Revised ages of blueschist metamorphism and the youngest pre-thrusting rocks in the San Juan Islands, Washington

E.H. Brown, T.J. Lapen, R. Mark Leckie, Isabella Premoli Silva, Davide Verga, and B.S. Singer

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Abstract: New ages of rocks in the San Juan Islands, northwest Washington, significantly change our understanding of the evolution of the San Juan Islands thrust system. Re-examination of foraminifera-bearing mudstones at Richardson on Lopez Island indicates a late Aptian (112–115 Ma), not late Albian (100 Ma) age as currently presented in the literature. The age brackets of thrusting, marked by these pre-thrusting mudstones and 84-Ma post-thrusting sedimentary rocks, span a much longer period than previously thought, diminishing controls on rates of displacement in the thrust system and the timing of regional deformation in western Washington. New ^{40}Ar/^{39}Ar plateau ages of phengite in blueschist-facies meta-volcanic rock, also at Richardson, are 124 ± 0.7 Ma (2σ, late Barremian). These blueschist-facies volcanic rocks are in fault contact with the fossiliferous mudstones. Therefore, the blueschist-facies metamorphism at Richardson, previously inferred to be associated with the thrusting, now appears to have occurred prior to thrusting. Further, the Ar ages demonstrate that blueschist-facies fabric formed earlier than the thrust event and is therefore not directly useful in analyzing the thrusting kinematics. The Richardson ^{40}Ar/^{39}Ar age is similar to isotopic ages found in the eastern San Juan Islands and in the Shuksan blueschist terrane in the northwest Cascades, and thus fits into an emerging regional age pattern of blueschist-facies metamorphism during Late Jurassic – Early Cretaceous (up to Barremian) but not late Albian – Cenomanian. If this pattern is more broadly confirmed for the San Juan Islands, all the blueschist-facies metamorphism can be regarded as having formed in subduction zones elsewhere along the continental margin rather than in the anomalous setting of an on-land thrust system, as in the San Juan Islands.

Résumé : De nouveaux âges pour les roches des îles San Juan, dans le nord-ouest de l'état de Washington, changent profondément notre compréhension de l'évolution du système de chevauchement San Juan. Un réexamen des mudstones foraminifères, à Richardson, sur l'île Lopez, indique un âge Aptien tardif (112–115 Ma) et non Albien tardif (100 Ma) tel qu'indiqué actuellement dans la littérature. Les plages d'âges pour le chevauchement, marquées par ces mudstones précédant le chevauchement et des roches sédimentaires 84 Ma postérieures au chevauchement, couvrent une période beaucoup plus grande que stipulée antérieurement, diminuant les contrôles sur les taux de déplacement dans le système de chevauchement et le moment de la déformation régionale dans l'ouest de l'état de Washington. De nouveaux âges plateaux ^{40}Ar/^{39}Ar de la phengite dans des roches volcaniques au faciès des schistes bleus, aussi à Richardson, datent de 124 ± 0,7 Ma (2σ, Barrémien tardif). Ces roches volcaniques au faciès des schistes bleus sont en contact de faille avec les mudstones fossilifères. Donc, à Richardson, le métamorphisme au faciès des schistes bleus, que l'on croyait antérieurement être associé au chevauchement, semble maintenant avoir eu lieu avant le chevauchement. De plus, les âges Ar démontrent que la texture du faciès des schistes bleus s'est formé avant l'événement de chevauchement et n'est donc pas directement utile pour analyser la cinématique du chevauchement. L'âge ^{40}Ar/^{30}Ar Richardson est semblable aux âges isotopiques trouvés dans les îles San Juan et dans le terrane de Shuksan au faciès des schistes bleus dans les monts Cascades du nord-ouest et concorde ainsi avec un patron d'âge régional de métamorphisme au faciès des schistes bleus durant le Jurassique tardif – Crétacé précoce (jusqu'au Barrémien) mais non pas Albien tardif – Cénomanien. Si ce patron est largement confirmé pour les îles San Juan, tout le métamorphisme au faciès des schistes bleus peut être perçu comme ayant été formé dans des zones de subduction ailleurs le long de la bordure continentale plutôt que dans l'environnement anormal d'un système de chevauchement sur terre, tel que dans les îles San Juan.

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E.H. Brown.[1] Department of Geology, Western Washington University, Bellingham, WA 98225, USA.
T.J. Lapen[2] **and B.S. Singer.** Department of Geology and Geophysics, University of Wisconsin-Madison; Madison, WI 53706, USA.
M. Leckie. Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA.
I.P. Silva and D. Verga. Dipartimento di Scienze della Terra, Università di Milano, 20133 Milan, Italy.

[1] Corresponding author (email: ehbrown@cc.wwu.edu).

[2] Present address: Department of Geosciences, University of Houston, Houston, TX 77204, USA.

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Introduction

The San Juan Islands thrust system in northwest Washington (Fig. 1) remains an enigmatic structural component of the western margin of the North American Cordillera. Although many of the terranes comprising the San Juan Islands (SJI) nappes can be matched with counterparts in the Coast Ranges and Klamath Province in California and Oregon (e.g., Blake and Engebretson 1994), their emplacement was more Complex than that of the relatively simple accretion by underplating understood for the Klamaths (e.g., Hamilton 1969; Irwin 1981). A history of significant "structural reworking" (Brandon et al. 1988) after initial accretion at the continental margin is suggested for the San Juan Islands nappes by (1) a younger and briefer accretionary event than in the Klamaths, (2) an assemblage of rocks indicating a prolonged residence along the continental margin prior to final emplacement in the San Juan Islands, and (3) an approximately reversed thrust stacking sequence from that found in the Klamaths. The SJI nappes were emplaced onto the edge of the continent, in contrast to underthrust accretion of the Klamath terranes. Another unusual aspect of the SJI thrust system is the apparent production of blueschist-facies assemblages in the hanging wall of an on-land thrust system, which is at odds with conventional thought that blueschists mark subducted materials (e.g., Ernst 1973; Miyashiro 1994).

In this study, we re-examined age relations at Richardson on Lopez Island, a critical locality for SJI tectonics, where the youngest fossiliferous rocks in the SJI thrust system occur and also where there are good metamorphic tectonite fabrics. Our purpose was to confirm and add precision to previous findings of the age of thrusting by re-analysis of foraminiferal ages and by $^{40}Ar/^{39}Ar$ dating of metamorphic white mica. We found departures from the expected ages that required significant modification of interpretation of SJI history: the maximum possible age of thrusting is 12–15 million years older than previously thought, and the blueschist metamorphism predates and is unrelated to the thrusting.

Regional geology

Four regional tectonic elements (Fig. 1) provide a context for development of the San Juan Islands thrust system:

(1) The Wrangellia terrane — lying northwest of the San Juan Islands and part of the large, composite Insular superterrane that extends along the coast to Alaska. This terrane is a fragment of juvenile continental crust derived from arc and oceanic rocks ranging from Proterozoic to Mesozoic age (e.g., Monger et al. 1982). Connections to the Intermontane terrane to the east began in the Middle Jurassic, evidenced by sedimentary overlap deposits and intrusions of the Coast Plutonic Complex (Nelson 1979; van der Heyden 1992; McClelland et al. 1992).

(2) The Nanaimo Group — a Late Cretaceous marine sedimentary assemblage formed in a basin on Wrangellia (Pacht 1984; Mustard 1994). Eocene deformation thrust the Nanaimo Group over the north edge of the San Juan Islands, long after the San Juan Islands thrusts were active (England and Calon 1991).

(3) The Coast Plutonic Complex — an Andean arc defined by an assemblage of metamorphosed accreted terranes and voluminous plutons. Major orogeny spanned Middle Jurassic to Eocene time (e.g., Woodsworth et al. 1991). The Cascades core is a distinctive mid-Cretaceous to Eocene component of the Coast Plutonic Complex that is cut and offset up to 160–170 km from British Columbia to Washington by the Eocene, dextral Straight Creek – Fraser River fault (e.g., Umhoefer and Schiarizza 1996).

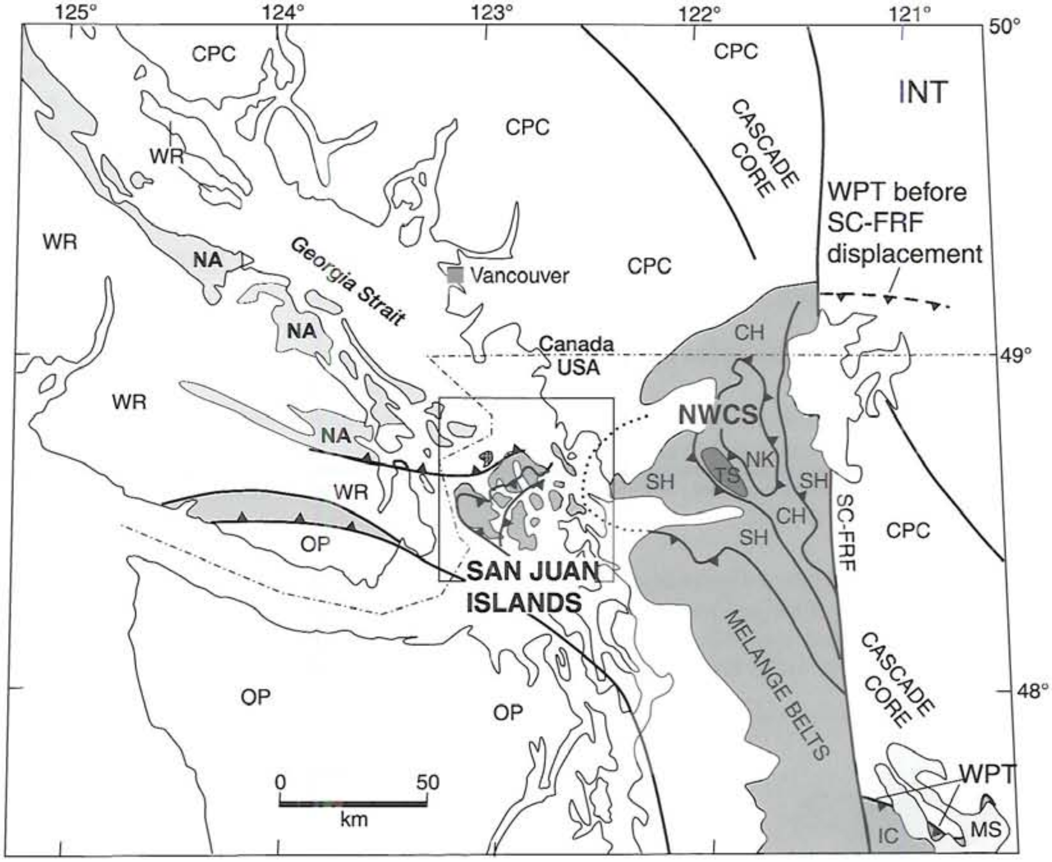
(4) The northwest Cascades thrust system (Misch 1966) — lying east of the San Juan Islands and apparently coextensive with the San Juan Islands thrust system based on correlation of terranes (Brown and Vance 1987). Components of the northwest Cascades thrust system are recognized in the central Cascades, including the Windy Pass thrust (Fig. 1), where they have been displaced relatively southward by the Straight Creek – Fraser River fault (Miller et al. 1993).

The San Juan Islands thrust system consists of Paleozoic to Cretaceous arc and oceanic rocks variably grouped by different workers into terranes that were emplaced in the San Juan Islands in the mid-Cretaceous, subsequent to their dispersal from primary accretionary settings (Vance 1975; Whetten et al. 1978; Brandon et al. 1988; Burchfiel et al. 1992; Burmester et al. 2000). The rock units together with major features of their tectonic history are given in Table 1, and map relations are shown on Fig. 2. The age of emplacement of SJI nappes is bracketed by the Lopez complex, which is involved in the thrusting and bears microfossils considered until now to be 100 Ma, and by the sedimentary rocks of the Nanaimo Group, which contain detritus of the SJI terranes and bear 84-Ma fossils (Whetten et al. 1978; Brandon et al. 1988).

Much about the structural evolution of the San Juan Islands remains obscure. Some of the thrust faults shown on Fig. 2 probably predate emplacement of the nappes in the San Juan Islands (as discussed later in the text). A large part of the major faults are underwater or covered by surficial sediment; thus, the depth geometry is poorly known. Published cross sections of the San Juan Islands and related northwest Cascades vary but have in common a sequence of nappes generally decreasing in age upward through the structural stack (Brandon et al. 1988; McGroder 1991; Cowan and Bruhn 1992; Brown and Dragovich 2003). Important additional tectonic uncertainties are the displacement direction and homeland of the SJI nappes, which are addressed by many papers (Brandon et al. 1988; Maekawa and Brown 1991; McGroder 1991; Brandon et al. 1993; Cowan and Brandon 1994; Monger and Journeay 1994; Bergh 2002).

Terranes of the San Juan Islands are variably metamorphosed and deformed (Table 1). An incipient blueschist-facies metamorphism characterized primarily by aragonite and lawsonite is widely, but not everywhere, developed (Vance 1968; Glassley et al. 1976). Some terranes, but not all, bear a pervasive metamorphic foliation defined by flattened grains, solution – mass-transfer residues, and alignment of metamorphic minerals. Various interpretations are given for the relative timing among events of high-pressure (high-*P*) metamorphism, development of penetrative foliation, and emplacement of the SJI nappes. Maekawa and Brown (1991) and Bergh (2002) suggested that metamorphism, foliation, and thrusting are broadly coeval. Cowan and Brandon (1994) and Feehan and Brandon (1999) interpreted that metamor-

Fig. 1. Regional geologic setting of the San Juan Islands. CH, Chilliwack Group; CPC, Coast Plutonic Complex; IC, Ingalls Complex; INT, Intermontane terrane; MS, Mt. Stuart batholith; NA, Nanaimo Group; NK, Nooksack Formation; NWCS, northwest Cascades thrust system; OP, Olympic Peninsula terranes; SC-FRF, Straight Creek – Fraser River fault; SH, Shuksan terrane; TS, Twin Sisters Dunite; WPT, Windy Pass thrust; WR, Wrangellia terrane. The Cascades core is a distinctive part of the Coast Plutonic Complex, marking offset along the SC-FRF. San Juan Islands detail is shown in Fig. 2.



phism was caused by thrust burial, but largely post-dated thrusting, and that foliation developed after the mineralogic imprint of high-*P* metamorphism. Lamb (2000) concluded that, for the area of the eastern San Juan Islands, high-*P* metamorphism and fabric development were coeval, and that they predate and are unrelated to San Juan Islands thrusting.

Linkages to the related northwest Cascades thrust system help in understanding the San Juan Islands thrust system. Radiometric ages of thrusting in the Cascades are given by (1) K–Ar whole-rock ages of 87 Ma and 91 ± 3 Ma from mylonitic diorite, with newly grown white mica, on the west flank of the Twin Sisters Dunite in the northwest Cascades (Brown 1987), and (2) brackets of 93–96 Ma provided by U–Pb ages from plutonic components of the Mt. Stuart batholith, which was involved in and crosscut the Windy Pass thrust in the central Cascades (Miller and Paterson 1992). These ages have been consistent with the previously inferred 100–84-Ma age brackets of thrusting that are based on fossils in the San Juan Islands, although we now believe that the maximum age bracket is 112–115 Ma.

The San Juan Islands and Cascades nappes were emplaced onto the nascent continental margin, which was composed of accreted terranes overprinted in part by an active Andean arc. The Wrangellia component of this continental margin is interpreted to underlie the San Juan Islands based on regional dips of SJI nappe structures to the southeast, away from nearby Wrangellia (Johnson et al. 1986). In the northwest Cascades, the Nooksack Group lies at the base of the nappe pile (Fig. 1) and was interpreted by Misch (1966) as autochthonous footwall because it is less deformed than the overlying thrust sheets. The Nooksack Group is suggested to be correlative with the Harrison Lake terrane which is embedded in the Coast Plutonic Complex (Monger and Journeay 1994). The Nooksack Group – Harrison Lake terrane correlation is considered to be important because the Coast Plutonic Complex is footwall to the thrust system in the central Cascades, where the Windy Pass thrust placed the Ingalls Complex over the plutonically active Cascades core (Fig. 1; Miller and Paterson 1992).

Richardson locality

The only locality in the San Juan Islands where the reported 100-Ma microfossils occur that provide the maximum age limit of thrusting is at Richardson on southern Lopez Island (Whetten et al. 1978; Brandon et al. 1988). In the same outcrop as the fossiliferous rocks, meta-volcanic rocks locally contain relatively coarse, aligned metamorphic white mica. We carried out ^{40}Ar/^{39}Ar dating of the mica, with the expectation that we would obtain a direct age of the metamorphic

Table 1. Rock units of the San Juan Islands and vicinity.

Unit	Protolith age	Protolith setting	Pervasive fabric?	Metamorphism
Nanaimo Group	Late Cretaceous	Epicontinental basin	No	Zeolite
Fidalgo Complex	Late Jurassic	Island arc	No	Prehnite–pumpellyite
Lummi assemblage	Late Jurassic – Early Cretaceous	Ocean floor and trench	Yes	Aragonite–lawsonite
Lopez structural complex	Late Jurassic – Middle Cretaceous	Ocean floor and trench	Yes	Aragonite–lawsonite
Constitution Formation	Late Jurassic – Early Cretaceous	Trench	No	Aragonite–lawsonite
Garrison Schist	Late Paleozoic	Ocean floor	Yes	Amphibolite with blueschist overprint
Orcas Chert	Triassic – Middle Jurassic	Ocean floor	No	Aragonite–lawsonite
Deadman Bay Volcanics	Permian	Ocean floor	No	Aragonite–lawsonite
Turtleback Complex	Early Paleozoic	Arc roots	No	Greenschist and amphibolite
East Sound Group	Middle to late Paleozoic	Arc sedimentary and volcanic rocks	No	Aragonite–lawsonite
Haro Formation and Speiden Group	Triassic – Early Cretaceous	Arc sedimentary rocks	No	Zeolite
Wrangellia	Devonian–Jurassic	Composite	No	Zeolite

Note: Table is complied from Danner 1966; Vance 1968, 1975; Glassley et al. 1976; Whetten et al. 1978; Brown et al. 1979; Brandon et al. 1988; England and Calon 1991; and Burmester et al. 2000.

Fig. 2. Rock units of the San Juan Islands and location of the Richardson study site. CO, Constitution Formation; DB, Deadman Bay Volcanics; ES, East Sound Group; FC, Fidalgo Complex; GA, Garrison Schist; HS, Haro Formation and Speiden Group; LM, Lummi tectonic assemblage; LS, Lopez structural zone; NA, Nanaimo Group; OC, Orcas Chert; SH. Shuksan terrane; TB, Turtleback Complex. References: Vance 1975; Whetten et al. 1978; Brandon et al. 1988; England and Calon 1991; and Burmester et al. 2000.

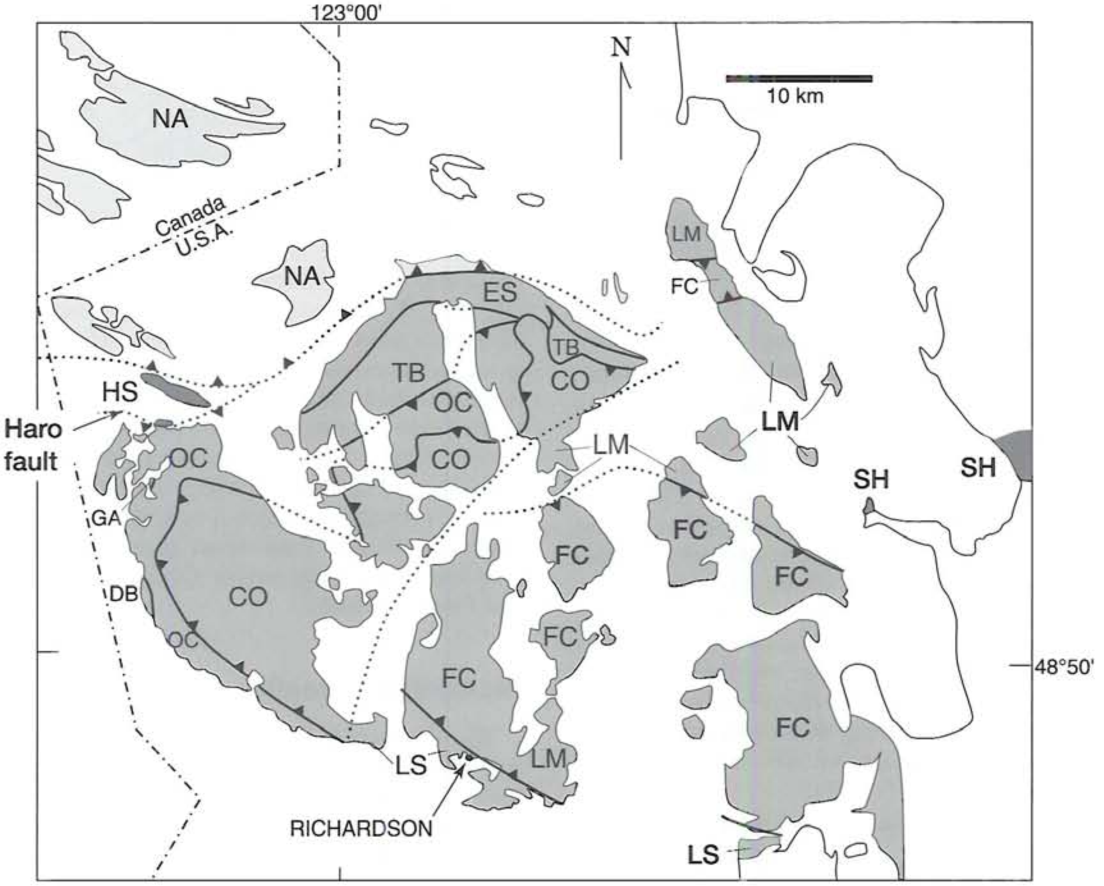
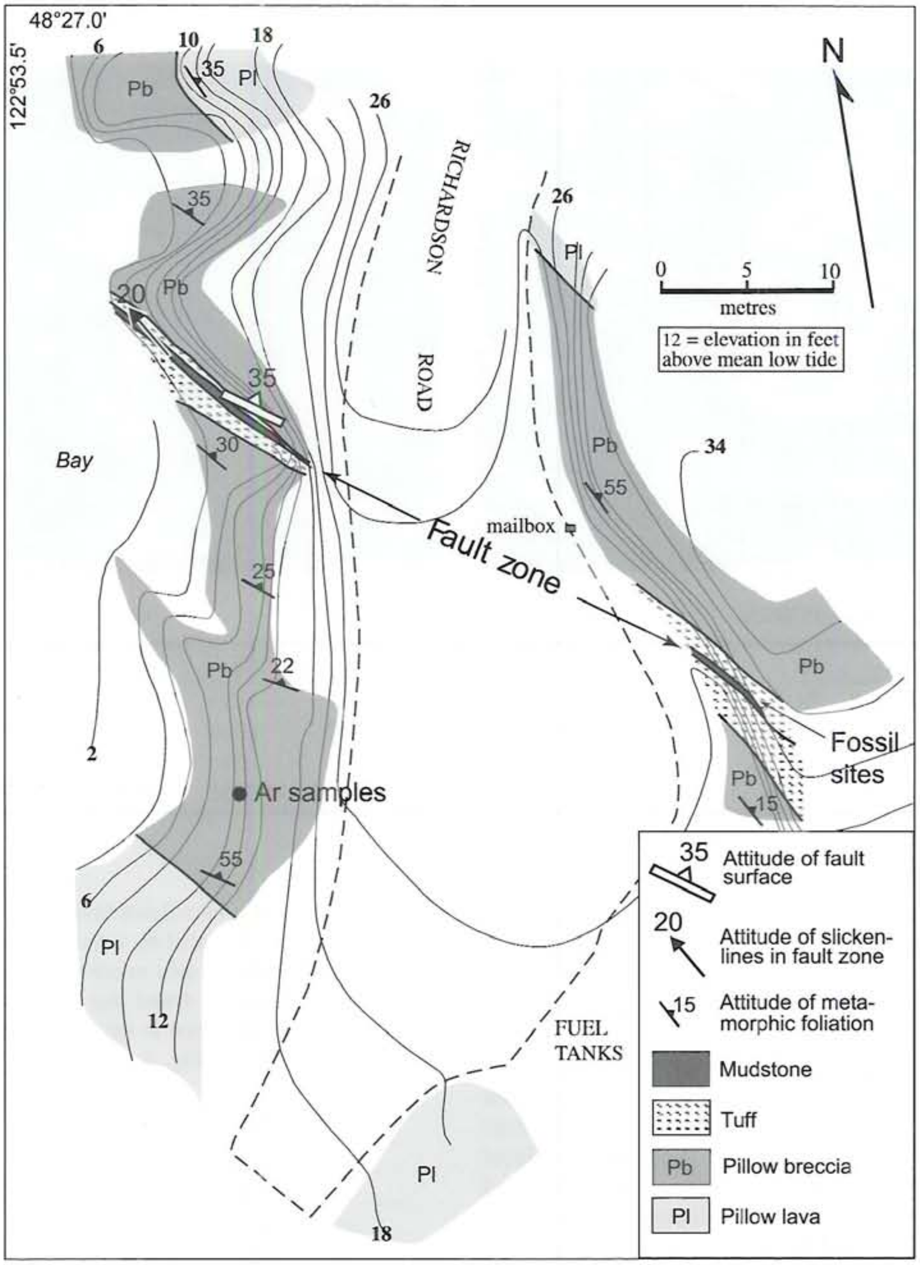


Fig. 3. Map of the Richardson locality (plane table survey). The "Fault zone" contains tectonic lenses (Fig. 5) and sheets of fossiliferous mudstone–siltstone. "Ar samples" yield a 124-Ma phengite–blueschist-facies metamorphic age.



fabric and therefore the age of the nappe emplacement event. Following current knowledge, we expected the age to be < 100 Ma. The results on two samples yield an average age of 124.4 ± 0.7 Ma (see later in the text). We were thus faced with a metamorphic age that is ~24 million years older than that reported for fossils in the same outcrop. To resolve this discrepancy, we returned to Richardson to confirm the fossil ages and to obtain further information on structural relations between the fossiliferous rocks and Ar-dated rocks.

Layered meta-volcanic rocks dominate the Richardson outcrop area (Fig. 3). The following occurs upward through the layered section: right-way-up pillow lava, pillow breccia, plagioclase-rich crystal tuff, more pillow breccias, and finally more upright pillow lava. The pillow lava shows little effect of deformation, but the breccias and tuff bear a well-developed foliation defined by flattening of volcanic fragments and alignment of metamorphic minerals, which is concordant with regional foliation in the Lopez structural zone as mapped by Bergh (2002). The pillow lavas are chemically similar to ocean-island basalts (Brandon et al. 1988).

The Ar-dated white mica occurs in flattened pillow breccia, where it is crystallized from glass in matrix material between pillow fragments (Fig. 4A). The micas are phengitic in composition (Table 2) and are similar to micas from blueschist terranes elsewhere (Ernst 1963). The mica is aligned in the foliation. Other synkinematic metamorphic minerals in the volcanic section are chlorite, pumpellyite, aragonite (x-ray identification), albite, and quartz. Metamorphosed crystal tuffs in the volcanic section also contain all these mentioned minerals.

Fig. 4. Photomicrographs. (A) Foliated meta-volcanic rock (sample R3) with 124-Ma phengite, mats of fine chlorite after volcanic glass, and altered plagioclase phenocrysts. (B) Pellet-rich mudstone, characteristic of the unit in which the 112–115-Ma foramanifera are found; note flattening foliation, S1 in Fig. 5.

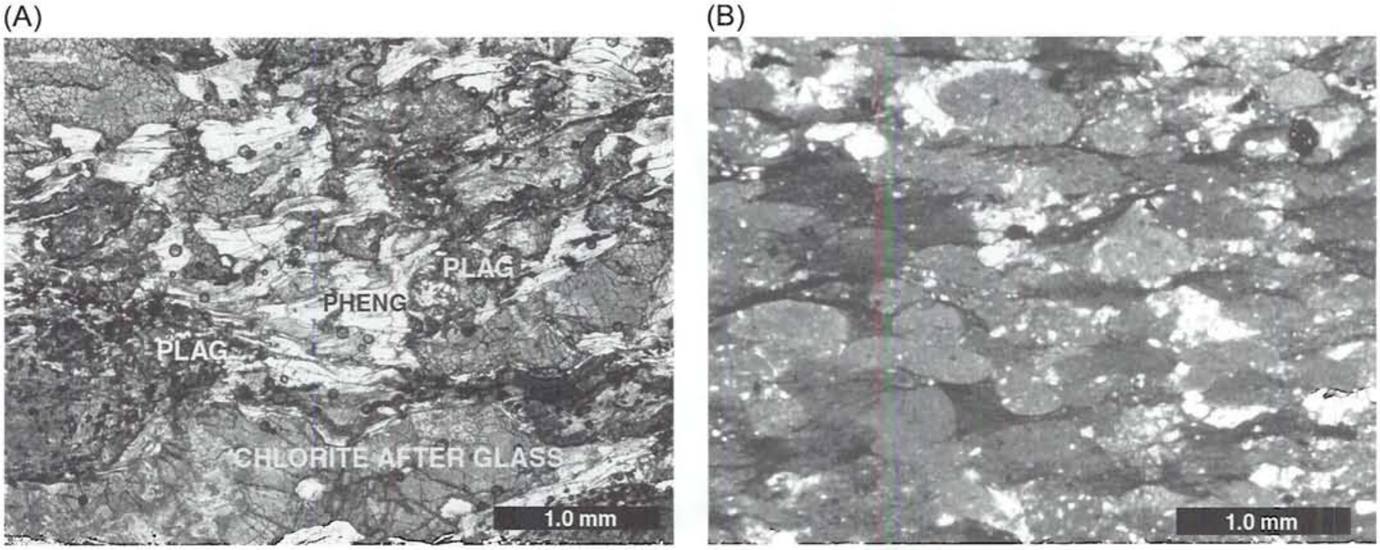


Table 2. Chemical composition of mica.

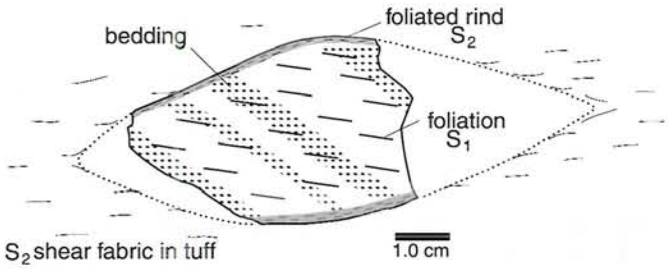
		Si	Al	Ti	Fe_3[a]	Fe_2[a]	Mn	Mg	Ca	Na	K	Total
R3	Oxide	52.8	23.4	0.05	2.97	2.68	0.03	4.03	0.08	0.11	9.97	96.3
	Cation[b]	7.03	3.67	0.005	0.298	0.298	0.003	0.800	0.011	0.028	1.69	13.8
R9	Oxide	52.9	23.9	0.03	2.69	2.42	0.02	4.08	0.07	0.12	10.13	96.4
	Cation[b]	7.01	3.74	0.003	0.268	0.268	0.002	0.806	0.010	0.030	1.71	13.9

[a] Fe arbitrarily split equally between ferrous and ferric ion.

[b] Based on 22 oxygens.

Distinctive fault-bound lenses of siltstone and mudstone occur within the tuff (Fig. 3). This is the lithology from which Danner (1966; personal communication, 2003) collected foraminifera-bearing rock. We found microfossils in one of 15 mudstone samples studied in thin section, a small tectonic lens (Fig. 5). Thin-section study of 70 other samples representing various volcanic and cherty rocks throughout the Richardson area revealed no other fossils. The fossiliferous rock is a brown, organic-rich mudstone dominated by fecal pellets (Fig. 4B). Bedding is marked by trains of pyrite and quartz–hematite laminations. A weak cleavage, at an angle to bedding (Fig. 5), is defined by flattened pellets, solution – mass-transfer residues, shear surfaces, and pull-apart structures in pyrites. Microfossils in the mudstone do not appear to be significantly deformed. Predominant minerals in the rock (identified in part by x-ray and refractive index) are chlorite and quartz. Feldspar and mica are sparse and show minimal or no x-ray peaks. Clay minerals appear to be absent; thus, the rock is at least somewhat recrystallized from a sedimentary parent that would likely have been rich in kaolinite and montmorillonite (Pryor 1975). Aragonite and pumpellyite or other significant metamorphic index minerals have not been found. Thin sections and x-ray patterns from the larger, unfossiliferous structural slices of siltstone and mudstone reveal mineralogy and fabric generally similar to that of the fossiliferous sample.

Fig. 5. Diagram of a microfossil-bearing lens showing that bedding and cleavage are truncated by a tectonic rind against the host meta-volcanic rock, as seen microscopically. Not all of this lens was collected, thus the dotted line shows the full extent of the tectonic fragment observed in the outcrop. The S_2 fabric is parallel to the "Fault zone" of Fig. 3.



Faults that bound the mid-Cretaceous mudstone below the road (Fig. 3) distinctly crosscut foliation in both the mudstone and in the tuff, but at a low angle. The narrow fault zones are marked by laminated quartz veins and slickensided surfaces. The fossiliferous mudstone lens in the road cut is wrapped by a thin selvedge of fine-grained chloritic material that crosscuts bedding and cleavage within the lens (Fig. 5), marking the structural contact of the mudstone with the host tuff. Slaty foliation in the tuff bends into the selvedge. At this road-cut locality, metamorphic foliation and fault surfaces appear to be parallel, and thus the faulting apparently reactivated the metamorphic foliation. The attitude of the fault surface across the width of the Richardson outcrop is approximately N55°W, 35°NE (Fig. 3). A N30°W trend and

20°NW plunge is a representative attitude of the slickenlines below the road cut. Steps on the slickensided surface indicate hanging-wall movement to the northwest. These observations are important because they represent the best information we have so far on fabric of a possible mid-Cretaceous thrust in the San Juan Islands.

Planktonic foraminiferal chronostratigraphy

Foraminifera-bearing rocks from the Richardson road-cut outcrop shown in Fig. 3 were identified as "Late Cretaceous or younger" by Danner (1966, p. 80). More samples collected from the same road cut by Danner in 1976 were studied by E. Pessagno and interpreted as "mid-Cretaceous" (reported in Whetten et al. 1978). We were not successful in our attempts to locate these previously collected samples for further study. And although we did find fossiliferous rock in the Richardson road cut, our sample does not bear age-definitive material. However, four thin sections of sample 77-46, which was by collected by John Whetten from the Richardson area in 1977 and studied by the late William Sliter of the United States Geological Survey, were recovered with Sliter's notes by Mary McGann of the United States Geological Survey and Sliter's former assistant. A late Albian age (~100 Ma) was determined by Sliter based on identification of *Planomalina buxtorfi* and published in Brandon et al. (1988), but no other detail was given. Sample 77-46 is the principle source of current knowledge of the age of the youngest rocks involved in San Juan Islands thrusting. The collection site of sample 77-46 is not at the road-cut outcrop (Fig. 3) where the other fossiliferous rocks were found, but is from a nearby unspecified locality noted by Whetten (Whetten et al. 1978, p. 122) as "probably same bed" as at the road cut.

A thorough re-examination of the four thin sections of sample 77-46 has resulted in a substantially older age determination. All slides contain common to abundant specimens of planktonic foraminifera with few specimens of calcareous and agglutinated benthic foraminifera. The planktonic foraminifera yield a late Aptian age of ~115–112 Ma, which is based on the following observations. No keeled species of planktonic foraminifera were observed in any of the four thin sections, including *Planomalina buxtorfi*, *Praeglobotruncana delrioensis*, or any species of the characteristic late Albian – Cenomanian genus *Rotalipora*. One interpretation for the absence of keeled taxa could be attributed to relatively cool waters. However, the absence of other age-diagnostic taxa does not support such an interpretation. For example, no specimens of the late Albian – Maastrichtian genera *Heterohelix*, *Schackoina*, or *Guembelitria* were observed. If these mudrocks accumulated in highly productive or relatively shallow environments, representatives of these genera would be expected, particularly *Heterohelix* (e.g., Leckie 1987; Leckie et al. 1998). In addition, no medium- to thick-walled, six- to eight-chambered specimens of the late early to late Albian genus *Ticinella* (e.g., *T. primula*, *T. roberti*) or late Albian *Biticinella breggiensis* were observed.

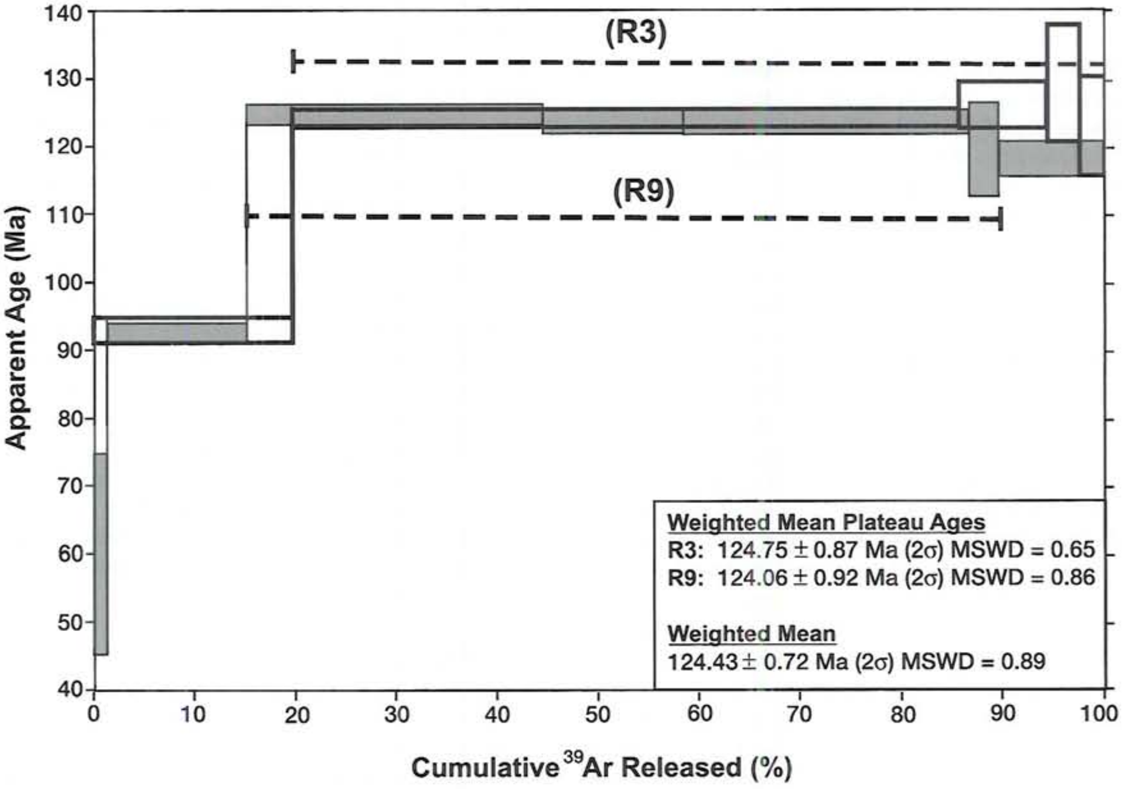
What dominates the assemblages in all four thin sections are tiny, thin-walled specimens of planktonic foraminifera, nearly all of which are < 200 μm in diameter. These morphological characteristics are typical of pre-Albian planktonic foraminifera (Sliter 1989; Premoli Silva and Sliter 1999; Leckie et al. 2002). One interpretation for the ubiquitous occurrence of tiny specimens is size sorting by currents or redepositional processes. However, the presence of rare, but distinctly larger, and thicker walled specimens of benthic foraminifera argue against this interpretation. Alternatively, small specimens are typically associated in highly productive or less than optimal environmental conditions but, again, the absence of *Heterohelix* suggests that, if this was the case, these rocks are not likely to be late Albian or younger in age. Rather, a low-diversity assemblage of relatively thin-walled planktonic foraminifera characterizes the samples. The assemblage is dominated by small, trochospirally coiled taxa and the co-occurrence of *Hedbergella gorbachikae*, *H. hispanae*, *H. occulta*, as well as rare specimens of the *H. praetrocoidea–trocoidea* Group indicate a late Aptian age. In addition, fragments or poorly preserved specimens of relatively large *Globigerinelloides ferreolensis*, *G. barri*, and *Planomalina cheniourensis* further support this age assignment (Verga and Premoli Silva 2003*a*, 2003*b*). The absence of *Leupoldina cabri*, while representing negative evidence, suggest that the rocks are confined to the latter part of the Aptian. Taken together, the small-sized and thinly walled specimens, the low diversity of the planktonic foraminiferal assemblages, and the absence of any of the diagnostic Albian genera and species supports a late Aptian age for these rocks.

^{40}Ar/^{39}Ar geochronology

About 20 mg of optically fresh phengite crystals (~100 μm × 400 μm) were hand-picked from two coarse-crushed samples of pillow breccia from the Richardson locality. Crystals were cleaned ultrasonically in twice distilled H_2O and then loaded into 1.6-cm aluminum discs that were irradiated for 40 hours (UW-14) at the Oregon State University Triga reactor. Roughly 2 mg (5 grains) of phengite from each of the two samples were analyzed by CO_2 -laser incremental heating techniques at the Rare Gas Geochronology Laboratory, University of Wisconsin-Madison. Analytical and data reduction procedures are outlined in Singer and Brown (2002).

Each sample yields a broad plateau at the high-temperature end of the age spectrum (Fig. 6). Weighted mean plateau ages for R3 and R9 are 124.8 ± 0.9 Ma (four of five steps used, 80.3% of total ^{39}Ar) and 124.1 ± 0.9 Ma (four of six steps used, 74.3% of total ^{39}Ar), respectively, with a mean age of the two samples at 124.4 ± 0.7 (2σ). The age spectra also indicate young ages for the lower temperature steps of samples R3 and R9 (Fig. 6). The young-age steps may be explained by three mechanisms. First, there is rough correlation among K/Cl, laser power, and age of step (Table 3) that suggests the lower temperature steps might represent a component of Ar liberated from fluid inclusions (e.g., Villa 2001; Challandes et al. 2003), which were not closed to Ar loss, or there are two generations of mica of different age and Cl content (e.g., Challandes et al. 2003). Second, because both samples show a lower temperature step at 92.7 ± 1.9 and 92.4 ± 1.4 Ma with a mean at 92.5 ± 1.2 Ma, a geologic disturbance (heating and (or) deformation?) may have caused an interval of Ar loss at 92.5 Ma — a time which is consistent with ages of thrusting determined elsewhere in the northwest Cascades. Alternatively, the low-temperature steps at 92 Ma may be an artifact of the laser step-heating experiment such

Fig. 6. Age spectrum diagram of samples R3 and R9. Data used for calculation of the age of phengite–mica crystallization are represented by the dashed lines. 80% and 74% of released ^{39}Ar was used for calculation of the mica age for R3 and R9, respectively. This age (mean of both samples = 124.4 ± 0.7 Ma) is inferred to represent blueschist metamorphism. The low-temperature age steps that are younger than the plateau might represent a late episode of Ar loss. Latitude and longitude of R3 and R9 are 48°26.9′N and 122°53.5′W.



that the age of these steps may not correlate to the age of Ar loss. At present, we do not know which mechanism had the most influence in causing the young ages.

The vast majority of Ar liberated from the micas is radiogenic ^{40}Ar (Table 3), and we are therefore unable to calculate isochron ages for these samples. This poses a problem in evaluating the effect of excess Ar because we cannot determine the isotopic composition of Ar trapped in the crystal lattice during crystallization. Although the possibility that the weighted plateau ages were affected by excess Ar cannot be ruled out, the step heating patterns (Fig. 6) and Ar isotope data (Table 3) do not indicate any anomalies that might suggest such a problem. We, therefore, interpret the weighted plateau ages of 124.4 Ma as the time of phengite crystallization.

Discussion

Accepting the validity of the new microfossil and mica ^{40}Ar/^{39}Ar ages at Richardson, one is led to the conclusion that the blueschist-facies metamorphism and related fabric development occurred > 10 Ma prior to juxtaposition of terranes. How well does this finding agree with other observations in the San Juan Islands and the Cascades? Most significantly, the only other direct measurements of metamorphic age of blueschist-facies metamorphism in the San Juan Islands and northwest Cascades are in agreement with the Richardson ages. Numerous K–Ar and Rb–Sr ages of minerals in the Shuksan terrane of the Cascades establish a period of blueschist metamorphism of 120–164 Ma (Brown et al. 1982; Armstrong and Misch 1987). The "Baker Lake blueschist" of Brown et al. (1987) is a distinctive tectonic fragment in the Cascades thrust system that yielded a K–Ar whole rock age of 127 ± 5 Ma. From the eastern San Juan Islands, Lamb (2000) obtained ^{40}Ar/^{39}Ar ages of 137 and 154 Ma for metamorphic white mica in semi-schists. The possibility of an inherited detrital component to these ages has somewhat clouded their significance, but they agree well with the Shuksan ages and are an important part of the developing regional data set. We tentatively conclude that blueschist metamorphism throughout to the San Juan Islands – northwest Cascades thrust system is Barremian and older.

The evidence presented in support of a syn- to post-thrusting age of metamorphism in the San Juan Islands (given by Brandon et al. 1988; and accepted as valid by Maekawa and Brown 1991) is (1) the development of high-*P* minerals in veins across boundaries between fault matrix and exotic tectonic blocks of Garrison Schist and Turtleback Complex, and (2) the uniformity of metamorphic grade across terrane boundaries. Addressing these points, we suggest that parts of the SJI thrust system were assembled, metamorphosed, and foliated prior to thrust emplacement in northwest Washington. This is not a new idea. Vance (1975) identified clastic detritus in the Constitution Formation as being derived from the Orcas Chert, Garrison Schist, and Turtleback Complex, and he interpreted the Constitution Formation to have been deposited

Table 3. $^{40}Ar/^{39}Ar$ incremental heating data from phengite of the Lopez structural complex.

Analysis #	Laser power	$\frac{^{40}Ar}{^{39}Ar}$ (±1σ)	$\frac{^{37}Ar}{^{39}Ar}$ (±1σ)[a]	$\frac{^{36}Ar}{^{39}Ar}$ (±1σ)	$^{40}Ar^{*}$ (%)	$^{40}Ar^{*}$ (10^{-15} mol)	^{39}Ar % (of total)	$\frac{^{40}Ar^{*}}{^{39}Ar_K}$ (±1σ)	$^{38}Ar_{(Cl)}$ (10^{-15} mol)	K/Cl[b]	Apparent age Ma (±2σ)
(A) **R3**											
AB4189	0.04 W	5.372±0.057	0.011±0.002	0.0029±0.0002	83.74	0.69504	19.67	4.502±0.048	0.00050	~2000	92.7±1.9
AB4190[c]	0.18 W	6.423±0.020	0.031±0.001	0.0011±0.0000	95.02	3.15138	65.72	6.108±0.019	0.00007	~40000	124.6±0.7
AB4191[c]	0.31 W	6.466±0.084	0.091±0.005	0.0010±0.0003	95.54	0.43074	8.88	6.182±0.080	0.00001	~30000	126.1±3.1
AB4192[c]	0.47 W	6.500±0.229	0.386±0.016	0.0005±0.0007	97.47	0.16731	3.36	6.340±0.223	0.00001	~20000	129.2±8.8
AB4194[c]	1.25 W	6.430±0.190	0.136±0.024	0.0013±0.0006	94.07	0.11275	2.37	6.053±0.179	0.00001	~20000	123.6±7.1
Weighted plateau age:											124.8±0.9
MSWD:											0.65
Total fusion age:											118.7±0.9
(B) **R9**											
AB4234	0.02 W	3.903±0.065	0.010±0.023	0.0035±0.0012	73.44	0.04046	1.64	2.870±0.364	0.00009	~1000	59.6±14.9
AB4235	0.04 W	5.011±0.054	0.015±0.002	0.0018±0.0001	89.44	0.52800	13.66	4.486±0.037	0.00020	~3000	92.4±1.5
AB4237[c]	0.10 W	6.392±0.050	0.014±0.001	0.0010±0.0001	95.40	1.41390	26.89	6.103±0.029	0.00006	~20000	124.5±1.2
AB4238[c]	0.14 W	6.256±0.049	0.015±0.002	0.0006±0.0001	96.94	0.83335	15.94	6.069±0.042	0.00000	n/a	123.9±1.7
AB4239[c]	0.18 W	6.278±0.050	0.018±0.002	0.0008±0.0001	96.38	1.47517	28.27	6.055±0.036	0.00009	~10000	123.6±1.4
AB4240[c]	0.22 W	6.189±0.051	0.121±0.010	0.0011±0.0006	94.75	0.16145	3.19	5.869±0.175	0.00001	~20000	119.9±6.9
AB4241	1.24 W	6.200±0.051	0.165±0.007	0.0014±0.0002	93.15	0.51897	10.42	5.780±0.059	0.00005	~10000	118.2±2.4
Weighted plateau age:											124.1±0.9
MSWD:											0.86
Total fusion age:											118.0±0.9

Note: For both R3 and R9, sample wt: ~2 mg (5 grains). Ages and errors were calculated using ArArCALC (Koppers 2002). Ages are calculated relative to 28.34 Ma for Taylor Creek sanidine. Corrections for undesirable neutron-induced reactions involving ^{40}K and ^{40}Ca are as follows: $[^{40}Ar/^{39}Ar]K$ = 0.00465, $[^{36}Ar/^{37}Ar]Ca$ = 0.00268, $[^{39}Ar/^{37}Ar]Ca$ = 0.00698. Methods used for extraction and analysis of Ar follow Singer and Brown (2002). K/Cl = $^{39}Ar_{(K)}/^{38}Ar_{(Cl)}$ * 5.22 (X. Zhang, personal communication, 2004). MSWD, mean square of weighted deviates.

[a] Corrected for ^{37}Ar and ^{39}Ar decay, half-lives of 35.1 days and 269 years, respectively. $J = 0.011712 \pm 0.000023$(1sd); mass bias = 1.0025 per amu.

[b] Precision of K/Cl ratio is estimated to be ± ~20%–50%.

[c] Data used in plateau age calculations.

over these older units. Similarly, Brandon et al. (1988) interpreted the East Sound Group to have been deposited on the Turtleback Complex. The conclusion we draw is that some of the SJI terranes were amalgamated prior to Late Jurassic deposition of the Constitution Formation and also prior to the 124-Ma blueschist metamorphism.

Metamorphic breaks can be identified in the San Juan Islands – Northwest Cascades system. In the northwest Cascades, the Shuksan terrane presents a definitive example of blueschist metamorphism acquired prior to thrust emplacement of the unit against lower grade nappes (Brown et al. 1981). In the San Juan Islands, Burmester et al. (2000) identified breaks in metamorphic grade among terranes based on distribution of high-P index minerals and development of foliation (Table 1). These authors also demonstrate that the San Juan Islands can be divided into zones of uniformly oriented remanent magnetism, which was acquired during metamorphism. Zones of different orientation are considered to have moved relative to one another since metamorphism.

The hypothesis that blueschist metamorphism in the SJI nappes is the consequence of their being thrust onto the continental margin is anomalous with respect to the subduction-zone setting interpreted for blueschists elsewhere on earth. Viewing the metamorphism as occurring prior to San Juan Islands thrusting allows a more sensible interpretation that a subduction-related process affected the terranes outside of their present setting. However, this interpretation creates another problem: an Early Cretaceous metamorphic age that long post-dates primary accretion of the older rocks of the region. Thus, a Cretaceous blueschist metamorphism of the Paleozoic East Sound and the Permian–Triassic Orcas Chert – Deadman Bay terranes is not readily explained as a consequence of simple accretionary subduction. Better understanding of the cause of metamorphism of these units does not come from age-equivalent accreted terranes in British Columbia, Oregon, and California that do not bear a Cretaceous blueschist imprint (e.g., Coleman et al. 1988).

A further consequence of the revised metamorphic history is a simpler understanding of the regional boundary effects of the emplacement of the SJI nappes. The lack of blueschist metamorphism in the subjacent Haro–Speiden assemblage and Wrangellia terrane (Fig. 1, Table 1) is more easily explained. The Haro fault, which juxtaposes blueschist terranes against the Haro–Speiden assemblage (Fig. 2, Table 1; Brown and Dragovich 2003, Fig. 2), can be considered to be one of the major structures related to emplacement of the SJI terranes rather than a late-thrusting uplift structure (Brandon et al. 1988).

The minimum age of San Juan Islands terranes, based on Richardson microfossils, is extended from 100 to 112–115 Ma. This age revision diminishes our grasp on the age of thrusting in the San Juan Islands – northwest Cascades system. A 90–95-Ma age of thrusting based on isotope dating (see earlier in the text) remains likely, but it is less well substantiated. Also as a consequence of the revised microfossil ages, the overall time frame of orogeny for SJI nappes, from sediment accumulation to uplift after thrusting, is considerably broadened from 16 to 28–31 Ma. Deformation rates and orogenic models based on this time frame (Brandon et al. 1988; Feehan and Brandon 1999) require revision.

The oceanic basalts at Richardson were originally considered to be ~100 Ma on the basis of their proximity to the microfossils at the site and, in this sense, they were quite anomalous in being some 40–50 Ma younger than all other dated oceanic rocks in the San Juan Islands and the Cascades (Whetten et al. 1978; Brown and Dragovich 2003). The Ar ages of this study, together with observed structural features at Richardson, indicate that the pillow lava is older than 124 Ma and is likely similar in age to other pillow lava in the Lopez structural Complex, which is dated as Jurassic by association with radiolarian chert (Whetten et al. 1978). A revised older age of the pillow lava significantly increases the minimum age of major accretion of oceanic rocks along this part of the Mesozoic continental margin.

Future work

Additional isotopic dating of metamorphic minerals is needed to confirm our interpretation that the blueschist metamorphism and related fabrics elsewhere in the San Juan Islands, beyond Richardson, predate San Juan Islands thrusting. Pending this further confirmation, we suggest that ongoing research embraces a working hypothesis that the San Juan Islands preserve structures recording a long history, including (at the least) events of subduction, uplift, and thrusting onto the continental margin. Further progress towards understanding the evolution of the San Juan Islands will require distinguishing a number of generations of structures. Studies of the blueschist-related fabric should be viewed as useful for understanding the hypothesized earlier subduction-related evolution and perhaps uplift of the terranes, but probably not their ultimate emplacement in the San Juan Islands thrust system.

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References

Armstrong, R.L., and Misch, P. 1987. Rb–Sr and K–Ar dating of mid-Mesozoic blueschist and late Paleozoic albite-epidote-amphibolite and blueschist metamorphism in the North Cascades, Washington and British Columbia, and Sr isotope fingerprinting of eugeosynclinal rock assemblages. *In* Selected papers on the geology of Washington. *Edited by* J.E. Schuster. Washington Division of Geology and Earth Resources, Bulletin 77, pp. 85–105.

Bergh, S.G. 2002. Linked thrust and strike-slip faulting during Late Cretaceous terrane accretion in the San Juan thrust system, Northwest Cascade orogen, Washington. Geological Society of America Bulletin, **114**: 934–949.

Blake, M.C., and Engebretson, D.C. 1994. Geology of the northern San Juan Islands: the California connection. Geological Society of America Abstracts with Programs, **26**: 188.

Brandon, M.T., Cowan, D.S., and Vance, J.A. 1988. The Late Cretaceous San Juan Island thrust system, San Juan Islands, Washington. Geological Society of America, Special Paper 221.

Brandon, M.T., Cowan, D.S., and Feehan, J.G. 1993. Kinematic analysis of the San Juan thrust system, Washington: discussion and reply. Geological Society of America Bulletin, **105**: 839–844.

Brown, E.H. 1987. Structural geology and accretionary history of the Northwest Cascades System, Washington and British Columbia. Geological Society of America Bulletin, **99**: 201–214.

Brown, E.H., and Dragovich, J.D. 2003. Tectonic elements and evolution of northwest Washington. Washington Division of Geology and Earth Resources, Map GM 52, scale 1 : 250 00.

Brown, E.H., and Vance, J.A. 1987. Correlation of pre-Tertiary thrust structures between the San Juan Islands and northwest Cascades, Washington. Geological Society of America Abstracts with Programs, **19**: 362.

Brown, E.H., Bradshaw, J.Y., and Mustoe, G.E. 1979. Plagiogranite and keratophyre in ophiolite on Fidalgo Island, Washington. Geological Society of America Bulletin, **90**: 493–507.

Brown, E.H., Bernardi, M.L., Christenson, B.W., Cruver, J.R., Haugerud, R.H., Rady, P.M. et al. 1981. Metamorphic facies and tectonics in part of the Cascade Range and Puget Lowland, northwestern Washington. Geological Society of America Bulletin, **92**: 170–178.

Brown, E.H., Wilson, D.L., Armstrong, R.L., and Harakal, J.E. 1982. Petrologic, structural, and age relations of serpentinite, amphibolite, and blueschist in the Shuksan Suite of the Iron Mountain-Gee Point area, North Cascades, Washington. Geological Society of America Bulletin, **93**: 1087–1098.

Brown, E.H., Blackwell, D.L., Christenson, B.W., Frasse, F.I., Haugerud, R.A., Jones, J.T. et al. 1987. Geologic map of the northwest Cascades, Washington. Geological Society of America Map and Chart Series MC-61, 1 sheet, scale 1 : 100 000.

Burchfiel, B.C., Cowan, D.S., and Davis, G.A. 1992. Tectonic overview of the Cordilleran orogen in the western United States. *In* The Cordilleran orogen: conterminous US. *Edited by* B.C. Burchfiel, P.W. Lipman, and M.L. Zoback. Geological Society of America, Boulder, Colo., The Geology of North America, Vol. G-3, pp. 407–479.

Burmester, R.F., Blake, M.C., and Engebretson, D.C. 2000. Remagnetization during Cretaceous Normal Superchron in Eastern San Juan Islands, WA: implications for tectonic history. Tectonophysics, **326**: 73–92.

Challandes, N., Marquer, D., and Villa, I.M. 2003. Dating the evolution of C–S microstructures: a combined 40Ar/39Ar step heating and UV laserprobe analysis of the Alpine Roffna shear zone. Chemical Geology, **197**: 3–9.

Coleman, R.G., Manning, C.E., Mortimer, N., Donato, M.M., and Hill, L.B. 1988. Tectonic and regional metamorphic framework of the Klamath Mountains and adjacent Coast Ranges, California and Oregon. *In* Metamorphism and crustal evolution of the western United States. *Edited by* W.G. Ernst. Prentice Hall, Englewood Cliffs, N.J., Rubey Vol. VII, pp. 1061–1097.

Cowan, D.S., and Brandon, M.T. 1994. A symmetry-based method for kinematic analysis of large-slip brittle fault zones. American Journal of Science, **294**: 257–306.

Cowan, D.S., and Bruhn, R.L. 1992. Late Jurassic to early Late Cretaceous geology of the US Cordillera. *In* The Cordilleran orogen: conterminous US. *Edited by* B.C. Burchfiel, P.W. Lipman, and M.L. Zoback. Geological Society of America, Boulder, Colo., The Geology of North America, Vol. G-3, pp. 169–203.

Danner, W.R. 1966. Limestone resources of western Washington. Washington Division of Mines and Geology, Bulletin 52.

England, T.D.J., and Calon, T.J. 1991. The Cowichan fold and thrust system, Vancouver Island, southwestern British Columbia. Geological Society of America Bulletin, **103**: 336–362.

Ernst, W.G. 1963. Significance of phengitic micas from low-grade schists. The American Mineralogist, **48**: 1357–1373.

Ernst, W.G. 1973. Blueschist metamorphism and *P–T* regimes in active subduction zones. Tectonophysics, **26**: 229–246.

Feehan, J.G., and Brandon, M.T. 1999. Contribution of dustile flow to exhumation of low-temperature, high pressure metamorphic rocks: San Juan-Cascade nappes, NW Washington State. Journal of Geophysical Research, **104**: 10 883 – 10 902.

Glassley, W.E., Whetten, J.T., Cowan, D.S., and Vance, J.A. 1976. Significance of coexisting lawsonite, prehnite, and aragonite in the San Juan Islands, Washington. Geology, **4**: 301–302.

Hamilton, W. 1969. Mesozoic California and the underflow of Pacific mantle. Geological Society of America Bulletin, **80**: 2409–2430.

Irwin, W.P. 1981. Tectonic accretion of the Klamath Mountains, California and Oregon. *In* The geotectonic development of California. Rubey Vol.1. *Edited by* W.G. Ernst. Prentice-Hall, Englewood Cliffs, N.J., pp. 29–49.

Johnson, S.J., Zimmermann, R.A., Naeser, C.W., and Whetten, J.T. 1986. Fission-track dating of the tectonic development of the San Juan Islands, Washington. Canadian Journal of Earth Sciences, **23**: 1318–1330.

Koppers, A.P. 2002. ArArCALC; software for 40Ar/39Ar age calculations. Computers & Geoscience, **28**: 605–619.

Lamb, R.M. 2000. Structural and tectonic history of the eastern San Juan Islands, Washington. M.S. thesis, Western Washington University, Bellingham, Wash.

Leckie, R.M. 1987. Paleoecology of mid-Cretaceous planktonic foraminifera: a comparison of open ocean and epicontinental sea assemblages. Micropaleontology, **33**(2): 164–176.

Leckie, R.M., Yuretich, R.F., West, O.L.O., Finkelstein, D., and Schmidt, M. 1998. Paleoceanography of the southwestern Greenhorn Sea during the time of the Cenomanian/Turonian boundary (Late Cretaceous). *In* Stratigraphy and paleoenvironments of the western interior seaway, USA. *Edited by* W. Dean and M.A. Arthur. Society for Sedimentary Geology (SEPM), Tulsa, Okla., Concepts in sedimentology and paleontology No. 6, pp. 101–126.

Leckie, R.M., Bralower, T., and Cashman, R. 2002. Oceanic anoxic events and plankton evolution: biotic response to tectonic forcing during the mid-Cretaceous. Paleoceanography, **17**(3): 10.1029/2001PA000623.

Maekawa, H., and Brown, E.H. 1991. Kinematic analysis of the San Juan thrust system, Washington. Geological Society of America Bulletin, **103**: 1007–1016.

McClelland, W.C., Gehrels, G.E., and Saleeby, J.B. 1992. Upper Jurassic – Lower Cretaceous basinal strata along the Cordilleran margin: implications for the accretionary history of the Alexander–Wrangellia–Peninsular terrane. Tectonics, **11**: 823–835.

McGroder, M.F. 1991. Reconciliation of two-sided thrusting, burial metamorphism, and diachronous uplift in the Cascades of Washington and British Columbia. Geological Society of America Bulletin, **103**: 189–209.

Miller, R.B., and Paterson, S.R. 1992. Tectonic implications of syn- and post-emplacement deformation of the Mount Stuart batholith for mid-Cretaceous orogenesis in the North Cascades. Canadian Journal of Earth Science, **29**: 479–485.

Miller, R.B., Mattinson, J.M., Funk, S.A.G., Hopson, C.A., and Treat, C.L. 1993. Tectonic evolution of Mesozoic rocks in the southern and central Washington Cascades. *In* Mesozoic paleogeography of the western United States — II. *Edited by* G. Dunne and K. McDougall. Pacific Section SEPM, Book 71, pp. 81–98.

Misch, P. 1966. Tectonic evolution of the Northern Cascades of Washington State — a west-Cordilleran case history. *In* A symposium on the tectonic history and mineral deposits of the western Cordillera in British Columbia and neighboring parts of the United States, Vancouver, B.C., 1964. *Edited by* H. C. Gunning. Canadian Institute of Mining and Metallurgy, pp. 101–148.

Miyashiro, A. 1994. Metamorphic petrology. Oxford University Press, New York.

Monger, J.W.H., and Journeay, J.M. 1994. Basement geology and tectonic evolution of the Vancouver region. *In* Geology and geologic hazards of the Vancouver Region, southwestern British Columbia. *Edited by* J.W.H. Monger. Geological Survey of Canada, Bulletin 481, pp. 3–25.

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

Mustard, P.S. 1994. The Upper Cretaceous Nanaimo Group, Georgia Basin. *In* Geology and geologic hazards of the Vancouver Region, southwestern British Columbia. *Edited by* J.W.H. Monger. Geological Survey of Canada, Bulletin 481, pp. 27–95.

Nelson, J.A. 1979. The western margin of the Coast Plutonic Complex on Hardwicke and West Thurlow Islands, British Columbia. Canadian Journal of Earth Sciences, **16**: 1166–1175.

Pacht, J.A. 1984. Petrologic evolution and paleogeography of the Late Cretaceous Nanaimo Basin, Washington and British Columbia: implications for Cretaceous tectonics. Geological Society of America Bulletin, **95**: 766–778.

Premoli Silva, I., and Sliter, W.V. 1999. Cretaceous paleoceanography: Evidence from planktonic foraminiferal evolution. *In* Evolution of the Cretaceous ocean–climate system. *Edited by* E. Barrera and C.C. Johnson. Geological Society of America, Special Paper 332, pp. 301–328.

Pryor, W.A. 1975. Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments. Geological Society of America Bulletin, **86**: 1244–1254.

Singer, B., and Brown, L.L. 2002. The Santa Rosa event: ^{40}Ar/^{39}Ar and paleomagnetic results from the Valles rhyolite near Jaramillo Creek, Jemez Mountains, New Mexico. Earth and Planetary Science Letters, **197**: 51–64.

Sliter, W.V. 1989. Biostratigraphic zonation for Cretaceous planktonic foraminifers examined in thin section. Journal of Foraminiferal Research, **19**: 1–19.

Umhoefer, P.J., and Schiarizza, P. 1996. Latest Cretaceous to early Teriary dextral strike-slip faulting on the southeastern Yalakom fault system, southeastern Coast Belt, British Columbia. Geological Society of America Bulletin, **108**: 768–785.

van der Heyden, P. 1992. A Middle Jurassic to early Tertiary Andean–Sierran subduction model for the Coast Belt of British Columbia. Tectonics, **11**: 82–97.

Vance, J.A. 1968. Metamorphic aragonite in the prehnite–pumpellyite facies, northwest Washington. American Journal of Science, **266**: 299–315.

Vance, J.A. 1975. Bedrock geology of San Juan County. *In* Geology and water resources of the San Juan Islands, San Juan County, Washington: Washington Department of Ecology, Water-Supply Bulletin 46. *Edited by* R.H. Russell. pp. 3–19.

Verga, D., and Premoli Silva, I. 2003*a*. Early Cretaceous planktonic Foraminifera from the Tethys. The small, few-chambered representatives of the genus *Globigerinelloides*. Cretaceous Research, **24**: 305–334.

Verga, D., and Premoli Silva, I. 2003*b*. Early Cretaceous planktonic Foraminifera from the Tethys. The large, many-chambered representatives of the genus *Globigerinelloides*. Cretaceous Research, **24**: 661–690.

Villa, I.M. 2001. Radiogenic isotopes in fluid inclusions. Lithos, **55**: 115–124

Whetten, J.T., Jones, D.L., Cowan, D.S., and Zartman, R.E. 1978. Ages of Mesozoic terranes in the San Juan Islands, Washington. *In* Mesozoic paleogeography of the western United States, Proceedings of the Pacific Coast Paleogeography Symposium. *Edited by* D.G. Howell and K.A. McDougall. Society of Economic Paleontologists and Mineralogists (SEPM), Pacific Section, Vol. 2, pp. 117–132.

Woodsworth, G.J., Anderson, R.G., and Armstrong, R.L. 1991. Plutonic regimes. *In* Geology of the Cordilleran Orogen in Canada. *Edited by* H. Gabrielse and C.J. Yorath. Geological Survey of Canada, Ottawa, Ont., Geology of Canada, no. 4, Chap. 15, pp. 491–531.