longer require ≈ 1300 km of northward translation of allochthonous CC since the Early Jurassic. Terrane I and at least southern Terrane II were in fact close to their present latitudinal positions with respect to North America, although large and variable rotations about vertical axes suggest that amalgamation of the large composite terranes was not yet complete. Inasmuch as these results from the Hazelton Group are characterized by the presence of several consistency tests, good geochronologic control and the use of detailed AF and thermal step demagnetization combined with PCA techniques it is unlikely that they will be subject to revision in the future. Recognizing the fact that the Early Jurassic reference pole has undergone many recent positional revisions, due to differences in data selection and analytical techniques, future revisions are quite possible. Thus, the interpretations based on the Hazelton Group results may also be subject to revision, although it seems unlikely that they would be sufficiently large to significantly change the interpretation in this study regarding the Cretaceous data.

Inasmuch as the Cretaceous paleomagnetic results are largely discordant, whereas the Permian–Early Jurassic and Middle Eocene data are latitudinally concordant, significant displacements of the allochthonous CC are constrained within the Cretaceous period. The significant implication which has not been considered by previous large scale (≈ 2400 km) displacement models is that the pre– and post–Cretaceous data requires first large scale southward displacement of allochthonous CC after the Early Jurassic, followed by large northward coast–wisc translation and final stabilization by the Middle Eocene. The required timing and magnitude of displacement in these models are not compatible with major CC tectonic events including known major fault offsets. Indeed, it seems difficult to reconcile geologically such large displacements and it is reasonable therefore to presuppose in the first instance that the Cretaceous data may be similarly latitudinally concordant. Thus local tilting, supported by geologic evidence that was consistently invoked by Symons and later corroborated by Butler *et al.*, to explain discordant data from Coast Belt intrusions appears to be well founded on geologic grounds. Critical to the "tilt vs. translation" controversy were results from rocks with reasonable paleohorizontal control which were provided by the Kasalka Group results and several other recent studies. Most significantly, the estimates of post–Cretaceous northward translation from these results with paleohorizontal control are in reasonably good agreement, considering inherent errors in the method. They indicate that northward translation is within the 900–1300 km range, which for the first time overlaps with geologic estimates. As such, the convergence of the Cretaceous data towards a CC displacement model in which moderate ($\approx$ 1000 km) northward translation has taken place, combined with local tilting of the Coast Belt intrusives and local block rotations principally in the Intermontane Belt, is in my view the best current explanation of the available Cretaceous CC paleomagnetic data. This model is consistent with recognized geologic structures and the evidence of known dextral offsets along the Tintina and NRMTF systems. It also has the desirable attribute of not requiring data selectivity as a prerequisite to the model as all the CC Cretaceous paleomagnetic results can be accommodated by this model. Further, it is consistent with moderate post mid–Cretaceous northward displacements originally proposed by Monger and Irving (1980) and later reconfirmed by Armstrong *et al.* (1985).

The Kasalka Group result requires further study to more tightly constrain the data and convincingly average out secular variation. Nevertheless, even with the liberal qualitative error assignment placed on this result it cannot be considered consistent with earlier CC tectonic models in which systematic clockwise rotation and large–scale northward translation have been invoked. Recall that one of the objectives of this study was to provide an integrated movement picture for a single terrane through time; with this in mind the implications of the Early Jurassic to Middle Eocene data provided by this study for mid–central Stikinia appear to extend to most of the allochthonous CC as has been shown.

This review exhibits some of the limitations of this data base. There are many CC paleomagnetic results which may be subject to revision in the future due to the less than detailed AF and thermal step demagnetization procedures used. With this in mind I highly recommend that all future paleomagnetic studies employ routine detailed AF and thermal step demagnetization procedures combined with PCA analysis techniques. The conclusions of this thesis are admittedly based on a less than satisfactory CC paleomagnetic data base as many additional paleomagnetic studies on rocks (preferably bedded) from the Permian through to the Paleocene are needed. Many periods within this time frame are still unrepresented and are vital to the critical assessment of the TMD model discussed herein. Nevertheless, one is obliged to make use of the available data, albeit not without its limitations of quantity and accuracy, to construct a coherent tectonic framework into which the data best fits. To this end I hope I have met with some success.

APPENDIX

PUBLISHED EOCENE AND EARLY JURASSIC PALEOMAGNETIC RESULTS

<u>Reprinted from</u>:

Canadian Journal of Earth Sciences
Volume 27, pages 212–218, 1990.

Upper limit of docking time for Stikinia and Terrane I: paleomagnetic evidence from the Eocene Ootsa Lake Group, British Columbia

T. A. VANDALL AND H. C. PALMER

Department of Geophysics, The University of Western Ontario, London, Ont., Canada N6A 5B7

Received August 3, 1989

Revision accepted October 16, 1989

The Middle Eocene Ootsa Lake Group is exposed in the central portion of the Stikine Terrane, where it was sampled along the shoreline of Tahtsa Reach and Whitesail Reach. The group consists of dominantly subaerial flows, which range in composition from basalt to rhyolite, that unconformably overly the Jurassic Hazelton Group. Detailed alternating-field and thermal stepwise demagnetizations were done on all specimens from the 21 sites collected. The presence of a normal- and reversed-polarity remanence, a positive fold test, and high coercivities and unblocking temperatures indicate that a prefolding primary remanence has been isolated. The mean tilt-corrected direction of $D = 002.2°$, $I = 69.2°$ ($\alpha_{95} = 7.4°$) from 13 sites for which paleohorizontal is well known yields a pole position at 354.6°E, 88.0°N ($A_{95} = 11.5°$), which is statistically indistinguishable from published 50 Ma reference poles for cratonic North America. This evidence demonstrates that the proposed large-scale northward displacement of Stikinia since mid-Cretaceous was completed by at least Middle Eocene time This result is consistent with other paleomagnetic results from Stikinia, Quesnellia, and the Coast Plutonic Complex indicating that much of the allochthonous Cordillera had assembled and docked with cratonic North America by the Middle Eocene.

Le Groupe d'Ootso Lake de l'Éocène moyen, qui affleure dans la partie centrale du terrane de Stikine, a été échantillonné le long des rives des parties droites Tahtsa et Whitesail. Le groupe, formé principalement de coulées subaériennes de composition de basalte à rhyolite, repose en discordance sur le Groupe d'Hazelton du Jurassique. Une étude détaillée des désaimantations par champ alternatif et par chauffage a porté sur tous les spécimens des 21 sites échantillonnés. La présence de rémanence de polarité normale et inverse, le test du pli positif et les champs coercitifs intenses ainsi que les températures de déblocage indiquent qu'une rémanence primaire acquise avant la phase de plissement a été isolée. La direction moyenne de 13 sites, de paléohorizontalité bien connue, et une fois corrigée sur l'inclinaison, est de $D = 002,2°$, $I = 69,2°$ ($\alpha_{95} = 7,4°$), elle fournit une position du pôle à 354,6°E, 88,0°N ($A_{95} = 11,5°$), ne différant pas statistiquement des pôles de la courbe 50 Ma du craton de l'Amérique du Nord. Cette étude démontre que le déplacement du Stikinia sur une grande distance vers le nord depuis le Crétacé moyen s'est terminé avant au moins le temps de l'Éocène moyen. Ces données s'accordent avec les résultats de d'autres études paléomagnétiques du Stikinia, Quesnellia et du Complexe plutonique côtier, indiquant qu'une partie importante de la Cordillère allochtone fut collée et arrimée au craton de l'Amérique du Nord avant l'Éocène moyen

[Traduit par la revue]

Can J Earth Sci 27, 212–218 (1990)

Introduction

Numerous paleomagnetic studies in the Cordillera of North America have recognized discordant paleomagnetic directions with respect to the craton. These aberrant directions have been explained by large-scale tectonic rotations and (or) translations of allochthonous terranes within the Cordillera, which have been independently supported to some extent by paleontologic, radiometric, and structural evidence. Much of the paleomagnetic evidence for large-scale northward displacement comes from Cretaceous paleomagnetic data (e.g., Rees *et al.* 1985; Marquis and Globerman 1988), since mid-Tertiary and later Cordilleran data are for the most part concordant.

Currently, the Cretaceous to mid-Tertiary paleomagnetic data base for the Cordillera includes relatively few studies from bedded sequences for which paleomagnetic horizontal is known. Recent paleomagnetic results from bedded sequences include work by Fox and Beck (1985), Symons and Wellings (1989), and Bardoux and Irving (1989). Their results demonstrate that Quesnellia had reached its present latitudinal position relative to North America by Middle Eocene. Although Symons and Wellings (1989) found no evidence of clockwise rotations, Fox and Beck (1985) observed declinations to the north-northeast that they interpreted as indicating 25° of clockwise rotation of their study area. Given the extensional tectonics of that time, this scenario is plausible. Bardoux and Irving (1989) also provided evidence to suggest a clockwise rotation of 28° of their study area if correction for full geologic tilt is applied to all their sites. However, they argued that the Kelowna volcanics magnetizations were acquired over a time spanning deposition and tilting, and therefore correction for full geologic tilt is unwarranted. They interpreted their data using partial tilt corrections for one group of sites, where precision is maximized, and no tilt correction for another group of sites. Their conclusion is consistent with the null hypothesis that, relative to the craton, there have been no large rotations. As pointed out by Kodama (1988), a maximum value of Fisher's (1953) precision parameter (k) at partial unfolding is a necessary, but insufficient, condition to ensure that the magnetization is synfolding in age. Evidence independent of the fold test must be used to substantiate a synfolding age of magnetization It is evident that in the middle Eocene some areas internal to Quesnellia may have undergone clockwise rotation about vertical axes. Given that the result of Symons and Wellings (1989) is the only unambiguous concordant Middle Eocene pole from bedded volcanics in Quesnellia and Terrane I (Fig. 1) (Monger *et al.* 1982; Monger 1984), further paleomagnetic studies on bedded rocks of this age are needed. Thus, the purpose of this study was to obtain paleomagnetic data from an Eocene volcanic suite with bedding control in order to establish whether large-scale rotations and (or) northward translations were ongoing during this time since the Cretaceous in Stikinia The Middle Eocene Ootsa Lake Group was chosen for this paleomagnetic study by

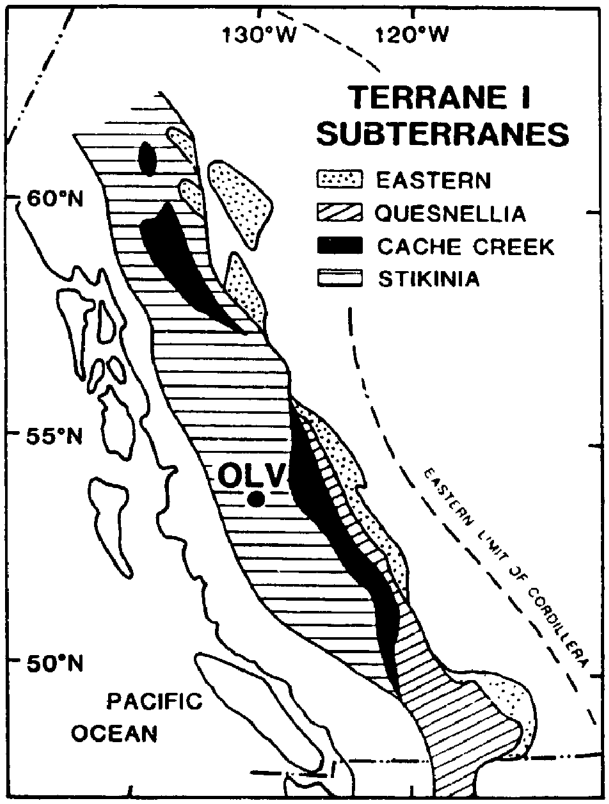

FIG. 1. Location map showing the Ootsa Lake Group study area and its relation to the subterranes of Terrane I from Monger *et al.* (1982). OLV, Ootsa Lake Group volcanics.

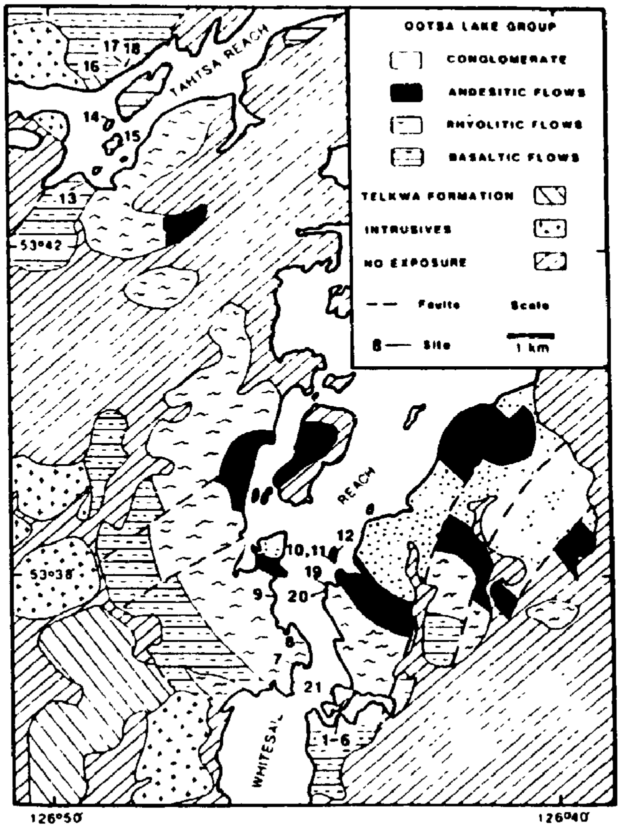

FIG. 2. Geology of the study area after Diakow and Mihalynuk (1987*a*), with site locations indicated.

virtue of its good stratigraphic exposure, age control, lack of post-emplacement intrusives, relatively fresh, unaltered appearance, and location in central Stikina (Fig. 1).

Geology

Much of the following has been discussed by Diakow and Mihalynuk (1987*b*). Stikinia is underlain by mildly deformed and faulted Lower Jurassic to Tertiary volcanic and sedimentary rocks. The Middle Eocene Ootsa Lake Group in the type area around Ootsa Lake comprises rhyolitic flows and less voluminous andesite and basalt, together with associated pyroclastic and sedimentary rocks (Duffell 1959). Recent mapping by Diakow and Mihalynuk (1987*a*) has identified similar Ootsa Lake Group rock types in the Whitesail Range to the west of Ootsa Lake, where subaerial flows, ranging in composition from basalt to rhyolite, and representing over 1000 m of volcanic stratigraphy, dominate. Diakow and Mihalynuk (1987*a*) divided the group into six rock units on the basis of outcrop appearance and lithology. In our study area (Fig. 2) only four of these units crop out: basalts in the lowest unit, overlain by rhyolites, which in turn are overlain by andesites capped by a conglomerate unit.

The Ootsa Lake Group in this area is essentially unmetamorphosed. The youngest intrusives are small Tertiary plugs that cut the Smithers Formation, upon which the Ootsa Lake Group unconformably rests. These plugs are likely intrusive equivalents of the Ootsa Lake Group. Thus, these volcanics were not likely exposed to subsequent thermal events. Localized hydrothermal alteration associated with fractures can be recognized by a cream–white appearance that weathers to rusty fragments. However, we have avoided sampling in these areas. Four K–Ar radiometric dates on biotites from the Ootsa Lake Group are in excellent agreement, ranging between 50.0 ± 1.7 and 49.1 ± 1.7 Ma, and suggest that the group may have erupted over a 1 Ma time span (Diakow and Koyanagi 1988).

Methods

The Ootsa Lake volcanics were sampled at 21 sites (Fig. 2) characterized by shallow- to moderately steep dipping flows of basalt, andesite, and rhyolite. Using a portable drill, we drilled at least five cores at each site and oriented them *in situ* by magnetic and solar compasses. Bedding attitudes were carefully measured as close as possible to each site and recorded. Wherever possible, two specimens were cut from each core. We analyzed the specimens using a Schonstedt DSM-1 spinner magnetometer, Schonstedt GSD-5 tumbling alternating field demagnetizer, and a Schonstedt TSD-1 thermal demagnetizer. After measuring the natural remanent magnetization (NRM), we subjected each specimen to detailed alternating-field (AF) and (or) thermal stepwise demagnetization in up to 14 steps. AF demagnetization was done up to maximum fields of 100 mT, and thermal demagnetization was done up to peak temperatures

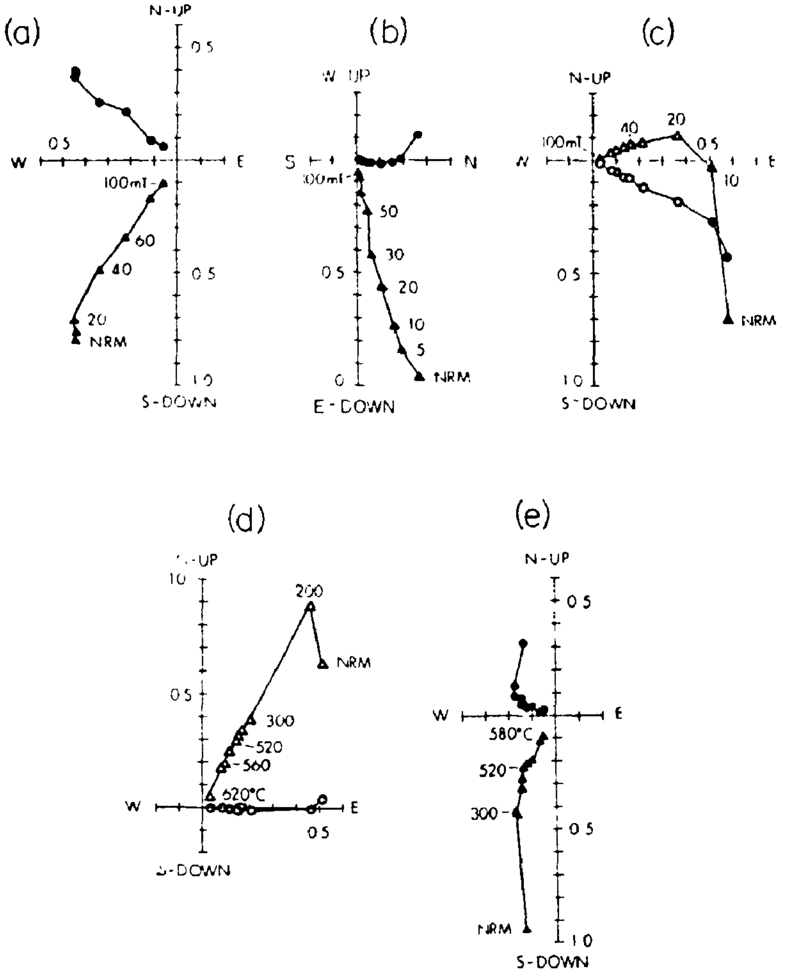

FIG. 3. Orthogonal-vector-decay plots for example specimens on AF and thermal stepwise demagnetization. Circles (triangles) represent vector projections on the horizontal (vertical) planes; solid (open) symbols denote down (up) directions; the AF-step intensities are in milliteslas (mT); thermal-step temperatures are in degrees Celsius (°C). The axial values are given as a ratio of the NMR intensity. The directions are before tilt correction. Specimens are from (*a*) site 12, (*b*) site 3, (*c*) site 14, (*d*) site 5, and (*e*) site 8.

of 700°C. Characteristic remanence directions in each specimen were obtained by a joint analysis of stereographic and orthogonal demagnetization diagrams and least-squares principal-component analysis following Kirschvink (1980). Directions of remanence were accepted with a mean angular deviation (MAD) of <10°; most were <5°. We calculated the site-mean remanence directions using conventional tiered statistics (Irving 1964; Fisher 1953).

Results

The majority of orthogonal-vector-decay and stereographic plots illustrated data of high quality, demonstrating very stable linear vector decay from all three volcanic rock types (Figs. 3*a*–3*e*). The plots indicated that single stable normal (Figs. 3*a*, 3*b*, and 3*e*) and reversed (Figs. 3*c*, 3*d*) components were isolated after demagnetization removed the "soft" viscous remanence magnetization (VRM) residing in low-coercivity and low-unblocking-temperature domains (Figs. 3*a*–3*e*). The VRM components often differed from one specimen to the next, indicating random directions, some of which were acquired during a storage test in the laboratory. After removal of the VRM components the majority of specimens decayed substantially and linearly towards the origin, with maximum AF's of 100 mT (Figs. 3*a*–3*c*) and (or) thermal unblocking temperatures in both the magnetite and the hematite ranges (Figs. 3*d*, 3*e*). This demonstrates that the same stable remanence is carried by both magnetite and hematite. Stable remanence directions were isolated in each of the 21 sites; their corresponding site means and unit means are shown in Tables 1 and 2.

Fold test

The attitudes of the Ootsa Lake Group volcanics are quite variable, with shallow to moderately steep dips, so a diagnostic fold test (Graham 1949) is possible. A comparison of *in situ* site means (Fig. 4*a*) with tilt-corrected site means (Fig. 4*b*) shows a substantial improvement in the clustering of directions. This much-improved clustering of directions after full tilt correction increases the estimate of *k* from 11.5 to 32.6, a maximum for

TABLE 1. Site-mean remanence data

Site	Unit	N	D (°)	I (°)	ϕ (°)	ψ (°)	D_C (°)	I_C (°)	R	k	α_{95} (°)
1	Basalt	7	244	72	047	40	034	66	6 959	145	5[a]
2	Basalt	7	248	67	047	40	024	70	6 971	210	4[a]
3	Basalt	6	355	75	045	25	026	54	5 971	171	5[a]
4	Basalt	4	086	−56	055	30	143	−73	3 960	75	10[a]
5	Basalt	4	080	−62	055	30	167	−78	3 986	211	6[a]
6	Basalt	6	106	−73	055	30	200	−67	5 923	65	8[a]
7	Rhyolite	5	296	71	045	30	006	61	4 965	61	11
8	Rhyolite	5	298	64	045	30	354	57	4 965	115	7
9	Rhyolite	5	316	62	065	30	010	58	4 896	39	13[a]
10	Andesite	7	352	69	025	20	007	51	6.619	16	16
11	Andesite	5	324	66	025	20	349	52	4 872	31	14[a]
12	Andesite	8	304	46	048	19	326	47	7 957	162	4
13	Basalt	5	109	−34	105	39	115	−73	4 495	8	29[a]
14	Basalt	9	117	−25	110	45	127	−69	8 905	84	6[a]
15	Basalt	5	132	−37	112	50	196	−73	4 995	593	3[a]
16	Basalt	2	143	−30	130	50	181	−76	1 999	1279	7[a]
17	Basalt	5	159	−27	120	35	191	−58	4 975	163	6
18	Basalt	11	134	−35	108	44	179	−68	10 994	1740	1
19	Rhyolite	7	010	74	025	20	018	55	6.965	171	5
20	Rhyolite	9	012	70	025	14	017	56	8 759	33	9[a]
21	Basalt	8	016	67	038	10	022	57	7 905	73	7

NOTES: N, number of samples, D and I, mean remanence vector's declination and inclination, respectively, relative to present horizontal; ϕ, down-dip azimuth of bedding, ψ, dip angle from horizontal, D_C and I_C, same as D and I but after tilt correction relative to bedding, R, resultant vector for the summation, k and α_{95}, precision parameter and radius of the circle of 95% confidence, respectively (Fisher 1953)

[a] Sites with *in situ* measured attitudes.

TABLE 2. Uncorrected and corrected unit means and their paleopoles

C or U mean	N	D (°)	I (°)	k	α_{95} (°)	d_p (°)	d_m (°)	Long	Lat
U	21	309 3	61 2	11 5	9 8	11 6	15 0	214 7°W	55 1°N
C	21	002 5	64 8	32 6	5 7	7.4	9 2	39 3°E	82 6°N
U	13	298.8	60 3	10.7	13.3	15 3	20 2	208 2°W	48 2°N
C	13	002 8	69 1	32.3	7 4	10.7	12 6	5 4°W	88 0°N

NOTES. C, tilt-corrected unit mean, U, uncorrected unit mean, N, number of site means, D, I, k, and α_{95} as in Table 1, d_p, radius of the ellipse of 95% confidence at the pole along the site–pole great circle, d_m, radius of this ellipse perpendicular to the site-pole great circle

the group mean. The variance-ratio test (Watson 1956) indicates a positive fold test at the 99% confidence level (McElhinny 1964). McFadden and Jones (1981) suggested that generally this test is too rigorous. Thus, the fold test asserts with at least 99% confidence that the remanence is prefolding in origin.

Magnetostratigraphy

Nine of the 21 sites studied (sites 4–6 and 13–18, Fig. 2) are of reversed polarity, and they all occur in the basalt flows of the lowest stratigraphic unit sampled. Basalt sites 1–6 on Whitesail Reach are stratigraphically ordered in successive flows downward through about 200 m of section. Sites 1–3 in the upper half are normally polarized, whereas 4–6 in the lower half are reversely polarized and likely record the same reversed chron as found in basalt sites 13–18 on Tahtsa Reach. Previously, sites 13–18 could only be roughly correlated on the basis of their basaltic composition. However, given that a reversal of the Earth's magnetic field only takes a few thousand years (Hospers 1954; Hoffman 1988), this stratigraphically confined reversed chron provides an accurate marker horizon for more precise stratigraphic correlation. Since the rhyolite and andesite units are stratigraphically above the basalt unit and are characterized by only normal polarity, this must represent the same normal-polarity chron observed in the upper basalt flows. This follows, given that the Ootsa Lake Group volcanics erupted over about a 1 Ma time span, with volcanic activity ending around 49.1 ± 1.7 Ma (Diakow and Koyanagi 1988), and polarity chron 21, spanning 47.46–49.91 Ma (Harland *et al.* 1982), is the only reasonable time-correlative chron. Polarity chron 20 is too young, spanning 44.31–47.46 Ma, and polarity chron 22 is too old, spanning 49.91–51.39 Ma (Harland *et al.* 1982). The two polarity chrons are assigned to the 21 reversed and 21 normal chrons (Harland *et al.* 1982) based on their excellent fit with the radiometric ages for the Ootsa Lake Group.

The isolation of a magnetization with both polarities is very convincing evidence that the remanence is primary, and if both polarities are combined, secular variation should be averaged out. The mean normal- and reversed-polarity remanence are roughly antipodal after tilt correcting each site and are separated by only 14° of arc

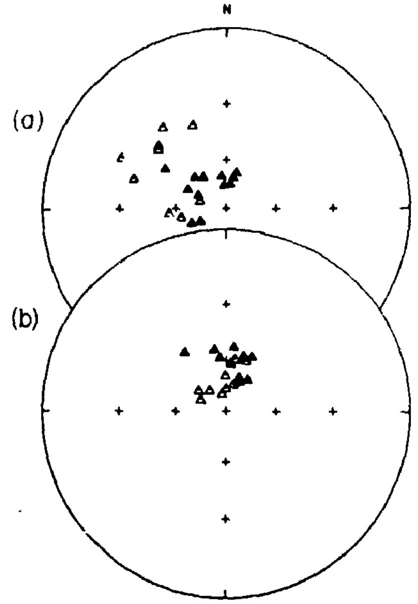

FIG. 4. Equal-area stereographic projection showing (*a*) the site-mean directions relative to present horizontal; and (*b*) the same, but tilt corrected relative to bedding. All triangles are downwardly directed vectors; however, those with open symbols have been converted from their antipodal reversed position.

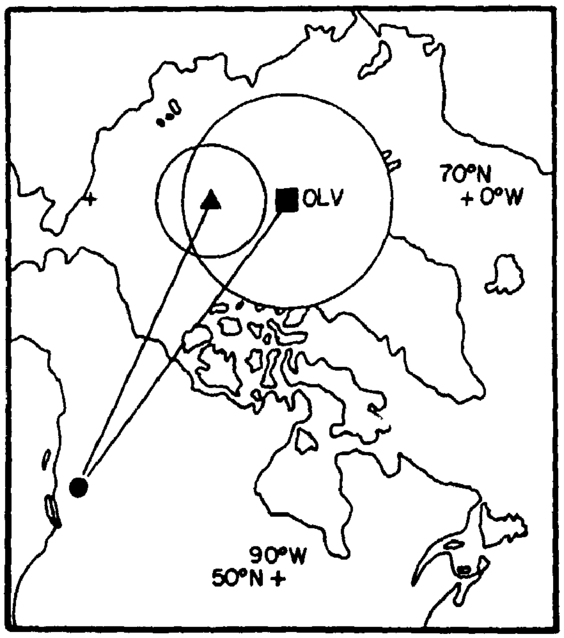

FIG. 5. Pole position for the Ootsa Lake Group volcanics (OLV) (corrected 13 sites, Table 2) shown by a square with its circle of 95% confidence. The study area is shown by the solid circle. The 50 Ma reference pole for the North American craton is shown by a triangle with its circle of 95% confidence (Bardoux and Irving 1989).

Discussion

Given a single stable remanence direction spanning two polarity chrons and a positive fold test at the 99% confidence level, we interpret this as a primary magnetization acquired upon cooling of the lava flows. The relatively small directional difference between normal and reversed polarities may suggest that secular variation has not been adequately averaged out within a single polarity. However, when data from the two polarities are combined, giving a k value of 32 with 95% confidence limits of $17 \leq 32 \leq 53$ (Cox 1969), secular variation appears to have been averaged out, since the expected k value of 20 (McFadden and McElhinny 1984) falls within this range at 95% confidence.

Since we are concerned with the tectonic implications of these results, the importance of accurately knowing the paleomagnetic horizontal of the sampling sites cannot be overemphasized. Equally important is accurately knowing the corresponding reference pole for cratonic North America.

There seem to be two philosophical approaches amongst the paleomagnetic community regarding the interpretation of paleomagnetic horizontal in bedded rocks. One approach prefers to apply well-understood regional bedding attitudes as tilt corrections for paleomagnetic sampling sites in an area. Another approach prefers accurate bedding measurements made *in situ* at each individual sampling site. Together, both attempt to accurately establish the most representative tilt corrections for prefolding and (or) synfolding magnetizations. In this study, because of quite variable bedding strikes and dips from one sampling locality to the next, the best tilt corrections should be obtained from accurately measured *in situ* bedding attitudes at each site. Unfortunately, this could only be done at 13 of the 21 sites collected for this study, so we calculated a second unit mean (Table 2) using only those sites where bedding attitudes could be directly measured. Importantly, this second unit mean from 13 sites combines six normal-polarity and seven reversed-polarity sites and minimizes the influence of bedding-attitudes errors, which can introduce large errors into the tectonic analysis of the data. It is possible that primary dips could be incorporated into these tilt corrections; however, a significant primary dip will manifest itself by high dispersion both before and after tilt correction, which is not the case here.

Tectonic analysis

Since popular North American reference poles calculated by a moving average-window technique may smooth out polar-wander details, it is more accurate to look at the data base specifically applicable to the Middle Eocene and narrow the time-averaging window within the tightest possible limits. This has been done by Bardoux and Irving (1989), who provided a reference pole (180°E, 83°N, A_{95} = 6.0°) from three well-dated studies that constrain the age of the pole to between 47 and 53 Ma.

The above reference paleopole of Bardoux and Irving (1989) and that for the Ootsa Lake Group (corrected 13 sites, Table 2) are in good agreement (Fig. 5). Carrying out the tectonic analysis outlined by Yole and Irving (1980), incorporating the error analysis of Demarest (1983), demonstrates that the Ootsa Lake Group paleopole is statistically indistinguishable from the cratonic reference pole for North America. Relative paleolatitude displacement is statistically nonsignificant at 4.8° ± 10.2° to the north, and relative rotation is also statistically nonsignificant at 13.2° ± 17.5° clockwise. Note that this result does not change significantly if the 50 Ma reference poles from Irving and Irving (1982), Harrison and Lindh (1982), or Diehl *et al* (1983) are used. The statistically nonsignificant magnitudes of northward displacement and clockwise rotation are arguably beyond the attainable precision of any single paleomagnetic study and are therefore, for all intents and purposes, equal to zero. This analysis indicates that Stikinia was in much the same latitudinal position relative to the North American craton during the Middle Eocene as it is at present.

Geotectonics

Stikinia is thought to have been assembled with several other subterranes in the Middle Triassic to form the allochthonous microplate Terrane I (Monger *et al.* 1982). As mentioned earlier, recent paleomagnetic studies on Middle Eocene volcanics from one of these subterranes, Quesnellia (Fox and Beck 1985; Symons and Wellings 1989; Bardoux and Irving 1989), have demonstrated that Quesnellia, which is inboard of Stikinia in Terrane I (Fig. 1), was in much the same latitudinal position in the Middle Eocene as it is now. It is significant that the Ootsa Lake Group, located in Stikinia, has not been rotated clockwise, unlike some areas in Quesnellia that may have been. This is likely due to its more central location in Terrane I, where there was greater stability. This is the first Middle Eocene paleomagnetic result from Stikinia. A previous study on the younger Late Miocene Cariboo plateau lavas and Cariboo gabbro plugs that overlie and intrude the Stikine, Quesnel, and Cache Creek subterranes also yielded concordant results (Symons 1969*a*, 1969*b*), consistent with the result from this study. Further middle Tertiary paleomagnetic data from intrusions of the Coast Plutonic Complex immediately west of Terrane I are also concordant, with the exception of a low-accuracy discordant result from the Mount Barr Complex (Symons 1973*b*). These concordant results include those from the Chilliwack batholith (Beck *et al.* 1982); the Hope Complex (Symons 1973*b*); the Grotto and Snoqualmie batholiths (Beske *et al.* 1973); the Spuzzum–Porteau plutons overprint (Irving *et al.* 1985); the Brown basalt dikes (Symons 1968); and the north-northwest-trending plutons of the Hawkesbury warp (Symons 1977). Middle Tertiary studies from rocks farther west in the Coast Plutonic Complex and Wrangellia do show divergences (e.g., Symons 1973*a*; Hicken and Irving 1977). However, in the main body of the Canadian Cordillera, paleopoles from volcanics and intrusives of mid-Tertiary age and younger are consistent with our result from Stikinia. This is strong evidence that stabilization and docking of Terrane I and much of the Canadian Cordillera with North America took place by at least the Middle Eocene.

Conclusions

The Ootsa Lake Group is characterized by a stable, two-polarity, prefolding, primary remanence that was acquired upon cooling when the lavas were extruded around 50 Ma. The polarity chrons correspond to 21 normal and 21 reversed chrons (Harland *et al.* 1982) and provide a useful stratigraphic marker horizon for the Ootsa Lake Group. The Ootsa Lake Group paleopole is statistically indistinguishable from several current estimates of the comparable cratonic reference pole. This tectonic analysis indicates that Stikinia was in much the same latitudinal position relative to the North American craton during the Middle Eocene as it is at present. This demonstrates that the proposed large-scale northward displacement of Stikinia since the mid-Cretaceous was completed by at least Middle Eocene time. This docking time is consistent with concordant paleomagnetic results from Stikinia, Quesnellia, and the Coast Plutonic Complex that also indicate that much of the allochthonous Cordillera had assembled and docked with North America by at least Middle Eocene.

Acknowledgments

The authors are grateful to Louise Vandall for her able assistance with the fieldwork. Many thanks for help go to Larry Diakow, with the British Columbia Department of Mines (BCDM), for logistical support in the study area and numerous helpful discussions concerning the geology of the Ootsa Lake Group; John Drobe and Pat Bartier, also with BCDM, for providing some hand samples; and D. T. A. Symons and an anonymous referee for helpful reviews. Funding for this project was provided through a research agreement from Energy, Mines and Resources Canada, Natural Sciences and Engineering Research Council of Canada grant A3544 to H C Palmer, and the Faculty of Science of The University of Western Ontario

Bardoux, M , and Irving, E 1989 Paleomagnetism of Eocene rocks of the Kelowna and Castlegar areas, British Columbia studies in determining paleohorizontal Canadian Journal of Earth Sciences, **26**. 829–844.

Beck, M. E , Burmester, R F , and Schoonover, R 1982 Tertiary paleomagnetism of the North Cascade Range, Washington Geophysical Research Letters, **9** 515–518

Beske, S J , Beck, M E , and Noson, L 1973 Paleomagnetism of the Miocene Grotto and Snoqualmie batholiths, central Cascades, Washington Journal of Geophysical Research, **78** 2601–2608

Cox, A. 1969 Confidence limits for the precision parameter *k* Geophysical Journal of the Royal Astronomical Society, **18**. 545–549

Demarest, H. H , Jr 1983 Error analysis for the determination of tectonic rotation from paleomagnetic data. Journal of Geophysical Research, **88** 4321–4328.

Diakow, L. J , and Koyanagi, V 1988 Stratigraphy and mineral occurrences of Chikamin Mountain and Whitesail Reach map areas *In* Geologic fieldwork 1987 British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1988-1, pp 155–168.

Diakow, L. J , and Mihalynuk, M 1987*a*. Geology of Whitesail Reach and Troitsa Lake areas, British Columbia Ministry of Energy, Mines and Petroleum Resources, Open File Map 1987-4

——— 1987*b*. Geology of Whitesail Reach and Troitsa Lake areas *In* Geologic fieldwork 1986 British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1987-1, pp 171–179

Diehl, J. F , Beck, M E , Beske-Diehl, S , Jacobson, D , and Hearn, B. C. 1983 Paleomagnetism of the Late Cretaceous – early Tertiary north-central Montana alkalic province Journal of Geophysical Research, **88**: 10 593–10 609

Duffell, S. 1959. Whitesail Lake map-area, British Columbia. Geological Survey of Canada, Memoir 299

Fisher, R. A. 1953 Dispersion on a sphere Proceedings of the Royal Society of London, Series A, **217** 295–305.

Fox, K. F., and Beck, M. E 1985. Paleomagnetic results for Eocene volcanic rocks from northeastern Washington and the Tertiary tectonics of the Pacific Northwest. Tectonics, **4**. 323–341

Graham, J. W. 1949 The stability and significance of magnetism in sedimentary rocks. Journal of Geophysical Research, **54**: 131–167.

Harland, W B., Cox, A. V , Llewellyn, P. G , Pickton, C A G., Smith, A G., and Walters, R 1982. A geologic time scale Cambridge University Press, Cambridge

Harrison, C G. A., and Lindh, T 1982 A polar wandering curve for North America during the Mesozoic and Cenozoic Journal of Geophysical Research, **87** 1903–1920

Hicken, A., and Irving, E 1977 Tectonic rotation in western Canada. Nature (London), 268: 219–220.

Hoffman, K. A. 1988 Ancient magnetic reversals: clues to the geodynamo. Scientific American, 258. 76–83.

Hospers, J. 1954. Reversals of the main geomagnetic field III. Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen, Series B: Physical Sciences, 57 112–121.

Irving, E 1964. Paleomagnetism and its application to geological and geophysical problems. Wiley, New York.

Irving, E, and Irving, G. A. 1982. Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana. Geophysical Surveys, 5: 141–188

Irving, E., Woodsworth, G. J, Wynne, P. J., and Morrison, A 1985. Paleomagnetic evidence for displacement from the south of the Coast Plutonic Complex, British Columbia Canadian Journal of Earth Sciences, 22: 584–598.

Kirschvink, J. L. 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophysical Journal of the Royal Astronomical Society, 62. 699–718

Kodama, K. P. 1988. Remanence rotation due to rock strain during folding and the stepwise application of the fold test. Journal of Geophysical Research, 93: 3357–3371

Marquis, G., and Globerman, B. R 1988 Northward motion of the Whitehorse Trough: paleomagnetic evidence from the Upper Cretaceous Carmacks Group. Canadian Journal of Earth Sciences, 25: 2005–2016.

McElhinny, M. W. 1964 Statistical significance of the fold test in palaeomagnetism. Geophysical Journal of the Royal Astronomical Society, 8: 338–340.

McFadden, P. L., and Jones, D. L. 1981 The fold test in palaeomagnetism. Geophysical Journal of the Royal Astronomical Society, 61: 53–58.

McFadden, P. L., and McElhinny, M. W. 1984 A physical model for paleosecular variation Geophysical Journal of the Royal Astronomical Society 78: 809-830

Monger, J. W. H. 1984. Cordilleran tectonics: a Canadian perspective. Bulletin de la Société géologique de France, 26 255–278.

Monger, J W. H., Price, R. A., and Tempelman-Kluit, D. J., 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera. Geology, 10: 70–75.

Rees, C. J., Irving, E., and Brown, R. L. 1985. Secondary magnetization of Triassic–Jurassic volcaniclastic rocks of the Quesnel Terrane, Quesnel Lake, B.C. Geophysical Research Letters, 12. 498–501.

Symons, D. T A. 1968. Geological implication of paleomagnetic studies in the Bella Coola and Laredo Sound map-areas, British Columbia. Geological Survey of Canada, Paper 68-72.

——— 1969*a*. Paleomagnetism of the Late Miocene plateau basalts in the Cariboo region of British Columbia. Geological Survey of Canada, Paper 69-43

——— 1969*b* Paleomagnetism of four Late Miocene gabbroic plugs in south-central British Columbia. Canadian Journal of Earth Sciences, 6: 653–662.

——— 1973*a* Paleomagnetic zones in the Oligocene East Sooke gabbro, Vancouver Island, British Columbia. Journal of Geophysical Research, 78: 5100–5109.

——— 1973*b*. Paleomagnetic results from the Tertiary Mount Barr and Hope plutonic complexes, British Columbia. Geological Survey of Canada, Paper 73-19

——— 1977. Geotectonics of Cretaceous and Eocene plutons in British Columbia a paleomagnetic fold test. Canadian Journal of Earth Sciences, 14: 1246–1262.

Symons, D. T. A, and Wellings, M. R. 1989 Paleomagnetism of the Eocene Kamloops Group and the cratonization of Terrane I of the Canadian Cordillera. Canadian Journal of Earth Sciences, 26: 821–828.

Watson, G. S. 1956. A test for randomness of directions Monthly Notices of the Royal Astronomical Society, Geophysical Supplement, 7: 160–161.

Yole, R W., and Irving, E. 1980. Displacement of Vancouver Island. paleomagnetic evidence from the Karmutsen Formation. Canadian Journal of Earth Sciences, 17: 1210–1228

<u>Reprinted from</u>:

Geophysical Journal International
Volume 103, pages 609–619, 1990.

Geophys. J. Int. (1990) **103**, 609–619

Canadian Cordilleran displacement: palaeomagnetic results from the Early Jurassic Hazelton Group, Terrane I, British Columbia, Canada

T. A. Vandall and H. C. Palmer
Department of Geophysics, University of Western Ontario, London, Ontario, Canada N6A 5B7

Accepted 1990 June 21 Received 1990 April 30, in original form 1989 December 16

SUMMARY

The Early Jurassic Telkwa Formation, comprising the base of the Hazelton Group, was sampled at three areas in the central part of the Stikine Terrane, British Columbia. Detailed alternating field and thermal step demagnetization on samples from nine sites from the Red Canyon area and 10 sites from the Zymoetz River area, both of which are in the Bulkley Ranges, and eight sites from the Telkwa Range area isolate stable remanence magnetization components. The components are interpreted to be primary magnetizations because of the presence of two polarities and the much improved agreement of their inclinations after full tilt correction of the sites from the Bulkley Ranges. Within-locality declinations agree well; between-locality declinations are discordant. The expected cratonic declination is ~340° whereas declinations from this study are 265°, 227° and 328° for the Red Canyon, Zymoetz River and Telkwa Range areas respectively. These results are similar to those of Monger & Irving (1980) and we concur that the discordant declinations are the result of differential rotation about vertical axes between sample localities. Our observed mean inclination of 52° is in good agreement with Monger & Irving's (1980) result of 54°. They interpreted this to indicate ~1300 km of northward displacement since the Early Jurassic and their interpretation was substantiated by several later studies. However, with revisions to the geologic time-scale and the Early Jurassic reference pole for North America, the Early Jurassic Canadian Cordillera palaeomagnetic data base appears latitudinally concordant. This indicates that Terrane I and southern Wrangellia were in much the same latitudinal position relative to the North American craton as they are now. Tectonic displacement models developed in view of discordant Cretaceous palaeomagnetic data from the Canadian Cordillera must now consider latitudinally concordant Permian to Early Jurassic data and Middle Eocene to Recent data. This tectonic senario appears more reconcilable with the regional tilt hypothesis. However, this hypothesis cannot account for discordant Cretaceous data from bedded volcanic rocks in Terrane I. It is therefore probable that Cretaceous Cordilleran tectonics were characterized by both regional tilting and moderate latitudinal displacement.

Key words: Cordilleran tectonics, Early Jurassic, Hazelton Group palaeomagnetism, Telkwa Formation, Terrane I.

1 INTRODUCTION

The tectonic development of the Canadian Cordillera reflects the complex evolution of a collage of allochthonous terranes. Palaeomagnetism has been useful in studying this development by providing quantitative analyses of large-scale tectonic motions within and between terranes. The first aberrant palaeomagnetic result in the western Cordillera of North America came from the Eocene Siletz River Volcanic series of Oregon (Cox 1957). However, it was not until later that Irving (1964) recognized that this aberrant result was caused by rotation about a vertical axis. Since then numerous discordant palaeomagnetic results, together with differences between Cordilleran and contiguous North American stratigraphies and differences between coeval faunas along the ancient cratonic margin, have led to the recognition that the Cordillera is a collage of terranes of different origin. This collage of allochthonous terranes assembled and collided with the ancient cratonic margin at different times.

There are numerous published palaeomagnetic studies with which to test for large-scale motions in the Canadian Cordillera. However, considerable controversy exists over the interpretation of discordant palaeomagnetic data from the Early Jurassic to mid-Cretaceous (e.g. Monger & Irving 1980; May & Butler 1986; Butler *et al.* 1989). It involves different perceptions of the geologic development of the Cordillera and differences in the analytical procedures used to calculate North American reference poles. The purpose of this study is to examine this controversy by a review of the data base with the addition of new palaeomagnetic data from the Early Jurassic Telkwa Formation, a volcanic suite from the Stikine Subterrane of Terrane I (Monger, Price & Tempelman-Kluit 1982; Monger 1984) (Fig. 1).

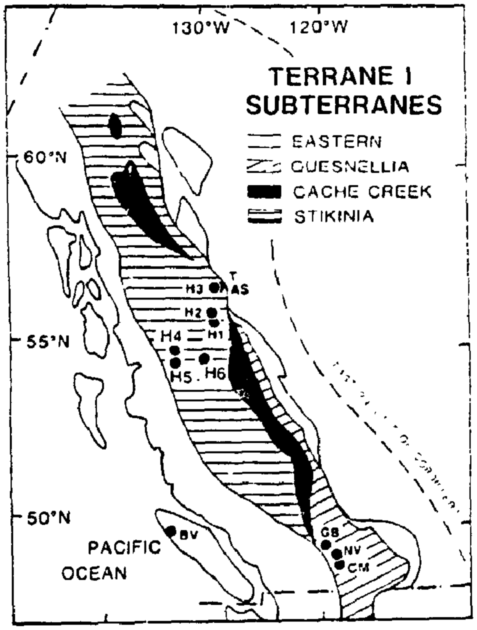

Figure 1. Terrane map with the study areas for the Hazelton Group [H1–H3. Manger & Irving (1980), and H4–H6, this study] Takla Group (T), Asitka Group (AS), Guichon Batholith (GB), Nicola Group (NV), Copper Mountain Intrusions (CM) and Bonanza Group (BV), in relation to the subterranes of Terrane I from Monger *et al.* (1982).

The Telkwa Formation is part of the Hazelton Group and was selected for this study because it has been biochronologically dated, crops out over an extensive region of the central Stikine Terrane, and has bedding attitudes to define the palaeohorizontal unlike plutonic rocks (e.g. Beck Burmester & Schoonover 1981; Irving *et al* 1985). Thus it is possible to relate the directions of remanent magnetizations to the estimated palaeohorizontal when the primary remanence is acquired.

Previous palaeomagnetic work on the volcanic rocks of the Hazelton Group by Monger & Irving (1980) was restricted to areas near the eastern margin of Stikinia (H1, H2, H3; Fig. 1). Their results suggested that Stikinia had been translated northward by ~ 1300 km as well as rotated substantially about vertical axes. This interpretation was based on the best available reference pole at that time (Irving 1979). Although, the precision of their Hazelton Group result is somewhat low, the interpretation was supported by results from the Takla Group and Axelgold intrusion (Monger & Irving 1980). Conclusions about northward displacement and large-scale variable rotations for parts of the Canadian Cordillera from several later studies on Early Jurassic rocks (e.g. Symons 1983; Symons & Litalien 1984; Symons 1985; Irving & Yole 1987) were consistent with Monger & Irving's (1980) result. However, these conclusions involved the use of different Early Jurassic North American reference poles. Thus, the proposed displacements and rotations were not calibrated with one another, and therefore, should not be compared. In addition, the North American Early Jurassic reference pole was imprecisely defined. This is demonstrated by numerous revisions over the last decade (e.g. Irving 1979; Irving & Irving 1982; Gordon, Cox & O'Hare 1984, May & Butler 1986; Irving & Yole 1987; Hodych & Hayatsu 1988). Unless the reference pole is accurately known within a very few degrees of error a tectonic analysis will be similarly inaccurate. Latitude displacement errors can be of the order of several hundred kilometres and rotation errors of several tens of degrees, both of which can be independent of the precision of the pole determination. Thus, in order to accurately evaluate the tectonic implications of these earlier palaeomagnetic studies of Early Jurassic rocks the tectonic displacements must be recalculated using the same, current, more precisely defined, Early Jurassic reference pole.

Recent reviews of the Early Jurassic palaeomagnetic data, which include Monger & Irving's (1980) work on the Hazelton Group, by May & Butler (1986) and Vandall, Palmer & Woodsworth (1989) suggest that originally proposed large-scale northward displacements of the Canadian Cordillera are no longer supported by current cratonic reference poles. This issue is addressed in this study along with the consequences for tectonic models developed in view of discordant Cretaceous palaeomagnetic data.

2 GEOLOGY AND SAMPLING

The Early to mid-Jurassic Hazelton Group (Leach 1910) is a continental to island-arc calcalkaline assemblage that was deposited in the northwest-trending Hazelton trough (MacIntyre & Desjardins 1988). Tipper & Richards (1976) divided it into three major formations that are, in ascending stratigraphic order, the Telkwa Formation, the Nilkitkwa Formation and the Smithers Formation. The Telkwa Formation, of Late Sinemurian to Early Pliensbachian age (206–198 Myr; Harland *et al.* 1982), crops out in mid-central Stikinia and comprises the thickest and most extensive formation of the Hazelton Group. It includes subaerial to submarine pyroclastic and flow rocks with lesser intercalated sedimentary rocks (MacIntyre & Desjardins 1988). Telkwa Formation volcanic units were sampled in the Red Canyon area (H4), Zymoetz River area (H5) and Telkwa Range (H6) (Figs 1 and 2).

The Red Canyon area (Fig. 2, H4) is characterized by a moderately shallow east-northeast dipping homoclinal succession of greenish-grey calcareous tuffs and red crystal

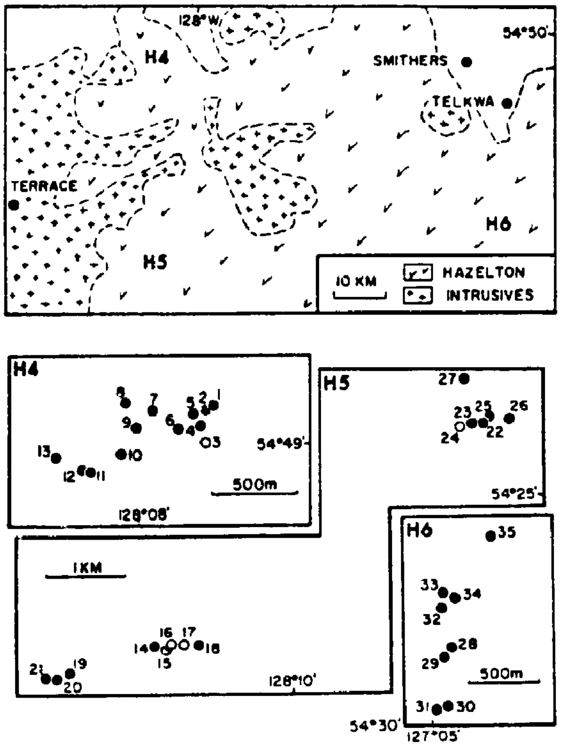

Figure 2. Regional setting of the Hazelton Group sample areas in mid-central Stikinia Base map modified from Tipper, Woodsworth & Gabrielse (1981) Sample areas. H4 Red Canyon sites 1–13, H5 Zymoetz River sites 14–27 and H6 Telwa Range sites 28–35 Solid circles are normal polarity sites and open circles are sites with reverse polarity

tuffs. The top of the ≥400 m sampled section contains Sinemurian fossils and is just below the Smithers Formation (Woodsworth, Hill & van der Heyden 1985). It is reasonably well exposed so that accurate bedding attitudes could be measured at or near the 13 sample sites. Most of these sites were sampled in the red crystal tuffs. The metamorphic grade appears to be very low as detailed studies of the adjacent Zymoetz River area (Mihalynuk 1987) and the Telkwa Range area (Dudley 1983) have indicated that regional metamorphism grades from zeolite to prehnite-pumpellyite facies. In addition, the area is far removed from known intrusive bodies (Woodsworth *et al.* 1985), and therefore, it is not likely that it has experienced any thermal remagnetization events since deposition.

The Zymoetz River area (Fig. 2, H5) is characterized by a moderately steep eastward-dipping homoclinical succession composed of intercalated bladed-feldspar porphyry flows, crystal tuffs and a mauve ignimbrite that crops out as a conspicuous marker horizon (Mihalynuk & Ghent 1986). The succession is exposed for 25 km in the down dip direction but some of the section is repeated by thrust faulting so that it probably represents about 6–7 km of Telkwa stratigraphy (Mihalynuk & Ghent 1986). West of the Zymoetz River area, the Telkwa Formation rocks have been intruded by the Coast Plutonic Complex but even there the higher metamorphic grades are restricted to narrow contact zones (Mihalynuk 1987). In the Zymoetz River area, 14 sites were sampled that represent more than 1 km of stratigraphic section. The exposures are very good so that bedding attitudes are easily determined.

The rocks of the Telkwa Formation in the Telkwa Range, southwest of Smithers (Fig. 2, H6), are dominantly lava flows (MacIntyre *et al.* 1989). Aphyric basalts were sampled at eight sites from a gently northward-dipping sequence with Sinemurian fossils in overlying sediments (MacIntyre *et al.* 1989). The eight sites are distributed over about 200 m of section. Again the bedding attitudes could be readily determined and most of the sample sites were subhorizontal. The regional metamorphic grade is zeolite facies (Dudley 1983) so that these flows are the most pristine Telkwa Formation rocks studied to date. The area is not known to have been intruded by later igneous rocks (MacIntyre *et al* 1989).

Sinemurian fossil localities immediately above two of the sampled sections indicate an age of 200–206 Myr on the geologic time-scale of Harland *et al.* (1982).

3 METHODS

In total, 35 palaeomagnetic sites in the Telkwa Formation were collected in flows and tuffs using a portable drill At least five cores were drilled and oriented by magnetic and/or solar compass at each site In the laboratory two specimens were cut from each core. The specimens were analysed using a Schonstedt DSM-1 spinner magnetometer, GSD-5 tumbling alternating field demagnetizer and TSD-1 thermal demagnetizer. After measuring the natural remanent magnetization (NRM), each specimen was subjected to detailed alternating field (AF) and/or thermal stepwise demagnetization in up to 12 steps. Alternating field demagnetization was done up to maximum fields of 100 mT and thermal demagnetization was done up to peak temperatures of 700 °C. Characteristic remanence directions in each specimen were obtained by a joint analysis of stereographic and orthogonal demagnetization diagrams and least-squares principal-component analysis following the method of Kirschvink (1980). Remanence directions were accepted with a mean angular deviation (MAD) < 10°. The site mean remanence directions were calculated using conventional tiered statistics (Fisher 1953; Irving 1964).

4 RESULTS

The majority of specimens exhibit stable linear vector decay (Fig. 3a–f). After the initial removal of low coercivity and low unblocking temperature viscous components (VRM), the majority of specimens decayed substantially and linearly towards the origin with maximum alternating fields of 100 mT (Fig. 3d–3f) and/or thermal unblocking temperatures typical of both magnetite and haematite (Fig. 3a–c), showing that the same stable remanence direction is carried by both magnetite and haematite. The VRM directions from one specimen to the next were quite different indicating randomly directed viscous components some of which were acquired during a storage test in the laboratory. The data from four Red Canyon sites (1, 2, 4 and 7) and four Zymoetz River sites (14, 19, 25, and 26)

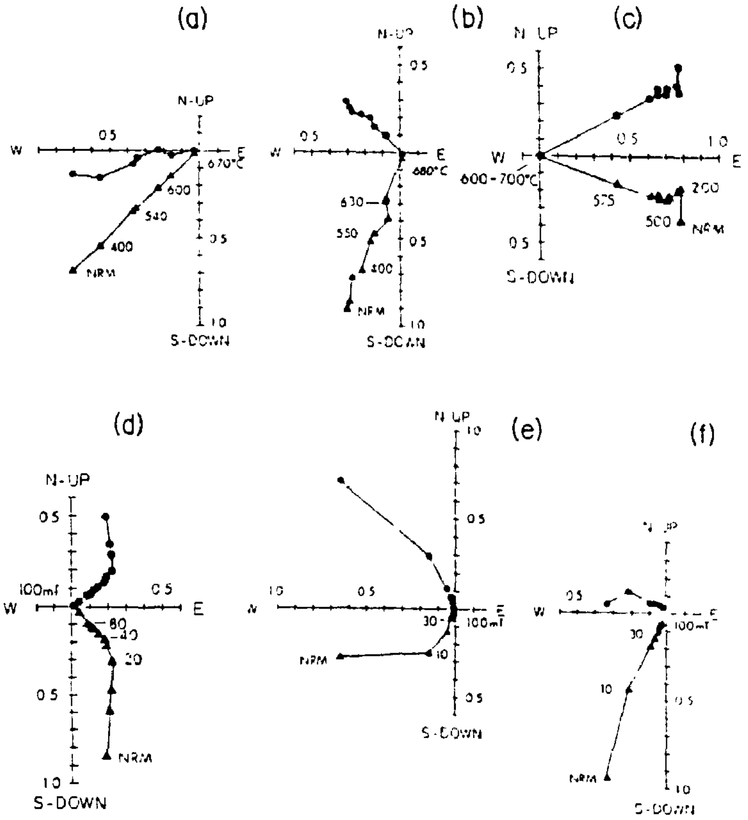

Figure 3. Orthogonal vector decay plots for example specimens on thermal and AF step demagnetization. Solid circles represent vector projections on the horizontal plane and solid triangles, vector projections on the vertical plane; all symbols denote down directions. The AF step intensities are in millitesla (mT), and the thermal step temperatures are in degrees Celsius (°C). The axial values are given as a ratio of the NRM intensity. The directions are before tilt correction. Specimens are from sites 9 (a), 13 (b), 17 (c), 17 (d), 29 (e) and 31 (f). Note specimens (c) and (d) from site 19 are reverse polarity after tilt correction.

were rejected because of unstable magnetic remanence, attributable to either very weak magnetic intensities of the order of 0.1 mA m^{-1} in some sites or to anomalously strong magnetic intensities in other sites that are indicative of lightning-induced isothermal remanence. Thus stable remanence directions were isolated in 27 of the 35 sites, and their corresponding site means and area means are shown in Tables 1 and 2.

Only downward directed magnetizations were isolated in the Telkwa Range and Red Canyon sites (Table 1, Fig. 4a) except for site 3 where both upward and downward directed vectors were observed in different layers of a thinly laminated tuff. The *in situ* site mean directions from the rocks in the Telkwa Range area where structural attitudes are subhorizontal form a reasonably tight cluster with a north-west directed moderately steep down direction (Fig. 4a) which is close to the expected Early Jurassic direction as calculated from results from the craton. In contrast, the *in situ* site mean westward-directed magnetizations from the Red Canyon area display greater scatter, specifically in declination; the shallow inclinations are reasonably well grouped. In the Zymoetz River area, both upward and downward directed *in situ* shallow magnetizations are roughly antipodal to the northeast and down, and southwest and up (Fig. 4a). Within a sample area, the site mean directions agree reasonably well before tilt correction. However, between sample areas the declinations and inclinations are quite scattered and in particular the directions from the Zymoetz River and Red Canyon areas are well removed from the expected Early Jurassic direction (Fig. 4a).

4.1 Tilt test

Given the very shallow subhorizontal attitude of the basalts of the Telkwa Range it is quite possible that the shallow northerly dip is primary and reflects a gently sloping surface away from a volcanic centre. This would suggest that the mean remanence direction for the Telkwa Range area should be closer to the expected cratonic reference pole before tilt correction than after and this is in fact the case (Table 2) but the differences are not statistically significant.

In contrast, the remanence data from the Red Canyon and Zymoetz River areas, hereafter referred to jointly as

Table 1. Site mean remanence data

Site	Area	N	D°	I°	φ°	ψ°	CD°	CI°	R	k	α95°
3	H4	6	266	35	099	24	273	62	5 599	13	29 *
5	"	2	238	13	099	21	295	66	1 527	–	–
6	"	7	260	27	099	24	261	51	6 862	43	9
8	"	7	248	23	095	25	237	50	6 859	45	9
9	"	9	244	32	095	25	230	52	8 748	32	9
10	"	8	278	20	095	25	279	45	7 818	39	9
11	"	8	238	23	075	28	231	49	7 883	60	7
12	"	9	265	32	075	28	272	60	8 865	60	7
13	"	3	274	30	075	28	265	55	2 776	9	41
15	H5	10	059	5	060	70	038	–57	9 810	48	7
16	"	9	018	7	060	70	027	–49	8 700	27	10
17	"	7	054	21	060	60	051	–31	6 818	39	10
18	"	5	263	–8	105	71	241	55	4 785	19	18
20	"	8	225	–20	090	74	215	47	7 789	33	10
21	"	6	230	–10	071	75	216	53	5 992	532	3
22	"	5	225	–17	090	70	225	40	4 815	22	17
23	"	3	259	2	090	70	247	69	2 654	6	53
24	"	5	073	21	090	70	067	–46	4 933	60	10
27	"	7	217	–15	093	70	215	43	6 910	66	8
28	H6	7	331	41	000	3	335	41	6 875	47	9
29	"	6	316	51	000	3	318	49	5 916	60	9
30	"	5	314	44	000	0	314	44	4 851	27	15
31	"	8	319	54	000	0	319	54	7 715	26	11
32	"	7	310	41	000	5	313	38	6 969	197	4
33	"	5	350	51	000	5	351	46	4 647	16	24
34	"	5	323	53	000	5	326	19	4 646	12	21
35	"	5	315	54	000	5	319	51	4 897	39	13

Notes N is the number of samples. D and I are the mean remanence vector's declination and inclination, respectively, relative to present horizontal, φ is the down dip azimuth of bedding and ψ is the dip angle from horizontal CD and CI are the the same as D and I but are after tilt correction relative to bedding. R is the resultant vector for the summation, k and α95 are the precision parameter and radius of the circle of 95% confidence (Fisher 1953) H4–Red Canyon Area, H5–Zymoetz River Area, H6–Telkwa Range Area. * – Site 3 is characterized by 3 normal polarity and 3 antipodal reverse polarity specimens

the Bulkley Ranges, come from much steeper dipping layers. The layers include thinly bedded airfall tuffs that were presumably deposited sub-horizontally and initial dip is not likely to be a problem. In the Bulkley Ranges the rocks come from homoclinal successions so that the within-area tilt corrections are similar for all sites and the within-area fold test (Graham 1949) is somewhat inconclusive. Thus the precision parameter (*k*) (Fisher 1953) for the Red Canyon area improves only marginally upon untilting (Table 2). Untilting of the directions from the steeply dipping section, the Zymoetz River section, does however improve the clustering of the mixed polarity data (Fig. 4b) with the precision parameter (*k*) (Fisher 1953) increasing from 28 to 38 (Table 2) On comparing the directions from all three localities, before and after full tilt corrections have been applied to the data from the Bulkley Ranges, the fold test is more conclusive in that the inclinations agree well after correction even though the declinations do not (Fig. 4b). The much improved agreement of site mean inclinations and the improved within-area precision of the Zymoetz River

Table 2. Uncorrected and corrected area means and their palaeopoles.

Area	U/C	N	D°	I°	k	α95°	Dp°	Dm°	Long°	Lat°
H4	U	9	256	32	21	11 5	7	13	158E	12N
"	C	9	255	56	21	10 7	11	15	163E	27N
H5	U	10	241	–12 9	28	9 3	5	10	162E	22N
"	C	10	227	50	38	8 0	7	11	013E	5N
H6	U	8	328	50	51	7 9	7	11	112E	56N
"	C	8	326	47	53	7 7	6	10	107E	55N

Notes: U corresponds to an uncorrected mean, C corresponds to a tilt corrected mean N is the number of site means. D, I, k, α95 are same as in Table 1 Dp is the radius of the ellipse of 95 per unit confidence at the pole along the site–pole great circle and Dm is the radius of this ellipse perpendicular to the site-pole great circle. Long is the pole longitude and Lat is the pole latitude. H4, H5 and H6 same as in Table 1.

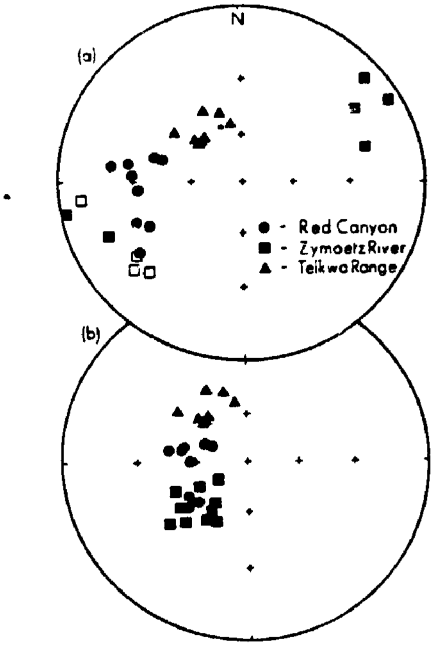

Figure 4. Equal-area lower hemisphere stereographic projection showing site mean directions (a) present horizontal where closed symbols are normal vectors and open symbols are reversed vectors and (b) the same but tilt corrected relative to bedding with five reverse sites plotted in their antipodal normal position.

area after tilt correction strongly suggest a positive fold test for the Bulkley Ranges. The declination differences are thought to reflect large rotations about vertical axes between the sample areas. To derive a precision estimate of the tilt test the magnitudes of rotations between areas were determined by calculating the angles between the observed mean declinations and the expected field declination and then applying these rotation angles to the individual site mean directions. The Telkwa unit mean was calculated then before and after tilt correction, resulting in an improvement of the precision parameter *k* from 7 to 35, respectively. This corresponds to a positive fold test passing at well above the 99 per cent confidence level (McElhinny 1964; McFadden & Jones 1981).

4.2 Magnetostratigraphy

Five of the 27 sites with stable magnetic remanence have reverse polarity magnetizations. One of these five sites in delicately laminated tuffs in the Red Canyon area has both normal and reverse magnetizations. The single mixed polarity site (3) is the uppermost stably magnetized site in the Red Canyon sequence (Fig. 2, H4). The other four reversed sites are from the bases of two sections separated by 5 km of poorly exposed and unsampled volcanic rocks within the Zymoetz River area (sites 15–17 and 24; Fig. 2, H5). Reversed polarity sites 15, 16 and 17 are stratigraphically ordered in successive units upwards within a ~200 m section. Reversed site 24 is overlain by normal polarity volcanic lava flows. Therefore at least one normal and one reversed polarity chron is recorded in both areas. As correlation between the areas is uncertain and duplication of stratigraphy by faulting is possible, suspected additional polarity chrons cannot be confirmed. It is known that the Early Jurassic was a period of many polarity reversals (Steiner & Ogg 1988), so that rocks of this age which retain a primary remanence can be expected to record polarity reversals. The isolation of a stratigraphically zoned magnetization with antipodal directions is good evidence that the remanence is primary and Sinemurian to Early Pliensbachian in age.

5 DISCUSSION

5.1 Hazelton Group

The stable magnetizations isolated in the Telkwa Formation rocks are characterized by high unblocking temperatures and high coercivities. In two of the three sample areas antipodal magnetic reversals are recorded. The tilt test, after rotation correction about vertical axes, is positive and indicates that the remanence from the Bulkley Ranges is pre-tilting at >99 per cent confidence. Therefore we interpret this to be a primary magnetization that was acquired upon cooling of the lava flows and deposition of the tuffs.

A characteristic feature of the Hazelton Group volcanic rocks sampled in Monger & Irving's (1980) study was the large apparent rotations between sampling areas. We attempted to minimize these effects by sampling farther from the Stikine Terrane boundaries where 'ball-bearing type' terrane margin rotations are probable (Beck 1980). However, our three ample areas are within large fault bounded blocks that have also been rotated but to a lesser extent. The central location of the Telkwa Range is likely to have undergone little 'ball-bearing type' terrane margin rotation, and this is confirmed by the close agreement of its mean direction with the expected cratonic direction.

Table 3. Summary of Hazelton Group palaeomagnetic results.

Sample Area	N	D°	I°	k	α_{95}°	Polarity	Mean I°
Results from Monger and Irving (1980)							
H1	7	359	55	15	16.0	mixed	
H2	4	212	56	29	18.0	normal	
H3	4	114	−52	14	25.0	reversed	54
Results from this study							
H4	9	265	56	21	10.7	mixed	
H5	10	227	50	36	8.0	mixed	
H6	8	328	50	51	7.9	normal	52

Notes N, D, I, k, α_{95}, H4, H5, H6 are same as in Table 2

H1 – Bait Range Area, H2 – Driftwood Range Area, and

H3 – Red Creek–Two Lake Creek Area (Monger and Irving 1980)

Our results are similar to those of Monger & Irving (1980) for the Hazelton Group (Table 3, Fig. 5). They also sampled the Hazelton Group in three areas (H1, H2, H3; Fig. 1) and discovered large variations in declination not only between sample areas but also within sample areas. Their area mean precisions were low, partly due to the declination scatter but also due to the low number of sites. This study substantiates, with improved precision, Monger & Irving's (1980) palaeomagnetic results and demonstrates that large block rotations about vertical axes have taken place on both the eastern and western margins of the Stikine Terrane since the Early Jurassic. Central Stikinia, represented by our Telkwa Range result, has apparently undergone relatively

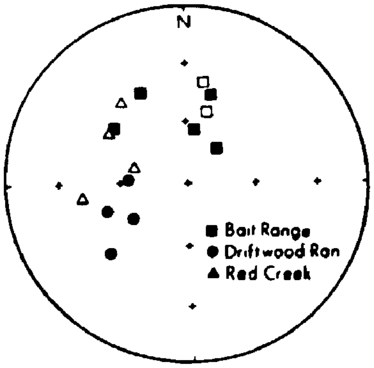

Figure 5. Equal-area stereographic projection showing the site mean directions which have been tilt corrected relative to bedding from Monger & Irving (1980). Closed symbols are normal vectors and open symbols are reverse vectors which have been plotted in their antipodal normal position.

little rotation. Assuming that rotation has been in the smallest angle sense, then post-Jurassic counterclockwise rotations have been observed on the west side of Stikinia in this study. In contrast, both counterclockwise and clockwise rotation have been observed on the east side of Stikinia by Monger & Irving (1980). This pattern suggests these localized rotations did not affect Stikinia as a whole, but are confined to areas proximal to the terrane margins where accretion tectonics on both sides of Stikinia could generate the block rotations.

5.2 Review of Early Jurassic data

Using the reference poles for cratonic North America of Irving (1979), Monger & Irving (1980) found that their poles from the three Hazelton Group sections, together with the Triassic Takla Group and the Cretaceous Axelgold intrusion poles, were discordant. Their tectonic analysis suggested a northward displacement of ~1300 km for Stikinia had taken place since the units had acquired their magnetizations. Results from several later studies on rocks within Terrane I and Wrangellia were consistent with the northward displacement hypothesis, including the Guichon batholith (Symons 1983; GB Fig. 1), Copper Mountain intrusions (Symons & Litalien 1984; CM), Nicola volcanics (Symons 1985; NV) and the Bonanza Group (Irving & Yole 1987; BV). Gordon *et al.* (1984) pointed out that Monger & Irving's (1980) interpretation, although based not only on palaeomagnetic evidence, but also on palaeontological and geological evidence, was not consistent with their updated Late Triassic to Early Jurassic reference poles. These poles were calculated by the palaeomagnetic Euler pole (PEP) analysis (Gordon *et al.* 1984) using the geological time-scale of Harland *et al.* (1982). They indicated a smaller northward displacement for the Takla Group and a southward displacement for the Hazelton Group. Although we question the PEP procedure of Gordon *et al.* (1984), as will be discussed, this work illustrated the need for a new tectonic analysis of the palaeomagnetic results in view of: the significantly revised geologic time-scale, the addition of new palaeomagnetic results to the North American data base, and the recent radiometric dating of palaeomagnetically studied rock units.

A recent tectonic analysis was carried out by May & Butler (1986) who recalculated the Jurassic apparent polar wander (APW) for North America. They also used the PEP analysis and reconsideration of the palaeomagnetic data from Terrane I led to the conclusion that Terrane I was in much the same position relative to North America as it is now. They also pointed out that owing to the poor precision of the Hazelton Group remanence data (Monger & Irving 1980), latitudinal resolution of the Hazelton results was limited. In as much as the data of this study substantiate the results of Monger & Irving (1980) but with greater precision, increased latitudinal resolution is now possible.

Three analytical procedures have been used to calculate reference poles for use in tectonic analyses. The earliest procedure involves a time-window moving average technique using intervals of equal time within which poles are averaged. This technique was used by Irving (1979), Harrison & Lindh (1982) and Irving & Irving (1982), typically with a 30 Myr time-window. Although this procedure is a very useful technique, it can only, at present, illustrate the first-order APW as it is limited by an incomplete and possibly time-biased palaeomagnetic data base, and therefore, tends to smooth out polar wander details especially in the vicinity of cusps. However, as the data base increases and becomes more complete much smaller time windows can be used to eliminate the undesirable smoothing of APW.

By another procedure, palaeomagnetic Euler poles (PEP) (Gordon *et al.* 1984) are calculated from palaeopoles that are fitted to small circles that are thought to represent a plate trajectory that remained constant over some 100 Myr. This technique is constrained by a tectonic model which assumes that plate trajectories do not change more frequently than every 100 Myr or so. However such changes can occur more frequently (Engbretson 1982). Poles over a range of ~100 Ma fitted to a small circle assume that information about the Triassic magnetic field direction, for example, can be obtained from the Late Jurassic magnetic field direction. This is a pre-judgment of the nature of APW being investigated.

The third technique (e.g. Irving & Yole 1987; Hodych & Hayatsu 1988) is very simple, relying directly on observations of the ancient magnetic field direction. One simply selects from the current cratonic data base, in our case North America, well-defined and dated cratonic palaeomagnetic poles of the relevant age within the narrowest possible time-window. These poles are then averaged giving each pole unit weight, to obtain a reference pole. This procedure is similar to the time-window moving average technique except that the size of the window is optimized (e.g. 5–10 Myr), centred about the mean age of the rock unit being studied. We agree with Irving & Yole (1987) that this is the most prudent, practical and accurate way of obtaining a reference pole suitable for use in tectonic analyses.

The ages of the Early Jurassic magnetizations from Terrane I and Wrangellia (Monger & Irving 1980; Symons 1983; Symons & Litalien 1984; Symons 1985; Irving & Yole 1987; this study) are ~200 Myr, using the geologic time-scale of Harland *et al.* (1982). Therefore, an accurate Early Jurassic North American cratonic reference pole is required for a tectonic analysis of these palaeomagnetic results. Irving & Yole (1987) calculated an Early Jurassic reference pole for their tectonic analysis of palaeomagnetic data from the Bonanza Group in Wrangellia on Vancouver Island. Their reference pole has its weaknesses. It is based on relatively few poles (6) from cratonic North America as data from the Colorado Plateau were omitted. Three of the six accepted poles are from intrusives which likely represent spot readings of the geomagnetic field. In addition, it includes poles (4) that were rotated into the North American reference frame from the African craton. We prefer the use of North American data, only to avoid the added complications that may be introduced when poles from other cratons are rotated into the North American reference frame. Prévot & McWilliams (1989) discuss problems with the Early Jurassic reference pole for North America and suggest it is possible that little geomagnetic secular variation has been recorded by each of the extrusive and intrusive units in the Mesozoic basins of eastern North

America and caution the weight assigned to them in tectonic interpretations.

It has been recognized by several workers that the Colorado Plateau has undergone clockwise rotation, suggested by both geologic (Hamilton 1981) and palaeomagnetic evidence (Steiner 1984). Recent estimates on the amount of clockwise rotation of the Colorado Plateau include: 4° (Bryan & Gordon 1986), 11° (Steiner 1986) and 10° (Irving & Yole 1987). Although Irving & Yole (1987) dismiss data from the Colorado Plateau on several grounds, their strongest argument is the rotation complication. Our approach is different. Much of the Early Jurassic Cordilleran data is characterized by large and variable declination differences so that the most useful information comes from their inclinations which are directly related to palaeolatitudes. Correcting the data from the Colorado Plateau for clockwise rotation of either 4° or 11° has a small effect on the longitude of a combined Colorado–Newark Early Jurassic reference pole and a negligible effect on its latitude. Since inclusion of these data does not change the expected cratonic reference latitude but does help to average out secular variation, we argue that a combined Colorado–Newark North American reference pole best averages out secular variation, and therefore, is the most accurate for the needs of this analysis.

Recently Hodych & Hayatsu (1988) have reviewed the age dating and palaeomagnetic work on the Newark Supergroup rocks that provide most of the Early Jurassic cratonic poles and have calculated an Early Jurassic reference pole. We used nine poles from the Newark Supergroup data combined with three poles from the Colorado Plateau corrected for 4° of clockwise rotation to calculate our Early Jurassic reference pole for North America (Table 4). A comparison of Early Jurassic reference poles (Table 4) shows how closely some of the various independant calculations agree in spite of the inclusion of different data.

Table 4. Early Jurassic reference poles for cratonic North America.

	Long°	Lat°	A95°	N	Reference
	64 N	94 E	2 8	16	Harrison and Lindh (1982)
	63 N	92 E	5 0	12	Irving and Irving (1982)
a	68 N	95 E	5 0	6	Irving and Yole (1987)
b	64 N	83 E	8 0	3	Irving and Yole (1987)
c	64 N	87 E	2 3	24 *	Smith and Noltimer (1979)
d	61 N	65 E	6 1	9	Hodych and Hayatsu (1988)
e	63 N	85 E	7 0	12	Combined Colorado–Newark

Notes Long, Lat and A95 same as before N is the number of poles averaged * is the number of site poles averaged a) Average of their selected North American Poles b) Average of their North American Poles omitting those poles believed not to have averaged secular variation c) Combined groups I and II of Smith and Noltimer (1979) d) Includes poles from the Newark rocks and equivalents e) Combined Colorado–Newark pole of this study includes nine poles from the Newark rocks and equivalents from Hodych and Hayatsu (1988) and three Colorado Plateau poles used by May and Butler (1986) corrected for 4° of clockwise rotation

Table 5. Tectonic analysis

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hazelton	a	0 ± 10	+11 +71 +117	(This study)*
"	b	−2 ± 8	+11 +78 +117	
Hazelton	a	−2 ± 17	−15 +50 +112	(Monger and Irving 1980)*
"	b	−3 ± 17	−15 + [illegible] +112	
Takla	a	2 ± [illegible]	+1.	(Monger and Irving 1980)
	b	[illegible] ± 7	+11	
Guichon	a	6 ± 9	−11	([illegible] 1980)
"	b	5 ± 9	−11	
Nicola	a	−3 ± 9	−53	(Symons 1985)
"	b	−4 ± 9	−63	
Copper	a	1 ± 7	−32	(Symons and Litalien 1984)
"	b	1 ± 7	−37	
Bonanza	a	3 ± 9	+11	(Irving and Yole 1987)
"	b	2 ± 9	+5	

Notes reference poles (a) 64N, 85E, A95 = 6 1 (Hodych & Hayatsu 1988) (b) 63E, 85E, A95 = 7 0 (This study) RPD—relative palaeolatitude displacement, positive is northward, negative is southward RR—relative rotations about vertical axes, positive is anticlockwise, negative is clockwise *—RPD was calculated using average inclinations and RR is reported for each of three study areas.

5.3 Tectonic analysis

The Early Jurassic reference pole of Hodych & Hayatsu (1988) and a combined Colorado–Newark reference pole calculated in this study (Table 4) have been used in the following tectonic analysis. Using the tectonic analysis outlined by Yole & Irving (1980) and incorporating the error analysis of Demarest (1983), the Hazelton Group remanences are latitudinally concordant within statistical error with either the combined Colorado–Newark reference pole (this study) or the Newark reference pole (Hodych & Hayatsu 1988) (Table 5). This result is consistent with our re-evaluation of Triassic and Early Jurassic palaeomagnetic results that previously supported the ~1300 km northward displacement hypothesis (Table 5). This result is also consistent with data from the Permian Asitka volcanic rocks from Stikinia that Irving & Monger (1987) have interpreted as latitudinally concordant. The average magnitude of northward displacement for the seven studies in Table 5 is 1° ± 9° for both the accepted reference poles. Such precision is beyond that of any single palaeomagnetic study and is for all intents and purposes equal to zero. This analysis indicates that Terrane I, from the Permian to Early Jurassic, was in its present latitudinal position relative to the craton, although it has undergone large and variable rotations especially near the margins of the Stikine Terrane. Similar latitudinal concordance of southern Wrangellia (Vancouver Island) with Terrane I and North America is suggested by the single Bonanza Group result from Vancouver Island (Table 5). The data from the Karmutsen Formation (Symons 1971, Schwartz, Muller & Clark 1980; Yole & Irving 1980), also on Vancouver Island, have not been included in this analysis as they appear to have a very complex magnetization history and the results are somewhat ambiguous.

5.4 Geotectonics

Terrane I, an allochthonous microplate, is thought to have been formed by the assembly of four subterranes in the Middle Triassic (Monger *et al.* 1982). The concordant palaeolatitudes obtained from the Stikine and Quesnel subterranes in Terrane I is consistent with this hypothesis, although the large and variable internal rotations suggest that the assembly of Terrane I was not complete by the Early Jurassic. It is suggested that southern Wrangellia (Vancouver Island), part of the outboard Insular belt, also characterized by large rotations and latitudinal concordance from the Bonanza Group data (Table 5), was also close to its present position relative to Terrane I and North America. Recent palaeomagnetic studies on Middle Eocene volcanics from Stikinia and Quesnellia, (Symons & Wellings 1989, Bardoux & Irving 1989; Vandall & Palmer 1990) show that Terrane I and much of the Canadian Cordillera had assembled and docked with North America by at least Middle Eocene. Thus Terrane I must have been stabilized by at least the Middle Eocene because the main body of the Canadian Cordillera palaeopoles from younger rocks in the Cordillera are concordant.

Cordilleran Cretaceous palaeomagnetic data remain largely discordant (e.g. Beck *et al.* 1981; Irving *et al.* 1985; Rees, Irving & Brown 1985; Butler, Harms & Gabrielse 1988; Marquis & Globerman 1988), and are interpreted to indicate that much of the western Canadian Cordillera was situated as far as 2000 km south of its present position at that time. Geologic evidence suggests that the various terranes of the western Canadian Cordillera were amalgamated by the mid-Cretaceous (Monger *et al.* 1982). This is supported by the Cretaceous palaeomagnetic data. Although discordant, Irving *et al.* (1985) suggest their vertical axis rotations are systematically ~60° clockwise which is in contrast to the Permian to Early Jurassic results, indicating that the various terranes of the western Canadian Cordillera had assembled as a unit by this time. The latitudinally concordant data both before and after the Cretaceous constrains the timing of large-scale displacements within this period. Displacement models based on the discordant Cretaceous data must accommodate large-scale southward displacement of western parts of the Canadian Cordillera after the Early Jurassic, followed by northward displacement with 60° clockwise rotation, and then stabilization of the Canadian Cordillera by Middle Eocene. Umhoefer (1987) developed a displacement model, based for the most part on palaeomagnetic evidence, which is interpreted to be consistent with the known geology of the reconstructed margin of western North America. It can accommodate up to ~2000 km of northward displacement of 'Baja British Columbia' (Insular and Intermontane composite terranes which are roughly comparable to Terranes I and II) as part of the Kula plate along a transform margin with North America between 85 and 66 Ma. However, clockwise rotation is limited to 20° (Umhoefer 1987) which conflicts with the inferred ~60° clockwise rotation (Irving *et al.* 1985) observed in mid-Cretaceous palaeomagnetic results. Also the model does not consider how 'Baja British Columbia' was first displaced to the south from its latitudinally concordant Permian to Early Jurassic palaeolatitudes. As pointed out by Butler *et al.* (1989) the magnitude and timing of this displacement is inconsistent with the currently perceived pre-mid-Cretaceous links between the North American miogeocline and parts of western Cordillera (Price & Carmichael 1986). Symons (1977), Beck *et al.* (1981) and Irving *et al.* (1985) indicated that mid-Cretaceous palaeomagnetic discordancy could also be explained by regional tilting of 30° to the SW. Recently Butler *et al.* (1989) have advanced this hypothesis with stratigraphic, petrologic and isotopic data that indicate that parts of the Coast Plutonic Complex and the North Cascade Range have been tilted by ~30° to the SW. Certainly the regional tilt hypothesis appears more reconcilable in view of the latitudinal concordancy of the Permian to Early Jurassic and Middle Eocene to Recent data. However, this hypothesis cannot account for discordant Cretaceous data from bedded volcanic rocks in Terrane I (e.g. Marquis & Globerman 1988). It is therefore probable that Cretaceous Cordilleran tectonics were characterized by both regional tilting in outboard terranes and moderate latitudinal displacement in the inboard terranes. Certainly many further palaeomagnetic studies of Cretaceous bedded rocks from the Canadian Cordillera are needed to resolve the tilt versus displacement controversy.

6 CONCLUSIONS

The Early Jurassic Telkwa Formation of the Hazelton Group is characterized by a stable, two polarity, pre-folding, primary remanence that was acquired upon cooling and deposition of volcanic lavas and tuffs. These palaeomagnetic results confirm the earlier but less precise results of Monger & Irving (1980). Palaeomagnetic results from the Permian to Early Jurassic are consistently characterized by large and variable clockwise and anticlockwise rotations about vertical axes, indicating that amalgamation of the large composite Terranes I and II was not yet complete. Because of the downward revision of the geologic time-scale and changes to the Early Jurassic reference pole for North America, Terrane I is no longer required to have been moved ~1300 km from the south since the Early Jurassic and was, in fact, close to its present latitudinal position with respect to North America. The interpretation of results from studies which were consistent with Monger & Irving's (1980) conclusion are shown to be latitudinally concordant with the expected Early Jurassic reference pole for North America. Given that palaeomagnetic data from the Permian to Early Jurassic and Middle Eocene to Recent are latitudinally concordant, displacement models based on the discordant Cretaceous data must accommodate large-scale southward displacement of western parts of the Canadian Cordillera after the Early Jurassic. This must be followed by northward displacement with 60° of clockwise rotation, and finally stabilization of the Canadian Cordillera by the Middle Eocene.

ACKNOWLEDGMENTS

The authors are grateful to Louise Vandall for her enthusiastic and able assistance with the field work in difficult conditions. Thanks to Don MacIntyre and Pat Desjardins of the British Columbia Department of Mines for their generous logistical support and numerous geological discussions, to Glen Woodsworth of the Geological Survey of Canada and Dave Woodsworth who provided logistical and sampling assistance in the Red Canyon area, and to Dave Symons for his helpful comments on an early draft of this manuscript. This manuscript benefited from the helpful reviews of Bill Morris and two anonymous referees Funding for this project was provided through a Energy Mines and Resources Research Agreement grant, NSERC grant A3544, and from the Faculty of Science of the University of Western Ontario.

REFERENCES

Bardoux, M. & Irving, E , 1989 Paleomagnetism of Eocene rocks of the Kelowna and Castlegar areas, British Columbia. studies in determining paleohorizontal. *Can. J Earth Sci* , **26**, 829–844

Beck, M. E., 1980 Discordant paleomagnetic pole positions as evidence of regional shear in the Western Cordillera of North America, *Am. J Sci.*, **276**, 694–712

Beck, M E. Jr, Burmester, R F & Schoonover, R . 1981 Paleomagnetism and tectonics of the Cretaceous Mt. Stuart batholith of Washington: translation or tilt, *Earth planet. Sci. Lett* , **56**, 336–342

Bryan, P & Gordon, R. G , 1986 Rotation of the Colorado Plateau An analysis of paleomagnetic data, *Tectonics*, **5**, 661–667

Butler, R. F , Harms, T A & Gabrielse, H , 1988. Cretaceou remagnetization in the Sylvester Allochthon· Limits to post-105 Ma northward displacement of north-central British Columbia, *Can. J Earth Sci* , **25**, 1316–1322

Butler, R. F , Gehrels, G E., McClelland, W C , May, S R & Klepacki, D , 1989 Discordant paleomagnetic poles from the Canadian Coast Plutonic Complex. regional tilt rather than large-scale displacement, *Geology*, **17**, 691–694

Cox, A., 1957 Remanent magnetism of lower to middle Eocene basalt flows from Oregon, *Nature*, **179**, 685–686

Demarest, H. H. Jr, 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data, *J geophys Res* , **88**, 4321–4328.

Dudley, J. S., 1983. Zeolitization of the Howson facies, Telkwa Formation, British Columbia, *PhD thesis*, University of Calgary

Engebretson, D C , 1982. Relative motions between oceanic and continental plates in the Pacific basin, *PhD thesis*, Stanford University

Fisher, R A , 1953. Dispersion on a sphere, *Proc R Soc Lond.*, A, **217**, 295–305.

Gordon, R. G , Cox, A , & O'Hare, S , 1984 Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous, *Tectonics*, **3**, 499–537

Graham, J W , 1949. The stability & significance of magnetism in sedimentary rocks, *J geophys Res* , **54**, 131–167

Hamilton, W., 1981. Plate-tectonic mechanism of Laramide deformation, *Contrib Geol.* (University of Wyoming), **19**, 87–92.

Harland, W. B ͜ox, A V , Llewellyn, P G , Pickton, C A G , Smith, A. G & Walters, R , 1982 *A Geologic Time Scale*, Cambridge University Press, Cambridge, UK

Harrison, C. G. A & Lindh, T , 1982 A polar wandering curve for North America during the Mesozoic and Cenozoic, *J. geophys. Res.*, **87**, 1903–1920

Hodych, J. P. & Hayatsu, A , 1988 Paleomagnetism and K–Ar isochron dates of Early Jurassic basalt flows and dikes of Atlantic Canada, *Can J Earth Sci* , **25**, 1972–1989

Irving, E., 1964 *Paleomagnetism and its Application to Geological and Geophysical Problems*, John Wiley & Sons, New York

Irving, E., 1979 Paleopoles and paleolatitudes of North America and speculations about displaced terraines, *Can J Earth Sci* , **16**, 669–694

Irving, E. & Irving, G A , 1982 Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana, *Geophys Surv* , **5**, 141–188

Irving, E. & Monger, J W H., 1987 Paleomagnetic results from the Permian Asitka Group, British Columbia, *Can J Earth Sci* , **24**, 1490–1497

Irving, E & Yole, R M , 1987 Tectonic rotations and translations in western Canada, new evidence from Jurassic rocks of Vancouver Island, *Geophys J R. astr Soc* , **91**, 1025–1048

Irving, E , Woodsworth, G J , Wynne, P J & Morrison, A , 1985 Paleomagnetic evidence for displacement from the south of the Coast Plutonic Complex, British Columbia, *Can J Earth Sci* , **22**, 584–598

Kirschvink, J L , 1980 The least-squares line and plane and the analysis of palaeomagnetic data, *Geophys J R astr Soc* , **62**, 699–718

Leach, W W , 1910 The Skeena River District, *Summary Report 1909*, Geological Survey of Canada

MacIntyre, D G & Desjardins, P , 1988 *Babine Project*, pp 181–193, British Columbia Ministry of Energy, Mines & Petroleum Resources, Geological Fieldwork 1987

MacIntyre, D G , Desjardins, P , Tercier P & Koo J , 1989 Geology of the Telkwa River Area, *Open File Map 1989–16*, British Columbia Ministry of Energy Mines & Petroleum Resources

Marquis, G & Globerman, B R , 1988 Northward motion of the Whitehorse Trough: paleomagnetic evidence from the Upper Cretaceous Carmacks Group, *Can J Earth Sci* , **25**, 2005–2016

May, S R & Butler, R. F , 1986 North American Jurassic apparent polar wander Implications for plate motion, paleogeography and Cordilleran tectonics, *J geophys Res* , **91**, 11 519–11 544

McElhinny, M W , 1964 Statistical significance of the fold test in palaeomagnetism, *Geophys J R. astr Soc* **8**, 338–340

McFadden, P L. & Jones, D L , 1981 The fold test in palaeomagnetism, *Geophys. J. R astr Soc.*, **61**, 53–58.

Mihalynuk, M G , 1987 Metamorphic, structural & stratigraphic evolution of the Telkwa Formation Zymoetz River area, near Terrace, British Columbia, *MSc thesis*, University of Calgary.

Mihalynuk, M G & Ghent, E D , 1986 Stratigraphy, deformation and low grade metamorphism of the Telkwa Formation near Terrace, British Columbia, Current Research, Part B, *Paper 86-1B*, pp 721–726, Geological Survey of Canada.

Monger, J W H , 1984 Cordilleran tectonics a Canadian perspective, *Bull Soc Geol France*, **26**, 255–278.

Monger, J. W H & Irving, E , 1980 Northward displacement of north-central British Columbia, *Nature*, **285**, 289–293

Monger, J. W H , Price, R A & Tempelman-Kluit, D J , 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera, *Geology*, **10**, 70–75

Prévot, M & McWilliams, M , 1989 Paleomagnetic correlation of Newark Supergroup volcanics, *Geology*, **17**, 1007–1010

Price, R A & Carmichael, D M [illegible] Geometric test for Late Cretaceous–Paleogene intracontinental transform faulting in the Canadian Cordillera, *Geology*, **14**, 468–471

Rees, C J , Irving, E & Brown, R L., 1985 Secondary Magnetization of Triassic–Jurassic volcaniclastic rocks of the Quesnel Terrane, Quesnel Lake, B C , *Geophys Res Lett* , **12**, 498–501

Schwartz, E J , Muller, J E & Clark, K R , 1980 Paleomagnetism of the Karmutsen basalts from southeast Vancouver Island, *Can J Earth Sci* , **17**, 389–399

Smith, T E & Noltimier, H C, 1979. Paleomagnetism of the Newark Trend igneous rocks of the north central Appalachians and the opening of the central Atlantic Ocean, *Am. J Sci*, **279**, 778–807

Steiner, M B, 1984 Is the Colorado Plateau rotated?, *EOS, Trans. Am geophys. Un*, **65**, 864

Steiner, M B, 1986 Rotation of the Colorado Plateau, *Tectonics*, **5**, 649–660

Steiner, M. B & Ogg, J. G., 1988. Early and Middle Jurassic magnetic polarity time scale, in *2nd International Symposium on Jurassic Stratigraphy*, vol II, pp. 1097–1111, eds Rocha, R. B & Soares, A F., Lisbon

Symons, D T A, 1971 Paleomagnetic notes on the Karmutsen basalts, Vancouver Island, British Columbia, *Paper 71–24*, pp 9–24, Geological Survey of Canada

Symons, D T. A, 1977. Paleomagnetism of Mesozoic plutons in the westernmost Coast Complex of British Columbia, *Can J. Earth Sci*, **14**, 2127–2139

Symons, D T A, 1983 New paleomagnetic data for the Triassic Guichon Batholith, south central British Columbia, and their bearing on Terrane I tectonics, *Can. J Earth Sci*, **20**, 1340–1344

Symons, D. T A., 1985 Paleomagnetism of the Triassic Nicola volcanics and geotectonics of the Quesnellia subterrane of Terrane I, British Columbia, *J Geodyn.*, **2**, 229–244

Symons, D T. A. & Litalien, C., 1984. Paleomagnetism of the lower Jurassic Copper Mountain Intrusions and the geotectonics of Terrane I, British Columbia, *Geophys Res. Lett.*, **11**, 685–688

Symons, D. T A & Wellings, M R, 1989 Paleomagnetism of the Eocene Kamloops Group and the cratonization of Terrane I of the Canadian Cordillera, *Can. J Earth Sci.*, **26**, 821–828.

Tipper, H. W. & Richards, T. A., 1976 Jurassic stratigraphy and history of north-central British Columbia, *Bulletin 270*, Geological Survey of Canada.

Tipper, H. W, Woodsworth, G. J & Gabrielse, H., 1981. Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America, *Map 1505A*, Geological Survey of Canada.

Umhoefer, P J, 1987 Northward translation of 'Baja British Columbia' along the Late Cretaceous to Paleocene margin of western North America, *Tectonics*, **6**, 377–394

Vandall, T. A. & Palmer, H. C, 1990 Middle Eocene docking time for the Stikine terrane with cratonic North America: Paleomagnetic evidence from the Ootsa Lake Group, B. C., *Can. J. Earth Sci.*, **27**, 212–218

Vandall, T. A, Palmer, H C & Woodsworth, G. J., 1989. A Review of the Proposed ~1300 km of Northward Displacement of Stikinia Since the Early Jurassic: New Paleomagnetic Results from the Hazelton Volcanics, *Canadian Geophysical Union 16th Annual General Meeting*, 16, A154, McGill University, Montreal

Woodsworth, G. J., Hill, M. L & van der Heyden, P, 1985. Preliminary geologic map of Terrace Map Area, British Columbia, *Open File Map 1136*, Geological Survey of Canada

Yole, R W & Irving, E, 1980 Displacement of Vancouver Island: paleomagnetic evidence from the Karmutsen Formation, *Can. J Earth Sci.*, **17**, 1210–1228

REFERENCES

Armstrong, R. L., 1988. Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera, Geological Society of America Special Paper 218, 55–91.

Armstrong, R. L., Monger, J. W. H., & Irving, E., 1985. Age of magnetization of the Axelgold gabbro, north–central British Columbia, Canadian Journal of Earth Sciences, 22, 1217–1222.

As, J. A., & Zijderveld, J. D. A., 1958. Magnetic cleaning of rocks in palaeomagnetic research, Geophysical Journal of the Royal Astronomical Society 1, 308–319.

Atwater, T., 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, Geological Scociety of America Bulletin, 81, 3513–3536.

Bardoux, M., & Irving, E., 1989. Paleomagnetism of Eocene rocks of the Kelowna and Castlegar areas, British Columbia; studies in determining paleohorizontal, Canadian Journal of Earth Sciences, 26, 829–844.

Bazard, D. R., Burmester, R. F., Beck, M. E. Jr., Granirer, J. L., & Schwarz, 1990. Paleomagnetism of the Methow region, north–central Washington: structural application of paleomagnetic data in a complexly deformed variably remagnetized terrane, Canadian Journal of Earth Sciences, 27, 330–343.

Beck, M. E. Jr., 1980a. Paleomagnetic record of plate–margin tectonic processes along the western edge of North America, Journal of Geophysical Research, 85, 7115–7131.

Beck, M. E. Jr., 1980b. Discordant paleomagnetic pole positions as evidence of regional shear in the Western Cordillera of North America, American Journal of Science, 276, 694–712.

Beck, M. E. Jr., 1983. On the mechanism of tectonic transport in zones of oblique subduction, Tectonophysics, 93, 1–11.

Beck, M. E. Jr., 1986. Model for Late Mesozoic–Early Teriary tectonics of coastal California and western Mexico and speculations on the origin of the San Andreas Fault, Tectonics, 5, 49–64.

Beck, M. E. Jr., 1989a. Block rotations in continental crust: examples from western North America, *In* Paleomagnetic Rotations and Continental Deformation. *Edited by* C. Kissel and C. Laj, Kluwer Academic Publishers, 1–16.

Beck, M. E. Jr., 1989b. Paleomagnetism of continental North America; Implications for displacement of crustal blocks within the Western Cordillera, Baja California to British Columbia, *In* Pakiser, L. C., and

Mooney, W. D., Geophysical framework of the continental United States: Boulder, Colorado, Geological Society of America Memoir 172, 471–492.

Beck, M. E. Jr., & Noson, L., 1972. Anomalous Palaeolatitudes in Cretaceous Granitic Rocks, Nature, 235, 11–13.

Beck, M. E. Jr., Burmester, R. F., & Schoonover, R., 1981. Paleomagnetism and tectonics of the Cretaceous Mt. Stuart batholith of Washington: translation or tilt?, Earth and Planetary Science Letters, 56, 336–342.

Beck, M. E. Jr., Burmester, R. F., & Schoonover, R. 1982. Tertiary paleomagnetism of the North Cascade Range, Washington. Geophysical Research Letters, 9, 515–518.

Beske, S. J., Beck, M. E., & Noson, L. 1973. Paleomagnetism of the Miocene Grotto and Snoqualmie batholiths, central Cascades, Washington, Journal of Geophysical Research, 78, 2601–2608.

Bryan, P., & Gordon, R. G., 1986. Rotation of the Colorado Plateau: an analysis of paleomagnetic data, Tectonics, 5, 661–667.

Bryan, P., & Gordon, R. G., 1990. Rotation of the Colorado Plateau: an updated analysis of paleomagnetic poles, Geophysical Research Letters, 17, 1501–1504.

Butler, R. F., 1990. Northward motion of the Whitehorse Trough: paleomagnetic evidence from the Upper Cretaceous Carmacks Group: Discussion, Canadian Journal of Earth Sciences, 27, 614–617.

Butler, R. F., Harms, T. A., & Gabrielse, H., 1988. Cretaceous remagnetization in the Sylvester Allochthon: limits to post–105 Ma northward displacement of north–central British Columbia, Canadian Journal of Earth Sciences, 25, 1316–1322.

Butler, R. F., Gehrels, G. E., McClelland, W. C., May, S. R., & Klepacki, D., 1989. Discordant paleomagnetic poles from the Canadian Coast Plutonic Complex: regional tilt rather than large–scale displacement, Geology, 17, 691–694.

Butler, R. F., Gehrels, G. E., McClelland, W. C., May, S. R., & Klepacki, D., 1990. Reply "Discordant paleomagnetic poles from the Canadian Coast Plutonic Complex: regional tilt rather than large–scale displacement", Geology, 18, 801–802.

Carey, S. W., 1958. The tectonic approach to continental drift, *In* Continental Drift Symposium. *Edited by* S. W. Carey, University of Hobart, Tasmania, 177–355.

Carter, N. C., 1981. Porphyry Copper and Molybdenum Deposits, West–Central British Columbia, British Columbia Ministry of Energy, Mines and Petroleum Resources, Geology Exploration and Mining in British Columbia, Bulletin 64, 150 p.

Chamberlain V. E., & Lambert, R. St J., 1985. Cordillera, a newly defined Canadian microcontinent, Nature, 314, 707–713.

Church, B. N., 1970. Geology of the Owen Lake, Parrott Lakes, and Goosly Lake area, British Columbia Ministry of Energy, Mines and Petroleum Resources, Geology Exploration and Mining in British Columbia, 119–125.

Church, B. N., 1972. Geology of the Buck Creek area, British Columbia Ministry of Energy, Mines and Petroleum Resources, Geology Exploration and Mining in British Columbia, 353–363.

Coney, P. J., Jones, D. L., & Monger, J. W. H., 1980. Cordilleran suspect terranes, Nature, 288, 329–333.

Cox, A., 1957. Remanent magnetism of lower to middle Eocene basalt flows from Oregon, Nature, 179, 685–686.

Cox, A., 1969. Confidence limits for the precision parameter κ. Geophysical Journal of the Royal Astronomical Society, 18: 545–549.

Davis, G. A., Monger, J. W. H., & Burchfiel, B. C., 1978. Mesozoic construction of the Cordilleran "Collage" central British Columbia to central California, *In* Mesozoic paleogeography of the western United States. *Edited by* D. G. Howell and K. A. Mc Dougall, Scociety of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposiom 2, 1–32.

Demarest, H. H. Jr., 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data, Journal of Geophysical Research, 88, 4321–4328.

Diakow, L. J., & Drobe, J., 1989. Geology and mineral occurrences in North Newcombe Lake map sheet (93E/14), British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork, 1988, Paper 1989–1, 183–188.

Diakow, L. J., & Koyanagi, V., 1988. Stratigraphy and mineral occurrences of Chikamin Mountain and Whitesail Reach map areas (93E/06, 10), British Columbia Ministry of Energy, Mines, and Petroleum Resources, Geological Fieldwork, 1987, Paper 1988–1, 155–168.

Diakow, L. J., & Mihalynuk, M., 1987. Geology of Whitesail Reach and Troitsa Lake map areas (93E/10W, 11E), British Columbia Ministry of Energy, Mines, and Petroleum Resources, Geological Fieldwork, 1986, Paper 1987–1, 171–179.

Diehl, J. F., Beck, M. E., Beske–Diehl, S., Jacobson, D., & Hearn, B. C. 1983. Paleomagnetism of the Late Cretaceous – Early Tertiary north–central Montana alkalic province, Journal of Geophysical Research, 88, 10593–10609.

Dover, J. H., 1990. Problems of terrane terminology–Causes and effects, Geology, 18, 487–488.

Doell, R. R., & Cox, A., 1963. The accuracy of the paleomagnetic method as evaluated from the historic Hawaiian lava flows, Journal of Geophysical Research, 68, 1997–2009.

Doell, R. R., & Cox, A., 1965. Paleomagnetism of Hawaiian lava flows, Journal of Geophysical Research, 70, 3377–3405.

Du Bois, P. M., 1959. Late Tertiary geomagnetic field in northwestern Canada, Nature, 183, 1617–1618.

Dunlop, D. J. 1971. Magnetic properties of fine particle hematite. Annales de Géophysique, 27, 269–293.

Dunlop, D. J., 1972. Magnetite: behavior near the single domain threshold. Science, 176, 41–43.

Dunlop, D. J., 1973. Thermoremanent magnetization in submicroscopic magnetite. Journal of Geophysical Research, 78, 7602–7613.

Dunlop, D. J., 1981. The rock magnetism of fine particles. Physics of the Earth and Planetary Interiors, 26, 1–26.

Fisher, R. A., 1953. Dispersion on a sphere, Proceedings of the Royal Society of London, A, 217, 295–305.

Fox, K. F., & Beck, M. E., 1985. Paleomagnetic results for Eocene volcanic rocks from northeastern Washington and the Tertiary tectonics of the Pacific Northwest, Tectonics, 4, 323–341.

Gabrielse, H., 1985. Major dextral transcurrent displacements along the Northern Rocky Mountain Trench and related lineaments in north–central British Columbia, Geological Society of America Bulletin, 96, 1–14.

Gabrielse, H., & Dodds, C. J., 1977. The structural significance of the Northern Rocky Mountain Trench and related lineaments in north–central British Columbia, GAC–MAC Joint Annual Meeting, Program with Abstracts, A19.

Gabrielse, H., & Yorath, C. J., 1989. DNAG #4. The Cordilleran Orogen in Canada, Geoscience Canada, 16, 67–83.

Gabrielse, H., Monger, J. W. H., Wheeler, J. O., & Yorath, C. J., *in press*. Morphogeological Belts, Tectonic Assemblages and Terranes; *in* Chapter 2, Tectonic Framework; *in* The Cordilleran Orogen: Canada, H. Gabrielse and C. J. Yorath *editors*, Geological Survey of Canada, no. 4. (*also* Geological Society of America, The Geology of North America, no. G–2).

Garfunkel, Z., 1989. Regional deformation by block translation and rotation, *In* Paleomagnetic Rotations and Continental Deformation, *Edited by* C. Kissel and C. Laj, Kluwer Academic Publishers, 181–208.

Globerman, B. R., 1988. Paleomagnetism of the ~100 Ma South Fork volcanics from east of the Tintina fault, Selwyn Basin, Eos Transactions, 69, 338.

Globerman, B. R., & Irving, E., 1988. Mid–Cretaceous paleomagnetic reference field for North America: restudy of 100 Ma intrusive rocks from Arkansas, Journal of Geophysical Research, 93, 11721–11733.

Gordon, R. G., Cox, A., & O'Hare, S., 1984. Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous, Tectonics, 3, 499–537.

Graham, J. W., 1949. The stability & significance of magnetism in sedimentary rocks, Journal of Geophysical Research, 54, 131–167.

Granirer, J. L., Burmester, R. F., and Beck, M. E. Jr., 1986. Cretaceous paleomagnetism of the Methow–Pasayten belt, Washington, Geophysical Research Letters, 13, 733–736.

Hamilton, W. B., 1981. Plate–tectonic mechanism of Laramide deformation, Contrib. Geol. (University of Wyoming), 19, 87–92.

Hamilton, T. S., & Evans, M. E., 1983. A magnetostratigraphic and secular variation study of Level Mountain, northern British Columbia, Geophysical Journal of the Royal Astronomical Society, 73, 39–49.

Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C. A. G., Smith, A. G., & Walters, R., 1982. A geologic time scale, Cambridge University Press, Cambridge, United Kingdom.

Harrison, C. G. A., & Lindh, T., 1982. A polar wandering curve for North America during the Mesozoic and Cenozoic. Journal of Geophysical Research, 87, 1903–1920.

Hicken, A., & Irving, E., 1977. Tectonic rotation in western Canada, Nature, 268, 219–220.

Hillhouse, J. W., 1989. Paleomagnetic methods, *In* Pakiser, L. C., and Mooney, W. D., Geophysical framework of the continental United States: Boulder, Colorado, Geological Society of America Memoir 172, 61–70.

Hillhouse, J. W., & McWilliams, M. O., 1987. Application of paleomagnetism to accretionary tectonics and structural geology, Reviews of Geophysics, 25, 951–959.

Hoffman, K. A., 1988. Ancient magnetic reversals: clues to the geodynamo, Scientific American, 258, 76–83.

Hospers, J., 1955. Rock magnetism and polar wandering, Journal of Geology, 63, 59–74

Hospers, J., 1954. Reversals of the main geomagnetic field III, Proceedings of the

Koninklijke Nederlandse Akademie van Wetenschappen, Series B: Physical Sciences, 57, 112–121.

Hodych, J. P., & Hayatsu, A., 1988. Paleomagnetism and K–Ar isochron dates of Early Jurassic basalt flows and dikes of Atlantic Canada, Canadian Journal of Earth Sciences, 25, 1972–1989.

Hudson, M. R., Reynolds, R. L., & Fishman, N. S., 1989. Synfolding magnetization in the Jurassic Preuss Sandstone, Wyoming–Idaho–Utah thrust belt, Journal of Geophysical Research, 94, 13681–13705.

Huschilt, J., 1983. Performance evaluation of a three layer, steel–alloy magnetically shielded room, Unpublished B.A.Sc. thesis, University of Windsor, 36p.

Irving, E., 1964. Paleomagnetism and its application to geological and geophysical problems, John Wiley & Sons, New York, 399 pp.

Irving, E., 1979. Paleopoles and paleolatitudes of North America and speculations about displaced terrains, Canadian Journal of Earth Sciences, 16, 669–694.

Irving, E., 1985. Whence British Columbia, Nature, 314, 673–674.

Irving, E., & Archibald, D. A., 1990. Bathozonal tilt corrections to paleomagnetic data from mid–Cretaceous plutonic rocks: examples from the Omineca belt, British Columbia, Journal of Geophysical Research, 95, 4579–4585.

Irving, E., & Brandon M. T., 1990. Paleomagnetism of the Flores volcanics, Vancouver Island, inplace by Eocene time, Canadian Journal of Earth Sciences, 27, 811–817.

Irving, E., & Irving, G. A., 1982. Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana, Geophysical Surveys, 5, 141–188.

Irving, E., & Monger, J. W. H., 1987. Paleomagnetic results from the Permian Asitka Group, British Columbia, Canadian Journal of Earth Sciences, 24, 1490–1497.

Irving, E., & Thorkelson, D. J., 1990. On determining paleohorizontal and latitudinal shifts: Paleomagnetism of Spences Bridge Group, British Columbia, Journal of Geophysical Research, 95, 0000–0000.

Irving, E., & Wynne, P. J., 1990. Paleomagnetic evidence bearing on the evolution of the Canadian Cordillera, Philosophical Transactions of the Royal Society of London A, 331, 487–508.

Irving, E., & Yole, R. M., 1972. Paleomagnetism and kinematic history of mafic and ultramafic rocks in fold mountain belts, *In* Publications of the Earth Physics Branch, Energy, Mines and Resources, Ottawa, 42, 87–95.

Irving, E., & Yole, R. M., 1987. Tectonic rotations and translations in western Canada; new evidence from Jurassic rocks of Vancouver Island, Geophysical Journal of the Royal Astronomical Society, 91, 1025–1048.

Irving, E., Monger, J. W. H., & Yole, R. W., 1980. New paleomagnetic evidence for displaced terranes in British Columbia, *In* The continental crust and its mineral deposits. *Edited by* D. W. Strangway. Geological Association of Canada Special Paper 20, 441–456.

Irving, E., Woodsworth, G. J., Wynne, P. J., & Morrison, A., 1985. Paleomagnetic evidence for displacement from the south of the Coast Plutonic Complex, British Columbia, Canadian Journal of Earth Sciences, 22, 584–598.

Irving, E., Wynne, P. J., Evans, M. E., and Gough, W., 1986. Anomalous paleomagnetism of the Crowsnest Formation of the Rocky Mountains, Canadian Journal of Earth Sciences, 23, 591–598.

Jones, D. L., Silberling, N. J., & Hillhouse, J., 1977. Wrangellia — A displaced terrane in northwestern North America, Canadian Journal of Earth Sciences, 14, 2565–2577.

Kent, D. V., & Gradstein, F. M., 1985. A Cretaceous and Jurassic geochronology, Geological Society of America Bulletin, 96, 1419–1427.

Kent, D. V., & May, S. R., 1987. Polar wander and paleomagnetic reference pole controversies, Reviews of Geophysics, 25, 961–970.

Kirschvink, J. L., 1980. The least–squares line and plane and the analysis of paleomagnetic data, Geophysical Journal of the Royal Astronomical Society, 62, 699–718.

Kodama, K. P., 1988. Remanence rotation due to rock strain during folding and the stepwise application of the fold test, Journal of Geophysical Research, 93, 3357–3371.

Lambert, R. ST J., & Chamberlain, V. E., 1988. Cordilleria revisited, with a three–dimensional model for Cretaceous tectonics in British Columbia, Journal of Geology, 96, 47–60.

MacIntyre, D. G., 1976. Evolution of Upper Cretaceous volcanic and plutonic centers and associated porphyry copper occurrences, Tahtsa Lake Area, British Columbia, Ph.D. thesis, University of Western Ontario, 149p.

MacIntyre, D. G., 1985. Geology and Mineral Deposits of the Tahtsa Lake District West Central British Columbia, British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin 75, 82 p.

MacIntyre, D. G., & Desjardins, P., 1988. Babine Project, British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork, 1987, Paper 1988–1, 181–193.

MacIntyre, D. G., Desjardins, P., & Tercier, P., 1989. Jurassic stratigraphic relationships in the Babine and Telkwa Ranges, British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork, 1988, Paper 1989–1, 195–208.

MacIntyre, D. G., Brown, D., Desjardins, P., & Mallet, P., 1987. Babine Project, British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork, 1986, Paper 1987–1, 201–228.

Marquis, G., & Globerman, B. R., 1988. Northward motion of the Whitehorse Trough: paleomagnetic evidence from the Upper Cretaceous Carmacks Group, Canadian Journal of Earth Sciences, 25, 2005–2016.

Marquis, G., Irving, E., & Globerman, B. R., 1990. Northward motion of the Whitehorse Trough: paleomagnetic evidence from the Upper Cretaceous Carmacks Group: Reply, Canadian Journal of Earth Sciences, 27, 617–618.

May, S. R., & Butler, R. F., 1986. North American Jurassic apparent polar wander: implications for plate motion, paleogeography and Cordilleran tectonics, Journal of Geophysical Research, 91, 11519–11544.

McElhinny, M. W., 1964. Statistical significance of the fold test in palaeomagnetism, Geophysical Journal of the Royal Astronomical Society, 8, 338–340.

McElhinny, M. W., 1973. Palaeomagnetism and Plate Tectonics, Cambridge University Press, p. 358.

McFadden, P. L., & Jones, D. L., 1981. The fold test in paleomagnetism, Geophysical Journal of the Royal Astronomical Society, 61, 53–58.

McFadden, P. L., and McElhinny, M. W., 1984. A physical model for paleosecular variation. Geophysical Journal of the Royal Astronomical Society, 78, 809–830.

Miller, J. D., & Kent, D. V., 1988. Paleomagnetism of the Silurian–Devonian Andreas redbeds: Evidence for an Early Devonian supercontinent?, Geology, 16, 195–198.

Monger, J. W. H., 1977. Upper Paleozoic rocks of the western Canadian Cordillera and their bearing on Cordilleran evolution, Canadian Journal of Earth Sciences, 14, 1832–1859.

Monger, J. W. H., 1984. Cordilleran tectonics: a Canadian perspective, Bull. Soc. Geol. France, 26, 255–278.

Monger, J. W. H., & Irving, E., 1980. Northward displacement of north–central British Columbia, Nature, 285, 289–293.

Monger, J. W. H., & Price, R. A., 1979. Geodynamic evolution of the Canadain Cordillera — progress and problems, Canadian Journal of Earth Sciences, 16, 770–791.

Monger, J. W. H., & Ross, C. A., 1971. Distribution of Fusulinaceans in the western Canadian Cordillera, Canadian Journal of Earth Sciences, 8, 259–278

Monger, J. W. H., Price, R. A., & Tempelman–Kluit, D. J., 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera, Geology, 10, 70–75.

Monger, J. W. H., Souther, J. G., & Gabrielse, H., 1972. Evolution of the Canadian Cordillera: A plate–tectonic model, American Journal of Science, 272, 577–602.

Norris, D. K., 1964. The lower Cretaceous of the southeastern Canadian Cordillera, Bulletin of Canadian Petroleum Geology, 12, 512–535.

Nur, A., Ron, H., & Scotti, O., 1986. Fault mechanics and the kinematics of block rotations, Geology, 14, 746–749.

Packer, D. R., & Stone, D. B., 1974. Paleomagnetism of Jurassic rocks from southern Alaska, and the tectonic implications, Canadian Journal of Earth Sciences, 11, 976–997.

Pullaiah, G., Irving, E., Buchan, K. L., & Dunlop, D. J., 1975. Magnetization changes caused by burial and uplift, Earth and Planetary Science Letters, 28, 133–143.

Prévot, M., & McWilliams, M., 1989. Paleomagnetic correlation of Newark Supergroup volcanics, Geology, 17, 1007–1010.

Price, R. A., 1981. The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains, *In* Thrust and Nappe Tectonics *Edited by* N. T. Price and K. MacClay, Geological Society of London, Special Paper 9, 427–448.

Price, R. A., & Carmichael, D. M., 1986. Geometric test for Late Cretaceous–Paleogene intracontinental transform faulting in the Canadian Cordillera, Geology, 14, 468–471.

Rees, C.J., Irving, E., & Brown, R. L., 1985. Secondary Magnetization of Triassic–Jurassic Volcaniclastic rocks of the Quesnel Terrane, Quesnel Lake, B.C., Geophysical Research Letters, 12, 298–501.

Ron, H., Freund, R., Garfunkel, Z., & Nur, A., 1984. Block rotation by strike–slip faulting: structural and paleomagnetic evidence, Journal of Geophysical Research, 89, 6256–6270.

Ron, H., Aydin, A., & Nur, A., 1986. Strike–slip faulting and block rotation in the Lake Mead fault system, Geology, 14, 1020–1023.

Schwarz, E. J., Muller, J. E., & Clark, K. R., 1980. Paleomagnetism of the

Karmutsen basalts from south east Vancouver Island, Canadian Journal of Earth Sciences, 17, 389–399.

Smith, P. L., & Tipper, H. W., 1986. Plate tectonics and paleobiogeography: Early Jurassic (Pliensbachian) Endemism and Diversity, Palaios, 1, 399–412.

Souther, J. G., & Symons, D. T. A., 1974. Stratigraphy and paleomagnetism of Mount Edziza volcanic complex, northwestern British Columbia, Geological Survey of Canada, Paper 73–32.

Steiner, M. B., 1984. Is the Colorado Plateau rotated? EOS Transactions, 65, p.864.

Steiner, M. B., 1986. Rotation of the Colorado Plateau, Tectonics, 5, 649–660.

Steiner, M. B., & Ogg, J. G., 1988. Early and Middle Jurassic magnetic polarity time scale, *In* 2nd International Symposium on Jurassic Stratigraphy, Vol II, *Edited by* R. B. Rocha and A. F. Soares, 1987, Lisbon, 1097–1111.

Stone, D. B., 1977. Proceedings of the 6th Annual Symposium of the Geological Society of Alaska.

Stone, D. B., 1989. Paleogeography and rotations of arctic Alaska – an unresolved problem, *In* Paleomagnetic Rotations and Continental Deformation. *Edited by* C. Kissel and C. Laj, Kluwer Academic Publishers, 343–364.

Struik, L. C., 1987. The ancient western North American Margin: an alpine rift model for the east–central Canadian Cordillera, Geological Survey of Canada, Paper 87–15.

Sutherland Brown, A., 1960. Geology of the Rocher Deboule Range, British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin 43.

Symons, D. T. A., 1968. Geological implication of paleomagnetic studies in the Bella Coola and Laredo Sound map areas, British Columbia, Geological Survey of Canada, Paper 68–72.

Symons, D. T. A., 1969a. Paleomagnetism of the Late Miocene plateau basalts in the Cariboo region of British Columbia, Geological Survey of Canada, Paper 69–43.

Symons, D. T. A., 1969b. Paleomagnetism of four late Miocene gabbroic plugs in south–central British Columbia, Canadian Journal of Earth Sciences, 6, 653–662.

Symons, D. T. A., 1971a. Paleomagnetism of the Triassic Guichon Batholith and rotation in the Interior Plateau, British Columbia, Canadian Journal of Earth Sciences, 8, 1388–1396.

Symons, D. T. A., 1971b. Paleomagnetic Notes on some minor Tertiary igneous bodies, Vancouver Island, British Columbia *and* Paleomagnetic notes on the Karmutsen basalts, Vancouver Island, British Columbia, Geological Survey of Canada, Paper 71–24, 24 p.

Symons, D. T. A., 1973a. Concordant Cretaceous Paleolatitudes from Felsic Plutons in the Canadian Cordillera, Nature, 241, 59–61

Symons, D. T. A., 1973b. Paleomagnetic results from the Jurassic Topley intrusions near Endako, British Columbia, Canadian Journal of Earth Sciences, 10, 1099–1108.

Symons, D. T. A., 1973c. Unit correlations and tectonic rotation from paleomagnetism of the Triassic Copper Mountain Intrusions, British Columbia, Geological Survey of Canada, Paper 73–19, 11–28.

Symons, D. T. A., 1973d. Paleomagnetic results from the Tertiary Mount Barr and Hope plutonic complexes, British Columbia, Geological Survey of Canada, Paper 73–19.

Symons, D. T. A., 1973e. Paleomagnetic zones in the Oligocene East Sooke gabbro, Vancouver Island, British Columbia, Journal of Geophysical Research, 78, 5100–5109.

Symons, D. T. A., 1974. Age and tectonic implications of paleomagnetic results from plutons near Prince Rupert, British Columbia, Journal of Geophysical Research, 79, 2690–2697.

Symons, D. T. A., 1977a. Paleomagnetism of Mesozoic plutons in the westernmost coast complex of British Columbia, Canadian Journal of Earth Sciences, 14, 2127–2139.

Symons, D. T. A., 1977b. Geotectonics of Cretaceous and Eocene plutons in British Columbia, a paleomagnetic fold test, Canadian Journal of Earth Sciences, 14, 1246–1262.

Symons, D. T. A., 1983a. Further Paleomagnetic results from the Jurassic Topley intrusives in the Stikinia subterrane of British Columbia, Geophysical Research Letters, 10, 1065–1068.

Symons, D. T. A., 1983b. New paleomagnetic data for the Triassic Guichon Batholith, south central British Columbia, and their bearing on Terrane I tectonics, Canadian Journal of Earth Sciences, 20, 1340–1344.

Symons, D. T. A., 1985a. Paleomagnetism of the Triassic Nicola volcanics and geotectonics of the Quesnellia subterrane of Terrane I, British Columbia, Journal of Geodynamics, 2, 229–244.

Symons, D. T. A., 1985b. Paleomagnetism of the Westcoast Complex and the geotectonics of the Vancouver Island segment of the Wrangellian Subterrane, Journal of Geodynamics, 2, 211–228.

Symons, D.T.A., & Litalien, C., 1984. Paleomagnetism of the lower Jurassic

Copper Mountain Intrusions and the geotectonics of Terrane I, British Columbia, Geophysical Research Letters, 11, 685–688.

Symons, D.T.A., & Wellings, M.R., 1989. Paleomagnetism of the Eocene Kamloops Group and the cratonization of Terrane I of the Canadian Cordillera, Canadian Journal of Earth Sciences, 26, 821–828.

Tarling, D. H., 1983. Palaeomagnetism: principles and applications in geology, geophysics and archaeology, Chapman and Hall, London, New York, p. 379.

Tarling, D. H., & Symons, D. T. A., 1967. A stability index of remanence in paleomagnetism, Geophysical Journal of the Royal Astronomical Society, 12, 443–448.

Thorkelson, D.J., & Smith, A. D., 1989. Arc and intraplate volcanism in the Spencers Bridge Group: Implications for Cretaceous tectonics in the Canadian Cordillera, Geology, 17, 1093–1096.

Tipper, H. W., 1981. Offset of an upper Pliensbachian geographic zonation in the North American Cordillera by transcurrent movement, Canadian Journal of Earth Sciences, 18, 1788–1792.

Tipper, H. W., 1984. The allochthonous Jurassic–Lower Cretaceous terranes of the Canadian Cordillera and their relation to correlative strata of the North American craton, *In* Jurassic–Cretaceous biochronology and paleogeography of North America. *Edited by* G. E. G. Westermann, Geological Association of Canada Special Paper 27, 113–120.

Tipper, H. W., Woodsworth, G. J., & Gabrielse, H., 1981. Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America, Map 1505A, Geological Survey of Canada.

Tozer, E. T., 1970. Marine Triassic faunas, *In* Geology and Economic Minerals of Canada, Geologic Survey of Canada, Economic Geology Report No. 1, 633–640.

Umhoefer, P. J., 1987. Northward translation of "Baja British Columbia" along the Late Cretaceous to paleocene margin of western North America, Tectonics, 6, 377–394.

Umhoefer, P. J., & Magloughlin, J. F., 1990. Comment on "Discordant paleomagnetic poles from the Canadian Coast Plutonic Complex: regional tilt rather than large–scale displacement", Geology, 18, 801–802.

Vandall, T. A., & Palmer, H. C., 1988. Paleomagnetism of the Middle Eocene Ootsa Lake Group volcanics in the Stikine terrane, B.C., EOS Transactions, 69, p.1165.

Vandall, T. A., Palmer, H. C., and Woodsworth, G. J., 1989. A review of the proposed ~ 1300 km of northward displacement of Stikinia since the Early Jurassic: new paleomagnetic results from the Hazelton volcanics, Canadian Geophysical Union 16th Annual General Meeting, Program with abstracts, A154.

Vandall, T. A., & Palmer, H. C., 1990a. Upper limit of docking time for Stikinia and Terrane I: paleomagnetic evidence from the Eocene Ootsa Lake Group, British Columbia, Canadian Journal of Earth Sciences, 27, 212–218.

Vandall, T. A., & Palmer, H. C., 1990b. Canadian Cordilleran displacement: palaeomagnetic results from the Early Jurassic Hazelton Group, Terrane I, British Columbia, Canada, Geophysical Journal International, 103, 609–619.

Vandall, T. A., & Palmer, H. C., 1990c. Discordant Cretaceous paleomagnetic data from the Canadian Cordillera, Canadian Geophysical Union 17th Annual General Meeting, Program with abstracts, A51.

Vandall, T. A., & Palmer, H. C., 1990d. A review of the Canadian Cordilleran paleomagnetic data base and the implications for large scale terrane displacements, EOS Transactions, 71, p.1295.

Van der Voo, R., 1989. Paleomagnetism of North America; The craton, its margins, and the Appalachian Belt, *In* Pakiser, L. C., and Mooney, W. D., Geophysical framework of the continental United States: Boulder, Colorado, Geological Society of America Memoir 172, 471–492.

Van Eysinga, F. W. B., 1975. Geologic time table, Elsevier, Amsterdam.

Watson, G. S., 1956. A test for randomness of directions, Monthly Notices of the Royal Astronomical Society, Geophysical Supplement, 7, 160–161.

Wernicke, B., & Klepacki, D. W. 1988. Escape hypothesis for the Stikine block, Geology, 16, 461–464.

Wise, D. U., 1963. An outrageous hypothesis for the tectonic pattern of the North American Cordillera, Geological Society of American Bulletin, 74, 357–362.

Yole, R. W., & Irving, E., 1980. Displacement of Vancouver Island: paleomagnetic evidence from the Karmutsen Formation, Canadian Journal of Earth Sciences, 17, 1210–1228.

Yole, R. W., & Irving, E., 1981. Errata: Displacement of Vancouver Island: paleomagnetic evidence from the Karmutsen Formation, Canadian Journal of Earth Sciences, 18, p. 828.