2002

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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. B10, 2254, doi:10.1029/2001JB001623, 2002

Concordant paleolatitudes for Neoproterozoic ophiolitic rocks of the Trinity Complex, Klamath Mountains, California

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Received 31 October 2001; revised 29 March 2002; accepted 13 April 2002; published 24 October 2002.

[1] New paleomagnetic results from the eastern Klamath Mountains of northern California show that Neoproterozoic rocks of the Trinity ophiolitic complex and overlying Middle Devonian volcanic rocks are latitudinally concordant with cratonal North America. Combining paleomagnetic data with regional geologic and faunal evidence suggests that the Trinity Complex and related terranes of the eastern Klamath plate were linked in some fashion to the North American craton throughout that time, but that distance between them may have varied considerably. A possible model that is consistent with our paleomagnetic results and the geologic evidence is that the Trinity Complex formed and migrated parallel to paleolatitude in the basin between Laurasia and Australia–East Antarctica as the Rodinian supercontinent began to break up. It then continued to move parallel to paleolatitude at least through Middle Devonian time. Although the eastern Klamath plate served as a nucleus against which more western components of the Klamath Mountains province amalgamated, the Klamath superterrane was not accreted to North America until Early Cretaceous time. *INDEX TERMS:* 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics (regional, global); 5475 Planetology: Solid Surface Planets: Tectonics (8149); 8157 Tectonophysics: Evolution of the Earth: Plate motions—past (3040); 9350 Information Related to Geographic Region: North America; 9619 Information Related to Geologic Time: Precambrian

Citation: Mankinen, E. A., N. Lindsley-Griffin, and J. R. Griffin, Concordant paleolatitudes for Neoproterozoic ophiolitic rocks of the Trinity Complex, Klamath Mountains, California, *J. Geophys. Res.*, *107*(B10), 2254, doi:10.1029/2001JB001623, 2002.

1. Introduction

[2] The Klamath Mountains province of northern California and southern Oregon consists of arcuate structural belts comprising large fragments of oceanic and island arc basement that were juxtaposed during repeated accretionary episodes from early Paleozoic to late Mesozoic time (Figure 1). The oldest rocks are in the Eastern Klamath plate [*Irwin*, 1981], which consists of Neoproterozoic, Paleozoic, and Mesozoic sedimentary and volcanic deposits, and an underlying slab of oceanic lithosphere represented by the Trinity mafic–ultramafic sheet [*Irwin*, 1977]. The latter is the largest expanse of ophiolitic rocks in western North America; its sheet-like nature has long been recognized [*Irwin and Bath*, 1962; *Irwin and Lipman*, 1962; *LaFehr*, 1966] because magnetic and gravity studies, combined with regional relationships, indicate that it is a relatively thin subhorizontal sheet overlying a less dense basement. Geophysical evidence [*LaFehr*, 1966; *Griscom*, 1973; *Fuis and Zucca*, 1984; *Blakely et al.*, 1985] further indicates that the Trinity sheet extends westward beneath Neoproterozoic to Middle Devonian rocks of the Yreka–Callahan area [*Potter et al.*, 1977; *Wallin et al.*, 1991, 1995] as far as the Central Metamorphic terrane (Figure 1), and eastward for an unknown distance beneath Middle Devonian through Middle Jurassic rocks of the Redding area [*Kinkel et al.*, 1956; *Sanborn*, 1960; *Albers and Robertson*, 1961]. Thus, the ophiolitic rocks form oceanic basement beneath the entire eastern Klamath Mountains. This assemblage later was referred to as the Eastern Klamath terrane and subdivided into the Yreka, Trinity, and Redding subterranes [*Irwin*, 1994]; it formed the nucleus against which more westerly terranes of the Klamath Mountains province accreted.

[3] Although ophiolitic rocks of what is now called the Trinity subterrane were long considered to be Ordovician in age, recent studies [*Wallin et al.*, 1988, 1991, 1995] have shown that Neoproterozoic and Early Devonian elements also are present (Table 1, a–b and k–l). Thus, the assemblage differs from typical ophiolites by being extremely long-lived and polygenetic [*Lindsley-Griffin*, 1991, 1994]. Lindsley-Griffin considered the term "Trinity Complex" as best describing the entire assemblage. The Trinity Complex includes plagiogranite (571–565 Ma, Table 1, b) and metagabbro (579–556 Ma, Table 1, a) that formed before the beginning of the Cambrian at 545 Ma [*Bowring and Erwin*, 1998], and pre-Late Ordovician peridotite (472 Ma, Table 1, e) with a different structural history. These oceanic blocks were juxtaposed along the now-vertical China

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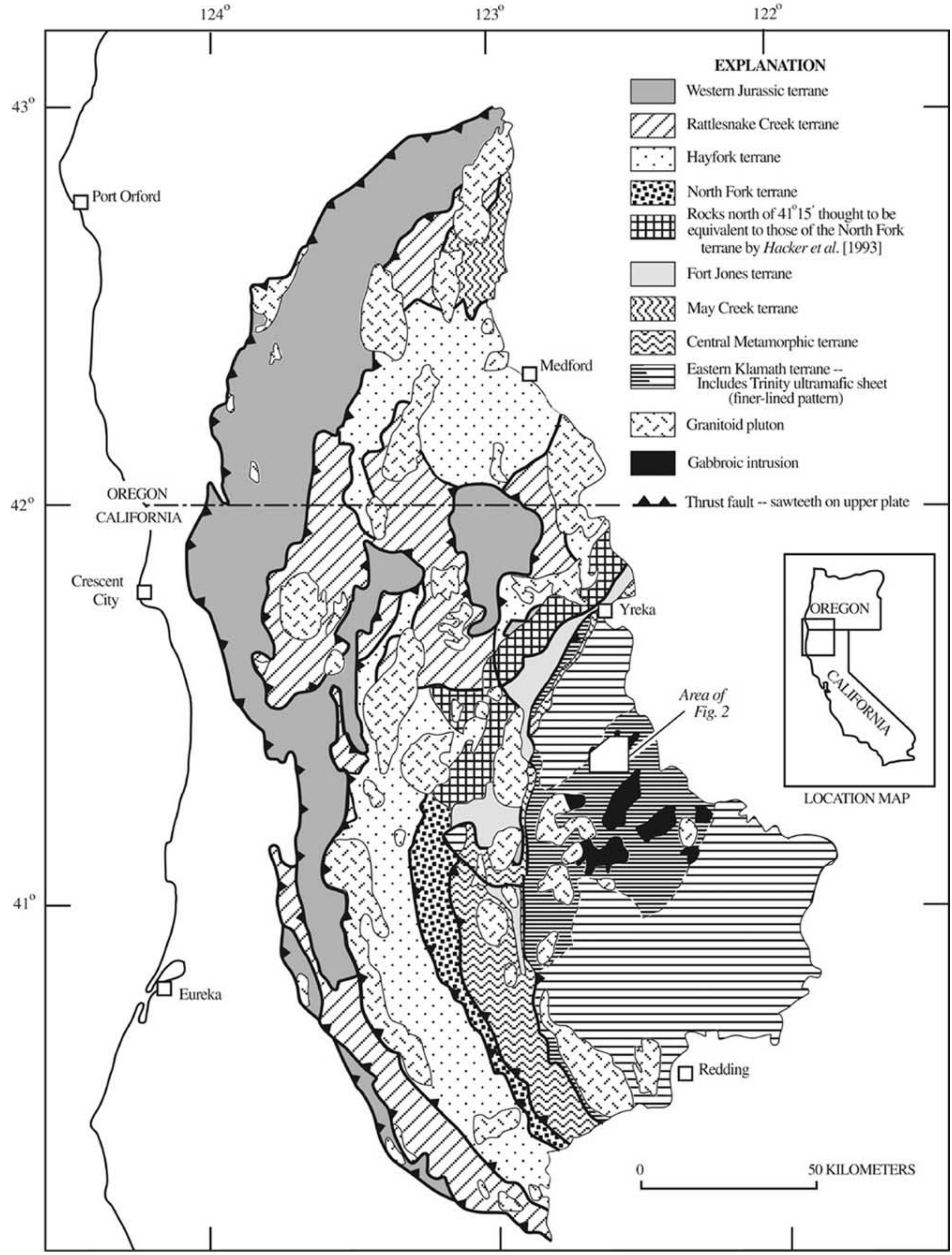

Figure 1. Map showing principal elements of the Klamath Mountains province and area sampled during the present study. Adapted from *Mankinen et al.* [1996] and *Wallin et al.* [1995].

Table 1. Selected Isotopic Ages for Trinity Terrane and Adjacent Regions

Rock Unit	Isotopic Age, Ma	Method
a. Neoproterozoic metagabbro (Trinity ophiolite)	579–556	U–Pb zircon[a]
b. Neoproterozoic plagiogranite (Trinity ophiolite)	571–565	U–Pb zircon[b]
c. Neoproterozoic tonalite blocks (mélange of Yreka terrane)	567 ± 78, 565 ± 5	U–Pb zircon[b]
d. Ordovician plagiogranite or gabbro (Trinity Complex)	475 ± 10	U–Pb zircon[b]
e. Ordovician late-stage partial melt segregate in plagioclase lherzolite (Trinity Complex)	472 ± 32	Sm–Nd isochron[c]
f. Ordovician hornblende gabbro dike (Trinity Complex)	480 – 470	U–Pb zircon[b,d]
g. Ordovician plagiogranite or gabbro (Trinity Complex)	469 ± 21	U–Pb zircon[b]
h. Ordovician tonalite block in Lower Devonian mélange of Gregg Ranch Complex	455, 440	U–Pb zircon[b,d]
i. Late Ordovician blueschist (Skookum Gulch schist)	447 ± 9	Rb–Sr phengite[e]
j. Silurian microgabbro (Trinity Complex)	435 ± 21	Sm–Nd isochron[c]
k. Early Devonian pegmatitic gabbro (Trinity Complex)	415 ± 3	U–Pb zircon[a]
l. Early Devonian pegmatitic trondhjemite dikes (Trinity Complex)	412 ± 10	U–Pb zircon[b]
m. Devonian metamorphism of Central Metamorphic terrane	398–407	K–Ar hornblende[f]
n. Devonian Mule Mountain Stock	400 ± 3	U–Pb zircon[d]
o. Devonian Schneider Hill stock	400	U–Pb zircon[g]

Boundaries of geologic periods same as Figure 8.
[a] *Wallin et al.* [1991].
[b] *Wallin et al.* [1988].
[c] *Jacobsen et al.* [1984].
[d] *Kistler et al.* [1985].
[e] *Cotkin et al.* [1992].
[f] *Kelley et al.* [1987].
[g] Wallin et al. (unpublished data, 1995).

Mountain fault zone (CMFZ), which was subsequently crosscut by Siluro-Devonian intrusions (Table 1, j–l).

[4] Ophiolite stratigraphy is preserved in these fault blocks along the northwestern edge of the Trinity Complex. The Neoproterozoic sequence consists of pillow basalts overlying plagiogranite and amphibole metagabbro. Although the ophiolite sequence lacks a sheeted dike complex, sills and feeder dikes along the base of the basalt crosscut the upper plagiogranite but not the metagabbro, suggesting that it is a conformable sequence formed at a slow-spreading oceanic ridge [*Lindsley-Griffin*, 1994].

[5] The areally most extensive unit within the Trinity Complex, herein referred to as the ''Trinity peridotite,'' consists of relatively undepleted feldspathic peridotite (lherzolite with local dunite and harzburgite), with compositional layering and mineral foliation typical of mantle tectonites. Although the Trinity peridotite has been considered Late Ordovician (472 Ma, Table 1, e), it must be older because the sample yielding that age was obtained from undeformed gabbroic partial melt trapped within and crosscutting the highly deformed peridotitic mantle tectonites [*Jacobsen et al.*, 1984; *Lindsley-Griffin*, 1991]. Small amounts of undeformed layered gabbro, associated with the Trinity ophiolite as fault blocks or intrusions, are also Late Ordovician in age (475–440 Ma, Table 1, d and g).

[6] The Trinity Complex also includes a suite of pegmatitic gabbros and related rocks (415–412 Ma, Table 1, k–l). Although these gabbros have been considered to be Silurian in age [e.g., *Wallin et al.*, 1995], recent advances in geochronology suggest that the base of the Devonian may be as old as 417 Ma [*Tucker and McKerrow*, 1995; *Matteson and Ebert*, 1997]. This Siluro-Devonian pegmatitic gabbro suite intrudes the pre-Late Ordovician blocks of the Trinity Complex, as well as the CMFZ suture zone between them, but does not intrude all of the rocks that were historically included [*Lipman*, 1964] with those of the Trinity subterrane. The Siluro-Devonian gabbros are completely absent from the thin septum of mafic and ultramafic rocks that extends along the western edge of the Yreka subterrane adjacent to the Central Metamorphic terrane (Figure 1). Thus, this western septum constitutes a separate and distinct block of oceanic lithosphere that probably represents a remnant of the oceanic plate that lay between the Central Metamorphic terrane and the Yreka–Trinity block. Amalgamation with the Yreka–Trinity composite terrane did not occur until after Silurian time [*Lindsley-Griffin*, 1991, 1994], most likely about 400 Ma when the Central Metamorphic terrane was metamorphosed (407–398 Ma, Table 1, m).

[7] Paleomagnetic studies can help understand the tectonic development of such complex areas and, indeed, several studies have been reported for rocks of the Klamath Mountains province (see summary by *Mankinen and Irwin* [1990] and also *Mankinen et al.* [1996]). Most previous studies have indicated large clockwise rotations for elements within the province, but only the results from chert of the North Fork terrane [*Mankinen et al.*, 1996] provide evidence for significant latitudinal displacements. Previous paleomagnetic studies have indicated that the Eastern Klamath terrane has been latitudinally concordant with the North American craton since Permian time. We initiated this paleomagnetic study of the Neoproterozoic and Middle Devonian rocks of the Eastern Klamath terrane to extend our knowledge of the tectonic history of this part of the region. To our knowledge, our results are the first obtained from rocks this old from any of the allochthonous terranes of the Circumpacific region.

2. Methods Used

2.1. Paleomagnetic Sampling and Measurement

[8] Paleomagnetic samples were collected by use of a portable core drill and were oriented with solar and mag-

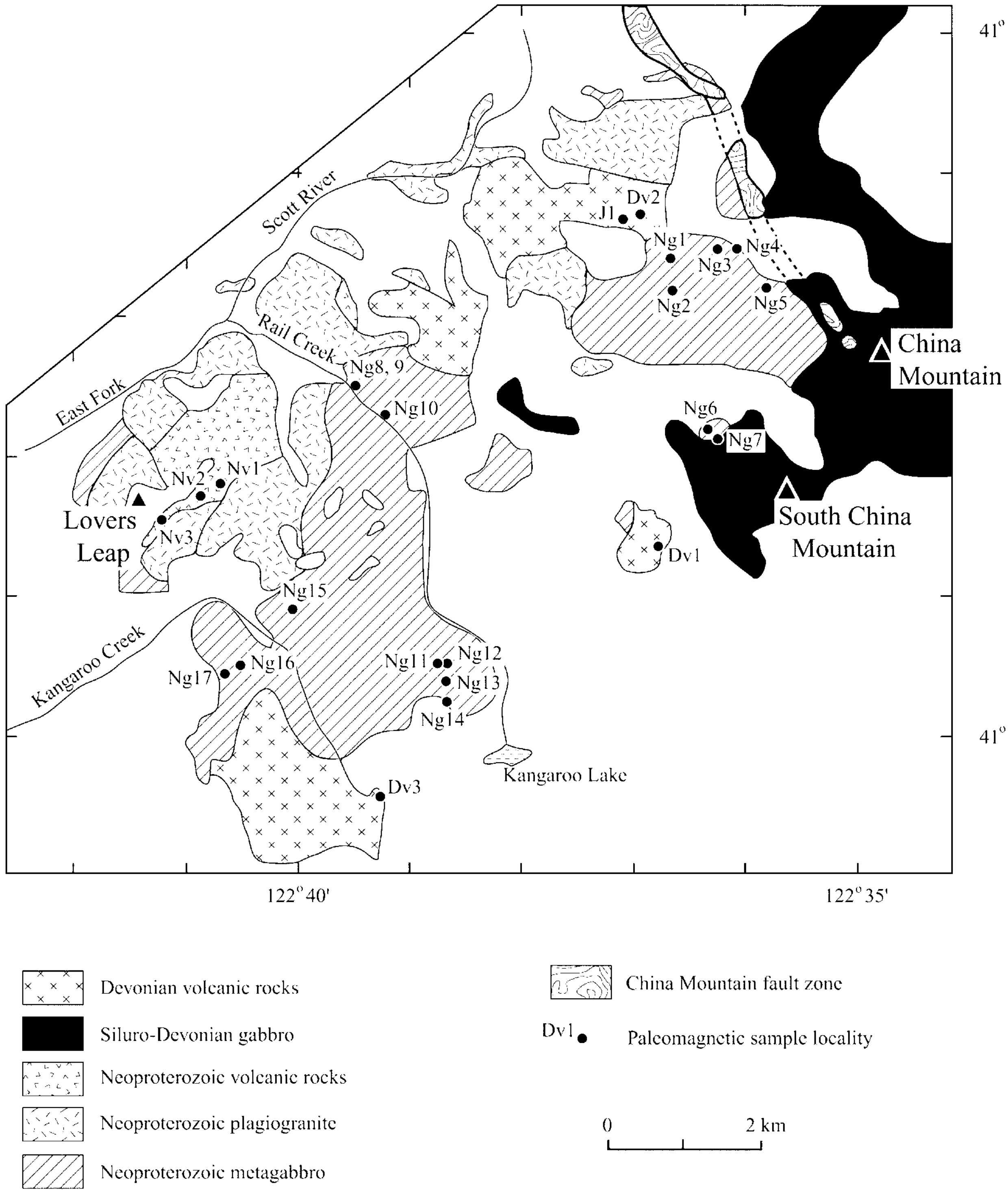

Figure 2. Map of area outlined in Figure 1. Shown are selected elements of the Trinity Complex and overlying rocks, and paleomagnetic sampling localities. Map adapted from *Lindsley-Griffin* [1982, 1991].

netic compasses. A total of 296 cores were obtained from 24 sites shown in Figure 2. Each core was cut into two or more specimens, and the natural remanent magnetization (NRM) of one specimen from each core was measured using a cryogenic magnetometer. The intensity of NRM at all except two sites (see below) was very weak with geometric means ranging between 38 and 0.6 mA/m. Representative specimens from each locality were subjected to alternating field and thermal demagnetization experiments. Thermal demagnetization proved to be the only effective means of obtaining characteristic magnetization directions for these rocks, and one specimen from each core was subjected to progressive thermal demagnetization. Thermal demagnetizations were performed in air using a magnetically shielded

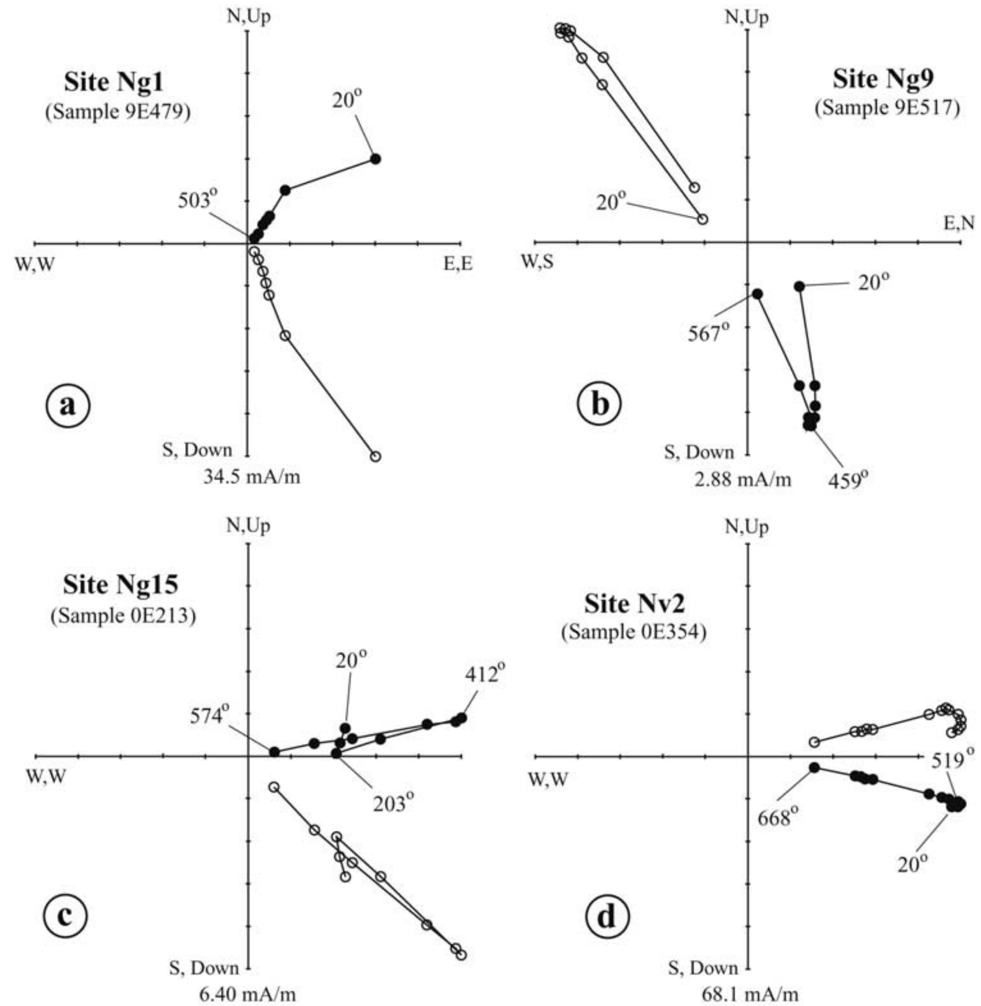

Figure 3. Orthogonal projection of remanence vector endpoints during progressive thermal demagnetization of representative samples from the Trinity Complex. Open (solid) circles are projections into the vertical (horizontal) plane. Data uncorrected for dip and strike.

oven with an internal field less than 5 nT. Unblocking temperatures typically ranged between 400° and 550°C, which indicates that the remanence is carried by magnetite or Ti-poor titanomagnetite. Representative vector component diagrams are shown in Figure 3. Only at one site, 0E351, did the unblocking temperatures range between 560° and 680°C indicating a remanence carried by hematite.

[9] Strong-field thermomagnetic measurements were made on representative samples from many of the sites within the complex. These measurements were performed in a nitrogen atmosphere using applied fields ranging from 400 to 600 mT at heating and cooling rates of 10°C/minute. Because of the strong applied fields required by many of the samples, the paramagnetic effect due to minerals such as pyroxene was quite pronounced (concave upward heating/cooling curves, Figure 4a) and a Curie temperature could not always be discerned. Where Curie temperatures could be determined (Figure 4b), they ranged between 540° and 580°C and confirmed that the main magnetic minerals were magnetite or Ti-poor titanomagnetite.

[10] Thermal demagnetization data were analyzed using the principal component analysis of *Kirschvink* [1980], and site-mean directions were calculated using *Fisher* [1953] or Bingham [*Onstott*, 1980] statistics. These mean directions and their associated statistical parameters are given in Table 3.

2.2. Structural Analysis

[11] The major problem in paleomagnetic studies of plutonic rocks is the determination of paleohorizontal at the time their remanent magnetization was acquired. In the sections that follow, we describe the local site geology and our assessment of structural attitude. In most cases, we use the average attitude of cumulate layering as paleohorizontal. Using cumulate layering in this way assumes that it results mainly by gravitational settling at the bottom of a magma chamber, an assumption that may not always be correct. Unfortunately, few paleomagnetic studies addressing this problem are available. Probably the most thorough, recent study is that by *Bogue et al.* [1995] of the 110-Ma, zoned ultramafic complex of Duke Island, Alaska. Their paleomagnetic/rock magnetic study convincingly shows that the remanence in those rocks passes the fold test when the layering is restored to horizontal. *Bogue et al.*'s [1995]

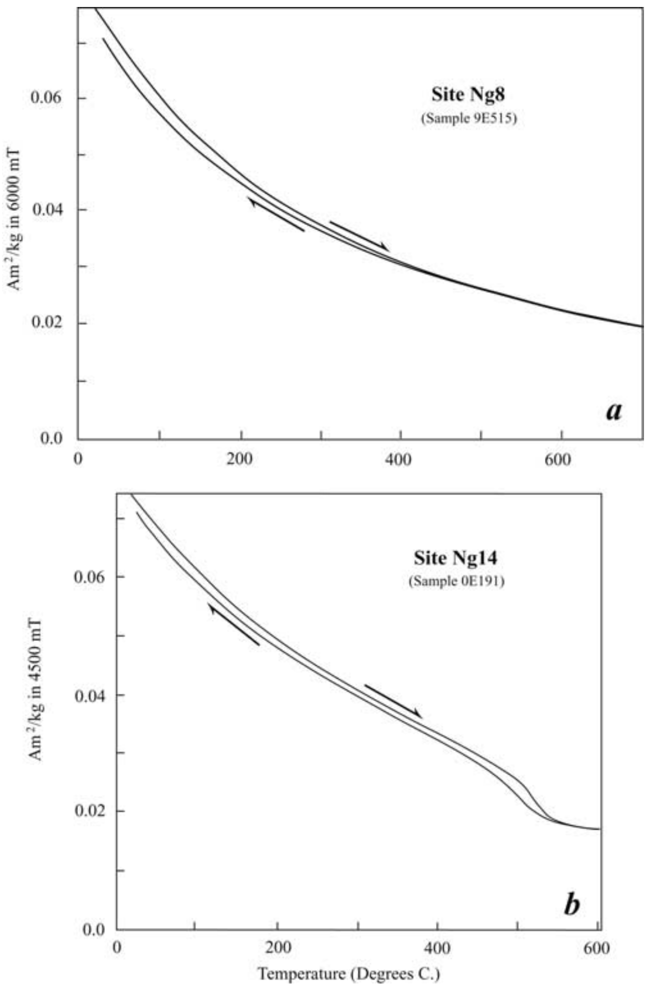

Figure 4. Strong-field thermomagnetic curves showing typical behaviors encountered in the Trinity Complex rocks. Heating and cooling curves indicated by arrow. Experiments were performed in a nitrogen atmosphere at heating and cooling rates of 10°C/min.

interpretation gains additional support because the restored paleomagnetic inclination yields a paleolatitude that agrees with other results from the Insular superterrane and Coast Plutonic Complex of British Columbia. (However, see *Butler et al.* [2001] for a differing opinion.)

[12] Although the *Bogue et al.* [1995] study seems compelling to us, their results may not apply to all similar intrusions or to others that are less mafic. One of the earliest successful applications of the use of cumulate layering for structural correction [*Gough and Van Niekerk*, 1959] was in a study of the gabbroic sequence of the Proterozoic Bushveld Complex, South Africa (see papers by *Hattingh* [1986a, 1986b] which supercede the earlier results). Following this early success, however, were several unsuccessful studies that led *Halls and Pesonen* [1982] to conclude that igneous layering should not be used for structural correction unless a positive fold test could be demonstrated. An excellent example of why igneous layering does not always provide a accurate measure of paleohorizontal is given by *Irvine et al.* [1998] in their detailed geologic description of the well-exposed Eocene Skaergaard intrusion in eastern Greenland. Noted were xenoliths of exotic rock types, as well as autoliths of native fragments that indent underlying layers, overlying layers that drape the blocks, and other features indicative of the many different processes that occurred during early stages of differentiation of the magma body. Particularly important in the context of this study is that the Layered Series of the Skaergaard pluton, which is most like the cumulate layering we describe, shows many complexities indicating deposition influenced by magmatic currents as well as gravitational settling.

[13] Paleomagnetic samples were obtained from the Layered Series of the Skaergaard intrusion by *Schwarz et al.* [1979] who reported that correcting for local attitude of layering produced poorer population statistics than the uncorrected directions. From this, they concluded that minor deformation of the intrusion took place between solidification and acquisition of remanence. However, the average direction before applying tilt corrections (inclination = −59°) is uncharacteristic for Greenland at any time since the pluton was emplaced. In contrast, correcting the layering either to horizontal, or to the proposed "initial tilt," produces paleomagnetic poles that differ slightly, if at all, from either the Paleocene (67–55 Ma) or Eocene (54–44 Ma) reference pole for North America [*Diehl et al.*, 1983].

[14] We speculate that the dynamics within Trinity-type magma chambers underlying a rifting oceanic basin may differ significantly from those described for the Skaergaard intrusion and perhaps other laccolith-like intrusions. The less confined environment, intuitively, would seem to favor gravitational settling over magmatic currents. Although *Irvine et al.*'s [1998] arguments for internal deformation and intense magmatic currents in the Skaergaard are persuasive, we believe that the absence of comparable features in Trinity Complex metagabbro argues equally persuasively for a relatively quiet environment. The Trinity Complex banding consists of rhythmic alternations between mafic and felsic minerals, in some cases with modally graded transitions and relict cumulate textures. Cross-lamination, cut-and-fill, and other features suggesting magmatic currents are rare. No autoliths, xenoliths, displaced slump blocks, or other structures suggesting internal deformation have ever been observed. Additional evidence for a relatively quiet environment include the lack of sheeted dikes and the presence of sills in the diabase zone, as well as the volumetrically significant plagiogranite, all suggesting a slow spreading, tectonically quiet environment. In any case, our initial assumption is that cumulate layering does approximate paleohorizontal for the Trinity Complex rocks; our results will provide an empirical test of this hypothesis.

[15] Because the Trinity Complex exhibits a rough stratigraphy (Figure 2), and mapped contacts between these units are subparallel, we assume that they represent an approximate paleohorizontal, at least for the lava unit. Although fault blocks in the Lovers Leap area have obviously been rotated relative to each other, we consider that the overall stratiform character of the main part of the Trinity Complex argues against rotation between many of the other sites. We restricted our sampling to the stratiform rocks and avoided the true "intrusive rocks," such as the pegmatitic gabbro, where paleohorizontal is indeterminate.

3. Neoproterozoic and Probable Neoproterozoic Rocks

3.1. China Mountain

[16] Localities in the China Mountain region are within the fault-bounded block of metagabbro (“amphibolitic gabbro”) of the Trinity ophiolite, from which U–Pb zircon ages ranging from 579 to 556 Ma (Table 1, a) were obtained. Because the amphibole metagabbro in the least deformed parts of the body exhibits undeformed cumulate layering, graded bedding, and rare cross-laminae, we interpret all layering within the metagabbro as representing modified primary, subhorizontal cumulate layering and use it to structurally correct the paleomagnetic data.

[17] Results were obtained from three of the five sites sampled (Ng1, Ng2, and Ng5, Figure 2). Site Ng1 has a mean direction that is very close to the major overprint seen over much of the Eastern Klamath and North Fork terranes [*Mankinen et al.*, 1989, 1996] so that site may have been remagnetized. Both normal- and reversed-polarities were found at site Ng5. A characteristic remanence could not be determined for sites Ng3 and Ng4. Some samples from these sites appear to yield a stable remanence but there is little agreement among samples. Where there is some grouping, the samples clearly fail the fold test. These two sites are located near the CMFZ, which juxtaposes the Neoproterozoic Trinity ophiolite and pre-Late Ordovician Trinity peridotite. Some unrecognized internal deformation of the outcrops is a distinct possibility. During stepwise demagnetization experiments, however, the remanence directions from a number of samples trended toward the upper hemisphere when corrected for strike and dip. Although considerable differences in magnetization direction were found between sites in many areas of the Trinity Complex, here Ng3 and Ng4 are in such close proximity that relative rotations between them are unlikely. With this possibility in mind, the data from both sites were combined and the principal component analysis technique was used to analyze the converging remagnetization circles. The attitudes at both sites are sufficiently different that a planes solution was possible and the result agrees reasonably well with the structurally corrected data from the other three sites (Figure 5a).

3.2. South China Mountain

[18] Localities in this area were sampled in a small area of “salt and pepper” layered gabbro high on South China Mountain. Much of the strongly deformed metagabbro throughout the area contains gneissic layers ductilely stretched into schlieren and boudins. The rock at this locality contains zones of microgabbro and ultramafic hornblendite that look like schlieren of original layering, which we use for structural correction. Although no radiometric age determinations are available from this block, it is correlated with the Neoproterozoic Trinity ophiolite because of similar lithology and structural style.

[19] Samples were obtained from two sites, Ng6 and Ng7 (Figure 2). Reasonable results were obtained from site Ng6 (Table 3) but the data from site Ng7 are problematic. Many of the samples from site Ng7 yielded what appears to be a stable remanence direction and both polarities are represented. However, there was little agreement in direction and, consequently, no site-mean direction could be calculated.

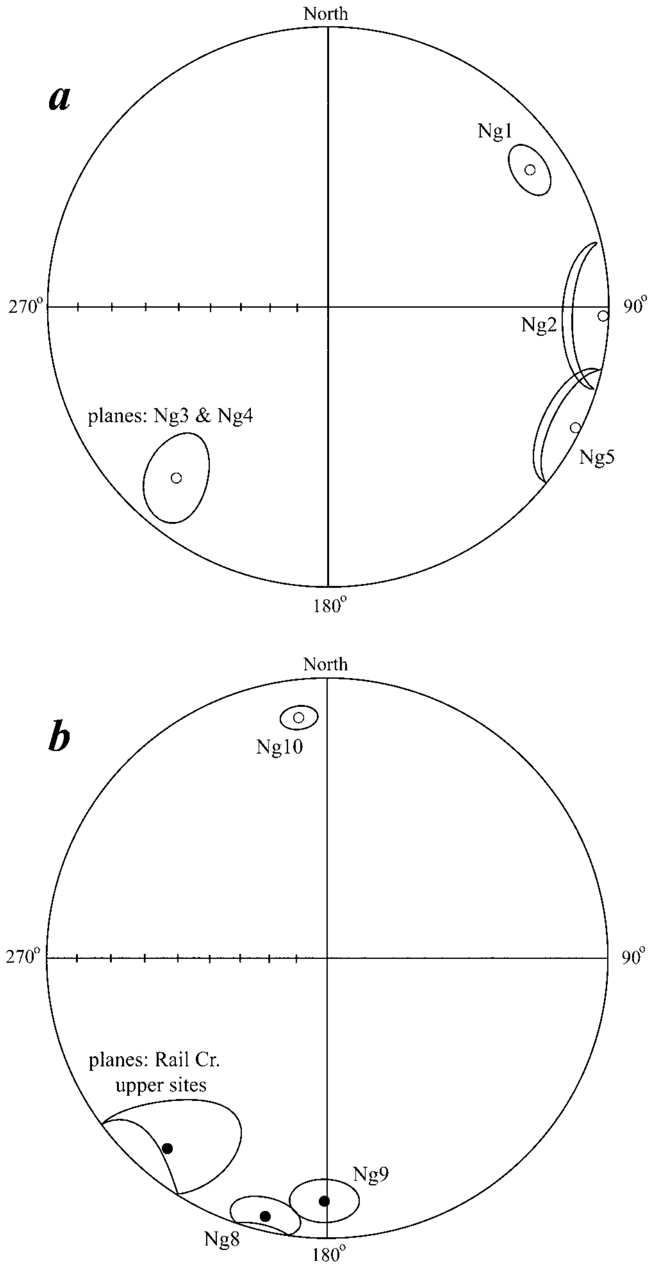

Figure 5. Structurally corrected, mean remanent magnetization directions for sites from (a) China Mountain and (b) Rail Creek. Plus signs are directions on lower hemisphere of equal-area projection; diamonds are directions on upper hemisphere. Ovals are 95% confidence limits calculated by the methods of *Fisher* [1953] and *Kirschvink* [1980].

Undetected internal deformation or multiple periods of overprinting are possible causes of the discrepancies. None of these “stable” directions found is likely to be correct because none is similar to those in samples from site Ng6 even though the sites are in close proximity.

3.3. Rail Creek

[20] Localities in this area are from an undated, enigmatic gabbro unit that appears to consist of intensely deformed Neoproterozoic metagabbro, which is intruded, both by slightly deformed Ordovician gabbro and undeformed

Siluro-Devonian pegmatitic gabbro. The unit also is cut by Ordovician?, Middle Devonian, Jurassic, and Cretaceous dikes. All of the paleomagnetic sites are considered to be within the Neoproterozoic metagabbro of the Trinity ophiolite because the rocks have a black and white "salt and pepper" appearance and a generally foliated structure. Structural corrections are based on relict cumulate layering, which is subparallel to the overall stratiform structure of the Trinity Complex.

[21] Samples from three sites (Ng8, Ng9, and Ng10) near the downstream reaches of Rail Creek (Figure 2) yielded good site-mean directions. Ng10 is opposite in polarity to Ng8 and Ng9 (Table 3), providing a positive consistency-of-reversals test. Results from four sites (Ng11, Ng12, Ng13, and Ng14) near the headwaters of Rail Creek, below Kangaroo Lake, were difficult to interpret. Some samples (including all from Ng11) seemed to yield a stable remanence but directions are inconsistent within a particular site or between sites. Causes for the discrepancies are, again, uncertain. Site Ng11 has a mean NRM intensity (1.3 A/m) that is two orders of magnitude above that typical of most other sites within the Trinity Complex, perhaps indicating deposition of "fresh" magnetite during more recent geologic times. Although overprints affecting this area have the same mean direction as we have seen elsewhere (see below), there is much more scatter, including a few samples with reversed polarity overprints. A principal component analysis (planes) solution was obtained from those samples at the four headwaters sites whose demagnetization vector endpoints fell on great circle paths on an equal area projection. The mean inclination (12°) calculated agrees well with tilt-corrected inclinations of the three downstream sites (Table 3, Figure 5b). Uncertainties about the mean are quite large but understandable because of the possibility of differential rotations between the outcrops.

3.4. Kangaroo Creek

[22] Three localities were sampled in the vicinity of Kangaroo Creek, Ng15, Ng16, and Ng17 (Figure 2). Lithology is ultramafic to mafic hornblendite and hornblende gabbro. Lithology and structure again point to this area being part of the Neoproterozoic Trinity ophiolite, although it is less deformed than some of the other sites. Structural corrections are based on foliation, which is parallel to layering in most outcrops where both are visible.

[23] Samples from site Ng15 on the northeast side of Kangaroo Creek yielded a well-determined site-mean direction, and both normal- and reversed-polarity overprints could easily be isolated in the demagnetization vector plots (Figure 3c). The normal-polarity overprint was isolated between temperatures of 20° to about 200° or 250°C. The reversed-polarity overprint was generally isolated between about 200° to about 400° or 450°C. In contrast, the two sites (Ng16 and Ng17) on the southwest side of Kangaroo Creek, failed to provide a consistent site-mean direction. Both overprints were seen in two of the samples from site Ng17 whereas with the other samples, only the normal-polarity overprint could be isolated. In none of the samples from site Ng16 could either overprint be isolated and, indeed, all 12 samples seemed to contain only a single component of magnetization. However, the individual directions recorded by these 12 samples are highly scattered. Here, as with site Ng11, anomalously high NRM intensities (150 mA/m) were found. None of the samples from these two sites yielded cleaning paths that could be analyzed using a planes solution.

3.5. Lovers Leap

[24] In this area, Neoproterozoic plagiogranite (565 Ma, Table 1, b) of the Trinity ophiolite sequence is cut by basaltic dikes and overlain by pillow lavas. None of these dikes cuts harzburgite or Neoproterozoic metagabbro of the Trinity ophiolite sequence, indicating that the basalt must have been erupted before the ophiolite sequence was dismembered [*Lindsley-Griffin*, 1991]. The similarity of the structural style of the basalt to that of the Neoproterozoic metagabbro and plagiogranite units also indicates that they have shared the same structural history, and that the basalt is probably of Neoproterozoic age. Structural correction for these volcanic rocks assumes that the mapped basal contact was approximately horizontal.

[25] Three localities were sampled in the Neoproterozoic basalt (Figure 2). The first of these, Nv1, was sampled at two outcrops about 50 meters apart. At one outcrop, four of eight samples yielded a characteristic magnetization whereas none of the six samples from the other retained a stable remanence. Of these 14 samples, one contained both normal- and reversed-polarity overprints, another only a reversed-polarity overprint, and the remaining samples a normal-polarity overprint. Site Nv2 was very stably magnetized and a mean direction was calculated using 14 of 15 samples. This was the only site within the Trinity Complex that we sampled in which the remanence resided in hematite. The hematite probably formed during hydrothermal alteration of the Neoproterozoic basalt, subsequent to its eruption. Flecks of hematite can be seen in thin sections, as well as inclusions of both red (hematitic) and green chert. Low coercivity magnetization components revealed no consistent overprinting field. Nine of twelve samples from site Nv3 also yielded a good site-mean direction. Here again we noticed several low coercivity magnetization components with most in the northeast quadrant but these were not as clearly defined as in most sites. Because well-defined cleaning paths were evident for many samples from these three sites, an intersecting planes solution was attempted as a check on the mean directions that were determined. The planes solutions can indicate whether all secondary components had been cleaned and reliable mean directions obtained. Cleaning paths were trending toward the upper hemisphere in the southeast quadrant for sites Nv1 and Nv2, and toward the lower hemisphere for samples from site Nv3. Cleaning paths for site Nv3 provided a well determined mean that agrees well with the calculated direction. Cleaning paths for sites Nv1 and Nv2 were so similar that a reasonable intersection could not be obtained unless data from the two sites were combined. Doing so, however, did provide a mean direction that seems quite reasonable. The fact that the uncertainty ellipse is elongate is not surprising because the two sites do have slightly different cleaned directions (Table 3).

4. Post Early Devonian Rocks

4.1. Middle Devonian Volcanic Rocks

[26] A suite of altered basaltic pillow lava, pillow breccia, hyaloclastite, and massive lava flows unconformably over-

Table 2. Ages and Faunal Affinities, Yreka Terrane, and Redding Section

Unit	Age	Fauna	Affinity[a]
Antelope Mtn. Quartzite	Neoproterozoic	cyclomedusoids[b]	Rodinian: AUS, NWT, YK
Gregg Ranch Complex	Ll.–Ash., M.–L. Ordovician	brachiopods[c]	Laurasian: CAR, GS, K, MLC, VTA, WMA
		conodonts[c]	Laurasian: AP, B, GB, GS, NEU, SCH
		gastropods[d]	Laurentian: WNA
		graptolites[e]	Laurasian: NV, PAC, YK
		rugose corals[c]	Laurentian: MLC, NME
		sponges[c]	Laurasian: AK, AU, YK
		tabulate corals[c]	Laurasian: AP, AT, AU, CH, MLC, UR
		trilobites[c]	Laurasian: AP, CDL, CH, ELV, K, NEU
	Wen.–Lud.	brachiopods[c,d]	Laurasian: CDL, UR
	M.–L. Silurian	tabulate corals[c]	Laurasian: AP, AT, AU, CH, SIB, UR
	E. Devonian	brachiopods[f,c]	Euramerican: CAR, NV, WCN, YK
		conodonts[c]	YT and ENV only, or Cosmopolitan
		gastropods[d]	YT only, or Laurasian: AK, SCO
		tabulate corals[c]	YT only or YT/ENV only
		tetracorals[c]	Euramerican: GB, WCN, YK
Gazelle Fm.	Sie.–Ems., E. Devonian	conodonts[c,g]	Euramerican: CDL
Copley, Balaklala	Eif., M. Devonian	placoderm fish plate[h]	Cosmopolitan
Kennett Fm.	Eif., M. Devonian	conodonts[c]	YT only, or
		tabulate corals[c]	Cosmopolitan Euramerican: ENV, SOR

Abbreviations: Are. = Arenigian, Ash. = Ashgillian, Eif. = Eifelian, Ems. = Emsian, Ll. = Llanvirnian, Lud. = Ludlovian, Sie. = Siegenian, Wen. = Wenlockian.

[a] Also found in: AK = Alaska; AP = Appalachians; AT = Altai Mts., central Asia; AU = Australia; B = Baltic area; CAR = Canadian Arctic; CDL = Cordilleran; CH = China; ELV = Effna Limestone, Virginia; ENV = Eureka, Nevada; EU = Europe; GB = Great Basin, North America; GS = Girvan, Scotland; K = Kazakhstan; MLC = Montgomery Limestone, northern Sierra Nevada, California; NME = northern Maine; NV = Nevada; NEU = northwestern and northern Europe; NWT = Northwest Territories, Canada; PAC = Pacific; SCH = southern China; SCO = Scotland; SIB = Siberia; SOR = Suplee, Oregon; SW = Sweden; UR = Ural Mts., Russia; VTA = Virginia–Tennessee–Alabama; WCN = western Canada or British Columbia; WMA = White Mts., Alaska; WNA = western North America; YK = Yukon, Canada; YT = Yreka terrane, California.

[b] Lindsley-Griffin et al. (unpublished data, 2001).

[c] *Potter et al.* [1990].

[d] *Rohr* [1980].

[e] *Berry et al.* [1973].

[f] *Boucot and Potter* [1977].

[g] *Savage* [1977].

[h] *Boucot et al.* [1974].

lies Neoproterozoic, Ordovician, and Siluro-Devonian elements of the Trinity Complex. These volcanic rocks also overlie the Early Devonian Gazelle Formation, and mélange of the Gregg Ranch Complex which contains fossiliferous rocks of Middle Ordovician to Early Devonian age (Table 2). Dikes of this lithology, including a distinctive diopside basalt, can be traced upwards through the older rocks into the pillow lavas. Thus these rocks were erupted in place after the thrusting that assembled the Yreka–Trinity composite terrane and are probably Middle (to Late?) Devonian in age [*Lindsley-Griffin*, 1991]. Because these deposits have irregular basal contacts, they appear to have erupted onto uneven surfaces. No postemplacement tilting can be demonstrated. These Devonian volcanic rocks may be cogenetic with similar rocks in the immature Devonian volcanic arc represented by the West Shasta sulfide district in the Redding section to the south [*Wallin et al.*, 1991], which are dated by an Eifelian, Middle Devonian fish plate (Copley–Balaklala, Table 2).

[27] Three localities were sampled in the Devonian rocks (Figure 2). One, Dv1, is within a massive (~20m exposed) amygdaloidal lava flow that is overlain by about 25 m of pillow basalt. The contact between the amygdaloidal flow and the pillow lavas seems to be welded, possibly indicating that the volcanic rocks represent a single eruption and that the entire pile cooled together. Site Dv2 also was sampled below the pillow basalts in a massive flow that is depositional over mélange of Early Devonian age. The third locality, Dv3, was sampled in massive basalt and breccia immediately below pillow basalt. Consistent results were obtained from localities Dv1 and Dv2 (Table 3).

4.2. Jurassic Sheeted Dike Complex

[28] Small to large packets of sheeted dikes of hornblende microgabbro and fine-grained basalt are found cutting various parts of the Trinity Complex. One of these packets yielded a $^{40}Ar/^{39}Ar$ age of 161 ± 4 Ma (E. T. Wallin as given by *Lindsley-Griffin* [1994]). Many of the dikes have similar compositions, exhibit the same cross-cutting relationships to older rocks, and, in the absence of evidence to the contrary, most are probably Jurassic in age [*Lindsley-Griffin*, 1994].

[29] The sheeted dike complex yielding the Jurassic isotopic age was sampled at locality J1 (Figure 2). Here are exposed several dozen dikes ranging from approximately 3 cm to 10 cm thick. The dikes are subparallel, have one-sided chilled zones and screens of pillows or pillow breccia. Some dikes are continuous over distances of 30–40 m. Attitudes of the dikes average to vertical, indicating no tilting of this outcrop. Eight of the ten dikes sampled yielded consistent results (Table 3).

5. Results

[30] Site-mean directions of magnetization for sites within the Neoproterozoic Trinity ophiolite are shown in

Table 3. Paleomagnetic Data for the Trinity Complex and Overlying Rocks of the Eastern Klamath Plate

				Uncorrected			Corrected				
Map No.	Lat., °	Long., °	N/N_o	Incl.	Decl.	Str/Dip	Incl.	Decl.	κ	α_{95}	Paleolatitude, °
						Jurassic Rocks					
J1	41.40	237.39	8/10	−70.7	234.8	None	–	–	140.6	4.7	50.3
						Devonian Volcanic Rocks					
Dv1	41.36	237.39	11/12	45.0	348.3	None	–	–	22.9	9.8	25.7
Dv2	41.40	237.39	9/12	56.1	67.9	None	–	–	42.6	8.0	34.7
Dv3	41.33	237.35	0/12	–	–	None	–	–	–	–	–
						Neoproterozoic Volcanic Rocks					
Nv1a	41.37	237.32	4/8	−16.1	113.8	280/20	−10.5	118.3	182.4	6.8	5.3
Nv1b	41.37	237.32	0/6	–	–	280/20	–	–	–	–	–
Nv2	41.36	237.32	14/15	−9.9	102.3	280/20	−8.4	105.9	19.2	9.3	4.2
Nv3	41.36	237.32	9/12	38.7	98.2	280/20	35.4	83.1	82.3	5.7	19.6
Planes, sites Nv2 & Nv3			11	–	–		−17.3	117.1	(31.3,2.9)	(6.0,14.1)	8.8
						Neoproterozoic Metagabbro					
Ng1	41.39	237.39	16/16	62.6	28.8	346/85	−13.6	55.7	34.1	6.4	7.1
Ng2	41.39	237.39	9/12	−54.1	142.2	146/85	−1.8	91.8	15.5	13.5	0.9
Ng3a	41.39	237.40	0/8	–	–	323/35	–	–	–	–	–
Ng3b	41.39	237.40	0/5	–	–	205/58	–	–	–	–	–
Ng4a	41.39	237.40	0/4	–	–	328/82	–	–	–	–	–
Ng4b	41.39	237.40	0/6	–	–	308/77	–	–	–	–	–
Planes, sites Ng3 & 4			13	–	–		−19.4	221.7	(18.2,2.7)	(7.6.16)	10.0
Ng5	41.39	237.41	7/13	49.5	157.4	346/85	−1.7	116.0	22.7	13.0	0.9
Ng6	41.37	237.40	9/12	47.5	9.5	214/34	27.0	347.7	44.2	7.8	14.3
Ng7	41.37	237.40	0/12	–	–	245/31	–	–	–	–	–
Ng8	41.38	237.34	8/9	−59.9	175.6	300/70	5.3	193.5	53.0	7.7	2.7
Ng9	41.38	237.34	10/13	−50.2	168.7	282/70	13.9	180.7	37.7	8.0	7.1
Ng10	41.37	237.35	14/15	30.4	344.1	313/70	−14.2	353.3	86.5	4.3	7.2
Ng11	41.35	237.36	0/11	–	–	19/56	–	–	–	–	–
Ng12	41.35	237.36	0/11	–	–	14/51	–	–	–	–	–
Ng13	41.34	237.36	0/10	–	–	326/55	–	–	–	–	–
Ng14	41.34	237.36	0/10	–	–	57/75	–	–	–	–	–
Planes, Ng11, 12, 13, & 14			14	–	–		12.2	219.8	(8.1,2.1)	(12,24.7)	6.2
Ng15	41.35	237.33	10/10	41.3	67.7	262/52	15.1	40.9	43.2	7.4	7.7
Ng16	41.34	237.33	0/12	–	–	198/25	–	–	–	–	–
Ng17	41.34	237.32	0/10	–	–	278/47	–	–	–	–	–

Map No. from Figure 2; Lat., Long. = north latitude and east longitude of site, respectively; N/N_o = number of samples used in the analysis/total number of samples collected; Incl., Decl. = inclination, positive downward and declination, east of north, respectively, of remanence vector uncorrected and corrected for tilt; Str/Dip = strike, east of north and dip, measured to right of strike; κ = concentration factor [*Fisher*, 1953]; and α_{95} = 95% confidence cone about average direction, values in parentheses were calculated using Bingham [*Onstott*, 1980] statistics.

Figure 6 along with their associated confidence ovals. The in situ and tilt-corrected directions are shown in Figures 6a and 6b, respectively. The consistency of magnetic inclinations improves markedly after correcting for tilt, indicating an early magnetization for these rocks. There was, however, a considerable amount of subsequent differential rotation between the different localities as evidenced by the lack of an improved grouping of directions after applying the tilt corrections. For this reason, these data were analyzed using the *McFadden and Reid* [1982] inclination-only statistics. The 11 in situ directions yield a mean inclination of 41.9°, α_{95} of 11.9°, and a concentration factor, k, of *Fisher* [1953] equal to 11.5. After tilt correction, the corresponding values are $I = 13.3$, $\alpha_{95} = 7.0°$, and $k = 31.7$. This increase in k after tectonic correction provides a fold test that is significant at 95% confidence [*McElhinny*, 1964]. To assess whether cumulate layering in these rocks could reflect an "initial tilt" of some 10° to 15° [e.g., *Irvine et al.*, 1998] rather than true horizontal, we repeated our calculations using both values for initial tilt. The improvements in statistical parameters for 15° and 10° of tilt (k = 19.3 and 23.6, respectively) both fail the fold test. This comparison reaffirms our belief that cumulate layering in the Trinity Complex provides a reasonable approximation of paleohorizontal.

[31] The positive fold test using cumulate layering to indicate paleohorizontal, and the positive consistency-of-reversals test among the Rail Creek sites, demonstrates that the magnetization in these rocks was acquired prior to folding and early in their history. Map relationships [*Lindsley-Griffin*, 1991] demonstrate that the Siluro-Devonian pegmatitic gabbro suite intruded after the juxtaposition of the Neoproterozoic and Ordovician oceanic terranes along the CMFZ, indicating that the magnetization must be pre-latest Silurian in age. In some areas, undeformed Ordovician gabbro intrudes previously deformed Neoproterozoic rocks [*Lindsley-Griffin*, 1991] indicating that the folding, and therefore the magnetization, must be pre-Early Ordovician in age. Considerable disruption of the Neoproterozoic Trinity ophiolite prior to intrusion of the Ordovician suite would be expected because the two suites of rocks formed in entirely different tectonic settings [e.g., *Wallin et al.*, 1991]. Although the magnetization recorded

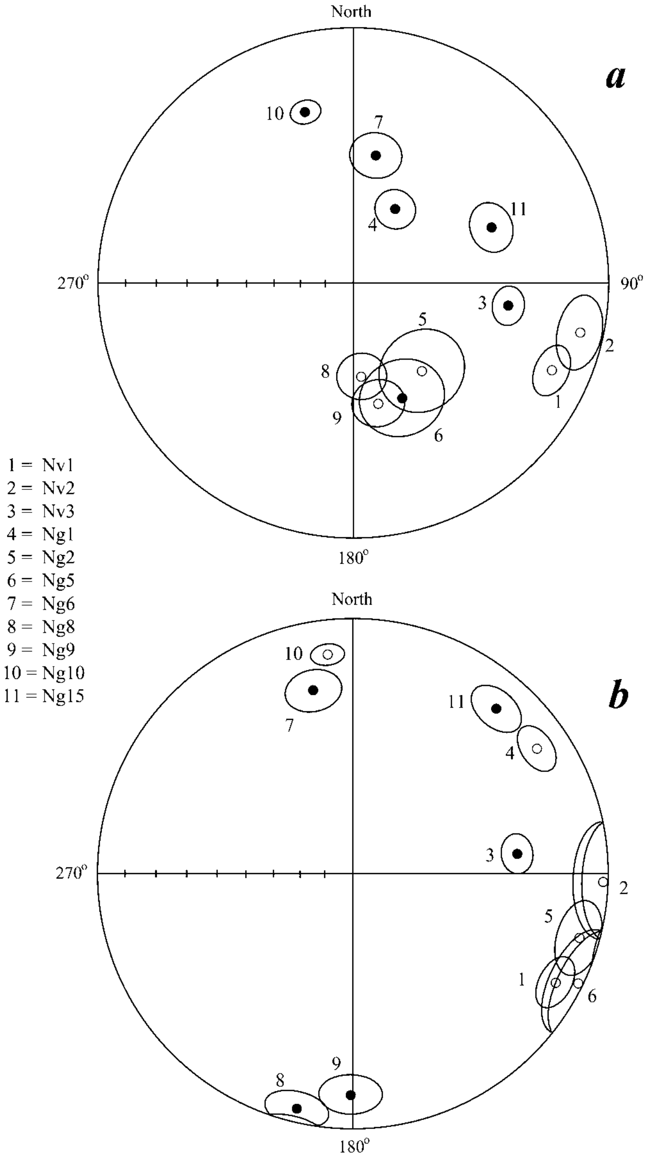

Figure 6. (a) In situ and (b) structurally corrected, site-mean remanent magnetization directions for sites within the Neoproterozoic ophiolitic rocks. See Figure 5 for additional explanation.

by the Neoproterozoic rocks clearly had an early origin, their lithology precludes a primary magnetization. Because alteration of plagioclase to albite, and of pyroxene to hornblende, are typical of subseafloor metamorphism, it is likely that the rocks were altered and the secondary magnetization acquired soon after their formation due to hydrothermal metamorphism produced by the geothermal systems that typically develop at newly formed oceanic crust [*Coleman*, 1977]. Paleomagnetic data from the Troodos ophiolite [*Varga et al.*, 1999] show that hydrothermal systems there developed during the earliest stages of structural extension, and hornblende–plagioclase thermometry [*Manning et al.*, 1996] indicates that metamorphism of the lower crust could be as rapid as several thousand years at fast spreading centers.

[32] Because the Devonian pillow basalts appear to have been erupted onto an uneven basement, the dip recorded by draped or flattened pillows is assumed to be an initial dip from the time of formation and not the result of subsequent tilting. Therefore, a fold test is unavailable to confirm a primary magnetization for these rocks. A statistically meaningful average direction could not be obtained by assigning unit weight to only two sites and so we used the *McFadden and Reid* [1982] inclination-only statistics by combining the individual specimen directions from each outcrop. The 20 samples yield a mean inclination of 48.9°, α_{95} of 5.7°, and a concentration factor, *k*, of *Fisher* [1953] equal to 23.5. It should be emphasized that the α_{95} about this mean is relatively small because of the large sample population, but it may underestimate the geologic uncertainty. For comparison, the angular standard deviation about the mean is 16.7°.

[33] The Jurassic (161 Ma) dikes are undeformed and essentially vertical, suggesting that no tilting of the outcrop has occurred subsequent to their emplacement. Because several dikes were sampled spanning the width of the outcrop, geomagnetic secular variation must have been sampled to some degree, but probably not its full range due to the relatively small size of the dike packet.

5.1. Post Folding Overprint Directions

[34] As mentioned above, many of the sites sampled have been affected by one or more episodes of post folding remagnetization, the most persistent occurring when the field was of normal polarity. The direction of the remagnetizing field was determined by principal component analysis [*Kirschvink*, 1980], most often by line fitting. The overprint directions recorded by eight sites where they could most reliably be determined are essentially identical. These directions, therefore, were averaged, and the overall mean (I = 58.7°, D = 25.2°, α_{95} = 6.8°) is shown in Figure 7 along with overprint directions reported from other studies within the Klamath Mountains province. The remarkable coincidence of normal-polarity overprint directions strongly indicates that all were acquired at about the same time. The Trinity Complex reversed-polarity overprint is not antipodal to the normal-polarity directions although this direction was determined at only one site; note that its inclination is consistent with the other two reversed-polarity overprints shown. *Mankinen et al.* [1989, 1996] present various lines of evidence indicating that the normal- and reversed-polarity overprints were acquired during Late Jurassic time. The result from the 161 Ma dike swarm sampled during this study (shown in Figure 7) is consistent with this interpretation.

6. Paleolatitude

[35] A mean inclination for the Neoproterozoic Trinity ophiolite was calculated [*McFadden and Reid*, 1982] using all 11 data as above, and including the planes solution for sites from China Mountain and the headwaters of Rail Creek. Including data from the latter two sites yields a mean I = 13.7°, with α_{95} = 5.8°, and k = 36.7; values that differ only slightly from those given above. Applying the *McFadden and Reid* [1982] calculations to site-mean virtual geomagnetic latitudes indicates that the rocks originated at a paleolatitude of 7.1° ± 3.2°. Whether the rocks formed in

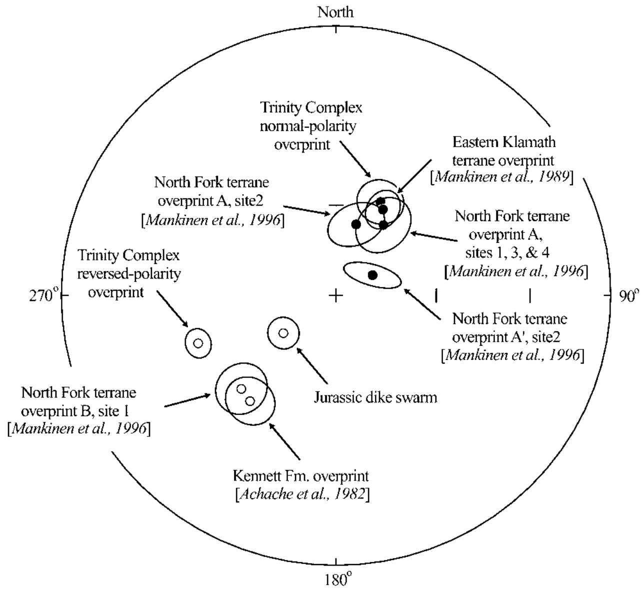

Figure 7. Remagnetization directions from various elements of the Klamath Mountains province that are pertinent to this study. Solid (open) circles are directions on lower (upper) hemisphere of equal-area projection.

the northern or southern hemisphere is unknown. For the purposes of our discussion we will assume an origin in the northern hemisphere, which is consistent with the expected position of western North America during late Proterozoic to earliest Cambrian time [*Smith et al.*, 1981; *McKerrow and Scotese*, 1990; *McKerrow et al.*, 1992].

[36] The data from the Devonian rocks indicate that they originated at a paleolatitude of 31.1° ± 5.0°, again using the *McFadden and Reid* [1982] statistics with virtual paleolatitudes as above. Although this result is based on data from only two sites, the protracted cooling of such thick accumulations of volcanic rocks may encompass enough time to have averaged geomagnetic secular variation and make this a valid estimation of paleolatitude. By way of comparison, the slightly older (~398 Ma [*Wallin and Metcalf*, 1998]) Billys Peak complex of the Trinity terrane yields a paleolatitude of 37.5° with an uncertainty range between 48° and 29° (E. T. Wallin et al., unpublished data, 1999). Here, we assume an origin in the southern hemisphere, which again is consistent with the expected position of western North America during Late Silurian to Late Devonian time [*Smith et al.*, 1981; *McKerrow and Scotese*, 1990; *McKerrow et al.*, 1992].

7. Tectonic Significance

7.1. Apparent Polar Wander

[37] Most pre-Cretaceous Phanerozoic paleomagnetic reference poles suffer from a lack of reliable data, resulting in a poorly determined apparent polar wander (APW) path for North America. To address this deficiency, *Van der Voo* [1990] compiled all reliable paleomagnetic poles from North America and Europe and combined them after "closing" the North Atlantic Ocean according to the *Bullard et al.* [1965] reconstruction to produce a series of more robust reference poles. We have used Van der Voo's reference poles to generate expected paleolatitudes for the Eastern Klamath plate between 575 and 177 Ma (Figure 8), assuming the terrane had a shared history with the North American craton. The expected paleolatitudes for Early to Middle Cretaceous time, and for Late Cretaceous time, were calculated using the paleomagnetic reference poles from *Globerman and Irving* [1988], and *Gunderson and Sheriff* [1991], respectively. Ruled areas show the uncertainties about each position. The timescale is from *Harland et al.* [1990], modified after *Tucker and McKerrow* [1995] and *Bowring and Erwin* [1998].

[38] Subsequent to *Van der Voo* [1990], *Mac Niocaill and Smethurst* [1994] reviewed paleomagnetic data from Laurentia and its Paleozoic margins (North America, northern Britain, Northern Ireland, and Greenland) and generated an APW path (570 to 250 Ma) for Laurentia. We rotated their APW path into North American coordinates using the *Bullard et al.* [1965] reconstruction and generated the paleolatitude curve labeled "A" in Figure 8. No uncertainty limits were assigned to the Laurentian curve although Mac Niocaill and Smethurst do consider the Early Cambrian segment of the path to be poorly constrained.

[39] No expected paleolatitudes were calculated for Middle to Late Jurassic time because this portion of the North American APW remains poorly defined and controversial (see summary by *Hagstrum* [1993]). In general, one set of data indicates that the APW remained at latitudes of about 60° (present-day coordinates) during Middle Jurassic time [e.g., *May and Butler*, 1986] whereas other data place the path at higher latitudes during the same interval [e.g., *Van Fossen and Kent*, 1990]. In order to overcome this problem, *Besse and Courtillot* [1988, 1991] and *Van der Voo* [1992] analyzed Jurassic data from the Atlantic-bordering continents, rotated them into North American coordinates and combined them with available North American data. However, the problem remained as to which North American data should be believed. For this reason, *Courtillot et al.* [1994] omitted all North American data when generating a synthetic APW path. The Courtillot et al. interpretation was used here to generate the paleolatitude curve labeled "B" in Figure 8. The shaded interval denotes the uncertainty limits about this path.

7.2. Paleomagnetic Results

[40] Paleomagnetic data from the Trinity Complex and overlying rocks of the Eastern Klamath terrane are plotted as circles on Figure 8. Our Neoproterozoic Trinity ophiolite result indicates a low paleolatitude origin for those rocks but one that is within the uncertainty limits of the reference pole if the rocks formed in the northern hemisphere. The result from our Devonian sites is concordant, given its lack of a precise age and its agreement with the 398-Ma Billys Peak Complex result (see above), if it formed in the southern hemisphere.

[41] Upward-directed magnetic inclinations [*Mankinen et al.*, 1989] recorded by the Permian Dekkas Andesite in the Redding subterrane of the Eastern Klamath plate show that those rocks formed in the northern hemisphere during the Kiaman Reversed-Polarity Superchron [*Irving and Parry*, 1963]. A northern hemisphere origin is therefore indicated [*Mankinen et al.*, 1989] for the Triassic Modin Formation,

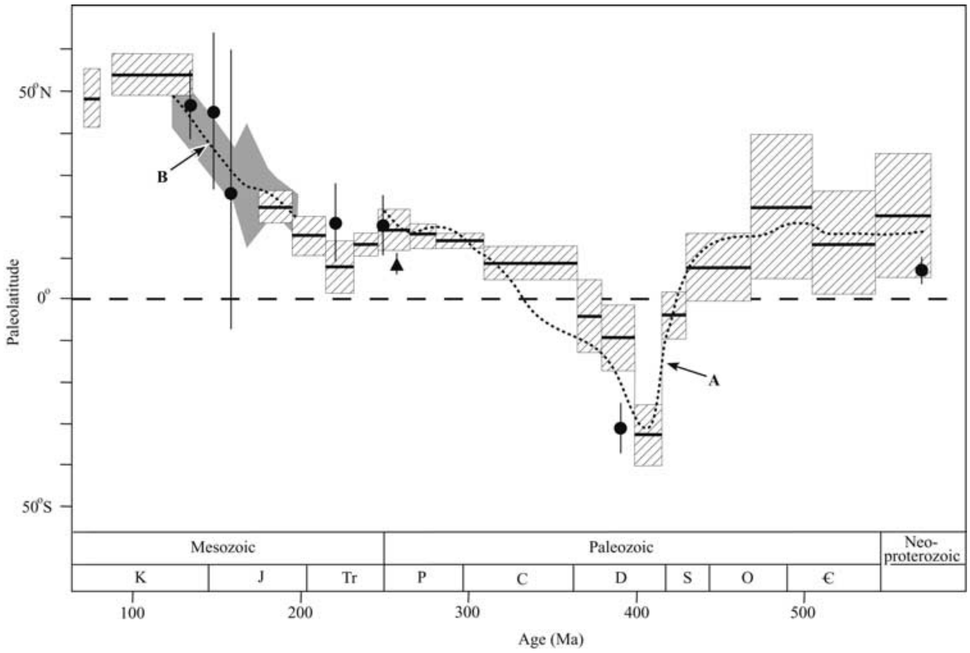

Figure 8. Expected position (short, horizontal line segments) of the Trinity Complex throughout late Neoproterozoic, Paleozoic, and Mesozoic time. Ruled areas are uncertainties about the expected positions. Positions for Cambrian to Jurassic time calculated from *Van der Voo* [1990], Early to Middle Cretaceous time from *Globerman and Irving* [1988], and Late Cretaceous time from *Gunderson and Sheriff* [1991]. Curve A is from *MacNiocaill and Smethurst* [1994] and curve B from *Courtillot et al.* [1994] (see text for discussion). Timescale is modified after [*Harland et al.*, 1982, 1990; *Tucker and McKerrow*, 1995; *Bowring and Erwin*, 1998]. Circles are data from the Eastern Klamath plate including results from this study. Triangle represents data from the North Fork terrane [*Mankinen et al.*, 1996].

and Jurassic strata of the Arvison Formation of *Sanborn* [1960] and the Potem Formation which overlie the Dekkas Andesite. Paleomagnetic results also are available from the youngest postamalgamation plutons (the Early Cretaceous Shasta Bally belt) of the Klamath Mountains province [*Mankinen et al.*, 1988]. The large uncertainties about the Jurassic results are due to the small number of data; the oldest data point is based on the mean of 3 sites and the younger on 4 sites. The angular standard deviations about the means of the oldest and youngest data points are 6° and 12°, respectively.

8. Discussion

[42] It is clear from previous studies that the Eastern Klamath terrane was in the northern hemisphere from Permian time to the present, but its earlier position was uncertain. Based on our new paleomagnetic data, there is now no reason to assume that the Trinity Complex has not been latitudinally concordant with the North American craton throughout its long history. However, paleomagnetic data are unable to provide any information on paleolongitude. Other lines of evidence—such as faunal affinities, structure, and lithology—must provide clues as to whether the Eastern Klamath terrane was near or far removed from the craton.

[43] Such evidence has led to many contrasting interpretations and no consensus has even been approached. Differences in Permian faunas from typical North American forms, for example, led *Stevens* [1977], *Stevens et al.* [1990], and *Belasky and Runnegar* [1994] to conclude that the Eastern Klamath terrane may have been several thousand kilometers away from the continent at that time. Provenance studies of the Mississippian Bragdon Formation by *Miller and Saleeby* [1991] indicate that it was deposited near an older continental margin, presumably North America. Miller and Saleeby note that modern island arcs fringe continents and are rarely separated from them by significant distances, although occasionally by as much as a few thousand kilometers. Other authors [e.g., *Gray*, 1986; *Cotkin*, 1992; *Hacker et al.*, 1993] believe that none of the Klamath Mountains terranes need be far traveled or even allochthonous. We examine some of the various lines of evidence below and compare them with results from our current investigations.

[44] Faunal evidence is not available directly from the Trinity Complex, but must come from the sedimentary sequences of the Yreka and Redding subterranes that structurally overlie it. During the late Precambrian–early Paleozoic, the Yreka subterrane was linked in some fashion to the Trinity Complex, because debris flows within mélange of the Gregg Ranch Complex contain detritus apparently eroded from the Trinity Complex [*Hopson and Mattinson*, 1973; *Lindsley-Griffin*, 1977]. Although many early Paleozoic faunas from the Yreka subterrane are fairly cosmopolitan, the more provincial faunas are tied to the edges of Laurasia, in areas that today are recognized as Cordilleran accreted terranes (Table 2). For example, *Potter et al.* [1977] reported that Ordovician fossils of the Yreka subterrane are mainly Old World types differing from

coeval faunas of Nevada. A small subset of corals, brachiopods, and gastropods (Table 2) is unique to the Yreka subterrane or in some cases to it and one or two other Cordilleran terranes [*Rohr*, 1980; *Potter et al.*, 1990]. The species that are unique to the Yreka subterrane are significant because they indicate that some tectonic or environmental factor acted to isolate these faunal elements from North America. These isolating elements, whether tectonic or oceanographic, were effective enough for some faunal elements to evolve their own distinctive characteristics, yet allowed other elements of the early Paleozoic faunas to communicate with more inboard parts of North America. Thus, during the period from early Middle Ordovician through Early Devonian the Yreka subterrane faunas were partially, but not completely, isolated from North America.

8.1. Neoproterozoic Period

[45] The Neoproterozoic Trinity ophiolite formed during the period from 579 Ma to 556 Ma at a slow-spreading ridge with both MORB and arc affinities; absence of sheeted dikes and extensive development of quartz–plagioclase plagiogranite support a slow spreading interpretation. *Bruckno* [1997] concluded that the geochemistry of the basalt, plagiogranite, and metagabbro of the Trinity ophiolite is most consistent with a back arc basin origin. Instead, we suggest that it could have formed in a rifting basin, perhaps one associated with the breakup of the supercontinent Rodinia and opening of the proto-Pacific Ocean, or Panthalassa [e.g., *Dalziel*, 1991; *Unrug*, 1997]. Consider the "SWEAT" hypothesis (southwest United States–East Antarctica connection) of *Dalziel* [1991] and *Moores* [1991], which suggested that at 570 Ma, Australia and East Antarctica were west of Laurentia. Our Figure 9 shows possible locations for the developing Trinity ophiolite at 570 Ma, at about 7° N or 7°S in the rifting basin between Laurentia and Australia–East Antarctica. At this time, the Trinity ophiolite would have been close to both the North American craton and the Australia–East Antarctic block [*Dalziel*, 1991; *Hoffman*, 1991; *Moores*, 1991]. *Dalziel* [1991] shows the 570-Ma margin in which the Trinity ophiolite could have formed as being oriented roughly north–south, so rifting most likely would have been east–west and parallel to latitude at that time. Thus, the Trinity ophiolite would have moved along latitude away from North America as the ocean basin opened, although not necessarily very far.

[46] The oldest sedimentary and metasedimentary rocks of the Eastern Klamath terrane are found in the Yreka subterrane and previously were considered to be Ordovician in age. Recently, however, an Ediacaran biota [*Lindsley-Griffin et al.*, 1989] (N. Lindsley-Griffin et al., unpublished data, 2001) has been recognized within argillite of the Antelope Mountain Quartzite of *Hotz* [1977], which argues strongly that this formation is Neoproterozoic in age [*Narbonne*, 1998]. The presence of this biota also supports the proximity of the Trinity Complex and Eastern Klamath terrane to Rodinia during this time (Table 2).

[47] Neoproterozoic tonalite blocks within the schist of Skookum Gulch, a mélange unit within the Yreka subterrane, were found to contain zircons with an inherited continental signature [*Wallin et al.*, 1991] and span the period during which the Trinity ophiolite was forming (Table 1, c). *Wallin et al.* [2000] also determined that detrital

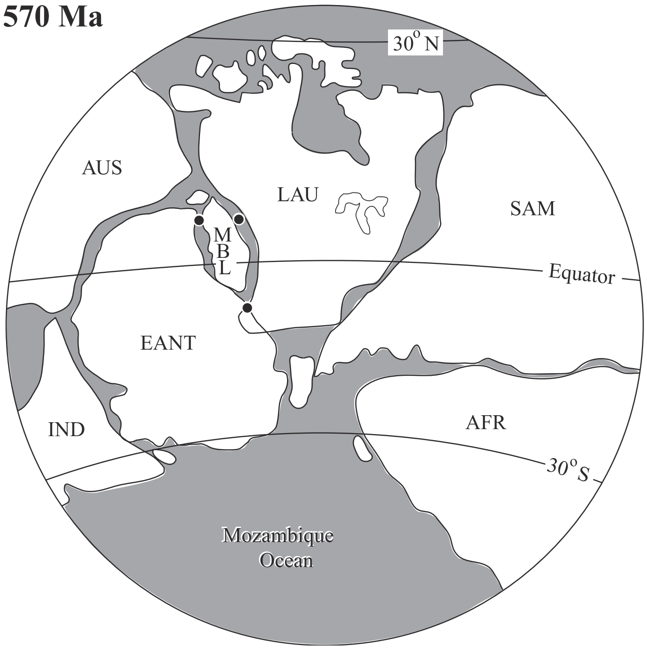

Figure 9. Possible locations of Neoproterozoic Trinity ophiolite during formation, 579–556 Ma, showing both northern and southern hemisphere interpretations (dots). Reconstruction of the Rodinian supercontinent after *Dalziel* [1991, Figure 3]. AFR, Africa; AUS, Australia; EANT, East Antarctica; IND, India; LAU, Laurentia; MBL, Marie Bird Land; SAM, South America.

Precambrian zircons within the Antelope Mountain Quartzite exhibit a continental signature and that sedimentary structures within the unit support a shallow water environment. They considered the most likely source for the continental zircons to be northern British Columbia, which would require as much as 1000 km of southward transport of the Yreka subterrane during late Paleozoic time. Northern British Columbia, however, would have been part of Rodinia (Figure 9) according to both *Dalziel* [1991] and the alternative reconstruction called AUSWUS (Australia–Southwest U.S.) by *Karlstrom et al.* [1999]. Thus, the tonalite blocks and the detrital zircons of the Yreka subterrane could have been derived from the Australia–Antarctica block, negating the need for significant southward transport.

8.2. Cambrian Period

[48] The breakup of Rodinia continued during Cambrian time (c. 545–490 Ma), and Laurentia moved away from the terranes that would become East Gondwanaland. Between 550 Ma and 480 Ma, elements of the Neoproterozoic Trinity ophiolite were intensely deformed [*Tozer and Lindsley-Griffin*, 1993; *Tozer*, 1994]. The textures of the plagiogranite show ductile shearing overprinted by brittle cataclasis, suggesting that it underwent uplift from the ductile deformation depth to the brittle deformation depth, i.e., it crossed the brittle–ductile transition zone, while deformation was still underway. At the same time, metagabbro of the Trinity ophiolite underwent intense ductile shearing, never crossing the brittle–ductile transition zone. Although these features could signal the beginning of some kind of "emplacement"

or collisional event, the style of deformation is more likely the result of shearing rather than compressional deformation. This interpretation is consistent with the suggestion by *Wallin et al.* [2000] that the Antelope Mountain Quartzite was emplaced in a transtensional or transpressional regime rather than a more typical convergent margin. The lack of thick deposits of volcanic and volcaniclastic rocks of this age also argues against a convergent margin setting.

8.3. Ordovician Period

[49] By Ordovician time (c. 490–440), the Neoproterozoic Trinity ophiolite could have been far removed from its place of origin, perhaps even increasing its separation from the continental fragments resulting from the breakup of Rodinia. Isotopic evidence [*Wallin et al.*, 1991] indicates that the pre-Late Ordovician Trinity peridotite is much more primitive than the Neoproterozoic Trinity ophiolite and formed in a different petrotectonic setting. *Quick* [1981] thought that the Trinity peridotite formed by the rise of an upper mantle diapir, perhaps within a volcanic arc or a back arc basin; other tectonic settings would also be consistent with the data. Deformation within the Trinity peridotite ended between about 480 Ma and 470 Ma, and uplift generated a pulse of pressure-release partial melting, forming Ordovician dikes and melt-pocket inclusions in the peridotite, and possibly the Ordovician gabbros associated with the Trinity ophiolite (Table 1, d and f–g). Between 470 Ma and 440 Ma, the CMFZ juxtaposed the Neoproterozoic Trinity ophiolite and the Ordovician Trinity peridotite. Deformation of the Trinity ophiolite cannot be entirely due to this suture zone, or the Trinity peridotite would show similar textures and structures near the suture zone. The CMFZ probably was responsible only for the local mylonitization of gabbro and ultramafic blocks trapped within the suture zone, although it also could have tilted and jumbled some blocks within the Neoproterozoic Trinity ophiolite.

[50] During the period of about 455–440 Ma, a tonalite block now within Yreka terrane mélange crystallized (Table 1, h), and the blueschist of Skookum Gulch was metamorphosed. The formation of blueschist mélange at 447 Ma (Table 1, i) suggests a convergent margin at this time [*Cotkin*, 1992], although subduction must have been short-lived because no accumulation of Late Ordovician volcanic rocks is known. The deformation and uplift events recorded by the Trinity Complex, combined with the Skookum Gulch evidence for magmatism and subduction-related metamorphism, could be interpreted as recording a complex series of small plate interactions that included closing of small ocean basins along transpressional boundaries and the migration of triple junctions.

8.4. Siluro-Devonian Rocks

[51] *Wallin et al.* [1991] cited isotopic evidence indicating that both the Siluro-Devonian pegmatitic gabbros and the Ordovician Trinity peridotite are much more primitive than the Neoproterozoic Trinity ophiolite and formed in a different petrotectonic setting. *Jacobsen et al.* [1984] studied a pyroxenite dike that is probably part of the Siluro-Devonian pegmatitic gabbro suite and concluded that it was not derived by partial melting of the Ordovician Trinity peridotite, but from a different mantle source. Although *Jacobson et al.* [1984] interpreted the differing isotopic signatures as resulting from mantle evolution, these rock suites instead may be documenting the travels of the Trinity Complex over mantle of varying composition.

[52] After the Yreka–Trinity block was amalgamated in early Middle Devonian time [*Lindsley-Griffin et al.*, 1991], Middle Devonian basalts were erupted over it, fed by dikes that penetrate both subterranes. These lava flows are too thin and volumetrically minor to represent a fully developed volcanic arc [*Lindsley-Griffin*, 1991]. Instead, they may be the northern manifestation of developing volcanism that now comprises the West Shasta massive sulfide district [*Albers and Bain*, 1985; *LaPierre et al.*, 1985]. Geochemical data [*Danielson*, 1988; *Wallin et al.*, 1991; *Bruckno*, 1997] indicate that the Middle Devonian basalts overlying the Yreka–Trinity block may be cogenetic with the Copley Greenstone at the base of the West Shasta sequence.

[53] Geochemical characteristics [*LaPierre et al.*, 1985; *Brouxel et al.*, 1987] and oxygen isotope data [*Taylor and South*, 1985] indicate that the Middle Devonian volcanic rocks were not near continental crust although lead isotope compositions [*Doe et al.*, 1985] are more equivocal. *Lindsley-Griffin* [1991, 1994] and *Wallin et al.* [1991] have suggested that the Middle Devonian basalts formed in a near-trench environment. Although the strata of the Redding subterrane are often inappropriately considered an island arc sequence [e.g., *Gehrels and Miller*, 2000], volcanism during the Paleozoic was intermittent and the volume of volcaniclastic debris was small, being restricted to the Middle Devonian Copley Greenstone and Balaklala Rhyolite, the Carboniferous pyroclastic rocks and keratophyre of the Baird Formation, and the Permian Dekkas Formation (andesite) [*Wagner and Saucedo*, 1987]. *Wallin et al.* [2000] argue that these facts support an origin along a transtensional or transpressive margin rather than a convergent margin during much of Paleozoic time.

9. Conclusions

[54] In summary, most of the available evidence seems to indicate that rocks of the Trinity Complex and overlying strata formed in a slowly rifting basin marginal to Rodinia and Laurentia. Paleomagnetic data presented herein provide permissive evidence that this basin remained somehow related to Laurentia during its large-scale movements since the early Neoproterozoic breakup of Rodinia. Whether or not the basin retained the same relative position with respect to the North American craton throughout its history is unknown. The fact that a number of fauna developed in the Eastern Klamath terrane that differed from typical North American forms argues for some sort of barrier between the two regions. The barrier could have been lateral distance, water depth, water currents, or water temperature differences. Isotopic evidence described above indicates that Trinity Complex and related rocks probably were not in close proximity to the craton during parts of their history. The large tectonic rotations indicated by the paleomagnetic data [*Mankinen et al.*, 1989; *Irwin and Mankinen*, 1998] also suggest that the Permian and Triassic arc must have been at a high angle to the trend of the continental margin, again indicating that the arc must have been at some distance from the craton at that time. We suggest that the

Eastern Klamath terrane (Trinity, Yreka, and Redding subterranes) probably was separated from North America by distances approaching the maximum found for modern day island arcs. Deposition of the Redding subterrane continued into the Jurassic, and the large numbers of Triassic and Jurassic marine fossils not reported elsewhere [e.g., *Sanborn*, 1960] indicates that the area continued to be isolated.

[55] The scenario just given applies only to the Eastern Klamath plate; terranes farther to the west may have had completely different histories. For example, a Tethyan foraminiferal fauna has been described from Permian limestone blocks in the Eastern Hayfork terrane [*Nestell et al.*, 1981; *Irwin et al.*, 1985; *Luken*, 1985], and paleomagnetic data show that Permian chert in the North Fork terrane originated at least 10° of latitude (∼1000 km) farther south than the Permian rocks of the Eastern Klamath terrane [*Mankinen et al.*, 1996]. What is known is that various elements of the western Klamath Mountains were swept against the Eastern Klamath nucleus beginning with the Middle Devonian amalgamation of the Central Metamorphic terrane with the Yreka–Trinity composite terrane about 398–407 Ma. Western Klamath elements continued to be added to the Eastern Klamath nucleus through latest Jurassic or earliest Cretaceous time when the Western Jurassic terrane was amalgamated [*Irwin*, 1981; *Irwin and Mankinen*, 1998; *Irwin and Wooden*, 1999]. Paleomagnetic data from Permian through Jurassic strata of the Redding subterrane [*Mankinen et al.*, 1989] show that tectonic events during this period in the evolution of the Klamath Mountains were accompanied by large amounts of rotation beginning in latest Triassic or earliest Jurassic time. Accretion of the Klamath Mountains to the North American continent probably was completed during Early Cretaceous time [*Mankinen et al.*, 1988].

[56] **Acknowledgments.** We thank R. Bogar for assistance in the field, and R. Bogar and L. Paulick for assistance with the magnetic measurements. Constructive reviews by W. P. Irwin, C. S. Grommé, S. W. Bogue, M. E. Beck, Jr., and JGR Associate Editor C. Laj also are appreciated.

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