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Strain analysis of the Ninemile fault zone, western Montana: insights into multiply deformed regions

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Abstract

By means of detailed field mapping and a systematic strain analysis we investigated the development of the Ninemile fault in western Montana. The fault has been considered to be either a Mesozoic or mid-Tertiary strike-slip fault, or a Late Eocene–Early Oligocene normal fault. The rock of the study area experienced a Mesozoic to early Tertiary NE–SW shortening expressed by thrusts, folds, and pervasive cleavage. We estimated total strain by measuring preferred orientation of chlorite grains in samples from within and near the Ninemile fault zone and by calculating the strain according to the March theory. Our goal was to explain how strain accumulated by successive superposition of strains during the two deformation events onto an early compaction strain. In all samples the minimum-elongation direction (= maximum shortening) is nearly vertical. The maximum-elongation directions of all the samples outside the Ninemile shear zone are subperpendicular to the strike of the shear zone, whereas in the shear zone they are either parallel to the strike of the shear zone or form an angle of about 45°. The systematic variation in the principal strain directions is the result of two deformational events expressed by local structures created by early NE–SW shortening and later NE–SW extension. The observed strain requires that the Ninemile fault, a normal fault during the Tertiary, had earlier been either a thrust or a zone of contractional shear deformation, along which there was fault-perpendicular shortening and fault-parallel extension. Although the average value of maximum elongation is greater within the Ninemile shear zone than outside, it varies significantly inside the fault zone, suggesting a highly inhomogeneous strain distribution created by a complex deformation history.

1. Introduction

The Ninemile fault is an important element of the E–W-trending Lewis-and-Clark line in Montana and Idaho, which consists of a series of NW–WNW-trending faults and folds (Billingsley and Locke, 1939; Fig. 1). This fault was interpreted either as a large-scale, Late Cretaceous left-slip fault on the basis of the apparent 170-km separation of the Mesozoic batholith north and south of the Lewis-and-Clark line (e.g., Sales, 1968), or as a right-slip fault because the Lewis-and-Clark line links the Purcell trench detachment fault to the north and the Bitterroot detach-

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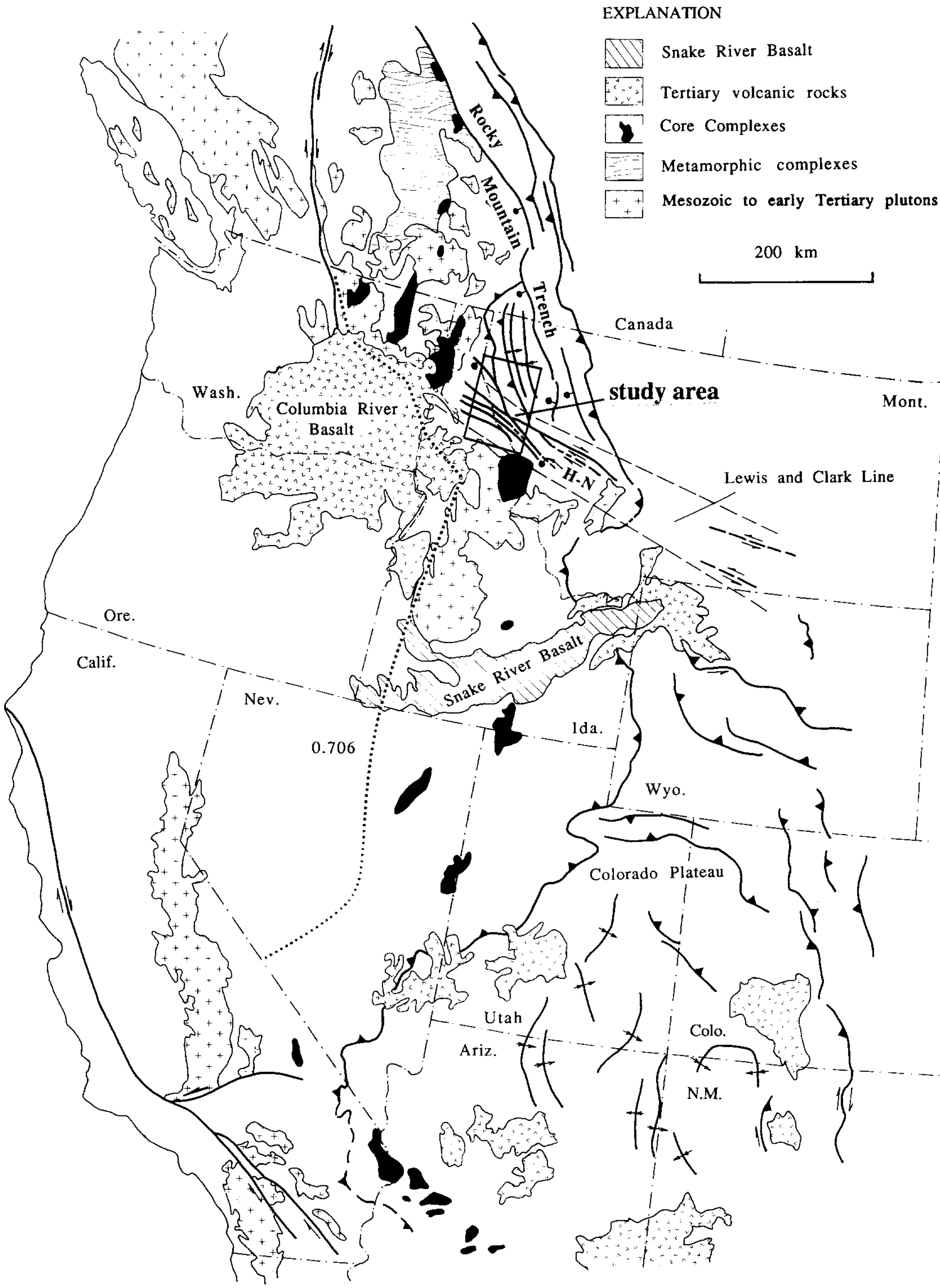

Fig. 1. Regional tectonic map of U.S. Cordillera and location of the study area. H–N = Hope–Ninemile fault system.

ment fault to the south (Fig. 1; Rehrig et al., 1987), a map relationship implying that the faults in the Lewis-and-Clark line are right-slip transfer faults that connect the two Eocene extensional domains. Recent field mapping and detailed kinematic studies along the Ninemile fault and its northern extension, the Hope fault, suggest that it is a Tertiary normal fault (Yin, 1991; Yin, 1992; Yin et al., 1994). The latter conclusion is based on: (1) the consistent younger-over-older relationship across the fault; (2) down-dip lineation on phyllonitic foliation surfaces in the fault zone, down-dip striations in the fault zone, and widespread minor normal faults directly below the fault; (3) microstructures, such as asymmetric strain shadows observed in thin sections, and mesoscopic structures, such as asymmetric folds and offset beds in the shear zone.

In this paper, we show that the Ninemile fault could have been a thrust during the Mesozoic to early Tertiary and was later reactivated as a normal fault in mid-Tertiary times. This interpretation is based on both field relations and strain patterns across the Ninemile fault. Strain was determined by measuring in each sample the preferred orientation of phyllosilicate minerals using an X-ray pole-figure goniometer. The corresponding total strain was calculated according to March's theory. We first describe the geologic structures in and adjacent to the Ninemile fault zone near Quinns, Montana, and then present the strain data, and finally discuss implications for the structural evolution of the region.

2. Regional geology

In the western Montana study area (Figs. 1 and 2), the major stratigraphic units include middle Proterozoic argillite and quartz arenite of the Belt Supergroup and Tertiary–Quaternary sandstone, mudstone, conglomerate. The latter are distributed either in fault-bounded basins or as alluvium and moraine deposits. The region experienced at least three major tectonic events: (1) rifting related to the formation of the Belt Basin in the Proterozoic (Harrison et al., 1974; cf. Winston, 1986); (2) Mesozoic to early Tertiary thrusting and folding (Harrison et al., 1986; Fillipone and Yin, 1994); and (3) Eocene to Early Oligocene extension (Hyndman et al., 1988; Fillipone et al., 1992; Fillipone, 1993). The first is expressed by numerous mafic sills in the Prichard Formation of the lower Belt Supergroup. These sills are interpreted to be synchronous with the deposition of the Prichard strata in the middle Proterozoic (Buckley and Sears, 1992). Thrusts and folds that developed during the Mesozoic and early Tertiary trend mostly N–S north of the Thompson Pass fault and WNW to NW south of it (Figs. 1 and 2). The Ninemile fault is parallel to folds and thrusts on both sides of it. Associated with them is a spaced cleavage, a common feature in western Montana (Fillipone and Yin, 1994; Fig. 3a). In the study area, Tertiary extension produced both the Ninemile fault and its northwestern extension, the Hope fault (Fig. 2). They formed synchronously with the Bitterroot and Purcell Trench detachment faults in western Montana and northern Idaho, respectively, and the Rocky Mountain Trench normal fault system that extends from southeastern British Columbia to western Montana (Rehrig et al., 1987; Harms and Price, 1992; Yin, 1992; Fillipone, 1993).

3. Structural geology

Geologic mapping at a scale of 1:24,000 defined the structural setting of the samples collected for the strain analysis (Figs. 2 and 3a). The Ninemile fault is well exposed where the Clark Fork River crosses the fault. The fault zone is 20 to 150 meters wide and is defined by a phyllonitic foliation with a down-dip stretching lineation on its surface (Figs. 4a and 4b). In thin section, the lineation is defined mostly by stretched quartz grains. Pyrite crystals are common, and many carry strain shadows, both symmetric and asymmetric.

The fault juxtaposes the Prichard Formation (older) against the Burke Formation (younger), both of the Proterozoic Belt Supergroup, but the Prichard Formation occurs in both the hanging wall and footwall. In addition to deformation related to motion along the Ninemile fault, emplacement of the mafic sills in the Prichard Formation produced minor folds and thrusts with variable orientations along their margins. In the northeastern corner of the study area, the major compressional structures of the footwall are NW-striking thrusts and NW-trending folds (Fig. 3a). Offsets along the thrusts do not exceed several hundred meters (Fig. 3). A well developed spaced cleavage dips steeply (Fig. 3a) and generally strikes N–S. However, near the thrusts and folds, its strike parallels the thrusts and folds (Fig. 3a). This relationship may be due to the effect of cleavage refraction controlled by lithologic contrast (e.g., Treagues, 1983), which would imply that strain rates varied spatially during the same episode of deformation.

Immediately above the Ninemile fault, intense contractional deformation is expressed by closely spaced thrusts and folds in the Burke Formation (Fig. 5 and its location in Fig. 3a). These thrusts and folds belong structurally to the eastern limb of a 60-km-long, locally overturned anticline (Fig. 2). Because the contractional structures are parallel to the Ninemile fault and found only along the trace and in the hanging wall of the Ninemile fault, we speculate that the Tertiary Ninemile

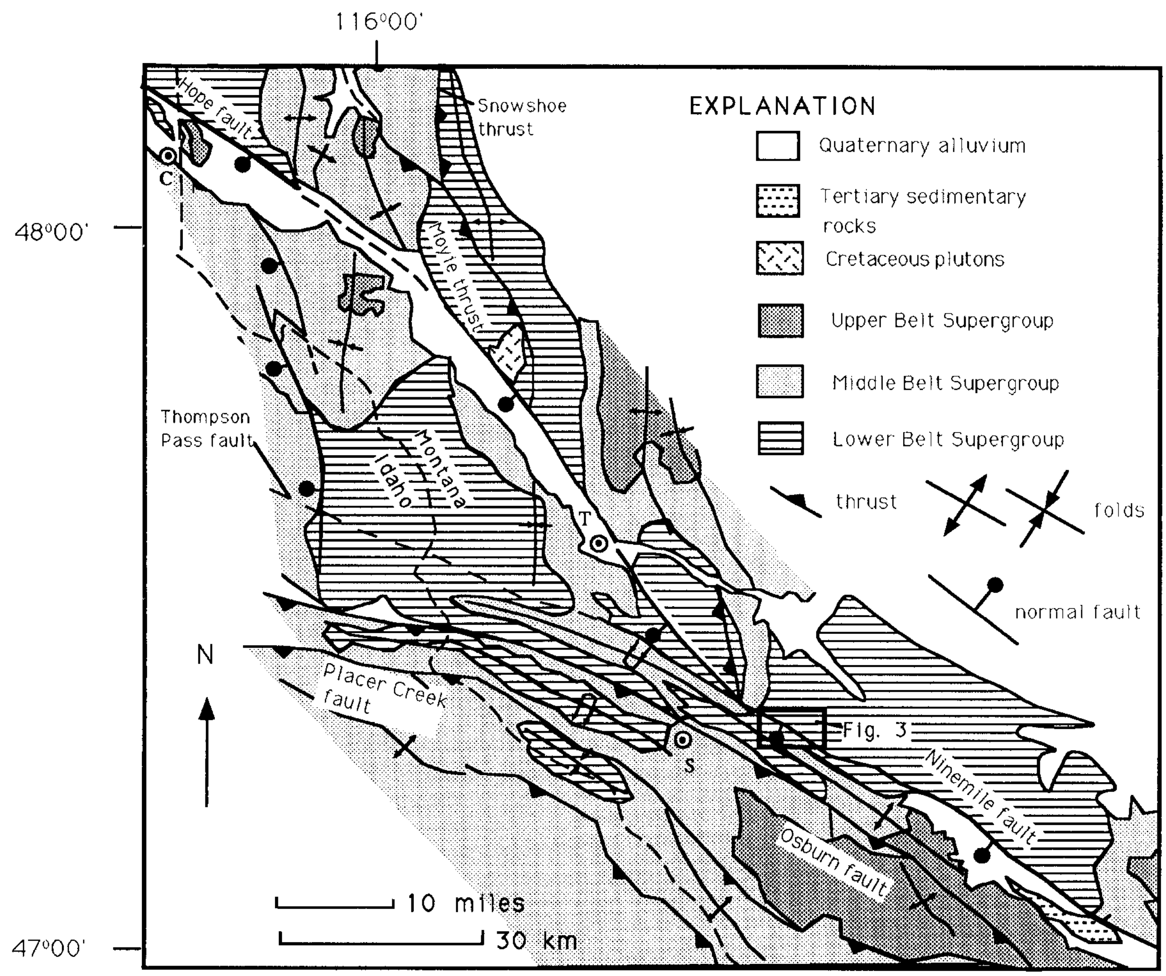

Fig. 2. Regional geology of western Montana and northern Idaho and structures along the western Lewis-and-Clark line. C = Clark Fork; T = Thompson Fall; S = Superior.

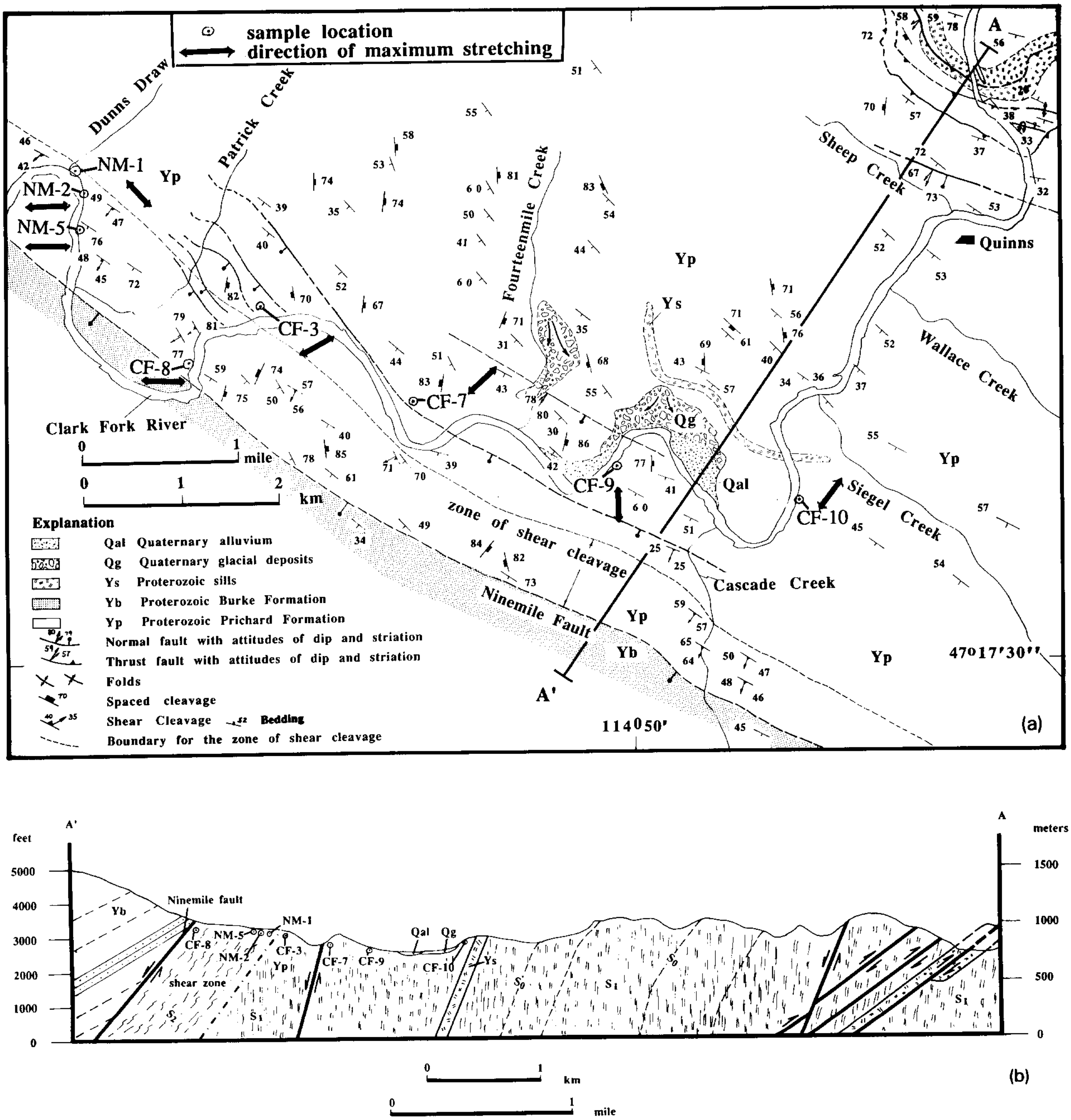

Fig. 3. (a) Sample locations and directions of maximum elongation in a detailed geologic strip map along the Clark Fork River near Quinns, Montana. (b) Geologic cross-section across the Ninemile fault (see Fig. 2 for location). Sample locations projected onto the section plane. Symbols: S_0 = bedding; S_1 = axial-plane cleavage formed during the Mesozoic to early Tertiary E–W shortening; S_2 = shear cleavage in the Ninemile shear zone; *Yb* = Burke Formation and *Yp* = Prichard Formation, both of the middle Proterozoic Belt Supergroup; *Ys* = middle Proterozoic sills in the Prichard Formation; *Qal* = Quaternary alluvium deposits; and *Qg* = Quaternary glacial deposits.

normal fault was reactivated from a thrust or a limb of an overturned anticline that had developed earlier.

4. Method

Figures 2 and 3 show the location and structural position of eight oriented samples in the Ninemile fault zone and its footwall. Directions and magnitudes of March strains (March, 1932; Oertel, 1983,1985) were measured for these samples, and the spatial relationship of the strains to bedding (S_0), cleavage (S_1), and phyllonitic foliation (S_2) are shown in Fig. 3a.

Based on measurements of the preferred orientation of chlorite grains in the individual samples on an X-ray pole-figure goniometer (Oertel, 1985; Wenk, 1985), we calculated March strains according to the theory of March (1932) by the procedure discussed in detail by Oertel (1983) and Oertel et al. (1989).

March's theory of the preferred orientation of platy mineral grains due to strain starts from the assumption that the platy grains were originally oriented at random, either at deposition or after subsequent bioturbation. Later, the grains develop a preferred orientation progressively more parallel to bedding as compaction proceeds and pores collapse, resulting in a pole distribution that is axially symmetric about the bedding pole. Where a tectonic strain follows compaction, or proceeds simultaneously with it, platy grains rotate so that their flat surfaces tend to face the

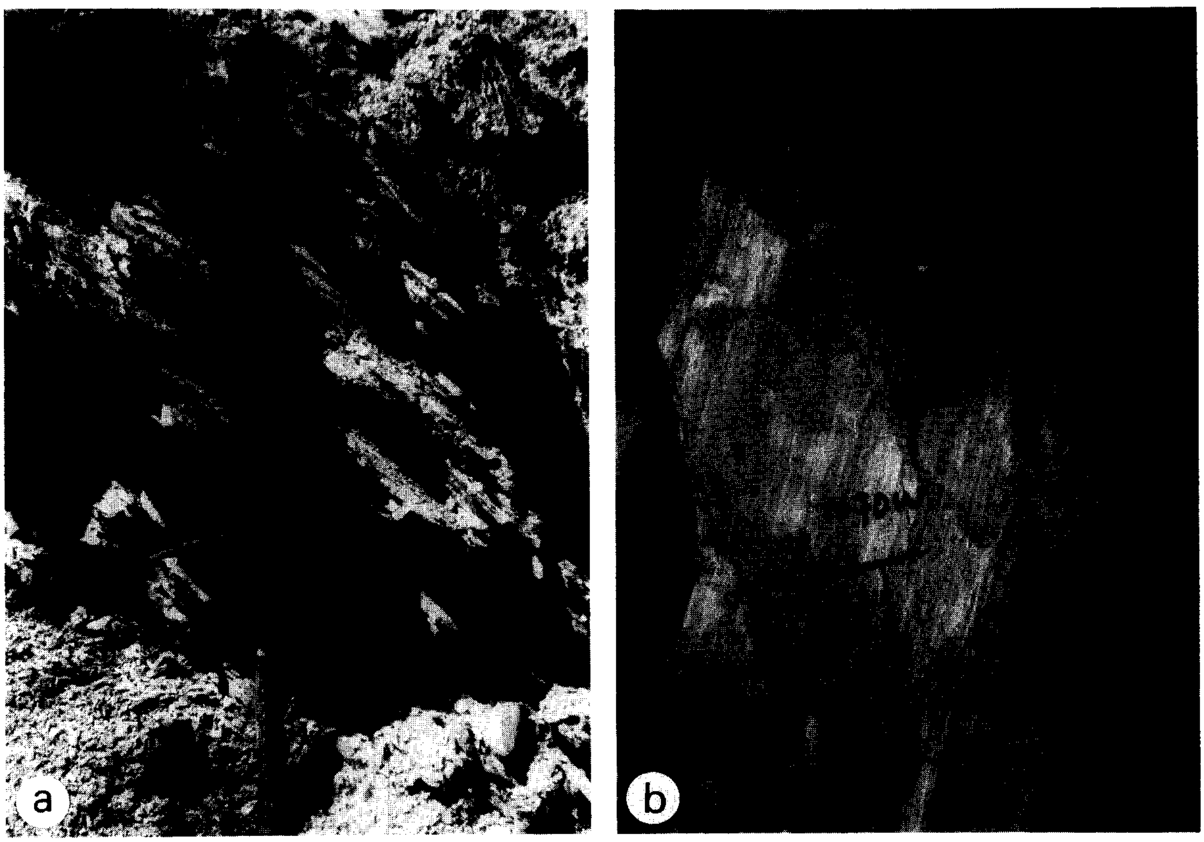

Fig. 4. (a) Shear zone along the Ninemile fault, characterized by a phyllonitic foliation with down-dip lineation, view to southeast. (b) Photomicrograph of stretching mineral lineation on the phyllonitic foliation, a pencil of ~ 10 cm long as scale.

direction of maximum tectonic compression. An observed preferred orientation in a mudrock thus reflects the cumulative strain from its deposition onward. Because grain preferred orientation provides no information on volume change, March strain is conventionally stated as strain at constant volume; this is not meant to imply that no volume loss has actually occurred.

The validity of strain estimates according to March depends on the preservation, since deposition, of actual detrital phyllosilicate grains, or of their crystallographic basal planes if they have been diagenetically transformed from clay-mineral to chlorite grains. Arguments in favor of such preservation have been adduced by Oertel (1983,1985, for rocks of lower greenschist or lesser metamorphic grade. Dollase (1986) has demonstrated that the assumptions of the March theory correctly describe the kinetic effects of compaction in X-ray diffraction powder samples.

5. Results

Four of the eight samples (NM-1, NM-2, NM-5, and CF-8) were collected in the Ninemile fault zone and another four (CF-3, CF-7, CF-9, and CF-10) from the footwall (Fig. 3a). The magnitudes and directions of the maximum (e_1), intermediate (e_2), and minimum (e_3) principal elongations are shown in Fig. 6 (see also Table 1). Note that all the principal strain directions are either nearly vertical or nearly horizontal, regardless of the attitude of bedding, S_1 cleavage, and S_2 phyllonitic foliation. The minimum-elongation direction is nearly vertical for all samples, and the maximum-elongation direction is thus nearly horizontal.

The maximum-elongation direction in the shear zone is either parallel (NM-1) to the strike of the phyllonitic foliation (S_2) and the Ninemile fault (Fig. 2), or it forms with them an angle of about 45° (NM-2, NM-5, and CF-8). Except for one sample (NM-1), the maximum-elongation directions from the shear zone are perpendicular to the strike of the spaced cleavage (S_1). If the cleavage were related to the measured strain, we would expect the minimum-elongation direction (e_3), not the maximum-elongation direction (e_1), to be perpendicular to the cleavage strike, suggesting that the cumulative strain is not directly related to its formation. The maximum-elongation direction of all samples outside the shear zone is perpendicular to the Ninemile fault, or nearly so (Fig. 2), but is oblique to the strike of the spaced cleavage (S_1). This relationship suggests that the strain outside the fault zone records a NE–SW extensional deformation, probably associated with the development of the Ninemile fault itself.

One may be tempted to explain the difference in direction between the maximum elongation in and outside the shear zone by a rigid-body rotation in the shear zone about a vertical axis, taking the strain axes with it; the direction of maximum elongation in the zone appears to be consistent with a right slip along the Ninemile fault which may also have caused the rigid rotation. Such an interpretation, however, is inconsistent with several field observations. First, neither the bedding (S_0) nor the older spaced cleavage (S_1) are rotated in the Ninemile shear zone (Fig. 3). Second,

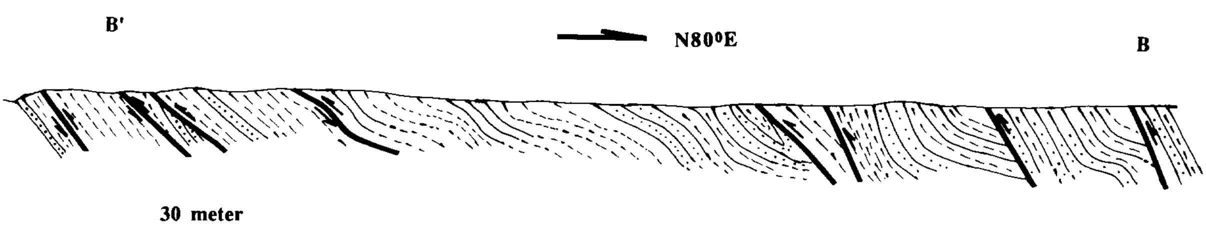

Fig. 5. Sketched cross-section across the hanging wall of the Ninemile fault (see Fig. 3a for location). Note the well-developed folds and thrusts are located in the eastern limb of a large anticline shown in Fig. 2.

Table 1
Table of principal elongations

CF-8	$e_1 = 1.43$	$e_2 = 0.95$	$e_3 = 0.74$
NM-5	$e_1 = 2.52$	$e_2 = 1.10$	$e_3 = 0.36$
NM-2	$e_1 = 1.79$	$e_2 = 0.93$	$e_3 = 0.60$
NM-1	$e_1 = 2.84$	$e_2 = 1.07$	$e_3 = 0.33$
CF-3	$e_1 = 1.61$	$e_2 = 0.89$	$e_3 = 0.70$
CF-7	$e_1 = 2.09$	$e_2 = 1.48$	$e_3 = 0.32$
CF-9	$e_1 = 1.30$	$e_2 = 0.97$	$e_3 = 0.79$
CF-10	$e_1 = 2.24$	$e_2 = 1.45$	$e_3 = 0.31$

the stretching mineral lineation on the phyllonitic foliation surface that is observed in the shear zone is oriented parallel to the foliation dip, indicating dip-slip rather than strike-slip motion on the Ninemile fault. An additional observation makes the strike-slip interpretation implausible, all measured strains in the study area have their minimum-elongation direction vertical, independently of the attitudes of bedding and cleavage. This strain pattern is rather more consistent with dip-slip than with strike-slip faulting.

Because March strain is a cumulative strain since deposition, its geologic interpretation involves consideration of the entire strain history in the area, taking into account both the whole deformational sequence and all constraints provided by field relationships. We interpret the sequence of deformation events in the study area as follows: (1) compaction during the deposition of the Belt Supergroup, producing a strain pattern that is axially symmetric about the bedding pole; (2) shortening in the NE–SW direction, creating thrusts, folds, rotation of beds about fold axes, an axial-plane cleavage (S_1), and strain with a horizontal NE–SW least-elongation direction; and (3) extension in the NE–SW direction, inducing normal faulting along the Ninemile fault and strain with a horizontal NE–SW maximum-elongation direction.

It is a puzzling feature of the observed strain field that the maximum-elongation directions away from the Ninemile fault appear to be more compatible with the Ninemile fault as a normal fault than those in the very shear zone which accompanies the fault (Fig. 2). This apparent contradiction can be resolved by assuming that the region had been pervasively but inhomogeneously deformed before the Ninemile fault existed and was later affected by another, more

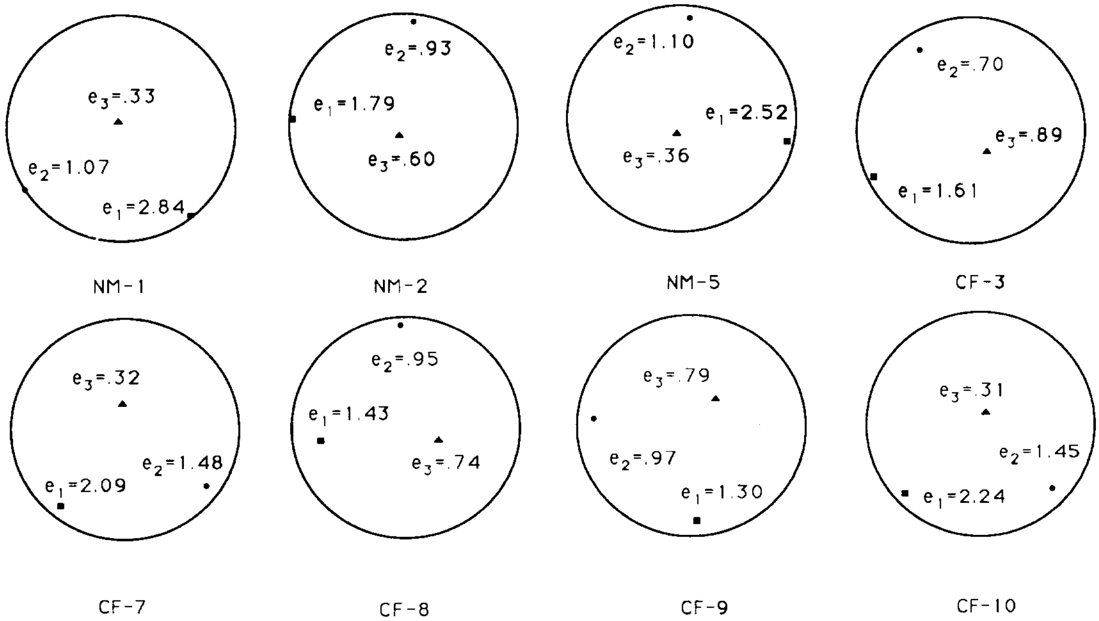

Fig. 6. Stereographic representation of principal elongations and directions of March strains in the footwall of the Ninemile fault (see Fig. 3a for locations). Maximum (e_1), intermediate (e_2), and minimum (e_3) principal elongations.

uniform, superposed, strain at the time of the formation of the fault. The most intensive contractional deformation is concentrated in the hanging wall of the Ninemile fault, near its trace.

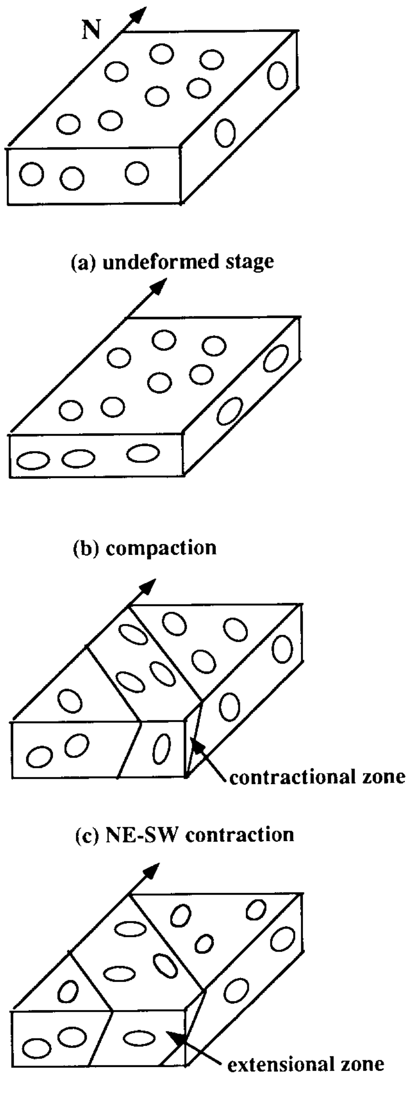

Fig. 7. Schematic diagram showing a possible strain history leading to the observed pattern. (a) Undeformed strain markers are spherical; (b) markers after compaction; (c) after NE–SW shortening and formation of the contractional zone along the Ninemile fault; and finally (d) after superposition of NE–SW extension.

This suggests one of two possibilities; either the Ninemile fault was a discrete thrust before it became active as a normal fault, or near its present trace a zone of strong horizontal contraction formed with its minimum elongation perpendicular to the strike of the future Ninemile fault. This strain, in turn, would have been superposed onto the earlier strain caused by compaction of the Belt strata under their own overburden.

The intensity of the NE–SW shortening strain was probably not uniform but greatest within a zone near the present Ninemile fault, and it generally tapered off outside that zone. Such a strain pattern is schematically shown in Fig. 7. When onto this strain field, and the corresponding early structural framework, the later NE–SW regional extension was superimposed, it modified the inherited principal strain directions. It did so most sharply where the older strains had been weak, but only slightly in the shear zone, where they had been intensive. The stress responsible for the late extension might also have reactivated the Ninemile fault as a normal fault.

Strain superposition must have 'moved' the old maximum-elongation direction toward the new, that is toward orthogonality with the Ninemile fault, except in those rare cases in which the early maximum-elongation direction was near-perfectly parallel to the shear zone and the superposed strain not very intensive, so that the principal strain directions would remain virtually unchanged. Such may be the case of sample NM-1. However, where the parallelism of the early maximum-elongation direction with the zone trend was imperfect and the superposed strain relatively intensive, the new principal directions could significantly differ from the old. The less coaxial with its predecessor the superimposed strain was, and the greater its relative intensity, the more the principal directions of the compound strain are affected. This could explain the axis orientations in the shear zone samples NM-2, NM-5, and CF-8 (Figs. 2 and 7).

Reactivation of thrusts as normal faults is known to be common in western Montana and southeastern British Columbia. For example, the normal Oligocene Flathead fault along the eastern edge of the Rocky Mountain Trench normal-

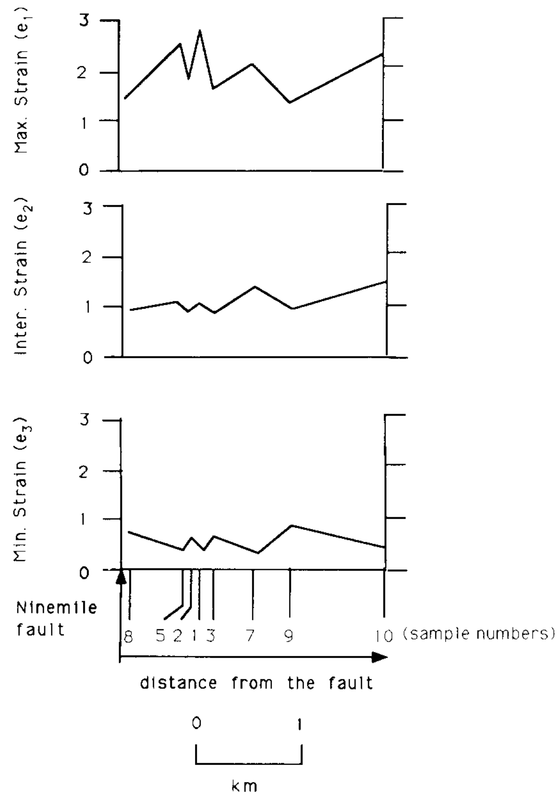

Fig. 8. Variation as a function of distance from the Ninemile fault of (a) maximum (e_1), (b) intermediate (e_2), and (c) minimum (e_3) principal elongations.

fault system was formed by reactivation of a ramp of the Lewis thrust (e.g., Bally et al., 1966).

The variation of the principal compound-strain elongations in the footwall of the Ninemile fault as a function of distance from the fault is shown in Fig. 8. Although the largest maximum elongation in every sample inside the fault zone exceeds that of every sample outside, none of the elongations vary systematically within either of the zones. Thus, the maximum elongations (e_1) both increase and decrease away from the Ninemile fault (Fig. 8). The same holds for the intermediate and minimum elongations.

6. Conclusions

(1) March strains in all samples have their minimum elongation (the direction of maximum shortening) nearly vertical and thus the maximum elongation nearly horizontal, independently of the attitudes of bedding, cleavage and foliation.

(2) The maximum elongations in all samples outside the Ninemile shear zone are perpendicular to its strike, whereas inside the zone they are either parallel to its strike or they form with it an angle of about 45°. This systematic difference in strain orientation can be interpreted as the superposition onto an early NE–SW shortening of a later NE–SW extension in the zone near the Ninemile fault. Together with the field relationships, this requires either that the Ninemile fault had been a discrete thrust that was reactivated as a normal fault, or that a diffuse contractional zone associated with early folding was later overprinted by NE–SW extension.

(3) Although the maximum elongation is greater inside the shear zone along the Ninemile fault than outside, it varies significantly within that zone, suggesting inhomogeneity of deformation.

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