JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. B8, PAGES 10,415–10,427, AUGUST 10, 1989

Paleomagnetic Evidence for Poleward Transport of Upper Jurassic Rocks in the Decatur Terrane, San Juan Islands, Washington

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The San Juan Islands are underlain by a west-vergent Late Cretaceous thrust and nappe system, part of a larger thrust belt exposed in the northwest Cascades of Washington and the southwestern Coast Mountains of British Columbia. Published paleomagnetic data from Cretaceous plutons (for example, the Coast Plutonic Complex) intruding the thrust belt suggest that it has been displaced northward by as much as 2400 km since 90-100 Ma. This study focuses on the preintrusive travel history of the Decatur terrane, one of the units involved in the San Juan thrusting. The Decatur terrane is of special interest because it may be correlative with the Coast Range ophiolite (CRO) and Great Valley sequence of the southern California Coast Ranges. We report new paleomagnetic data from the James Island Formation, an Upper Jurassic, preintrusive turbidite unit, and from the Obstruction Formation, a terrigenous sandstone unit deposited on the Decatur terrane in the Late Cretaceous. Nine sites in the Obstruction Formation yield a single remanence direction (grand mean $D=90.7°$, $I=67.9°$) that is clearly a postfolding overprint, possibly of Late Cretaceous age. The six site mean remanence directions from the James Island Formation cluster well only after restoring the beds to horizontal by a scheme that takes account of their complex structure. This positive fold test and the presence of two polarities provide evidence that the remanence is primary. The mean paleolatitude corresponding to the corrected remanence direction from the James Island Formation is $0° \pm 9.2°$. The data thus corroborate equatorial paleolatitudes derived from parts of the CRO by others and suggest that the Decatur terrane and CRO represent fragments of a larger terrane originally located near the Jurassic equator. Unlike the CRO, however, the Decatur terrane was still near the equator at 145 Ma. If the plutons intruding the San Juan-north Cascades thrust belt formed 2400 km to the south, then the paleomagnetism of the Decatur terrane suggests it moved 20° farther poleward in the interval 145 Ma to 97 Ma than did an equivalent site on North America. A much smaller amount of pre-Late Cretaceous motion is allowed by error limits on the paleolatitudes, but more is required if tilting is partly responsible for the shallow paleomagnetism of the Cretaceous plutons.

INTRODUCTION

The San Juan Islands of northwest Washington state (Figure 1) are underlain by a west-vergent Late Cretaceous thrust and nappe system that was emplaced onto Wrangellia [*Brandon et al.*, 1988]. The thrust sheets comprise diverse rock units, ranging in age from early Paleozoic to middle Cretaceous (late Albian). In a brief interval between about 99 Ma and 84 Ma, the sheets were imbricated, tectonically buried, and subsequently uplifted. Some of the nappes constitute tectonostratigraphic terranes; by definition, each records a prethrusting geological history different from the histories of other terranes in the thrust system. *Misch* [1966], *Brandon and Cowan* [1985], and *Brown* [1987] interpret the San Juan system to be part of a larger thrust belt exposed in the northwest Cascades of Washington and the southwestern Coast Mountains of British Columbia.

In light of the impressive evidence that significant parts of the western Cordillera of North America have been displaced northward greater than 1000 km relative to the craton [e.g., *Beck*, 1980], it is logical to ask two questions about the San Juan-northwest Cascades thrust system: "At what paleolatitude did Late Cretaceous thrusting occur?" and "At what paleolatitudes did the individual rock units and terranes juxtaposed during thrusting originate?" Some existing paleomagnetic data from 90-100 Ma granitoid plutons that synkinematically and postkinematically intruded elements of the northwest Cascades system [*Beck et al.*, 1981; *Irving et al.*, 1985] bear on the first question. The anomalously shallow paleomagnetism of the plutons has been interpreted as evidence of emplacement at paleolatitudes of 27(±3)°N to 37(±5)°N, significantly south of the expected paleolatitude (59°N) had this region been fixed with respect to North America in the early Late Cretaceous. Because of the probable contiguity of the northwest Cascades and San Juan thrust systems [*Brandon et al.*, 1988], the paleomagnetic data from plutons intruding the former apply to the latter as well. In other words, the entire thrust belt and plutons intruding it may have been displaced northward, possibly by as much as 2400 km, since approximately 90 Ma [*Irving et al.*, 1985]. An alternative interpretation is that the anomalous paleomagnetism of the plutons is at least partially due to post-90 Ma tilting, so that less relative displacement is required. In either case, regional considerations combined with paleomagnetic data suggest that the entire block was fixed at essentially its present position with respect to continental North America by early Tertiary time [e.g., *Fox and Beck*, 1985; *Bardoux et al.*, 1988].

This paper will focus on the second question, the original latitudinal position of the Decatur terrane, a preintrusive rock unit involved in the thrusting. The new evidence consists of two paleomagnetic results: one from the James Island Formation, which is Upper Jurassic and appears to retain an ancient remanence of two polarities; and the other from the

Paper number 89JB00637.
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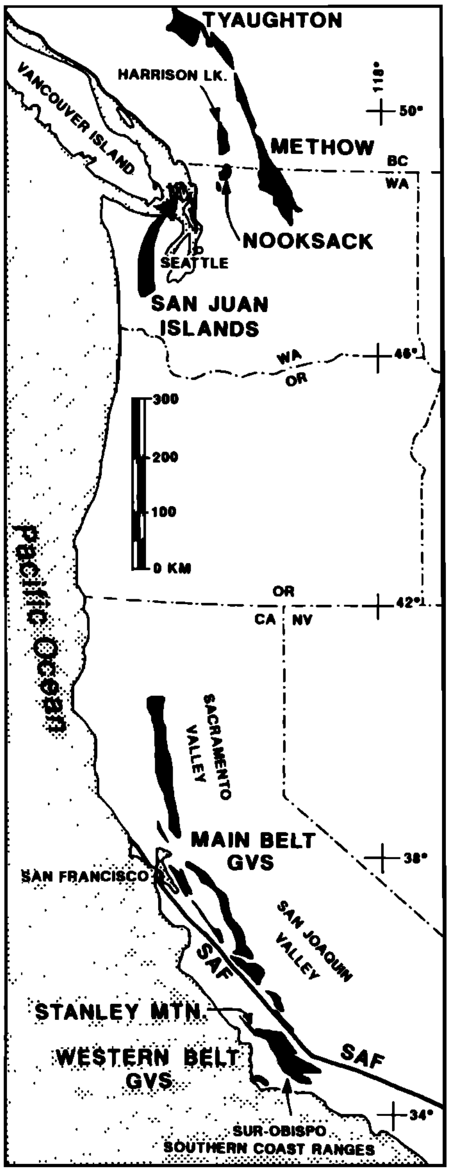

Fig. 1. Location map showing the San Juan Islands and other localities mentioned in the text. Solid areas denote regions underlain by Jurassic and Cretaceous rocks discussed in the text. In California, "Main Belt GVS" refers to the essentially continuous outcrop belt of the Great Valley sequence that lies east of the San Andreas fault (SAF). "Western Belt GVS" refers to exposures of the Great Valley sequence that occur west of the San Andreas fault and adjacent to the Sur-Nacimento fault zone in Southern Coast Ranges.

Obstruction Formation, which is Upper Cretaceous and has been thoroughly remagnetized. The data from the James Island Formation suggest that the Decatur terrane originated near the Jurassic equator and remained at low latitudes until after 145 Ma. This finding has specific implications for the relation between rocks of the Decatur terrane and those of the Great Valley sequence and Coast Range ophiolite of the southern California Coast Ranges [*Garver*, 1988*b*].

DECATUR TERRANE

The structurally highest thrust sheet in the San Juan system is the Decatur terrane, which comprises two elements: (1) a highly disrupted complex of Middle to Upper Jurassic ophiolitic rocks and Upper Jurassic arc-related volcanic and sedimentary rocks [*Brandon et al.* 1988; *Garver*, 1988*a*]; (2) an overlying, well-bedded, volcaniclastic-rich terrigenous blanket called the Lummi Group [*Garver*, 1988*a*]. In the study area, the Upper Jurassic (upper Tithonian) turbidites of the Lummi Group unconformably overlie Upper Jurassic (Tithonian) pelagic and volcanogenic sedimentary rocks of the Fidalgo Complex. Strata of the James Island Formation, which are well dated by the upper Tithonian bivalve *Buchia piochii*, constitute the base of the Lummi Group. The Lummi Group may also include Lower Cretaceous strata (Valanginian [see *Garver*, 1988*a*]). Because of its structural position and age, we infer that the James Island Formation underwent the very low temperature, moderate pressure metamorphism that affected the other San Juan nappes between and 99 Ma and 84 Ma.

The stratigraphy, sandstone petrography, and petrotectonic elements of the Decatur terrane are quite different from those of coeval sequences in the Pacific Northwest (for example, Nooksack Group, Harrison Lake sequence, and the Methow-Tyaughton sequence [*Garver*, 1988*b*]) and therefore the terrane has no obvious homeland in the San Juan-North Cascades thrust system. The stratigraphic elements of the Fidalgo Complex and Lummi Group, however, are strikingly similar to both the age-correlative Coast Range ophiolite and Great Valley sequence (CRO/GVS) on the west side of the San Joaquin valley in California (Figure 1) and CRO/GVS-like rocks west of the San Andreas fault (Figure 1) in the Sur-Obispo terrane of southern California [*Garver*, 1988*b*]. This correlation could mean that the James Island Formation is a fragment of the Great Valley sequence that has been tectonically transported to the San Juan Islands (see model 2 of *Garver* [1988*b*] and *McLaughlin* [1988]). Alternatively, the sediments could have accumulated in a forearc setting similar to that of the Great Valley sequence, but located elsewhere (see models 1 and 3 of *Garver* [1988*b*]). Substantial tectonic transport may or may not be implied by this alternative, depending on where the similar forearc happened to be located.

A related question is when did the Decatur terrane assumed its current position next to the structural block that includes Wrangellia and the Coast Plutonic Complex? As described by *Brandon et al.* [1988], the San Juan nappes were rapidly uplifted from depths as great as 20 km in the early Late Cretaceous. Two clastic units are interpreted to record this uplift. The older of the two is the Obstruction Formation, which was apparently deposited syn-tectonically as a terrigenous blanket on the deformed and metamorphosed Decatur terrane in the early Late Cretaceous (?Cenomanian-Turonian [*Garver*, 1988*a*]). Later folding of the Obstruction Formation, perhaps associated with the latest stages of thrusting and uplift, produced a prominent cleavage. Sediments shed from the thrust sheets also accumulated in the Nanaimo Group, basal conglomerates of which are dated at 84 Ma. These sediments contain pebbles of Tithonian (C. Blome, personal communication, 1985) chert and red argillite probably derived from the Decatur terrane. Since the Nanaimo Group rests depositionally on rocks of the Wrangellia terrane near Vancouver Island, it is clear that Decatur terrane had become appended to the southern end of the Wrangellia-Coast Plutonic Complex block by 84 Ma. Regional geologic relations [*Brandon et al.*, 1988] that tie the San Juan and North Cascade thrust systems imply an even earlier juxtaposition. These sedimentologic and regional considerations, plus the paleomagnetic evidence discussed below, are not compatible with

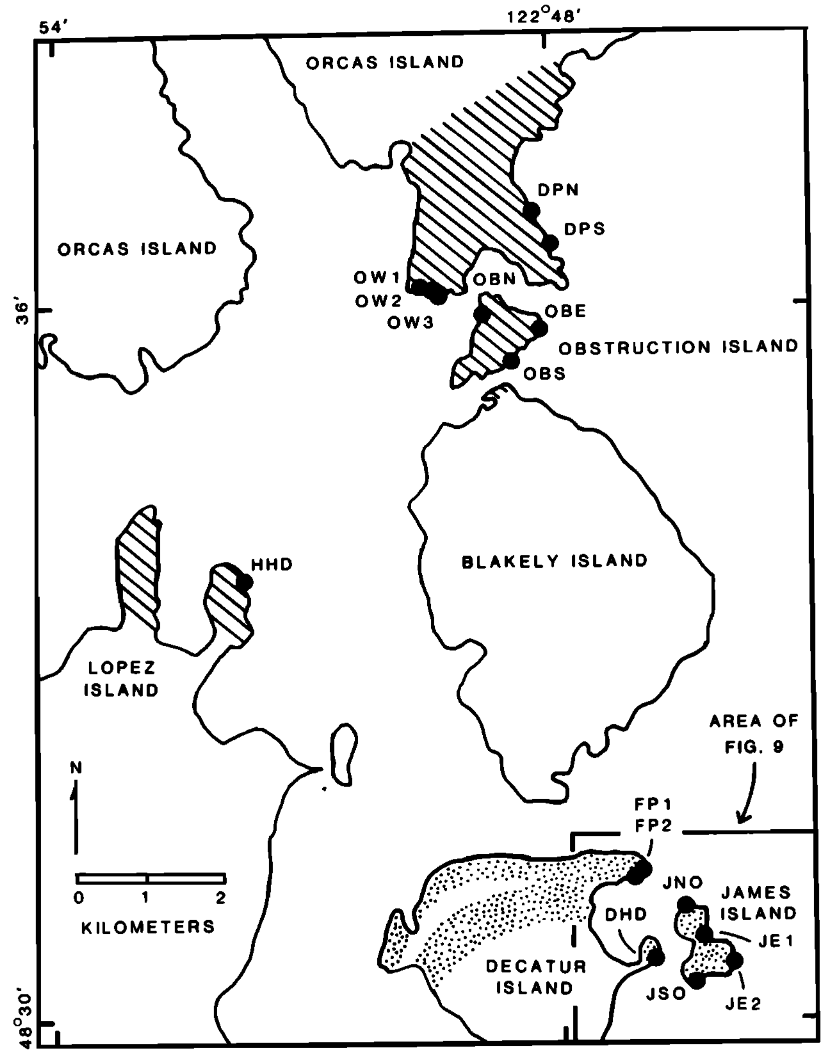

Fig. 2. Paleomagnetic site map showing outcrop extent of James Island Formation (dots) and the Obstruction Formation (hachured).

the travel history and early Tertiary accretion of the Decatur terrane proposed by *McLaughlin et al.* [1988].

PALEOMAGNETIC METHOD

Our paleomagnetic study comprises 54 samples from 7 sites in the James Island Formation and 64 samples from 8 sites in the Obstruction Formation (see Figure 2 for site locations). The outcrops sampled were shoreline exposures of well-bedded, fine-grained, volcanic-lithic and chert-lithic sandstone. Samples were collected with a portable gasoline-powered diamond drill and oriented to ± 1.5 degree precision using a magnetic compass. Routine backsighting to distant landmarks allowed us to correct for local magnetic anomalies; these corrections never exceeded 2°. We typically took three to five separate readings of the bedding attitude and used an average value (with an estimated ± 3 degree precision) for structurally correcting the paleomagnetic data.

All remanence component directions reported here were determined by analyzing sample behavior during detailed, stepwise alternating field (AF) or thermal demagnetization experiments. The apparatus for AF demagnetization employed a 400-Hz coil, capable of peak fields of 100 mT, and a tumbling specimen holder. The thermal experiments were performed in air and in a magnetic field of less than 5 nT. The first step in the analysis of demagnetization results was the examination of orthogonal vector endpoint diagrams (Figures 3, 5, and 6), which show the endpoints of the paleomagnetic vector remaining after successive demagnetization steps, in order to identify (by eye) demagnetization intervals in which it appeared that a single component of remanence was being removed. A least-squares line-fitting technique, like that described by *Kirschvink* [1980], was then applied to the selected interval to define the remanence direction. In the samples from the site at Decatur Head (DHD, Figure 2), it was evident that two remanence components were being removed over most of the demagnetization experiment. The planes defined by the two components [*Kirschvink*, 1980] differed from sample to sample, but intersected about an axis coincident with the component direction common to the samples. We report the direction of this axis (along with an error estimate described below) as the remanence direction for the Decatur Head site.

In order to estimate the relative importance of hematite and magnetite as remanence carriers, we determined isothermal remanent magnetization (IRM) acquisition curves for a specimen from each of the sites in the James Island For-

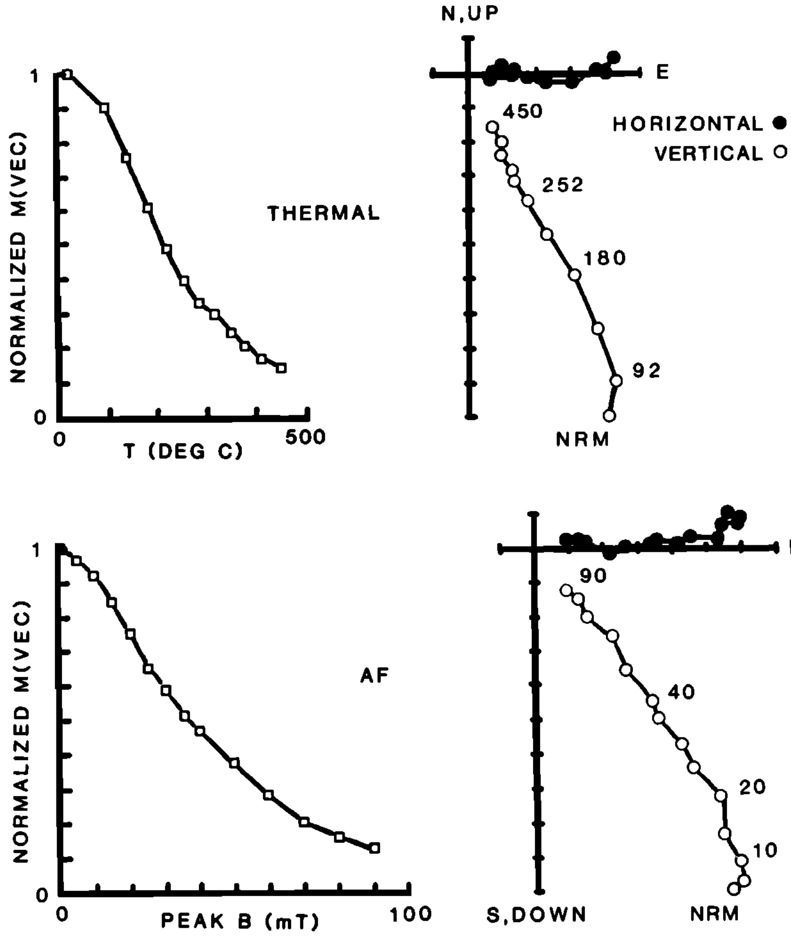

Fig. 3. Thermal (upper) and alternating field (lower) demagnetization of two samples from the Obstruction Formation. For the left-side figures, the vertical scales are normalized by the (arithmetic) sum of the magnitudes of vector components removed plus the magnitude of the component remaining. The partial sums remaining after each demagnetization step are plotted against demagnetization level. The right-side figures are standard orthogonal vector endpoint diagrams [e.g., *Zijderveld*, 1967].

mation. The largest field employed in these experiments was 0.7 T. An examination of polished thin sections of several specimens under transmitted and reflected light was helpful in interpreting the results of these IRM acquisition experiments.

PALEOMAGNETIC RESULTS

Obstruction Formation

Figure 3 shows the demagnetization behavior of specimens typical of the sites in the Obstruction Formation. Notice that in plots of M(vec) versus demagnetization level (T or B), we are plotting fractions of the (arithmetic) sum of the vector magnitudes removed during the demagnetization experiment. This technique displays the blocking temperature or coercivity distribution more clearly than a conventional plot (i.e., intensity versus B or T) whenever the remanence comprises multiple, nonparallel components.

As illustrated by Figure 3, the Obstruction Formation samples are characterized by mean destructive fields of 40 mT to 50 mT. The first few steps of AF demagnetization remove a very small component that is most likely a viscous remanent magnetization (VRM) approximately parallel to the present Earth's field. The remainder of the magnetization decays toward the origin in a univectorial fashion. Slightly more than 10% of the magnetization remains after treatment at 90 mT. The thermal experiments typically show a small VRM removed by 200°C and then a component characterized by distributed blocking temperatures well below the Curie temperatures of either magnetite or hematite. The thermal experiment shown in the figure continued only to 450°C; the few samples taken to higher temperatures began to redden noticeably and acquire spurious magnetizations, presumably due to the very low (but nonzero) field in the demagnetization apparatus. These changes clearly indicate the onset of chemical alteration affecting the magnetic mineralogy of the samples. Nevertheless, the component removed from about 10 mT to 90 mT in the AF experiments and from 100°C to 450°C in the thermal experiments is well-defined, univectorial, and constitutes the characteristic remanence of the sites in the Obstruction Formation.

Table 1 lists the site mean directions and associated statistics from the 9 sites in the Obstruction Formation. The very low dispersion of sample directions found at each site is indicated by the relatively high values of the precision parameter k [*Fisher*, 1953], which range from 72.6 to 409.9. The associated α_{95} values [*Fisher*, 1953] are all less than 6°. Even more remarkable is the excellent agreement of the nine in situ mean directions (see Figure 4); the k describing the dispersion is 168.8 and the α_{95} is 4.0°. There appears to be no

TABLE 1. Obstruction Formation

Site	N	D	I	α_{95}	k	Strike	Dip	DC	IC
OW1	5	108.2	67.6	5.1	223.7	337	212	228.1	-39.2
OW2	7	094.0	69.2	3.7	269.9	234	81	341.0	21.8
OW3	6	084.7	67.9	3.7	333.2	013	232	290.1	-16.8
OBN	6	089.3	73.8	3.3	409.9	052	43	126.1	35.9
OBS	5	081.1	61.9	4.3	316.0	116	20	123.2	67.1
DPN	9	088.3	61.1	6.1	72.6	216	36	001.2	68.9
HHD	8	104.9	77.0	3.5	248.2	316	64	057.7	18.8
DPS	7	091.1	66.6	6.0	103.2	278	08	074.1	64.4
OBE	8	084.8	63.7	5.1	117.2	148	14	108.1	74.9

N is number of samples used to calculate site mean. D and I are east declination and downward inclination of site mean direction. The components listed in the first five rows are from analysis of AF demagnetization experiments, and the last four are from thermal experiments. The α_{95} and k are the 95% confidence interval about the mean and precision parameter of *Fisher* [1953]. Add 90° to strike for direction of dip. DC and IC are the site mean declination and inclination after tectonic correction.

difference between site means determined by AF demagnetization (the first five sites listed in Table 1) and those determined by thermal demagnetization (the last four sites in Table 1). The bedding attitudes vary considerably from site to site, and so the tilt correction broadly disperses the remanence directions (see Figure 4). This very negative fold test provides compelling evidence that the Obstruction Formation has been thoroughly remagnetized since it was deformed.

The in situ overprint direction (D=90.7°, I=67.9°), does not resemble the present geomagnetic field direction or any axial dipole field direction that would have been expected at the San Juan Islands for the last 140 m.y. It is reminiscent, however, of the clockwise deflections that have been detected paleomagnetically in many rocks of the western Cordillera [e.g., *Beck*, 1976]. These declination anomalies are commonly interpreted as evidence of tectonic rotation about near-vertical axes. If the easterly declination from the Obstruction Formation has a similar origin, then the mean inclination may provide information about the latitude of the Obstruction Formation (and hence the Decatur terrane) at the time of overprinting. It seems reasonable to suppose that the remagnetization is synchronous with the rapid uplift of the San Juan nappes that neared completion by 85 Ma. If the travel history of the Coast Plutonic Complex described by *Irving et al.* [1985] is correct, then the Decatur terrane may have been near the United States-Mexico border at the time of remagnetization. The ancient field inclination would have been approximately 62°, slightly shallower than overprint direction. If instead the Decatur terrane was near its present position with respect to North America at 85 Ma, then expected inclination would be 73°, slightly steeper than observed. There is considerable uncertainty in these speculations because neither the age of the remagnetization, the longitude of the Decatur terrane, nor the amount of postoverprint tilting is well-constrained. What can be said is that the observed inclination is at least grossly consistent with the hypothesis of Late Cretaceous remagnetization and subsequent tectonic rotation (>90°) about a vertical axis. The evidence, however, favors no particular model of tectonic transport of the Decatur terrane.

James Island Formation

Figure 5 shows the response to thermal demagnetization of two samples from the James Island Formation. As was true in the Obstruction Formation, a presumably Brunhes-age VRM was present in most samples and could be greatly reduced in magnitude by heating them to about 200°C. Subsequent heatings to temperatures of about 450°C removed the characteristic magnetization. Although there was sometimes evidence of a still higher temperature component (for example, curve A of Figure 5), the onset of chemical alteration between 450°C and 500°C made it impossible to proceed fruitfully to higher temperatures. Site mean directions (Table 2) were determined for all sites (7) we sampled in the James Island Formation except the one at the northern tip of James Island; samples from this site displayed incoherent behavior during AF and thermal demagnetization.

Figure 5 illustrates the variability in sample behavior that is typical of the James Island Formation samples. The M(vec) versus T plots show that the blocking temperature distributions varied more from sample to sample than they did in the samples from the Obstruction Formation. Furthermore, the direction of characteristic magnetization for many of the samples from the James Island Formation had to be picked off of relatively "noisy" segments of the orthogonal vector diagrams. Points in these segments, while displaying a recognizable linear trend, were less colinear than was typical for

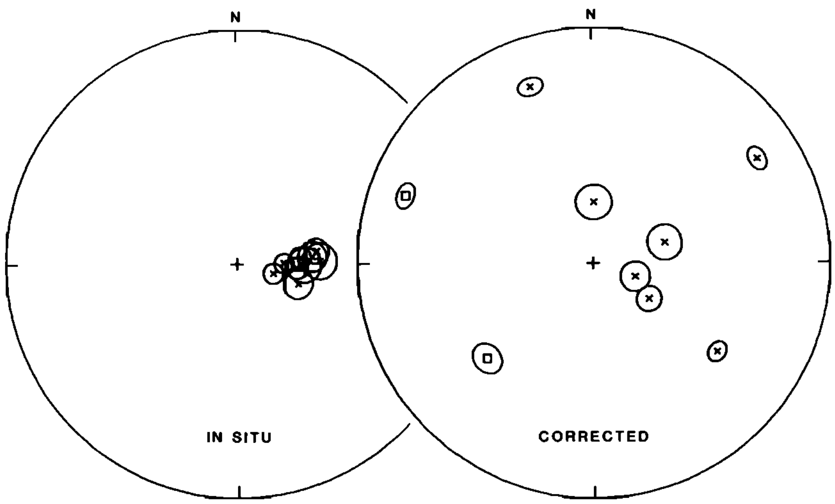

Fig. 4. Equal-area plot of site mean remanence directions from the Obstruction Formation. Solid (open) symbols are for points in lower (upper) hemisphere. The 95% confidence region about each site mean direction is also shown.

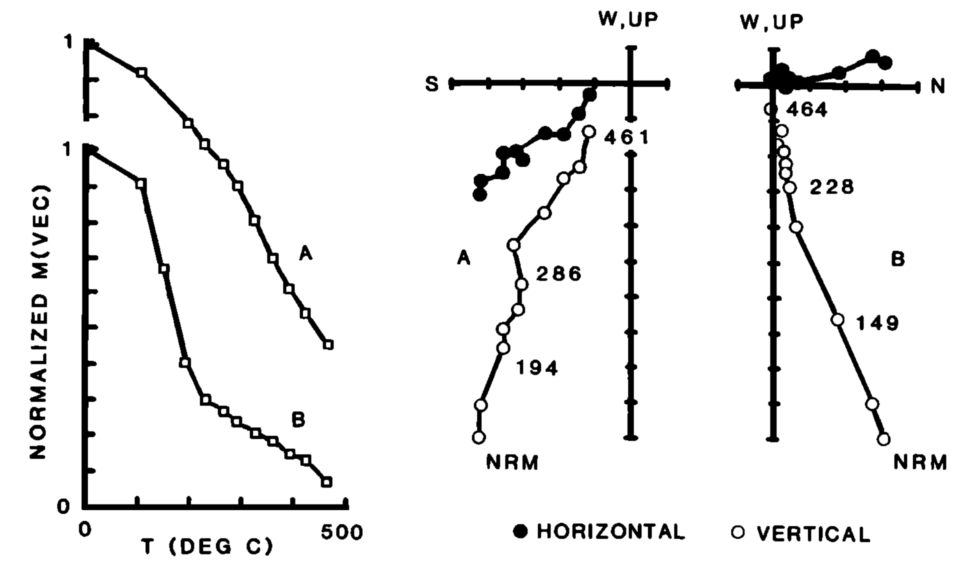

Fig. 5. Thermal demagnetization of two samples from the James Island Formation. See Figure 3 for explanation of plots.

samples from the Obstruction Formation. We emphasize that the behavior of the samples from the James Island Formation differed significantly from that of the remagnetized material from the younger Obstruction Formation.

Figure 6 shows the thermal demagnetization of a sample from Decatur Head, one of three sites collected on Decatur Island. The sample magnetization moved from its northerly and downward natural remanent magnetization (NRM) direction toward a southerly and upward direction. This southerly component, however, was never isolated. Instead, it is apparent that two components of magnetization with overlapping blocking temperature distributions were being removed up to about 350°C. At higher temperature, irreversible alteration of the magnetic minerals caused the directional change from successive heatings to become erratic. We fit great circles to the curved part of the vector demagnetization trajectory for the six samples from Decatur Head that demagnetized coherently. As can be seen in Figure 7, the great circle paths are quite varied yet show a strong intersection. This pattern is commonly observed when each sample in a group possesses a composite magnetization consisting of a common component (the great circle intersection) and a presumably secondary component that varies from sample to sample.

We estimated the position of the common component by fitting a great circle to the poles to great circles defined by the sample demagnetization experiments. Bingham statistics [e.g., *Onstott*, 1980] provide a measure of how tightly the poles constrain the orientation of this great circle and hence an approximate way of estimating an error on the intersection point. The error angle we report in Table 1 (6.0°) is comparable to Fisher's α_{95} (i.e., 95% confidence interval on the mean direction) and is the largest of such values that can be derived from the three Bingham parameters (see *Onstott*, [1980]).

The IRM acquisition curves in Figure 8 are characterized by very steep slopes in the range from zero to 150 or 200 mT. From 300 mT to 700 mT, none of the IRMs increase by more than 5 percent. Behavior of this kind is typical of sediments in which the predominant magnetic mineral is (titano?)magnetite. A small amount of higher-coercivity material is clearly present as well. Under the microscope, a patchy reddish-brown to brown stain was commonly visible in the dark, mottled dark to opaque material that filled pore spaces between grains. Both lines of evidence point to the presence of very fine-grained goethite or hematite. It seems likely that these minerals carry the VRM removed early in the AF or thermal experiments. Abundant chalcopyrite and pyrite are visible in the samples. The pyrite is commonly framboidal, sometimes with euhedral overgrowths of chalcopyrite or pyrite. Fram-

TABLE 2. James Island Formation

Site	N	D	I	α_{95}	k	Strike	Dip	DC	IC	Plon	Plat
JNO	6	-	-	-	-	-	-	-	-	-	-
JE1	8	132.6	52.9	5.8	92.5	194	145	343.0	-20.5	076.4	29.0
JSO	8	332.4	81.9	7.6	54.0	251	73	339.8	9.0	085.2	42.8
FP1	7	002.9	75.5	3.1	392.0	219	63	336.2	18.0	092.1	45.9
FP2	7	330.6	83.2	5.1	141.7	285	65	350.6	20.1	072.0	51.1
DHD	6	152.2	-35.0	6.0*	-	267	53	156.2	14.4	084.8	30.4
JE2	8	145.8	77.5	11.9	22.5	198	121	356.8	-20.9	060.9	30.6

All components listed are from analysis of thermal demagnetization experiments. Structural corrections: for FP1 and FP2, the fold geometry is assumed to be a plunging cylindrical fold; for JNO, JE1, and JE2, an additional 77° of clockwise rotation about a vertical axis is applied as described in the text. Plon and Plat describe the corresponding virtual geomagnetic pole (calculated for a site at 237.2°E, 48.5°N). See Table 1 for further explanation.

*Largest 95% confidence radius about great-circle intersection [*Onstott*, 1980].

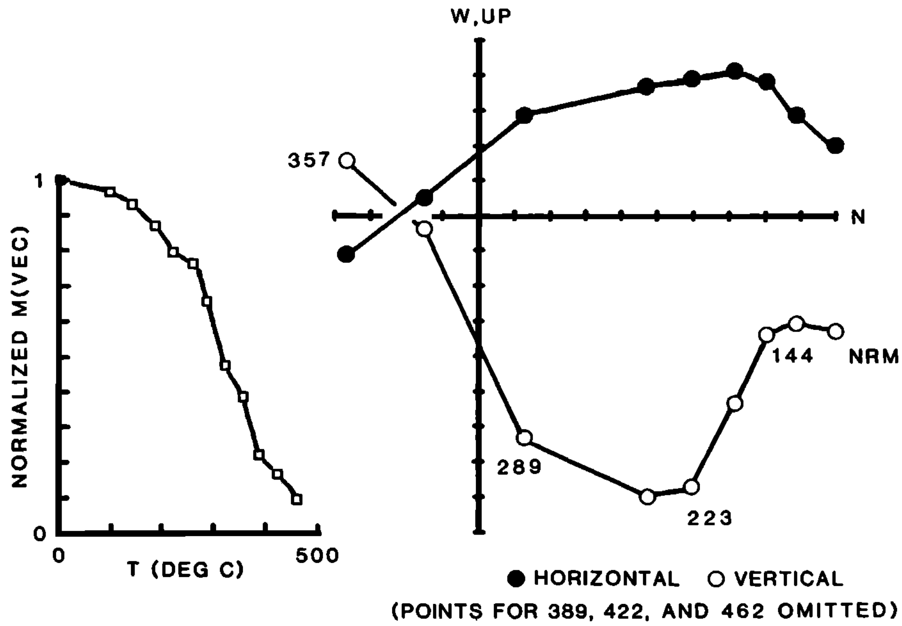

Fig. 6. Thermal demagnetization of a sample from site DHD (Decatur Head, James Island Formation) on Decatur Island (see Figure 3 for explanation of plot). The upward and southerly directed remanence is not isolated in the demagnetization experiment, but can be inferred by comparing results from several samples (see Figure 7).

boidal pyrite is generally interpreted as diagenetic in origin (see the summary in *Sassano and Schrijver* [1989]). The magnetite series mineral that dominates the low-field portion of the IRM acquisition curves is not readily apparent in thin section under either transmitted or reflected light.

Age of the Remanence

The structure of the rocks in the vicinity of James Island (see Figure 9) makes it possible to constrain the age of the remanence by a fold test. The structure is complex, however, and our knowledge of the actual geometry and history of deformation is limited. In the paragraphs that follow, we discuss how this problem affects the outcome of the fold test and describe a scheme that appears to properly restore the beds to their prefolding orientation. A fold test based on this scheme and several additional lines of evidence strongly suggest that the remanence of the James Island Formation predates folding.

A preliminary observation is that the paleomagnetic inclinations at all sites are shallow with respect to stratigraphic horizontal. Nevertheless, if the strata are restored back to horizontal by rotation about their strikes, the result is an

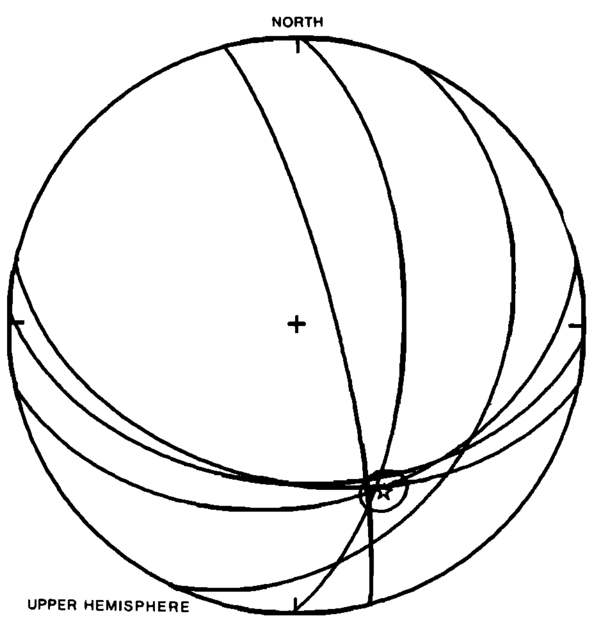

Fig. 7. Upper hemisphere equal area plot of great circles fit to demagnetization trajectories of six samples from site DHD (Decatur Head, James Island Formation). The intersection of these great circles (marked by star and an approximate 95% confidence region) is interpreted as a remanence component common to all six samples.

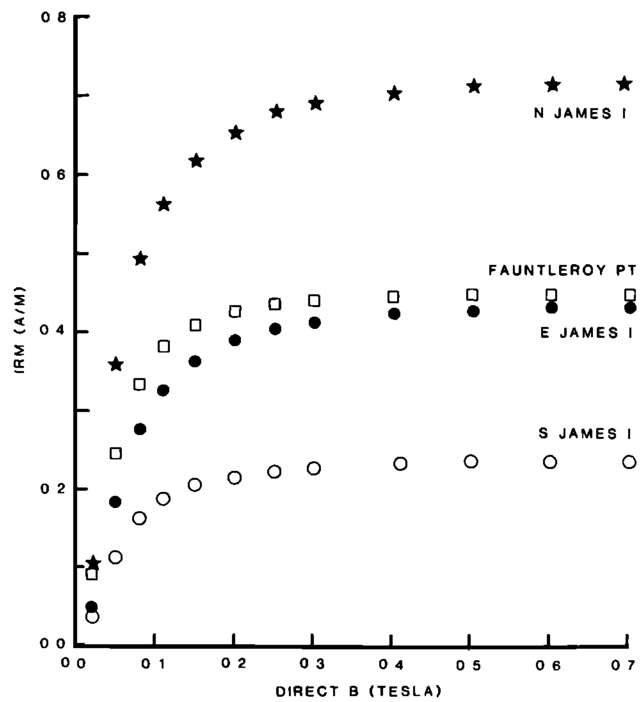

Fig. 8. Curves of isothermal remanent magnetization versus direct field for samples from the James Island Formation.

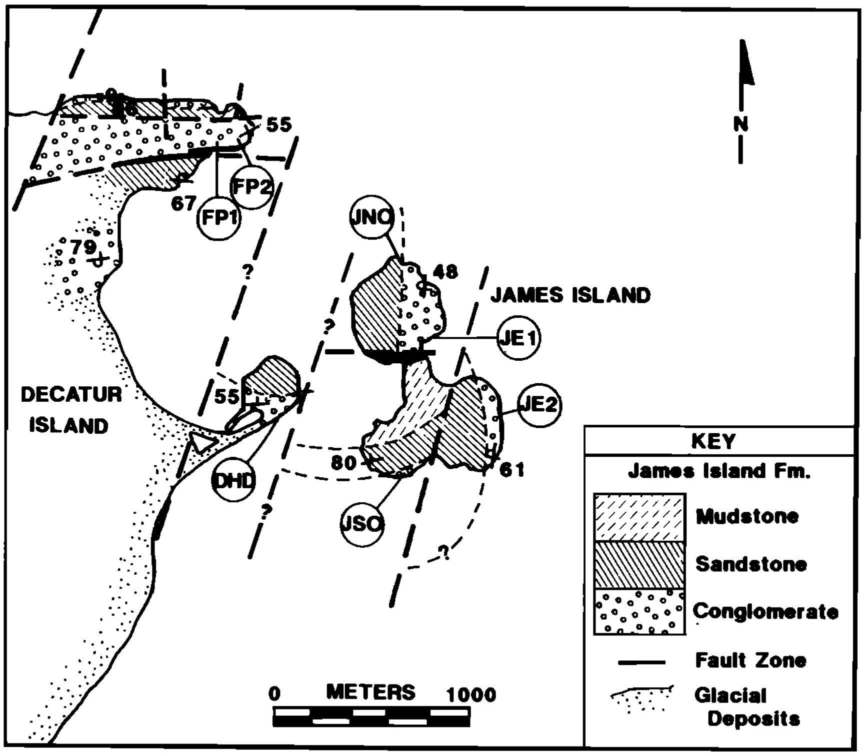

Fig. 9. Detailed geologic map of lithologic subunits in the James Island Formation; see text for discussion. Circled localities (for example, JNO) are paleomagnetic sites. Location of figure is shown in Figure 2.

increase in the scatter of remanence directions. The increase is not large enough to be significant at the 90% confidence level according to the fold test of *McElhinny* [1964]. *McFadden and Jones* [1981] have shown, however, that the test of *McElhinny* [1964] is too conservative; that is, a change in dispersion judged inconclusive by the test may in fact be conclusive. Unfortunately, the alternative test proposed by *McFadden and Jones* [1981] is not applicable to situations (such as James Island) where limited exposure makes it impractical to collect multiple sites on each fold limb.

Statistics aside, what is the meaning of scatter produced by the simple tilt correction? The simplest explanation is that the remanence is an overprint (later disrupted) acquired after folding of the beds. This possibility relegates to chance the positive results of the complicated correction scheme described below. The alternative explanation that we prefer is that neglect of the actual fold geometry has introduced an artificial scatter to the tilt-corrected declinations [*MacDonald*, 1980]. The observation that supports this interpretation is that the tilt-corrected inclinations span 41°, 9° less than the in situ values. The increase in directional dispersion resulting from the tilt correction, therefore, is reflected entirely in the declinations. This is precisely the behavior to be expected when prefolding components are restored to horizontal about axes different than those about which they were folded. The decrease in the scatter of the inclinations is quite small, and so a rigorous fold test on the inclinations alone, such as that proposed by *McFadden and Reid* [1982], would be inconclusive. It therefore appears impossible to interpret the age of the remanence in the James Island Formation without also interpreting the structure of the unit, thus introducing an added degree of uncertainty into the analysis and subsequent interpretations.

In order to accommodate the heterogeneous geological structure of James and Decatur islands, it seems reasonable to determine tectonic corrections for the paleomagnetic sites on a domain-by-domain basis. Consider first the two sites located on opposite limbs of a plunging fold at Fauntleroy Point on Decatur Island (Figure 9). The in situ site mean remanence directions are 9.5° apart, and a simple tilt correction leaves them over 45° apart. This negative fold test is clearly not consistent with the hypothesis that the remanence predates the folding. A much different result, however, is obtained by taking into account the steep plunge of the fold (trend = 338°, plunge = 60°). The directions, corrected by first removing the plunge and then unfolding the beds about strike, are left only 13.8° apart (Figure 10). With respect to the in situ directions, this difference is not large and the fold test on the Fauntleroy Point sites alone is thus inconclusive rather than negative.

The beds on southern James Island and Decatur Head strike parallel to one another but yield very different remanence directions. After correcting the site means by simple rotation about strike, the directions become roughly antiparallel to each other (Figure 10) and furthermore group well with the corrected directions from Fauntleroy Point. Both lines of evidence suggest that the remanence is prefolding.

The two sites from eastern James Island are in overturned strata; a simple tilt correction brings the inclinations into rough accord with the other sites but leaves the declinations far from the rest of the group. A possible explanation for this discrepancy (assuming that the magnetizations are predeformation) is that this part of James Island has rotated with respect to sites to the west and south. Inferred strike-slip faults separate the north and east sides of James Island from the southwest part of the island, and the trends of lithologic contacts in the two areas are roughly perpendicular (see Figure 9 and *Garver* [1988*a*]). The mean of the strikes (194°) at the three paleomagnetic sites on north and east James Island

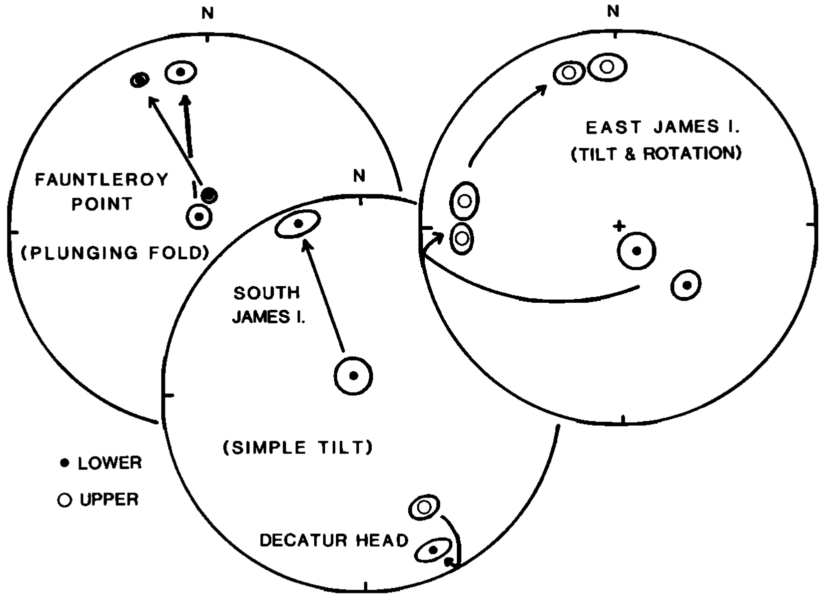

Fig. 10. Equal area plots of site mean remanence directions from the James Island Formation. Arrows connect in situ directions from those in stratigraphic coordinates, corrected by the schemes described in the text. Solid (open) symbols are for points in lower (upper) hemisphere. The 95% confidence region about each site mean direction is also shown.

differs by 77° from an average strike of 271° that we determined by hand fitting a line to a map of the structure on the north shore of Decatur Island. A 77° clockwise rotation brings the stratigraphy and structure of north and east James Island into much better accord with that on Decatur and southern James Island and would appear to offer a reasonable mechanism for restoring the paleomagnetic directions as well. We find that a 77° clockwise rotation brings the site mean directions from east James Island into excellent agreement with the rest from the James Island Formation (Figure 10). Indeed, this rotation differs by only 9° from that needed to bring the mean declinations into perfect agreement. Rotation of small-scale blocks is a geologically plausible explanation of the discrepant declinations because strike-slip faults separate the paleomagnetic sites (Figure 9).

After performing these restorations, the six site means with northerly declinations group well and are roughly antiparallel to the southerly directed remanence from Decatur Head. Figure 11 shows these data plotted as virtual geomagnetic poles (VGPs), with the result for Decatur Head inverted through the origin. The precision parameter k for the VGPs improves from 3.8 for the in situ directions to 39.5 for the corrected directions, an increase that is significant at greater than 99% confidence [*McElhinny*, 1964]. This result strongly suggests that the remanence of the James Island Formation predates the deformation.

Several features of the corrected data set further suggest that the remanence may be original: (1) The presence of reversed and normal directions, while possible thorough multiple remagnetizations, is more easily explained if the magnetization is primary. Furthermore, any overprint associated with uplift of the San Juan nappes should be of normal polarity because the uplift occurred during the long Cretaceous normal chron. The postfolding, normal remanence of the Obstruction Formation is consistent with this timing, but the remanence of the James Island Formation is clearly not; (2) The roughly symmetrical scatter of the corrected VGPs (angular standard deviation = 12.9°) is comparable in magnitude to that expected (approximately 14° in most models) for a site at low paleolatitude [e.g., *Merrill and McElhinny*, 1983]. If this agreement is not fortuitous, the implication is that our paleomagnetic sites, which typically comprise several turbidite beds, span time that is short on the scale of geomagnetic secular variation; (3) The composite structural corrections can be checked by applying them to paleocurrent indicators from tilted strata. Paleocurrent indicators corrected by simple rotation about strike display a distinctly bimodal distribution (see Figure 12), whereas 7 of 8 corrected by the composite rotation scheme form a single cluster oriented roughly east-west. This consistent orientation is typical of midfan turbidites and provides additional evidence for the validity of the structural corrections.

Having made the case for the James Island remanence being primary, we will now briefly discuss the two main difficulties with this hypothesis. The first is the general similarity of the in situ directions from James Island to overprint directions seen in the other units from the San Juan Islands; the Obstruction Formation is a good example. All in situ site mean directions we have obtained from sites in the San Juan Islands, except those from Decatur Head and a site in the Permian volcanic rocks on western San Juan Island, are moderately to steeply downward with easterly to southerly declinations. The successful fold test for data from the James Island Formation puts us in the awkward position of arguing that the only primary remanence we have found in rocks of the San Juan Islands has been folded so that it broadly resembles a regionally extensive overprint direction. In essence, the likelihood of this coincidence must be weighed against the likelihood that the positive fold test is fortuitous. Tipping the scales in favor of the remanence being primary is the upward and southerly directed (in situ) magnetization from Decatur Head, which is especially hard to explain if the James Island remanence is secondary.

The other difficulty is explaining how the James Island Formation avoided remagnetization. The stratigraphically higher rocks of the Obstruction Formation lie only 8 km away

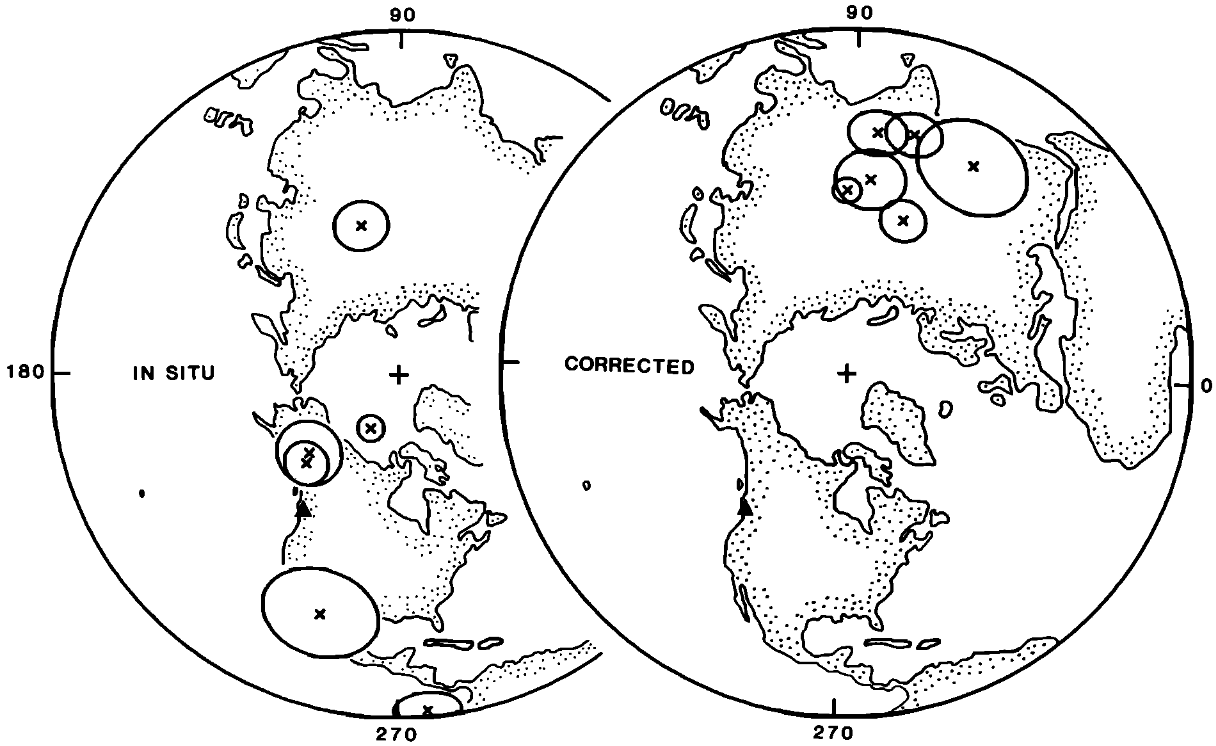

Fig. 11. Upper hemisphere equal area plot showing the positive fold test on VGPs for sites in the James Island Formation. The triangle marks the study area. The datum for Decatur Head (in Asia on the in situ plot) is the south VGP.

from James Island, and yet are thoroughly overprinted. We suggested above that this secondary remanence may relate to burial and uplift in the Late Cretaceous, an event presumably experienced by all pre-Late Cretaceous rocks in the San Juan Islands. Although sharing this common history, rocks of the James Island and Obstruction Formations exhibit at least two important differences. The first is compositional. Sediments of the James Island Formation are rich in volcanic and ultramafic detritus, whereas the Obstruction Formation is chert-rich. It is therefore plausible that quite different magnetic mineralogies characterized the two units, making them unequally susceptible to remagnetization. The second difference is the well-developed cleavage that is present throughout the Obstruction Formation. This texture is completely absent from the James Island Formation, both in outcrop and in thin section, even though the beds are folded and commonly overturned. The two units apparently illustrate contrasting responses to the Late Cretaceous deformational event. Although the differences listed here allow many possibilities, the problem of how the remanence of the James Island Formation has survived remains unresolved.

Fig. 12. Paleocurrent azimuths from inclined strata at the paleomagnetic sites. The left figure shows the azimuths after restoring the beds to horizontal by simple rotation about the strike. The same data are shown in the right figure, but after being restored to horizontal by the various methods used to correct the paleomagnetic results.

IMPLICATIONS OF THE PALEOMAGNETIC RESULTS

Accepting the very positive fold test as evidence that the characteristic magnetization of the James Island Formation is primary, we next explore the tectonic implications of the result. The mean of the site mean VGPs yields a paleolatitude of ±0.8° with 95% confidence interval of 8.4° [*Demarest*, 1983]. Since the northern and southern latitude options overlap almost completely, we will estimate the paleolatitude of the James Island Formation to have been 0° with confidence limits that contain the uncertainty of either hemisphere option (i.e., ±9.2°). Because the corrected inclinations are very shallow, the magnitude of any depositional inclination error would be very small.

Our data from the James Island Formation appear on a graph of time versus paleolatitude in Figure 13 as a box representing an age range of 145-150 Ma and a mean paleolatitude of 0°. We also show the data of *Irving et al.* [1985] from granitoid rocks of the Coast Plutonic Complex as a box with age range 95-110 Ma and a mean paleolatitude of 34.3°. This value is derived from the mean poles of the Spuzzum and Porteau plutons (I=56.7° [*Irving et al.*, 1985]) with a slight correction for the more southerly location of the San Juan Islands. Figure 13 also depicts the motion of a point that is now at the position of the San Juan Islands but which has moved with North America since the Jurassic. The curve for North Amer-

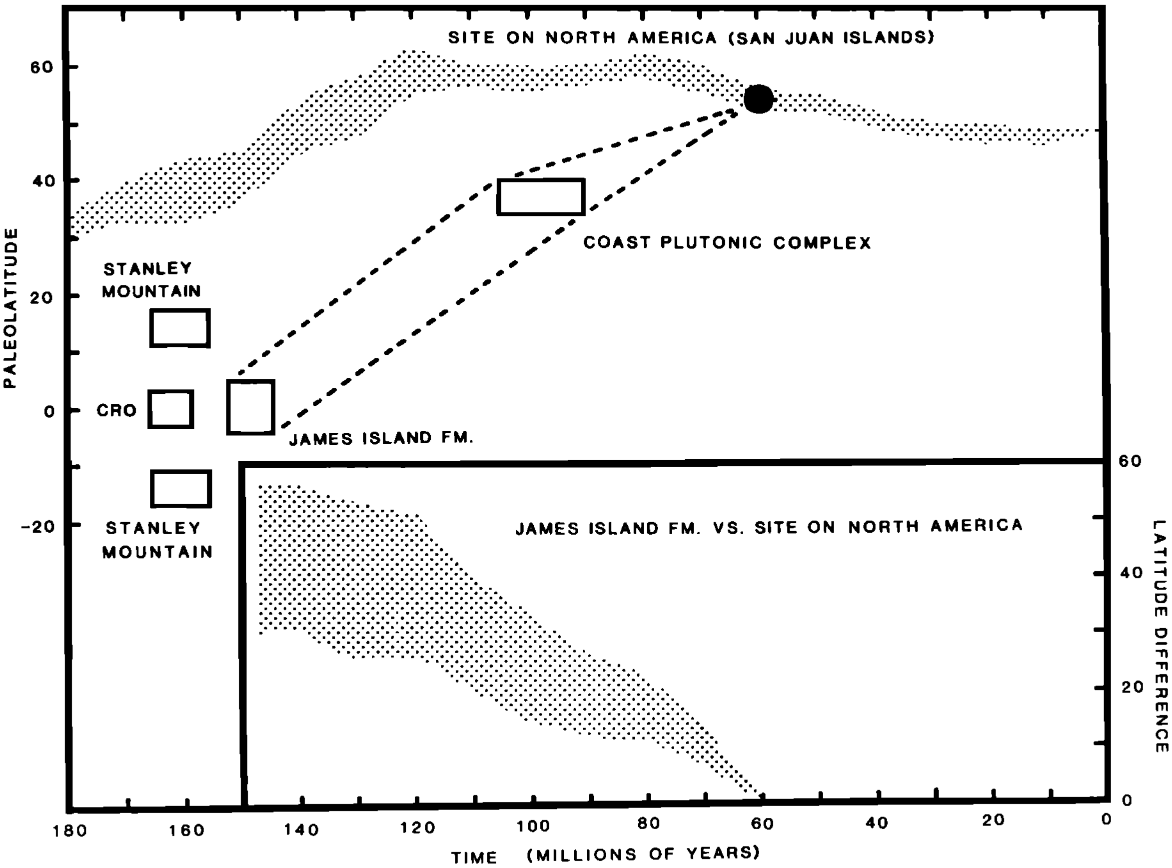

Fig. 13. Paleolatitudes versus time for North America; the Coast Range ophiolite (CRO; data cited by *Hopson et al.* [1986]); the Stanley Mountain terrane [*McWilliams and Howell*, 1982], northern and southern hemisphere options; James Island Formation (this study); and the Coast Plutonic Complex [*Irving et. al.*, 1985]. The paleolatitude uncertainty (i.e., height of boxes for terranes; width of shaded curve for North America) is at the 1 standard deviation level (i.e., the α_{67} value [*Fisher*, 1953] on the VGPs corrected for latitude-only information [*Demarest*, 1983]). The overlap (or nonoverlap) of the data being shown is thus significant at the 95% confidence level. Width of box expresses age ranges quoted in text. The inset shows the paleolatitude difference between North America and James Island Formation versus time. The shaded area is bounded by maximum and minimum differences between the North American curve and the area (shown with dashed lines) enveloping the data from the James Island Formation and Coast Plutonic Complex. Notice that the confidence limits allow the hypothesis that no relative displacement occurred until after 95 Ma.

ica is based on paleomagnetic data summarized in *Irving and Irving* [1982].

The following alternative models can be drawn from Figure 13:

(1) The Decatur terrane was thousands of kilometers (42°) south of its expected latitude (i.e., the paleolatitude of the San Juan Islands had they been part of North America) when it acquired its primary stable remanence 145-150 m.y. ago. The Decatur terrane then moved 36° northward between 145 Ma (Late Jurassic) and about 97 Ma (early Late Cretaceous) when its paleolatitude is again fixed by the paleomagnetic results from the Coast Plutonic Complex. Had the Decatur terrane been at its present location on North America during this interval, its poleward motion would have been only 16°. A straightforward interpretation of the paleomagnetic results is thus that approximately 20° of relative poleward displacement occurred between North America and the Decatur terrane between 145 Ma and 97 Ma. The average rate of this relative poleward displacement would have been 46 mm/yr. At 97 Ma, the terrane and the encompassing San Juan-northwest Cascades thrust system were approximately 22° (2400 km) south of their expected paleolatitude along the North American margin.

(2) A different displacement history is allowed by the 95% confidence limits on the paleolatitude difference between the Decatur terrane and an equivalent site on North America. At 145 Ma, the latitude difference may have been as small as 30°. Furthermore, the error limits allow this difference of 30° to have persisted until approximately 95 Ma. In other words, the data do not require (at 95% confidence) that any relative poleward displacement between the Decatur terrane and North America occurred until after 95 Ma.

Let us first examine the implications if model 1 above is correct. *Garver* [1988*b*] suggests that the Decatur terrane may be correlative with the GVS/CRO in California (Figure 1). It is therefore reasonable to compare our results to paleomagnetic data from these possibly correlative units. Of particular interest are the results of *McWilliams and Howell* [1982] from the 160-Ma pillow basalts at Stanley Mountain (Figure 13), located in the southern California Coast Ranges southwest of San Andreas fault. The remanence of these rocks suggests that they formed 15° north or south of the Jurassic paleoequator. *Hopson et al.* [1986] cite paleomagnetic data from two other sites in the CRO that also yield equatorial paleolatitudes. Taken together, the geological correlation and paleomagnetic results imply that the Fidalgo Complex and the CRO are dispersed fragments of a Middle to Upper Jurassic ophiolite complex located near the Jurassic equator.

The post-160 Ma displacement histories of these fragments, however, are quite distinct. Transport models for the CRO [e.g., *Hopson et al.*, 1986; *McLaughlin et al.*, 1988] require the ophiolite fragments to arrive by 145 Ma at mid-northerly latitudes in California where they constitute basement for the deposition of upper Tithonian basal strata of the Great Valley sequence. In contrast, our paleomagnetic data suggest that ophiolitic rocks of the Fidalgo Complex remained at equatorial latitudes through deposition of the upper Tithonian James Island Formation. The data are not consistent with the model of *McLaughlin et al.* [1988] in which the James Island Formation was deposited well north of the equator as part of Great Valley sequence and was later sliced off and translated to its present position along the North American margin. At issue is the nature of the correlation between the James Island Formation and the GVS; our data favor a model (option 3 of *Garver* [1988*b*]) in which the James Island sediments accumulated in a setting that was geologically identical to, but well south of, the forearc basin of the Great Valley sequence.

The Early Cretaceous northward movement of the Decatur terrane with respect to North America hypothesized in model 1 is difficult to reconcile with existing models for relative plate motions even though the average rate of displacement (46 mm/yr) is geologically plausible. For example, *Engebretson et al.* [1985, Figure 8] show the Farallon plate in contact with the entire west coast of North America and Central America during the interval 150-90 Ma. From 150 to 120 Ma, the convergence of the Farallon plate with North America was slightly oblique, and *Engebretson et al.* [1985, Figure 9] predict a component of left-lateral slip along the continental margin. This sense of slip is not compatible with right-lateral motion of the Decatur terrane that model 1 implies, so it is highly unlikely that the northward moving Decatur terrane could have been part of the Farallon plate. As an alternative, we hypothesize that in Late Jurassic and Early Cretaceous time, the Decatur terrane was part of a cryptic, now vanished plate that was situated between the Farallon and North American plates.

If model 2 above pertains, then the Decatur terrane was either part of North America, or it was associated with another plate not moving rapidly northward or southward with respect to North America until 95 Ma. In either case, the terrane would have been situated about 30° south of its present location on the North American margin (and south of any part of California attached to the North American plate) during the interval 145 to 95 Ma. Poleward transport of the Decatur terrane resulted from the right-lateral motion occurring between North America and oceanic plates throughout the Late Cretaceous.

There is an additional possibility to consider (model 3). If part of the anomalous paleomagnetic inclination of the Coast Plutonic Complex [*Irving et al.*, 1985] is due to tectonic tilting rather than latitudinal displacement, then the Late Jurassic to early Tertiary travel history of the Decatur terrane is less well-constrained. For example, consider the extreme case in which tilting is fully responsible for the shallow paleomagnetism. If true, and the Coast Plutonic Complex formed near its present position with respect to North America, then geologic relations require the Decatur terrane to be near its present position with respect to North America by at 84 Ma, or perhaps even earlier. The implied travel history for the Decatur terrane is then the opposite of our model 2; that is, the entire trip from the equator to final docking against North America had to be complete by middle Late Cretaceous time. This extreme scenario is almost surely not correct, however, because fault reconstructions [*Gabrielse*, 1985] suggest that western British Columbia underwent northwestward transport of the order of 1000 km between middle Cretaceous and early Tertiary time. A more reasonable possibility to consider is that the shallow inclinations are in part due to tilting and in part due to a southerly position of the Coast Plutonic Complex. The displacement path on Figure 13 must then be adjusted to show more relative poleward transport prior to the Late Cretaceous and less after.

In summary, our paleomagnetic data imply that the Decatur terrane was situated well south of its expected (North American) latitude when it acquired its primary remanence about 145 Ma. Our displacement models 1 and 2 differ from one another in the amounts of poleward transport (20° versus 0°) of the terrane with respect to North America from 145 to 95 Ma. Both models incorporate the data of *Irving et al.* [1985] from the Coast Plutonic Complex which suggest southerly position for the larger tectonic element that had encompassed the Decatur terrane by 90 Ma. Model 3 adjusts the travel histories of models 1 and 2 for the possibility that the shallow paleomagnetism of the Coast Plutonic Complex may partly be due to tilting. Finally, the data clarify the nature of the stratigraphic correlation proposed by *Garver* [1988*b*] by implying that the James Island Formation is not simply a displaced crustal fragment native to California.

Acknowledgments. We thank Margi Rusmore, Dan Villaume, Song Xu, Ben Garver, and Scott Tucker for their help during the fieldwork, and Mark Brandon for first showing one of us (S.B.) the geology of the San Juan Islands. Thanks also to everyone at the U.S. Geological Survey Rock Magnetics Laboratory, where all magnetic measurements were performed. Discussions with Duane Champion concerning saw blade remanence were particularly helpful. This research was supported by the National Science Foundation (grant EAR-8211961).

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(Received September 6, 1988;
revised March 17, 1989;
accepted March 21, 1989.)