This discussion is followed by the reply from Maekawa and Brandon, which is included for completeness.

Kinematic analysis of the San Juan thrust system, Washington: Discussion and reply

Discussion

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Maekawa and Brown, 1991, herein referred to as M&B, is the latest in a series of papers by E. H. Brown and coworkers (Brown, 1987; Smith, 1988; Brown and Talbot, 1989) that have utilized structural fabrics to infer that strike-parallel (northwest-southeast) transpressive shear was the primary tectonic process responsible for forming the Late Cretaceous San Juan–Cascade orogen of northwest Washington State and south British Columbia. An alternative interpretation is that the orogen formed by northeast-southwest contraction, perpendicular to the strike of the orogen, in association with the collision of the more outboard Wrangellia terrane (Monger, 1986; Brandon and others, 1988; Brandon, 1989; Journeay, 1990; Rubin and others, 1990; McGroder, 1991). M&B is noteworthy in that it provides the first opportunity for us to compare structural observations and interpretations from the same field area, the San Juan Islands of west Washington State, where two major fault zones, the Rosario fault and the Lopez structural complex, are superbly exposed in coastal outcrops.

We argue here that M&B have misinterpreted the kinematic significance of structures associated with these fault zones, which we have concluded are major top-to-the-southwest thrust faults. At the root of our disagreement is the interpretation of the mesoscale deformational fabric of the fault zones. M&B have argued that this fabric is due solely to shearing in association with slip on the fault zones. We have argued (Brandon, 1980; Cowan and Miller, 1981; Brandon and others, 1988; Brandon, 1989) that there are two superimposed deformational fabrics: an early cataclastic fabric that is confined to the fault zone, and a later widespread cleavage that postdates major fault slip and was imposed on both the fault zone and the thrust sheets alike. In this discussion, we focus mainly on the character, relative timing, and kinematic significance of the cleavage because much of our work on this topic has already been published. Our conclusions about the kinematic interpretation of the precleavage fault-related structures (that is, asymmetric folds and Riedel composite structures) (Cowan and Brandon, 1990) will be presented in a future paper.

APPEARANCE OF THE CLEAVAGE

The regional cleavage in the San Juan Islands was formed at low temperatures (<200 °C) by pressure solution or solution mass transfer (SMT) (Brandon and others, 1988, 1991; Brandon, 1989). In outcrop, the SMT cleavage is expressed as a penetrative slaty cleavage in mud-rich rocks and fine-grained fault rocks; as a semipenetrative, rough cleavage in sandstone, conglomerate, and ribbon chert; and as a hackly, crudely developed cleavage in fragments and layers of basalt. At the microscale, the cleavage is defined by subparallel, anastomosing, dark brown to opaque selvages and oriented fibrous overgrowths composed mainly of phyllosilicates and quartz. In addition, very fine phyllosilicates oriented parallel to the selvages are present in mudstones and some sandstones. We interpret the selvages as insoluble residues formed by dissolution as indicated by common truncation of detrital grains and radiolaria microfossils (compare with p. 114 in Ramsay and Huber, 1983). This SMT cleavage is typically the *only* prominent and measurable penetrative fabric element in outcrop, although it may be locally absent in certain rock types, such as pillowed basalts and plutonic rocks.

SPATIAL RELATIONSHIP OF CLEAVAGE TO THE FAULT ZONES

M&B (p. 1010–1011) described the fault zones that they studied as being dominated by a "strong planar fabric . . . marked by foliation defined by newly grown phyllosilicates and by flattened porphyroclasts, . . . by microscopic slaty cleavages . . . and flattened pretectonic grains." This fabric is the SMT cleavage described above. Brandon (1980) and Brandon and others (1988) showed that this cleavage is widespread throughout the San Juan Islands and is not restricted to the Lopez, Rosario, or other similar Late Cretaceous fault zones. This evidence alone is incompatible with M&B's interpretation that the foliation is exclusively the product of shear within the fault zones. Instead, it supports our previously published interpretation that the SMT cleavage was superimposed regionally on an already assembled sequence of thrust nappes.

KINEMATIC SIGNIFICANCE OF THE FOLIATION

M&B used the SMT cleavage fabric and a "commonly associated . . . stretching lineation" to infer the slip direction associated with the fault zones. In sections cut parallel to principal fabric directions, M&B noted the flattened or elongate aspect of detrital grains, pull-apart features (micro-boudinage), and microscale "pressure shadows filled with recrystallized chlorite and muscovite around quartz, plagioclase, and rock fragments." They interpreted both the foliation and apparent stretching lineation as "shear-related." Using what they referred to as the "modern interpretation" for such fabrics

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(p. 1014), M&B concluded that the cleavage was formed subparallel to the shear plane in the fault zones (Fig. 3 in M&B), and the stretching lineation, subparallel to the direction of fault slip.

Our past work (Brandon and others, 1991), plus work in progress by Feehan and Brandon, on the SMT-cleavage fabric, both within and outside the Lopez and Rosario fault zones, has yielded the following observations. (a) The apparent flattening of most detrital grains, other than shale lithic clasts, is due primarily to dissolution along grain surfaces parallel to the cleavage, as recorded by selvages. (b) Detrital grains are mantled by fiber overgrowths of phyllosilicates and quartz, which are oriented parallel to the SMT cleavage and are interpreted to have formed at the same time. These directed overgrowths are pervasive in all of the cleaved sedimentary rocks and are consistently oriented at the scale of a thin section. (c) Measurements of the strains indicated by the fibers indicate that the true maximum extensional strains are low, averaging ~+20%, and that the maximum extension direction has a weakly defined average orientation in the down-dip direction of the cleavage. In almost all cases, fiber overgrowths are straight, not curved as would be predicted from the shear-zone interpretation of M&B. (d) Our measurements indicate that the largest strains are associated with the maximum shortening direction, which has an average strain of ~−50%.

On the basis of this information, we conclude that the foliation and lineation, presumed to be a "shear fabric" by M&B, are actually fabric elements that formed during a coaxial deformation that affected the fault zones and wall rocks alike. The consistent northwest strike and moderate northeast dip of the cleavage is compatible with the interpretation that the cleavage formed within a southwest-facing orogenic wedge (Brandon and others, 1988; Brandon, 1989). Moreover, we consider that the strongly flattened and elongated fabric of these rocks was formed mainly by dissolution and loss of mass along the cleavage selvages, with only minor strain in the maximum extension direction.

It would not be fair to expect M&B to comment on the results of our strain study, which has not yet been published. Our intent, instead, is to show that their kinematic analysis of what they consider to be a shear-induced tectonic fabric is incomplete. M&B present aspect ratio data for deformed objects (Fig. 8 in M&B) to support their conclusion that the so-called stretching lineation formed by bulk extension in the direction parallel to the lineation. It is important to recognize, however, that strain ratios provide only a relative measure of the strain. In the absence of information about volume strain, it is impossible to estimate the amount of true extension (see p. 170–172 in Ramsay and Huber, 1983).

RELATIVE TIMING OF FAULTING, METAMORPHISM, AND CLEAVAGE FORMATION

M&B (p. 1010) stated that they "have endeavored to measure fabrics coeval with metamorphic recrystallization" and (p. 1012) "recrystallization at blueschist-facies conditions occurred during deformation, a conclusion also reached by previous workers." M&B implied that faulting; the growth of high-P mineral assemblages, including lawsonite, prehnite, and aragonite; and the growth of the fine-grained minerals that define the SMT cleavage were all exactly synchronous. In fact, the "previous workers" (for example, Brandon, 1980, 1989; Cowan and Miller, 1981; Brandon and others, 1988) actually reached a very different conclusion: high-P metamorphism clearly postdated major slip on the Rosario and Lopez fault zones, and formation of the SMT cleavage appears to have largely postdated high-P metamorphism. Our conclusion is based on several lines of evidence. (a) Tectonic slices and blocks of lower Paleozoic tonalite and Permian-Triassic amphibolite in the Lopez and Rosario fault zones are brecciated at both the meso- and microscale, which we attribute to low (<200 °C) temperature deformation associated with emplacement of these blocks along the fault zones. These brittle features are cut by static veins of aragonite, prehnite, and lawsonite. (b) Veins of lawsonite in cleaved sandstone from the Lopez zone were either folded (shortened) or pulled apart (extended), depending on their orientation with respect to the SMT cleavage (Brandon, 1980). (c) The dominant textural habits of minerals related to high-P metamorphism (that is, lawsonite, aragonite, prehnite), on the one hand, and the fine-grained phyllosilicates defining the SMT cleavage fabric, on the other, are utterly different. With few exceptions, the high-P minerals show static, nondirected textures in the rocks of the fault zones and the nappes alike. Newly grown, very fine-grained white mica and chlorite are typically strongly directed and define a penetrative planar fabric at the microscale. High-P metamorphic conditions might have persisted locally during the development of the SMT cleavage, given that aragonite fills some extension fractures (for example, Fig. 7 in M&B), but we have yet to find clear-cut cases where such a vein formed concurrent with cleavage development.

KINEMATIC INDICATORS FROM THE FAULT ZONES

M&B also use kinematic indicators from the Rosario and Lopez faults to support their interpretation of a top-to-the-northwest direction of transport. It is important to note that these indicators give contrary directions: 38 indicated top-to-the-northwest, and 16 indicated top-to-the-southeast. Brown (1987) also found mixed results for his study of kinematic indicators from related Late Cretaceous fault zones to the east, in the North Cascade Mountains. Neither of these papers considers why the indicators give conflicting results. Instead, the authors jump to the conclusion that the transport direction corresponds to the dominant mode in distribution of the data. Can this approach be justified? Our observations (Cowan and Brandon, 1990) suggest that the kinematic indicators in the Lopez and Rosario fault zones were widely dispersed within the plane of the fault zones by random rotations around a fault-normal axis. On the basis of synoptic analysis of these structures, we conclude that transport was generally in a top-to-the-southwest direction.

CONCLUSIONS

Our observations in the southern San Juan Islands show that there are two temporally distinct sets of mesoscale structures and fabric elements of Late Cretaceous age. M&B (p. 1014) lumped them together as "tectonite fabrics . . . coeval with the thrusting [that] record the kinematics of this event." In our view, the earlier family of nonpenetrative mesoscale structures is restricted to fault zones and can indeed be used to interpret the kinematics associated with thrust faulting (Cowan and Brandon, 1990). The penetrative foliation and local weak lineation, developed after thrusting and superimposed on fault rocks and nappes alike, are related to the formation of an SMT cleavage. Straight fiber overgrowths indicate that deformation attending cleavage formation was coaxial. There is no evidence of transpressive shear at this stage of deformation. The cleavage records large amounts of shortening in a southwest-northeast direction. We interpret this penetrative cleavage to have formed while the nappes were in residence within a southwest-facing orogenic wedge (Brandon and others, 1988). Fisher and Byrne (1992) present a similar interpretation for a penetrative dissolution cleavage in the Kodiak Formation, part of a Late Cretaceous accretionary wedge in southwest Alaska.

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Reply

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INTRODUCTION

We initiated our study of kinematic features in the San Juan thrust system because knowledge of the transport direction is of considerable importance in understanding the mechanics of mid-Cretaceous orogeny in the Pacific Northwest, and because no one else had worked on this problem. The previous studies (especially Brandon and others, 1988) provided an excellent base in terms of defining the lithology, age, and origin of units; the metamorphic grade; and the age of faulting; but very little fabric description was given in these studies and virtually no kinematic analysis based on outcrop study. In reviewing the observations reported by previous workers and new ones given in the Discussion of our paper by Brandon, Cowan, and Feehan, herein referred to as BC&F, we find considerable agreement with our own observations, but also some important differences. This exchange helps us all focus on the critical fabric elements that have led to such different interpretations for these rocks. We suggest a follow-up discussion on the outcrop.

THE FABRIC

BC&F state that there are two deformational fabrics associated with the San Juan thrusts, "an early cataclastic fabric that is confined to the fault zone, and a later widespread cleavage that postdates major fault slip." Their discussion focuses on the second fabric, and virtually nothing more is reported by BC&F or in earlier papers by Brandon and co-workers about the fabric in the fault zones. Our analysis focuses on both the fault zone fabric and the more widely developed sandstone fabric. We think the two fabrics are related and that both are the product of thrusting, for reasons given in our paper and again below. This disagreement not withstanding, however, the most significant kinematic features are seen in the fault zone fabric; this structure is not addressed by BC&F and we think therein lies a good part of our disagreement on the kinematics.

BC&F say that the widely developed cleavage in sandstone is not related to the thrust faulting but is superposed on the fault zones. We find that the strongly developed foliation in fault zone mylonitic rocks is parallel to the weaker cleavage in the blocks, and thus we relate the two structures. We have studied the published reports of Brandon and Cowan for description of evidence supporting their interpretation. Brandon (1980) states that the "S_1 cleavage must postdate movement of the major thrust faults in order to preserve its regionally consistent orientation." In the region over which this statement applies, however, the Rosario fault zone on southeast San Juan Island, our finding is that the faults have more or less the same orientations as the foliations. We find no evidence given in papers by Brandon that the faults and cleavage have different orientations. In agreement with our observations, Cowan and Miller (1981, p. 487) report that slaty cleavage in mudstone of the Lopez fault zone is "approximately parallel to the macroscopic, faulting-related fabric"; they also report that the cleavage is "superimposed upon the earlier features recording fault-related fragmentation." We have not observed a significant degree of cleavage development overprinting fault zone mylonitic rocks. We do, however, note some folding of the shear zone fabrics on northwest trending axes (our paper [Maekawa and Brown, 1991], p. 1012 and Fig. 3). This secondary deformation is post-thrusting and may represent southwest-northeast shortening.

In fault zone mylonitic rocks, lineations are defined by elongate porphyroclasts (including pulled-apart grains) and slickenlines. We illustrated and briefly described these lineations in our paper (p. 1010, Figs. 3 and 4). In more highly strained rocks, the lineations are defined by light-colored mineral "streaks" in an argillaceous matrix. The "streaks" are very fine-grained quartzofeldspathic mineral aggregates. They appear on the cleavage breakage surface as irregular elongate shapes about one to ten wide and with a five to ten times greater length than width. The origin of this material appears to be primarily disrupted veins and detrital clastic grains. In places, this structure is comparable to the "debris streaking" slickenline described by Means (1987), but it is transitional to a penetrative structure better termed a *stretching lineation.* Also on the breakage surface is a lineation defined by corrugations and grooves a few to ten or so millimeters in wavelength, similar to the ridge and groove slickenlines of Means (1987). In less-strained rocks, the fabrics contain elongate porphyroclasts and pulled-apart angular grains like the "cataclastic lineations" reported by Tanaka (1992) in a fault zone of central Japan. Lineations in the sandstone and in the fault zones are mutually parallel, and we see no overprinting relations between them, so our interpretation is that they represent a single deformational regime. In contrast to BC&F's observation of dominantly down-dip lineations (southwest trend), our measurements of 332 lineations in fault zones throughout the San Juan Islands (our paper, p. 1013) have a pronounced strike-parallel (northwest) trend.

DEFORMATION MECHANISM

BC&F emphasize the importance of solution mass transfer as a deformation mechanism in the San Juan thrust system. Brandon and others (1991) stated that a third of the rock in the San Juan nappe system has been lost by solution. Their technique for measuring solution deformation is based on the assumption that the present non-equant shape of clastic grains is due entirely to solution loss, that is, the longest dimension "provides an estimate of the mean grain dimensions in all directions" prior to solution loss. We note that if part of the present grain shape is due to mechanisms other than solution, then this technique for calculating volume loss is invalid. Thus, it seems that Brandon and others (1991) did not recognize any strain mechanism in the San Juan nappes other than pressure solution. We accept that pressure solution was operative to a degree (our paper, p. 1012) but question the concept that solution was the exclusive, or dominant, deformational mechanism producing fabric in these rocks. Most deformed grains in sandstone that we have looked at lack the planar truncation surfaces and bordering concentrations of dark insoluble materials that one expects from pressure solution (Gray, 1978; Ramsay and Huber, 1983, p. 117), as illustrated in our paper (Figs. 5 and 6). We do see some pressure solution effects, but in addition, we see abundant evidence for non-solution deformation (Fig. 1), including (1) cataclastic shear surfaces cutting grains, (2) extension fractures and broad pull-apart features normal to the direction of grain elongation, and (3) strained grains with undulatory extinction indicating that some change of grain shape was caused by crystal-plastic deformation (Ramsay and Huber, 1983, p. 117). We are surprised that BC&F have apparently not observed shear fabric in the San Juan nappes.

RELATIVE TIMING OF FAULTING, METAMORPHISM, AND FABRIC

The timing of events and formation of structures according to BC&F is first, thrust faulting and associated brecciation; second, high-pressure metamorphism; and third, formation of the solution cleavage and associated lineation. They emphasize a temporal discontinuity in this sequence. They say we have misrepresented their earlier publications in equating the time of high-pressure metamorphism with that of the faulting. Brandon and others (1988, p. 38), however, stated that "high-pressure metamorphism was related to structural burial during thrusting." In support of this interpretation, they cited fabric relations: "cataclastic fabrics in these [tectonic] slices, which were developed during their emplacement along the San Juan thrusts, are overprinted by undeformed aggregates and veins of lawsonite, prehnite, and aragonite" and "broken and folded veins of prehnite and lawsonite are present locally in Constitution sandstones . . . indicating that some deformation postdated metamorphism." We see the same kind of evidence and arrive at the same conclusion, that high-pressure metamorphism occurred during deformation (p. 1012).

BC&F interpret foliation defined by white mica and chlorite to be the product of a deformation that postdates high-pressure metamorphism because the high-pressure index minerals are typically not well aligned. We do not understand this argument. To decide which came first, foliation or high-pressure minerals, we need to see an overprinting relation. We find the chlorite-mica foliation commonly crosscut by undeformed aragonite veins and thus interpret the foliation to predate the high-pressure veins.

KINEMATIC ANALYSIS

BC&F question the kinematic significance of shear-sense features we report because of our mixed results (38 give top to the northwest, 16 give top to the southeast), and they suggest that we do not offer an explanation for this heterogeneity. In fact, we do present an explanation in our paper (p. 1012). We refer to the paper by Ghosh and Ramberg (1976) that reported experimental studies and theoretical considerations implying that deformation in a shear regime in which there are components of both pure and simple shear may lead to a mixed sense of rotation of inclusions in matrix, depending on the ratio of the rates of pure to simple shear, and the orientation and axial ratio of the inclusion. This approach to vorticity analysis has been adopted by numerous other workers (for example, Passchier, 1987; Cowan, 1990; Simpson and De Paor, 1991). The San Juan fabrics suggest to us that both pure and simple shear were operative, and pending further analysis, we are satisfied with this explanation.

Our kinematic study is based in large part on the cataclastic rocks developed along the margins of the exotic tectonic slices of Garrison Schist and Turtleback Complex and in fault zones. Brandon and others (1988) reported such rocks and, like us, attribute their origin to thrusting. The exotic nature of the tectonic slices (barroisite schist) relative to the dominant regional units (graywacke and chert) is testimony to considerable movement along the thrusts, as stated by Brandon and Cowan (1987) and Brandon (1989). The cataclastic rocks in the fault zones have evidence of translation; they are mylonitic rocks with well-developed foliation and less well-developed, but locally prominent, stretching and slickenline lineations. These lineations are northwest trending and, together with shear sense features, provide evidence for northwest-directed, orogen-parallel transport of the San Juan nappes.

BC&F's interpretation that the San Juans have experienced post-thrusting southwest-northeast contraction seems reasonable to us based on the weak northwest-southeast–trending folds we have seen overprinting fault zone mylonitic rocks, and also the apparently folded nature of the Rosario thrust on a regional scale (map pattern in Fig. 2 of Brandon and others, 1988). We do not, however, agree with their assertion that the prominent deformational fabric in the region is related to this event.

SUMMARY

In agreement with Brandon and co-authors, we view the presence of exotic slices in the Rosario and Lopez fault zones as indicating large translation along these fault zones, and that cataclastic fabrics in the fault zones are the product of faulting. Departing from the findings of

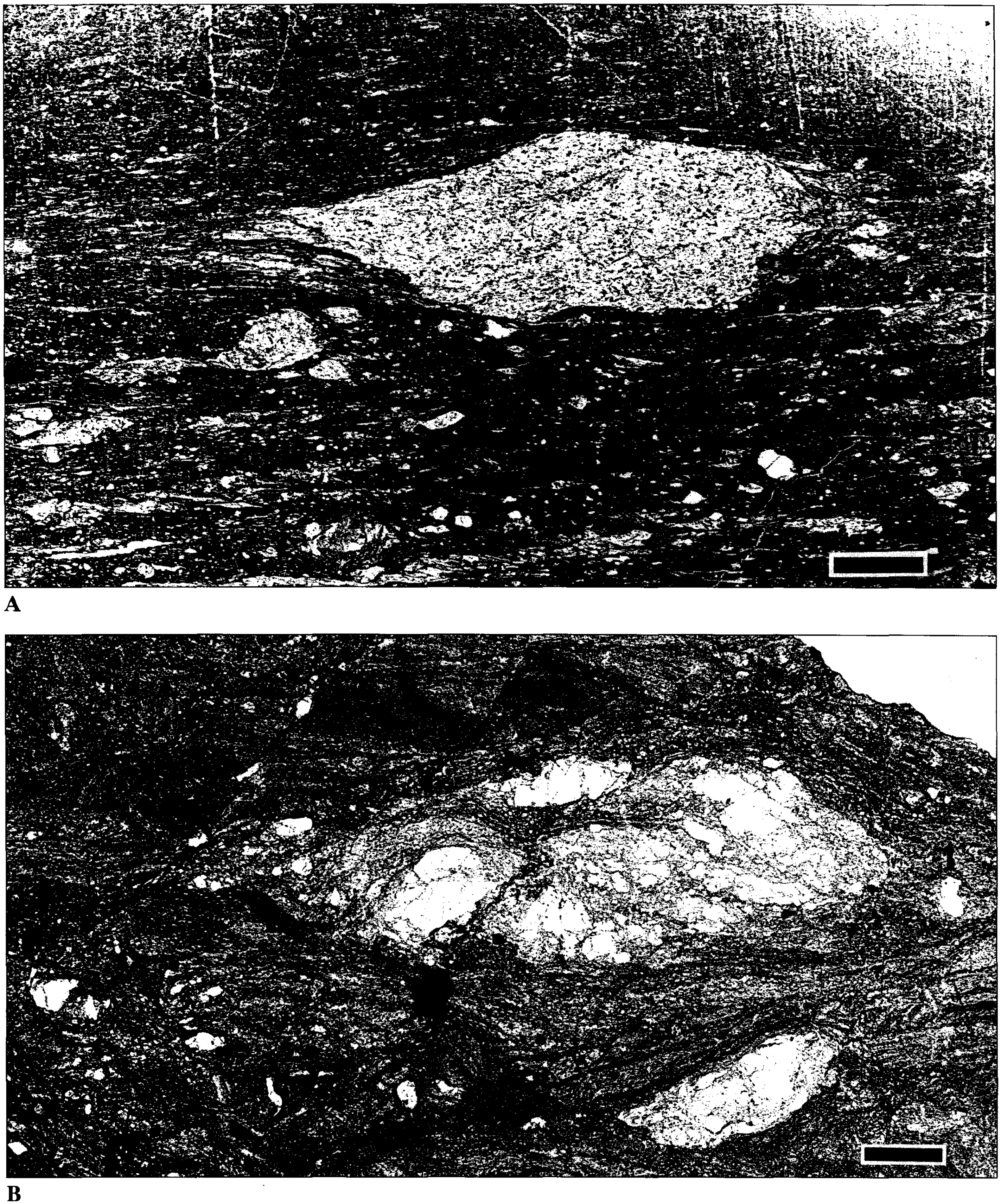

Figure 1. Cataclastic textures in thrust fabrics of the San Juan Islands. Scale bar in both samples is 2 mm. A. Deformed sandstone containing siltstone lithic fragments in sheared argillaceous matrix. B. Fault breccia consisting of broken quartzofeldspathic porphyroclasts in sheared matrix. Quartz grains have strong undulatory extinction in microscope view.

these workers, we have observed foliation, stretching lineations, and noncoaxial shear features in the fault-zone fabrics. We observe similar, but less-pronounced, fabrics in blocks of sandstone near the faults. Because the sandstone fabrics display the same orientations, kinematics, and relative age as the shear-zone fabrics, we interpret them also to be the product of thrusting. Although we agree that a component of the deformation resulted from solution mass transfer, we see abundant evidence for cataclastic and crystal-plastic strain and do not accept the concept that coaxial solution mass transfer was the exclusive strain mechanism. Our measurements of the fault zone and sandstone fabrics indicate northwest-southeast–trending shallow plunge lineations and a predominant upper plate to the northwest sense of shear.

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