Kink band development in the Darrington Phyllite on Samish Island, northwestern Washington

Rachel E. (Rachel Eliades) Dunham

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KINK BAND DEVELOPMENT IN THE DARRINGTON PHYLLITE
ON SAMISH ISLAND, NORTHWESTERN WASHINGTON

BY

RACHEL ELIADES DUNHAM

Accepted in Partial Completion
of the Requirements for the Degree

Master of Science

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Rachel Dunham
July 9, 2010
KINK BAND DEVELOPMENT IN THE DARRINGTON PHYLLITE
ON SAMISH ISLAND, NORTHWESTERN WASHINGTON

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Rachel Eliades Dunham
July 2010
ABSTRACT

Kink bands are sharp-hinged monoclinal folds that are common contractional deformation features in fine-grained, foliated rocks. Two competing geometric models of kink band formation are mobile-hinge kinking, where a kink band grows by lateral expansion of kink band hinges, and fixed-hinge kinking, where a kink band initiates at a given width and rotates to accommodate shortening. This study investigates previously identified but poorly characterized kink bands in the Darrington Phyllite on Samish Island, northwestern Washington, in order to evaluate the applicability of each model and to characterize the complex geometries of kink bands in plan view.

Two sets of kink bands are present on Samish Island, kinking a steeply south-dipping foliation. The majority of bands have axial surfaces that dip moderately NE, and a small number of bands have axial surfaces that dip steeply SW; true conjugate bands are rare. Mapping and measurements of more than 500 kink bands in the field indicate that bands are generally narrow (<1 cm) and closely spaced (<10 cm), with small populations of wide and widely spaced bands. Kink band angles measured in the field indicate that many bands conform to an ideal kink band geometry with equal internal and external angles between the kinked and unkinked foliations; however, a significant number of bands deviate from the ideal case. Veins are closely associated with many kink bands; sigmoidal veins crossing kink bands and triangular voids along kink band boundaries suggest dilation during kinking.

This is the first study to apply geometric curvature analysis to kink bands in order to quantitatively describe kink band morphologies in plan view. 3D scans of hand
samples produced digital elevation maps of complicated kink band patterns and intersections, and geometric curvature calculations based on these scans provide detailed maps of kink band hinges, intersections, and locations of elevated strain. Curvature maps clearly outline the behavior of intersecting bands in crossing (X), bifurcating or merging (Y), and previously unrecognized oblique (λ) intersections. Statistical analyses on values extracted from the curvature maps show relationships between relief, gradient, and curvature of hinges. Shortening accommodated by kink bands is less than 5%, comparable to shortening of less than 10% calculated from field data.

Thin section and magnetic fabric analyses indicate that interlayer slip occurred during kinking. Interlayer slip during kinking may have sheared the magnetic fabric within the band, producing less anisotropic and more shallowly rotated fabric than predicted from the kink band geometry. Dilation spaces are also visible in thin section, where unrecrystallized quartz and/or calcite fill dilation spaces, and mica layers protrude into the dilation spaces from inside the kink bands due to interlayer slip. No broken grains or other evidence for boundary migration were observed in thin section.

The variability of kink band angles, prominence of dilation spaces along kink band hinges and inside bands, and the lack of migration structures in the field or in thin section all suggest fixed-hinge, rotational kinking was the dominant mechanism of kink band development for these bands in the Darrington Phyllite. The orientation of the monoclinal kink band sets, the small amount of shortening, and the interpretation of fixed-hinge kinking are all consistent with kink band development during late-stage unroofing at low confining pressure under northeast/southwest compression.
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CHAPTER 1: INTRODUCTION

Kink bands are small monoclinal folds with sharp hinges that occur in fine-grained, foliated rocks. Kink bands commonly occur in sets, and are generally associated with late stages of contractional deformation. Kink bands are very common in contractional deformation zones but are still poorly understood; further investigation of natural kink bands is essential for evaluating previously proposed kinematic models for their development and understanding the fundamental behaviors of deforming rocks.

Kink bands have been well studied in the field in a variety of locations, including Caledonian slates, shales, and sandstones (e.g. Anderson, 1964; Anderson, 1968; Hobson, 1973), the slate belts of western Europe (e.g. Verbeek, 1978; Kirschner and Teixell, 1996; Julivert and Soldevila, 1998; Debacker et al., 2008), and slates and siltstones of eastern Canada (e.g. Clifford, 1968; Fyson, 1968). The majority of work on kink bands was published in the late 1960s to 1970s, though there have been a few recent papers further investigating kink band geometries and association with regional structures. Several models were proposed by various authors as possibilities for the initiation and propagation of kink folds; however, no consensus has been reached on a single model for kink band development. Continued study of kink bands provides more observations to evaluate the viability and applicability of previous geometric and kinematic models to natural kink bands.

The study presented in this thesis characterizes a well-developed set of kink bands in the Darrington Phyllite at several scales: in outcrop, hand sample, and microstructures via thin section and magnetic fabrics. The kink bands of the Darrington Phyllite have not
been well characterized; they are documented by one previous study (Lamb, 2000). Full characterization of the kink bands requires careful measurements of many geometric parameters (e.g. spacing, width, kink angles) as well as structural parameters (e.g. axial plane and hinge line orientations, foliation and lineation orientations) in order to assess patterns within outcrops and across the entire exposure. The variety of exposures in the field area on Samish Island (Figure 1.1) provide a three-dimensional view of the kink bands, so variation in the plane of the foliation as well as in cross section (the traditional view) can be measured. Outcrop maps provide a macroscopic view of kink bands in situ, demonstrating the dense networks of bands and complicated morphologies and intersections in the plane of the foliation, as well as providing a reference for field measurements. Hand samples allow for close examination of kink band shapes and geometries, and geometric curvature analysis can quantify the shapes of kink bands and the geometry of kink band hinges. Thin sections and magnetic fabric analyses provide a microscopic look at the mineral fabric and microstructures that accommodate deformation.

This study uses the comprehensive characterization of kink bands in the Darrington Phyllite to evaluate several models for kink band development proposed by previous workers. Dewey (1965) proposed several geometric models for kinking based on field investigations of kink bands; Weiss (1980) further developed two of these geometric models: the migration model and the rotation model. Other workers (e.g. Verbeek, 1978; Stewart and Alvarez, 1991) discussed the applicability of such geometric models to field observations and analog experiments, but there is still no consensus on a single mode of kink band development. Honea and Johnson (1976) developed theoretical
Figure 1.1. Schematic geologic map of Samish Island. Jurassic bedrock (Darrington Phyllite) is exposed only on the northern point of the island as beach exposures and in a quarry (X); the remainder of the island consists mainly of Quaternary glacial deposits. Geology from Jones (1999); topographic underlay from Google Maps.
equations of kink band initiation based on buckle folding but did not expand their
equations to the propagation and development of nucleated kink bands. Other studies of
natural kink bands (e.g. Anderson, 1968; Clifford, 1968; Hobson, 1973; Verbeek, 1978;
Kirschner and Teixell, 1996; Debacker et al., 2008) focused mainly on outcrop-scale
features and geometries, usually qualitatively and in the context of a regional deformation
framework. Analog and rock experiments (e.g. Paterson and Weiss, 1966; Stewart and
Alvarez, 1991) reported some observations of microstructures and fabric in thin section,
but detailed descriptions of natural kink bands in thin section are uncommon in the
literature. The geometric and mathematical parameters of the principal kink band
models, coupled with previous descriptions of kink bands in outcrop and in experiments,
describe different expected characteristics for each model that can be tested with data
collected from the kink bands in the Darrington Phyllite.

Kink Band Background
 Geometry of Kink Bands

Kink bands are a special form of folds with straight limbs, sharp hinges, and
strong asymmetry between the two limbs (Figure 1.2a). They occur in strongly
anisotropic (e.g. foliated) rocks. A single kink band consists of two long (undeformed)
limbs bracketing a shorter “kinked” (deformed) limb, and the traces of the axial planes of
the hinges mark the boundaries of the kink band. Previous workers have defined a
number of special angles between the foliation, both inside and outside the kink band,
and the kink band boundaries (e.g. Verbeek, 1978; Figure 1.2b): the external (acute)
angle ($\alpha$) between the foliation (undeformed) and the kink band boundary; the internal
Figure 1.2. Schematic illustrations of kink band geometry. (a) A kink band deforming a well-developed foliation and lineation. Sharp, angular hinges delineate the change from uninked to kinked material. (b) Angular relationships between the kinked and uninked foliation and the kink band boundaries and geometric dimensions, based on Verbeek (1978).
angle ($\beta$) between the foliation (kinked) and the kink band boundary; and the rotation angle ($\kappa$) between the kinked and uninked foliation, where $\kappa=180^\circ-\alpha-\beta$ (Weiss, 1980; Twiss and Moores, 1992). Kink bands can occur singly or as conjugate sets (Figure 1.3); ideal conjugate kink bands have equal external and internal kink angles of 60º (Ramsay, 1967). Conjugate kink bands persist up to about 25% shortening; beyond this point, kink bands begin to converge as chevron folds (Ramsay, 1967).

**Previous Work**

Field studies (e.g. Anderson, 1964; Dewey, 1965; Anderson, 1968; Clifford, 1968; Hobson, 1973; Verbeek, 1978; Kirschner and Teixell, 1996), deformation experiments with analog materials (e.g. Gay and Weiss, 1974; Honea and Johnson, 1976) and foliated rock (e.g. Paterson and Weiss, 1966; Donath, 1968), and modeling studies (e.g. Honea and Johnson, 1976; Weiss, 1980) have investigated the geometric and mechanical characteristics of kink bands in fine-grained, anisotropic rocks and analog materials. Early deformation experiments in natural phyllite by Paterson and Weiss (1966) showed that kink bands occur when the principal compressive stress ($\sigma_1$) is parallel or subparallel to the foliation, and the geometry and orientation of the kink bands are closely related to the angle between $\sigma_1$ and the foliation. Compression parallel to the foliation at high confining pressures produced conjugate kink bands with axial planes oriented roughly 60º from the direction of shortening; as the direction of shortening became more oblique, the subset of kink bands dipping opposite to the foliation became more dominant, and eventually produced a system of monoclinical kink bands. Kink bands
Figure 1.3. Development of a conjugate kink fold in a foliated rock. Conjugate kink bands require that $\alpha = \beta = 60^\circ$ at all times. Redrawn from Ramsay (1967).
initiated at low (1-5%) strains and persisted up to roughly 45% strain, at which point folding became pervasive and evolved to chevron folding.

Gay and Weiss (1974) made similar observations in experimentally deformed paper card decks and natural slate, and determined that the transition from conjugate to monoclinal kink bands occurred when $\sigma_1$ was 5-15° from the foliation. The orientations of kink bands as defined by the angles $\alpha$, $\beta$, and $\kappa$ were directly related to the orientation of $\sigma_1$, and plots of the kink angles vs. the angle between $\sigma_1$ and the foliation produced linear relationships that can be used to determine the orientation of $\sigma_1$ based on measured kink angles alone.

Honea and Johnson (1976) investigated the mechanics of kink fold initiation by deforming packets of rubber strips and modeling the observed structures as deformation of viscous multilayers. Their experiments showed that kink bands initiate via frictional slip between foliation layers as sinusoidal buckle folds, localized to imperfections in the multilayers. The mathematical solutions derived from these experiments suggest that kink folding is the preferred mode of deformation when the number of layers is great, the initial folding amplitude is low, frictional strength exists between the layers, and the axial load is low compared to the maximum allowed for kink folding. The theory put forth by Honea and Johnson (1976) applies only to the initiation of kink folds in ideal elastic multilayers, and does not address the growth and propagation of kink folds.

Weiss (1980) proposed that kink bands propagate by rotation of the internal foliation and/or outward migration of the kink band hinges, based on previous analog experiments (e.g. Paterson and Weiss, 1966; Donath, 1968; Gay and Weiss, 1974) and the geometric properties of kink bands. Lateral propagation of kink bands from lens-like
nucleation sites is accomplished by either of two modes (or a combination) of kink band growth: mode I involves progressive rotation of the internal foliation coupled with lateral migration of the kink band boundaries (Figure 1.4a), and mode II involves purely lateral migration with no internal rotation (Figure 1.4b). Deformation may transition from mode I to mode II to maximize the mechanical work done by the kink band, and this transition effectively “locks” the kink band at some fixed angle $\kappa$. This angle is predicted by Weiss’ (1980) mechanical work calculations to be $\sim 57^\circ$, which corresponds to experimental averages observed by Paterson and Weiss (1966). Stewart and Alvarez (1991) tested Weiss’ (1980) predictions and models based on paper card experiments, and showed that at low strains (0-10%) mode I growth dominates and shortening is accommodated by nucleation of new bands rather than expansion of preexisting bands; at higher strains (10-35%) new bands cease to nucleate and existing bands expand via mode II growth. Nucleation of new bands should result in a denser network of kink bands (more closely spaced bands), and the relationship between spacing and maturity parameters (e.g. kink angles, rotation angle, width) may be used to determine whether nucleation was a dominant mechanism. Alternatively, if width and spacing are fixed at initiation, there should be no correlation with maturity and no nucleation of new bands as deformation progresses (Hobson, 1973).

Observations of kink bands in the field have provided a wealth of information on the geometries and physical characteristics of both conjugate and monoclinal kink band sets. In cross-section, kink bands are generally straight and parallel, either in conjugate or monoclinal sets, and have angular relationships that in many cases deviate from the ideal $\alpha = \beta$ (e.g. Dewey, 1965; Anderson, 1968; Clifford, 1968; Hobson, 1973; Stewart
Mobile-hinge (migration) models

(a) Mode I  
(b) Mode II

Fixed-hinge (rotation) models

(c) Mode III  
(d) Mode IV

Figure 1.4. Four kinematic models for kink band development. Mobile-hinge kinking models are shown in (a) and (b): the kink band grows by incorporating new material, either by (a) increasing the kink angle $\kappa$ and decreasing the external and internal kink angles (shown here as $\gamma$ and $\gamma_k$), or (b) maintaining its orientation and laterally migrating outwards. Fixed-hinge models are shown in (c) and (d): the kink band is initiated at a fixed kinked width and progresses by (c) shear along the kink band boundaries, increasing $\kappa$ and changing both $\gamma$ and $\gamma_k$ independently, or (d) rigid rotation of the internal foliation, resulting in dilation within the kink band, reaching maximum dilation when the internal kink angle is 90° and decreasing to no dilation when $\gamma = \gamma_k$ (locking of the kink band). Reproduced from Twiss and Moores (1992).
and Alvarez, 1991). Hobson (1973) observed three types of kink band terminations in cross section: monoclinal flexures, or decreasing amplitude without convergence of the kink band boundaries; thinning and tapering of kink bands to points defined by convergence of the boundaries; and truncation against large quartz veins or coarse-grained layers. Tension gashes, en echelon veins, and quartz- or calcite-filled void spaces are also commonly associated with kink bands, but absent in the adjacent, undeformed foliation (Dewey, 1965; Hobson, 1973; Verbeek, 1978). Statistical analyses of measured parameters such as spacing, width, kink angles, and rotation angles indicate variable correlations between geometric parameters that yield insight on possible formation mechanisms (e.g. Clifford, 1968; Fyson, 1968; Hobson, 1973). Shortening accommodated by kink bands is generally small, less than 10% (Anderson, 1964; Dewey, 1965; Anderson, 1968; Verbeek, 1978).

The geometry and behavior of kink bands in the third dimension (i.e. on the foliation surface) is poorly understood, and few descriptions have been published. Verbeek (1978) and Kirchner and Teixell (1996) describe a set of kink bands in the Somport Slates of the western Pyrenees that are characterized by curved kink boundaries and closely spaced, anastomosing bands. The kink bands form a monoclinal set, and conjugate bands are not observed (Verbeek, 1978). Kirchner and Teixell (1996) described three distinct geometries of intersecting kink bands on the foliation surface: truncating “T,” crossing “X,” and bifurcating or merging “Y,” (Figure 1.5); the intersections were all interpreted to be coeval in age and products of one deformation event. The lack of conjugate sets and the presence of curved kink boundaries are presented as evidence for possible stress field reorientation during kinking, though the
Figure 1.5. Field sketches of three types of kink band intersections. Reproduced from Kirschner and Teixell (1996).
authors acknowledge that this cannot fully explain the magnitude of curvature; further investigation is required to understand kink band formation due to non-plane-strain deformation.

**Kinematic Models of Kinking**

Two major kinematic models of kinking have been developed based on the field studies and deformation experiments described above; each of the models has two possible modes of kinking (Figure 1.4). The mobile-hinge model initiates with a kinked lens that widens by incorporation of new material with $\alpha = \beta$ at all times (Weiss, 1980; Stewart and Alvarez, 1991). New material is incorporated either by increasing the kink angle $\kappa$ and simultaneously decreasing $\alpha$ and $\beta$ equally (rotation + migration) or widening laterally with constant $\alpha = \beta$ (migration only) (Stewart and Alvarez, 1991); these two growth mechanisms correspond to growth modes I and II, respectively, of Weiss (1980). The fixed-hinge kink model initiates a kink band of fixed width at low $\kappa$ and progressively rotates the kinked limb to steeper $\kappa$, ideally locking when $\alpha = \beta$ (Dewey, 1965; Verbeek, 1978). Rotation is accomplished either by shear along the kink band boundaries, resulting in a volume loss inside the kink band and simple shear of the internal foliation (mode III), or rigid rotation of the internal foliation, requiring dilation between the internal foliation planes and along the kink band hinges and ceasing deformation (“locking”) when $\alpha = \beta$ (mode IV) (Verbeek, 1978; Stewart and Alvarez, 1991).

The kinematic models for kinking can be distinguished in their initiation and propagation mechanisms, and the distinct characteristics of each model can be tested by
further observations. The study presented in this thesis uses field outcrop observations, hand sample curvature analyses, and thin section and magnetic fabric analyses to characterize kink bands in the Darrington Phyllite and use those data to test the applicability, strengths, and weaknesses of the proposed models.

Geologic Setting

Darrington Phyllite

The Darrington Phyllite is part of the Shuksan Metamorphic Suite (Misch, 1966; Brown, 1986; Gallagher et al., 1988) (Figure 1.6). The Shuksan Metamorphic Suite represents ocean floor sedimentary and igneous rocks that have undergone subduction-related metamorphism and several subsequent deformational events (Haugerud, 1980; Haugerud et al., 1981; Brown, 1986). The Darrington Phyllite is a micaceous quartzose phyllite derived from Jurassic pelitic marine sediments (Misch, 1966; Haugerud et al., 1981; Gallagher et al., 1988). These sediments underwent subduction-related blueschist metamorphism at 120-130 Ma (Brown et al., 1981; Brown, 1987). The primary foliation of the phyllite is defined by aligned micas and graphite as a result of the high-pressure, low-temperature conditions during the blueschist facies event (Haugerud, 1980; Brown, 1987). Post-metamorphic deformation due to emplacement via thrusting in the late Cretaceous caused folding and the development of secondary foliation and lineation (Haugerud, 1980; Brown, 1986; Brown, 1987). A later deformation event produced a crenulation cleavage and small folds, including kink bands, with primary fold axes oriented roughly northwest/southeast (Haugerud, 1980; Haugerud et al., 1981).
Figure 1.6. Regional geologic map of northwestern Washington. The Darrington Phyllite is part of the Easton Terrane (green, EA), and is shown by the hachured areas. The study area for this thesis, Samish Island, is outlined by a box and labeled SI. Excerpted and modified from Brown and Dragovich (2003).
Samish Island

Kink bands in the Darrington Phyllite are well exposed in a series of outcrops along the northern point of Samish Island, south of Bellingham (Figure 1.1), and were previously identified in part of a broader structural study of the San Juan Islands (Lamb, 2000). The rocks fine from south to north along the shoreline, with the finest-grained and most micaceous phyllite found on the northern end. The rocks are derived from oceanic sediments, rich in quartz, feldspar, and lithic fragments, with metamorphic muscovite and chlorite. The rocks are recrystallized, with structures indicating deformation temperatures of 300 +/- 50º (Lamb, 2000), consistent with the metamorphic mineral phases of actinolite and pumpellyite that suggest metamorphic conditions of 200-350º C and 2-7 kbar (Lamb, 2000).

The structural history of Samish Island is multistage and complex, with at least five deformation events identified by Lamb (2000); that history is summarized here from Lamb’s work. The primary metamorphic fabric (S1) is strongly developed in most rocks, with V1 veins parallel to the foliation in many cases. A folding event (F2) produced isoclinal folds of S1/V1 and resulted in S2 axial plane fabrics and L2 lineations. A second folding event (F3) produced irregular folds and a weak pressure solution cleavage (S3). The folding events were followed by multiple faulting events and vein development during a period of extension. The most recent deformation events interpreted by Lamb (2000) include development of kink folds, strike-slip faults, and possibly further open folding of all preexisting structures. Lamb (2000) reports an Ar-Ar metamorphic age of ~ 154 Ma, which follows very closely on the late Jurassic depositional age of the rocks, indicating rapid subduction and metamorphism of the original sediments.
Kink bands in the Darrington Phyllite are well exposed in a series of coastal outcrops and an abandoned quarry along the northern point of Samish Island, Washington (Figure 2.1; Lamb, 2000). Kink bands range from several millimeters to several centimeters wide and are separated by up to tens of centimeters. The kink bands are laterally continuous for up to several meters along an outcrop and in many places can be traced around the side of an outcrop in three dimensions. On foliation surfaces, kink bands have highly curved boundaries, with complicated intersections forming anastomosing and lens-like patterns. There is a high density (10-100) of kink bands per outcrop, providing the opportunity to build a robust data set to characterize the kinks and assess relationships between different geometric parameters. The goal for field work was to characterize the geometries of kink bands in situ, to document their orientations and relationships with each other and with other structures (e.g. folds), and to determine spatial patterns or controls on the occurrence or appearance of kink bands across the exposures. The field observations are used to evaluate the four conceptual models of kinking described in Chapter 1.

**Methods**

Beach and quarry exposures were surveyed prior to measurements to locate outcrops with measureable kink bands. Measureable sections were limited to 1-3 meters wide and high for more accurate mapping and accessibility. Outcrops were photographed
Figure 2.1. Locations of major kink band outcrops on Samish Island. Detailed maps and measurements were made at outcrops labeled with bold italics.
using an Olympus 10.1 megapixel digital camera; each outcrop was broken into panels and high resolution photographs were taken for each section. The outcrops were mapped by hand in the field on prints of the photographs (Appendix A).

Scanline techniques (Priest and Hudson, 1981) were used to collect quantitative data from each outcrop. Measurements on the foliation surface were taken parallel to the mineral lineation that was generally perpendicular to the main kink band trend; measurements in cross section were taken parallel to the foliation trace (see Figure 1.2 for explanation of measured variables). Both surfaces were measured whenever possible for a three-dimensional view of the kink band patterns. The structural attitudes of the foliation and surface mineral lineation were recorded for each outcrop (Figure 2.2). For foliation surfaces, a tape measure was laid on the outcrop parallel to the mineral lineation, crossing the sequence of kink bands. Each kink band was numbered and the spacing between kink bands was recorded. Relief of the kink band on the surface was measured with a ruler, and the internal kinked width and perpendicular width of each band was measured with millimeter-scale calipers. The trend and plunge of kink band hinges where the tape measure crossed the kink band was measured with a Brunton compass. For perpendicular sections, the tape measure was laid parallel to the trace of the foliation, again crossing kink band boundaries. Spacing and widths were measured as before, and the axial plane of each kink fold was measured. Kink band boundaries in cross section are parallel; therefore, only one axial plane was recorded, and represents both hinges of the kink band. The external and internal kink angles were measured using a protractor; both angles were measured for both kink band boundaries and then averaged for one of each value per kink band.
Figure 2.2. Structural map of Samish Island. Representative foliations, lineations, and kink band orientations are shown for outcrops around the island. Black dots represent the locations of measurements and correspond to outcrop numbers shown in Figure 2.1; foliation/lineation orientations are shown to the left and kink band orientations are shown to the right of each dot. Kink band hinges were not always clearly measurable in all locations.
Samples were collected from multiple locations around the island for thin section and other laboratory analyses. Oriented samples were collected at six locations (outcrops Q4a, Q4, Q6, QX, B10, and B13; Figures 3.1 and 3.2), and other samples were collected from the float at the base of and near measured outcrops.

**Kink Band Exposures**

The quarry (Figure 2.3) exposes roughly 70 continuous meters of phyllite with visible kink bands, and extends as inaccessibly fractured and tightly folded rock for another 50 m. Kink bands are prevalent in the northwestern portion of the quarry, in many places running perpendicular to southwest-plunging, meter-scale folds (Figure 2.4). Meter-scale folds are also visible in the eastern portion, but kink bands are not readily observable. Throughout the quarry, pervasive fracturing has created blocks of phyllite that may or may not be in place; surfaces are irregular and most outcrops are only continuous for up to 1 or 2 meters. In beach outcrops, weathering controls kink band expression: small, fine bands are obscured in highly weathered outcrops and wide and long bands are highlighted. Fracturing is very common, and consistent fracture sets are apparent in many outcrops with kink bands. Kink bands are conspicuously absent in areas with intense folding and thick quartz veins in both the quarry and on the beach.

The dominant foliation (S1) on Samish Island strikes east and dips steeply southward (Figure 2.2), and in many places is gently to tightly folded around southwest-plunging axes. A pronounced mineral lineation is visible on most foliation surfaces, also plunging southwest (Figure 2.2). A second foliation (S2) is present in some places, most notably in the quarry (sections Q4, Q6, Q7), striking southeast and dipping moderately to
Figure 2.3. Map of the northern quarry wall and locations of kink band maps, samples, or photographs. The main quarry wall rises 8-10 meters above outcrops Q6 and Q7 and arcs to run north-south above outcrop Q8, which is a ground-level outcrop inside the quarry walls. Kink bands are concentrated along the northern wall due to the east-west trend that exposes the foliation surface; the north-south trend of the unstable eastern quarry wall (above Q8 and continuing to the south) is roughly parallel with the kink band trends and therefore does not expose the bands well. Mapped outcrops are labeled in bold; samples used for thin sections and magnetic fabric analyses were collected at dots labeled with italics.
Figure 2.4. Kink bands (red arrows) running perpendicular to southwest-plunging fold axes (black arrows), outcrop Q2. Large numbers on the tape measure are inches. Photo facing north/northeast.
the southwest; this foliation may represent an axial plane cleavage. Crenulation folds are present in the quarry (sections Q5 and QX); the crenulations are closely spaced (cm’s) and parallel the major fold axes. A third, spaced foliation (S3) is present on the northeastern side of the island (outcrop B13) and is poorly developed in most places. The majority of bands deform the primary (S1) foliation; a small subset of bands in the quarry kink S2 or the crenulation folds, and no kink bands clearly interact with S3.

Where a cross-sectional view of the foliation is visible, kink bands are roughly straight and parallel, are inclined to the foliation at high angles (Figure 2.2), and have dominantly “S” asymmetry. Intersections are rare in this plane, though some bifurcating (Y) and crossing (X) intersections are observed. Kink bands are dominantly monoclinal; true conjugate kink bands are very rare. Two sets of kink bands can be distinguished by their axial plane orientations (Figure 2.5a): the majority of kink bands (n=170) have axial planes dipping moderately northeast (set A); a small subset (n=40) have axial planes dipping steeply southwest (set B). When axial planes were not measurable, bands were not separated into the sets. The hinges of kink bands in both sets have shallow to moderate plunges that lie along a great circle striking northwest/southeast (Figure 2.5b). In many cases the hinges were close to horizontal and the foliation surface gently folded, so there is large scatter in the data. However, the girdle of hinges along a great circle is consistent with gentle folding after kinking; Lamb (2000) also suggested open folding after the kinking event.

Bands of set A are found in all outcrops except B6, B7, and B8; bands of set B are localized to those three outcrops, as well as Q5 and Q7. In outcrop Q7, both sets occur together (Figure 2.6a) but kink separate foliations: set A kinks S1, and set B kinks S2.
Figure 2.5. Stereoplots of (a) axial plane orientations and (b) hinge orientations for measured kink bands. Kink bands are divided into sets based on axial plane orientations: bands of set A have axial planes that generally dip moderately northeast, and bands of set B have axial planes that dip steeply southwest. For most hinge measurements it was not possible to determine the axial plane orientation of the kink band, so most are not divided into sets; however, hinges known to be in set A plunge moderately east/northeast, and those in set B plunge shallowly south/southeast.
Figure 2.6. Two kink band sets in outcrop Q7. (a) Bands of set A kink the main foliation of the quarry (S1) with relief on the surface of S1; bands of set B kink a secondary foliation (S2) that is close to perpendicular to S1. Axial planes of set A dip northeast, and those of set B dip southwest (photo looking north/northwest). (b) A band of set B cross-cuts two bands of set A. Both photos facing north/northwest.
In a meter-long exposure, there are twice as many kink bands of set A and set B, and those of set A are narrower and more closely spaced than those of B. Set A here consists of coherent kink bands with continuous traces of the foliation and lineation across the kink band boundaries; the bands of set B have fractured boundaries and are less coherent, and appear to taper at the ends. Set B appears to crosscut set A in several places (Figure 2.6b), implying that the two sets did not form concurrently.

Crossing kink sets similar to those seen in outcrop Q7 are also exposed on the beach in outcrop B10b; however, unlike in the quarry, both kink sets in B10b kink the same foliation and may represent a conjugate set. Thin (<1 cm) kink bands in a parallel set are cut by a few wider (1-3 cm) lens-like kinks with broken boundaries (Figure 2.7). The parallel set has axial planes that dip steeply northeast, consistent with the dominant kink set of the island; however, the lens-like kinks have a unique orientation, with axial planes dipping moderately southeast. Few intersections between the two orientations are clearly visible, though in at least one place it appears that the wider bands kink the parallel set (Figure 2.7).

On the foliation surface, kink bands commonly intersect due to curving or non-parallel trends of adjacent bands. Three types of intersections are visible: crossing (X), merging or bifurcating (Y), and truncating (T); some bands also end diffusely (D) (Figure 2.8). The most common intersections are Y-type, followed by T and/or D, and finally X; true crossing kinks are uncommon. In many places it is difficult to distinguish Y-type from X-type intersections, due to the very fine scale of the foliation and weathering that obscures the true path of a single kink band. In some places, a kink band will bifurcate and subsequently rejoin into a single band several centimeters away, creating a lozenge-
Figure 2.7. Crossing (conjugate?) kink bands in outcrop B10b. Most bands are thin and have axial planes dipping northeast (K1); two lens-like kinks are wider and have axial planes dipping southeast (K2). Most intersections between the two orientations are fractured or obscured by weathering/biogenic material; one less fractured intersection shows one of K2 kinking K1 in a conjugate geometry (expanded image). Photos facing southwest.
Figure 2.8. Kink band intersections on the foliation surface. (a) Bifurcating (Y) and crossing (X) intersections in outcrop Q4a. (b) Truncating (T) intersections in outcrop B13; note that two such intersections with similar orientations occur in adjacent bands here. (c) Diffuse (D) kink band end in outcrop Q4 that curves slightly towards an adjacent, continuous band. Photos facing north and down.
shaped zone of unkinked material between the bifurcated lines (especially common in section Q4a; Figure 2.9). In most T-type intersections the truncated band is thinner than the continuous band (Figure 2.8c) and join at a low angle; the true behavior of T-type intersections is better illuminated by describing the behavior of the hinges using geometric curvature (see Chapter 3).

Kink band patterns on the foliation surface are difficult to unravel due to an abundance of intersections and anastomosing kink band trends that are not always easily traced. Section Q4a exposes several meters of a relatively continuous foliation surface with kink bands running roughly horizontally across the outcrop (Appendix A4). In this section, most if not all kink bands curve to some degree as they travel across the surface, ranging from gentle curvature to very tight arcs. The amount of curvature is not consistent between adjacent kink bands; in several places a series of gently curving kinks is cut by a thick, tightly arced kink (Figure 2.10).

A consistent parallel set of kink bands is exposed on a moderately weathered foliation surface on the northwestern side of the island (outcrop B10). Thin (~1 cm) kink bands are spaced several centimeters apart at regular intervals along several meters of continuous outcrop; the cross-sectional view is too weathered for any confidence in mapping. Intersections between kink bands are limited, almost exclusively Y-type, and split kink bands commonly recombine with adjacent kinks, rather than forming lenses of unkinked material bounded by a single split band. Most striking about this outcrop is a regular fracture set that parallels the kink bands and occurs roughly every three kinks (Figure 2.11). The fractures are clearly associated with the kink bands but appear to occur in the middle of bands, not along the boundaries; kinked foliation is visible on both
Figure 2.9. Doubly-merging bands in outcrop Q4a. Yellow dashed lines outline the traces of two kink bands that bifurcate and rejoin within several centimeters, forming a lozenge-shaped zone of unkinked material between the two strands. Photo facing north.
Figure 2.10. Variably curving bands in outcrop Q4a. Most bands are gently curved and run left-right on the outcrop face; one wide band (red arrow) curves sharply across the general band trend. Photograph facing north.
Figure 2.11. Fractures parallel to kink bands in outcrop B10. Kink bands are more closely spaced than the fractures, with roughly three kink bands between each fracture. Fractures do not occur on the kink band boundaries themselves, but are bounded by kinked material on both sides (e.g. along the central through-going fracture). Two Y-type intersections (arrows) are seen in the bands to the left.
sides of several fractures, and on at least one side in almost all fractures. Kink band boundaries serve as natural planes of weakness along which stress can concentrate, and fracturing along the boundaries could be associated with deformation post-locking of the kink bands; however, fractures within the kink bands, not associated with the planes of weakness suggests that the fractures are post-kinking and are not related to the phase of deformation that produced the kink bands.

In coarser-grained, quartz-rich outcrops on the southwestern side of the island, kink bands appear to be wider and with slightly rounded hinges; however, outcrops are very wave-worn, which may obscure or artificially smooth kink band expressions. Kink bands in these outcrops (B5-B9) are widely spaced (tens of centimeters) and do not form clear parallel sets (Appendix A10). In a few, less worn locations (B2, B3, B4), dense sequences of parallel kink bands are visible (Appendix A9), though difficult to resolve in photographs or to measure in the field. Close examination of wave-worn outcrops indicates that thinner kink bands may exist between the wider, still visible kink bands, but are more easily obscured by weathering. Measurements were taken on the least weathered exposures to minimize a bias against thin bands.

In more micaceous and fine-grained rocks on the northeastern side (B13), complicated kink bands are well exposed on the foliation surface, and step-like breaks in the outcrop allow for cross-sectional views as well. Kink bands are very thin (millimeters to 1 centimeter) and very closely spaced (millimeters to a few centimeters), and extend for tens of centimeters to meters in length. Cross-sectional views show generally straight and parallel kink bands deforming the foliation (Figure 2.12) but on the foliation surface all three types of intersections (X, Y, and T) are very common.
Figure 2.12. Kink bands in the plane perpendicular to the foliation in outcrop B13. In cross-section, kink bands are relatively straight and parallel, with few intersections. On the foliation surface (oblique to the photograph), kink bands curve and intersect. Photograph facing east.
In many places, the density of intersections makes it difficult to trace the paths of individual kink bands. There is also variation in the relief of the kink surface, ranging from less than a millimeter to several millimeters; there is no clear sequence or spacing for high relief kinks, though areas with many kink bands intersecting tend to have more relief than single kinks alone.

The widest kink bands (Figure 2.13a) are in section Q5, an area with many small folds. In several meters of outcrop only a few kink bands are present, unlike the more common dense population of kinks within a smaller area. The bands are very wide (many centimeters) and widely spaced (tens of centimeters), and are very long (at least 1.5 m exposed). The outcrop surface is complexly warped, and foliation vs. lineation is difficult to interpret due to a closely spaced sequence of small folds and crenulations on the folded surface. The kink bands run at a high angle to the fold axes, and the smaller kinks appear to thin into an hourglass shape near the fold hinges; wider kinks do not appear to be affected by folding. In several places kink bands deformed the crenulated folds (Figure 2.12b); kinked crenulation cleavage is also visible several meters west of outcrop Q6.

Veins

Veins are closely associated with kink bands in many places. Three generations of veins were distinguished by Lamb (2000) in her study of the rocks and structure of Samish Island: thin quartz/calcite veins (V1) parallel to the main foliation (S2); thicker, intensely folded quartz/calcite veins (V2) associated with larger scale folds; and undeformed extensional quartz veins (V3) that occur as en echelon sets in many places.
Figure 2.13. Extremely wide kink bands in outcrop Q5.  (a) Oblique view of the exposed face at Q5 showing at least 5 widely spaced, wide kink bands (arrows) with associated veins.  The outcrop faces south; photograph taken facing northwest.  (b) Wide kink band deforming a crenulated surface above Q5.  The crenulation parallels fold hinges in this outcrop that plunge southwest.  White quartz precipitation is visible along the kink band hinges.  Photograph facing northwest.
All three generations of veins have relationships with kink bands, showing both pre- and post-kinking development, and in several places multiple generations of veins occur within an outcrop. In addition, void fill and quartz/calcite precipitation are associated with many kink band hinges and internal foliations, which has bearing on the question of dilation during kinking. Veins were not measured in detail for this study; however, observations were made on the geometries of veins and their relationships with kink bands.

V1 veins are visible in several beach outcrops, with and without associated kink bands. Where kink bands occur, V1 veins highlight the trace of the kinked foliation through the kink band boundaries (Figure 2.14a). V1 veins are generally thin (<5 mm) and occur in both deformed and undeformed areas. V2 veins are associated with intense outcrop-scale folding, and are parasitically folded within larger-scale folds. Thick (2-10 cm) V2 veins are composed mainly of quartz, confirmed by their high relief on outcrop surfaces due to higher resistance to weathering. Areas of intense folding occur all over the island but are not continuous; several meters of intense folding are usually bracketed by meters of relatively undeformed phyllite. Kink bands were not observed to occur in areas with intense folding and thick, folded veins; these structures disrupt the planar fabric of the phyllite and therefore may act as local barriers to kink band development. Undeformed, en echelon V3 veins are associated with kink bands in many places, away from areas of major folding. Where V3 veins occur with kink bands, the trends of the en echelon sets usually cross the kink bands at low angles; however, V3 veins are not always associated with kink bands.
Figure 2.14. Veins associated with kink bands on the beach. (a) V1 veins parallel to the foliation are visibly kinked. The main kink band in the center of the photograph kinks several quartz veins; the thin kink band on the right kinks the thinner quartz veins but ends at the thicker quartz vein near the center, while a new kink band initiates just below the quartz vein and continues. Photo taken about 15 m north of outcrop B13, facing south. (b) A quartz vein cuts and offsets a kink band in outcrop B13, indicating post-kinking vein growth. Photo facing east.
Many outcrops expose veins with variable orientations crossing or adjacent to kink bands. Where veins cross kink bands, the deflection angle for the vein is usually not the same as the foliation deflection angle; that is, the vein crosses the kink band boundaries at a different angle than the kinked foliation or lineation (Figure 2.15a). Veins commonly thicken within the kinks themselves, especially adjacent to the kink band boundaries. In section Q2, a series of relatively evenly spaced quartz veins cut a single kink band at high angles but do not remain continuous through the kink band itself (Figure 2.15b). Veins crossing the lower kink boundary continue to and then parallel the upper boundary for 1-2 cm; paired veins begin on the lower boundary and then cut upward across the upper boundary and through the undeformed rock. Individual veins also cross kink bands and in a few places visibly offset the kinks (Figure 2.14b).

Sigmoidal veins and triangular voids are closely associated with kink bands in many places. Small (1-2 cm long, millimeters wide), delicate sigmoidal veins are arranged en echelon across kink band boundaries in several locations (e.g. Q4, Q5). In some cases, small void spaces along the boundaries are connected by thin veins through the kink band itself (Figure 2.16a). The portion of the veins inside the kink bands are not parallel to the kinked foliation, but cross the foliation at very low angles. Larger sigmoidal veins (5-10 cm long, up to 2 cm wide) are associated with exceptionally wide kink bands in section Q5 of the quarry (Figure 2.16b). These veins appear to have disaggregated the kink band into sections and further rotated these sections to high $\kappa$ values. Roughly triangular voids filled with quartz along kink band hinges are also common in outcrops regardless of other vein fill (Figure 2.16c, 2.17a). In the coarse-grained kinked rocks on the southwestern side beach, wave-worn exposures show
Figure 2.15. Veins crossing kink bands in the quarry. (a) In outcrop Q1, a thin vein (yellow dashed line) approaches a kink band obliquely on the foliation surface, angles across the kink band, and continues on the other side along its original trajectory. Note that the vein thickens inside the kink band but does not kink at the same angle as the kinked lineation (red). (b) En echelon veins cut kink bands in outcrop Q2. Each set of veins approach the kink band along similar trajectories but travel along the kink band boundaries rather than joining as one vein; one such set is outlined in black. Here, veins appear to be controlled by the kinked lineation. Both photographs facing north.
Figure 2.16. Vein and void fill associated with wide kink bands in outcrop Q5.  
(a) Small dilation spaces along the kink band hinges are connected through the 
kink band by thin, wispy veins that cut across the kinked foliation.  (b) Very wide 
en echelon sigmoidal veins that have disaggregated the kink band into variably-
rotated packets.  (c) Triangular void spaces along the kink band hinges at the 
lower end of the same band shown in (b).  All photographs facing north.
Figure 2.17. Dilation spaces along kink band boundaries are highlighted in wave-worn beach rocks near outcrop B5. (a) Small pockets of white quartz are visible along the kink band boundaries; V1 veins are also kinked in this rock. (b) Triangular hollows in this kink suggest that the voids were once filled with quartz or calcite that has since been dissolved away. Photos facing southeast and down.
triangular hollows within the kink band hinges that were likely once filled with quartz or calcite that has since been dissolved away (Figure 2.17b).

**Analysis of Field Measurements**

Field measurements were analyzed for possible relationships between the measured parameters (see Figure 1.2 for illustration of variables). Analyses were conducted separately for both kink band sets A and B discussed above. Histograms of measured parameters were made for each set, as well as for subsets within the data (see Tables 2.1-2.3 for statistical summaries). Correlation coefficient matrices and scatter plots were used to evaluate if any linear correlations or spatial patterns occur. Measurements in both the traditional two-dimensional view (perpendicular to the foliation) and along the foliation surface were compared.

There is a wide range of kink band geometries and spacings throughout the Samish Island exposures. Spacings for all bands range from <1 cm up to >50 cm, averaging 6.6 cm but mostly commonly 3-4 cm (Figure 2.18a). Kinked widths in both views are generally narrow, averaging 0.9 cm but most commonly 0.2-0.6 cm (range: <0.2 cm to >2 cm; Figure 2.18b); plan widths are slightly narrower (average 0.7 cm) but have a similar range (Figure 2.18c). Relief on the foliation surface is very low (average 0.1 cm) but almost a third of bands have less than 1 mm relief (Figure 2.18d); a very small number of bands have relief greater than 0.5 cm. There is no clear correlation between spacing and kinked width ($R^2 = 0.18$), plan width ($R^2 = 0.27$), or relief ($R^2 = 0.20$) for the complete population of measured kink bands.
Table 2.1 General statistics for all measured bands.

<table>
<thead>
<tr>
<th></th>
<th>Spacing width</th>
<th>Plan width</th>
<th>Kinked width</th>
<th>α</th>
<th>β</th>
<th>β/α</th>
<th>κ</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>222</td>
<td>134</td>
<td>214</td>
<td>189</td>
<td>187</td>
<td>187</td>
<td>188</td>
</tr>
<tr>
<td>Mean</td>
<td>6.6</td>
<td>0.8</td>
<td>0.8</td>
<td>73</td>
<td>71</td>
<td>1.0</td>
<td>36</td>
</tr>
<tr>
<td>Median</td>
<td>4.6</td>
<td>0.6</td>
<td>0.5</td>
<td>73</td>
<td>71</td>
<td>1.0</td>
<td>36</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.6</td>
<td>0.1</td>
<td>0.1</td>
<td>50</td>
<td>33</td>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>50.7</td>
<td>4.7</td>
<td>5.5</td>
<td>95</td>
<td>93</td>
<td>1.5</td>
<td>102</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>6.2</td>
<td>0.6</td>
<td>0.9</td>
<td>8</td>
<td>12</td>
<td>0.2</td>
<td>14</td>
</tr>
</tbody>
</table>

Note: Spacing is the average of spacings on either side of each kink band. α and β based on averages for each kink band. Spacing and widths in cm.
Table 2.2. General statistics for bands separated by $\beta/\alpha$ ratios.

<table>
<thead>
<tr>
<th></th>
<th>Plan Spacing</th>
<th>Kinked width</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\beta/\alpha$</th>
<th>$\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Immature bands ($\beta/\alpha &gt; 1$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>N</td>
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<td>38</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>Mean</td>
<td>8.6</td>
<td>0.9</td>
<td>0.9</td>
<td>67</td>
<td>84</td>
<td>1.3</td>
</tr>
<tr>
<td>Median</td>
<td>6.7</td>
<td>0.6</td>
<td>0.6</td>
<td>66</td>
<td>85</td>
<td>1.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.6</td>
<td>0.2</td>
<td>0.2</td>
<td>50</td>
<td>60</td>
<td>1.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>29.5</td>
<td>4.7</td>
<td>4.8</td>
<td>78</td>
<td>93</td>
<td>1.5</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>6.7</td>
<td>0.8</td>
<td>0.9</td>
<td>6</td>
<td>6</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mature bands ($\beta/\alpha = 1$)</strong></td>
<td></td>
<td></td>
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<td></td>
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<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Mean</td>
<td>5.5</td>
<td>0.7</td>
<td>0.8</td>
<td>73</td>
<td>73</td>
<td>1.0</td>
</tr>
<tr>
<td>Median</td>
<td>3.9</td>
<td>0.6</td>
<td>0.5</td>
<td>73</td>
<td>72</td>
<td>1.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.0</td>
<td>0.1</td>
<td>0.1</td>
<td>57</td>
<td>59</td>
<td>0.9</td>
</tr>
<tr>
<td>Maximum</td>
<td>26.1</td>
<td>1.9</td>
<td>5.5</td>
<td>90</td>
<td>90</td>
<td>1.1</td>
</tr>
<tr>
<td>St. Dev.</td>
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<td>0.4</td>
<td>1.0</td>
<td>7</td>
<td>8</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Over-rotated bands ($\beta/\alpha &lt; 1$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>60</td>
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<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Mean</td>
<td>6.4</td>
<td>0.8</td>
<td>0.8</td>
<td>79</td>
<td>59</td>
<td>0.8</td>
</tr>
<tr>
<td>Median</td>
<td>4.3</td>
<td>0.6</td>
<td>0.6</td>
<td>77</td>
<td>61</td>
<td>0.8</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.0</td>
<td>0.2</td>
<td>0.2</td>
<td>62</td>
<td>33</td>
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<tr>
<td>Maximum</td>
<td>50.7</td>
<td>4.3</td>
<td>4.2</td>
<td>95</td>
<td>78</td>
<td>0.9</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>7.7</td>
<td>0.7</td>
<td>0.7</td>
<td>7</td>
<td>8</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Note: Spacing is the average of spacings on either side of each kink band. $\alpha$ and $\beta$ based on averages for each kink band. Spacing and widths in cm.
Table 2.3. General statistics for bands separated by kinked width.

<table>
<thead>
<tr>
<th>Plan Spacing width</th>
<th>Kinked width</th>
<th>α</th>
<th>β</th>
<th>β/α</th>
<th>κ</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>αββ/ακ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N 179 114 179 159 157 157 158</td>
<td>Mean 5.4 0.6 0.5 73 70 1.0 37</td>
<td>Median 4.1 0.6 0.5 73 70 1.0 36</td>
<td>Minimum 0.6 0.1 0.1 50 33 0.4 0</td>
<td>Maximum 27.9 1.5 1.0 95 91 1.5 102</td>
</tr>
<tr>
<td>Kinked width &lt;1 cm</td>
<td>N 3 51 73 53 03 03 03 0</td>
<td>Mean 12.8 1.9 2.4 73 77 1.1 30</td>
<td>Median 10.5 1.5 1.8 73 77 1.0 30</td>
<td>Minimum 2.4 0.6 1.0 59 58 0.7 6</td>
<td>Maximum 50.7 4.7 5.5 90 93 1.4 58</td>
</tr>
<tr>
<td></td>
<td>Kinked width &gt;1 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Spacing is the average of spacings on either side of each kink band. α and β based on averages for each kink band. Spacing and widths in cm.
Figure 2.18. Histograms of measured parameters for all kink bands on Samish Island. (a) Spacing between bands; (b) kinked width of bands; (c) plan width of bands; (d) relief on the foliation surface. XS = measured in the plane perpendicular to the foliation; FS = measured on the foliation surface. The total number of kink bands measured was 226 (XS) and 332 (FS); counts for measured parameters may be less due to suboptimal kink band expression in places. All measurements in cm.
The angular relationships (see Figure 1.2) of the kinked and unkinked foliations across kink band boundaries also vary: the external angle ($\alpha$) is generally between 60° and 80° (average: 73°; Figure 2.19a), and the internal kink angle ($\beta$) has an even wider range of 55°-90° (average: 71°; Figure 2.19b). Bands with $\alpha = \beta$ ($\beta/\alpha = 1 \pm 0.1$) are most common, but bands with $\beta/\alpha < 1$ and $\beta/\alpha > 1$ are also prevalent (Figure 2.19c). The rotation angle ($\kappa$) through which the foliation has been kinked averages 36° but ranges from <10° to 70° (Figure 2.19d).

The angular parameter distributions (especially $\beta/\alpha$ and $\kappa$) are Gaussian with a single central peak, but both spacing and width have peak distributions with modal peaks in the lower range. Based on the angular and kinked width distributions, the data were split into subsets to assess relationships within certain populations. The angular parameter $\beta/\alpha$ was used to separate bands into groups of $\beta > \alpha$, $\beta = \alpha$, and $\beta < \alpha$, corresponding to low rotation, moderate rotation, and high rotation, respectively. Bands were also separated into groups with kinked widths less than 1 cm (the end of the Gaussian peak) and greater than 1 cm (abnormally wide). Measured parameters were again compared for each population.

The ratio of $\beta/\alpha$ can be used as a proxy for maturity of the kink bands. For ideal or “locked” kink bands, the two angles should be equal, resulting in $\beta/\alpha = 1$; for this study, ratios between 0.9 and 1.1 were considered “mature,” with the range allowing for error of ±5° on angle measurements. For immature kink bands initiating by the rotation models (modes I, III, and IV), $\beta$ will initially be large, resulting in a ratio greater than 1 (if modes III or IV) or equal to 1 (if mode I); as rotation progresses, $\beta/\alpha$ decreases to 1, when the band should become locked. In order for $\beta/\alpha$ to be less than 1, the band must
Figure 2.19. Histograms of angular parameters for all kink bands measured in the field. (a) External kink angle, $\alpha$; (b) internal kink angle, $\beta$; (c) $\beta/\alpha$; (d) rotation angle, $\kappa$. Angles were measured in the plane perpendicular to the foliation.
have over-rotated, requiring thinning of the internal layers or shearing along the kink band boundaries, or the external foliation may have rotated, changing the relationship between $\alpha$ and $\beta$. For 186 bands with both $\alpha$ and $\beta$ values recorded, all three conditions occur, though $\beta = \alpha$ is most common (Figure 2.19c).

Comparing all measured parameters for mature, immature, and over-rotated bands indicates there are some differences between the populations. Both immature and mature bands have average spacing of 3-4 cm (Figure 2.20a), though there is more variety in the spacing of immature bands (Std. Dev. = 6.7 for immature vs. 4.7 for mature); over-rotated bands, however, tend to be more closely spaced (mode of 2-3 cm, and fewer bands with large spacing). All three populations have similar kinked width distributions, peaking between 0.2 and 0.6 cm (Figure 2.20b), but immature and over-rotated bands have higher plan widths than mature bands (Figure 2.20c). All three subsets have close to Gaussian distributions for the three angles $\alpha$, $\beta$, and $\kappa$ (Figure 2.21); $\alpha$ and $\kappa$ increase and $\beta$ decreases as bands mature. Few correlations are seen within the three populations. For immature and mature bands, there is no clear correlation between spacing, width, or angles ($R^2$ all <0.5). For bands with $\beta < \alpha$ (over-rotated), however, there is a positive correlation between spacing and both kinked and plan widths ($R^2 = 0.8$ for both).

Separating bands by widths yielded no significant correlations between spacing, widths, and angles. Bands with kinked widths >1 cm generally also have plan widths >1 cm, but not always: 3 of 35 bands have plan widths <1 cm (Figure 2.22b). Wider bands also have a wider range of spacings, from 2 to >>20 cm; bands with kinked widths <1 cm are much more closely spaced (mean of 5.4 cm, only 16 of 179 are more than 10 cm apart; Figure 2.22a). Both width populations have Gaussian distributions of $\beta/\alpha$ with
Figure 2.20. Spacing and width distributions for 217 bands divided by $\beta/\alpha$ ratios. (a) Spacing for the three populations; (b) kinked width distribution; (c) plan width distribution. For average spacing and kinked width, $n=52$ for $\beta>\alpha$, $n=75$ for $\beta=\alpha$, $n=52$ for $\beta<\alpha$; for plan width, $n=38$, 39, and 40, respectively.
Figure 2.21. Distribution of angular parameters $\alpha$, $\beta$, and $\kappa$ for 217 bands divided by $\beta/\alpha$ ratios.  (a) $\alpha$ for each population; (b) $\beta$; (c) $\kappa$.  $N=52$ for $\beta>\alpha$; $n=75$ for $\beta=\alpha$; $n=60$ for $\beta<\alpha$. 

53
Figure 2.22. Histograms of measured parameters for 214 bands split by kinked widths. (a) Spacing, (b) plan width, (c) $\beta/\alpha$, (d) $\alpha$, (e) $\beta$, and (f) $\kappa$. (d)-(f) on the following page.
Figure 2.22, continued.
higher concentrations of mature bands (Figure 2.22c), though the wider bands have a higher proportion of immature $\beta/\alpha$ ratios. The ranges of $\alpha$ and $\kappa$ are similar for both sets (excluding 3 bands with very high $\kappa$; Figure 2.22d, f), and the mean $\alpha$ for both populations is the same (73º). There is a broader range of $\beta$ for the thinner bands (Figure 2.22e), but the wider bands have higher mean $\beta$ and lower mean $\kappa$ values (Table 2.3).

The two sets of kink bands (A and B) distinguished by axial plane orientations were also compared. Kink bands of set A are more closely spaced and have smaller widths than those of set B (Figure 2.23a-c). Set B also has higher $\beta$ and lower $\alpha$, resulting in more immature $\beta/\alpha$ ratios (Figure 2.23d-f) but also higher rotation angles (Figure 2.23g). Splitting the two sets into populations based on $\beta/\alpha$ ratios as before revealed several interesting distributions. For set A, the trends match those of the bands as a whole, with similar spacing, width, and rotation distributions for all three levels of maturity; the range of widths increases slightly with maturity, and the distributions of most parameters becomes more Gaussian. There is no clear pattern between spacing and maturity (Figure 2.24a). For set B, however, immature bands are very widely spaced, with spacing decreasing with increasing maturity (Figure 2.24b). The majority of set A are mature or over-rotated (115 of 154 bands), while the majority of set B are immature or mature (26 of 33 bands). There are no clear correlations between any of the measured parameters for either set.

Shortening could not be directly calculated from the field measurements presented here due to the high uncertainties for plan width and relief (0.5 mm uncertainty for widths and relief on the scale of millimeters). However, Ramsay (1967) presented an equation to calculate shortening within the kink band based on the rotation angle $\kappa$ and the kinked
Figure 2.23. Histograms of measured parameters for set A (n=161) and set B (n=35). Note that not all parameters were measureable for each band, so the sum for each graph may be less than 196. (a) Spacing, (b) plan width, (c) kinked width, (d) $\alpha$, (e) $\beta$, (f) $\beta/\alpha$, and (g) $\kappa$. (d)-(g) on the following page.
Figure 2.23 continued.
Figure 2.24. Scatter plots of spacing vs. $\beta/\alpha$ for kink band sets A and B. (a) There is no clear trend for bands of set A; spacing is generally <10 cm for all ranges of maturity. (b) Bands of set B show a decrease in spacing with increasing maturity. Error on spacing is 0.1 cm; error on $\beta/\alpha$ is +/- 0.05.
width, for which the uncertainties are less. The shortening \( e \) inside the kink band due to slip on the foliation is a function of the kinked width (KW), the rotation angle (\( \kappa \)), and the thickness of the foliation layers (\( t \)):

\[
e = \left( \frac{KW - \kappa t}{KW} \right) \cos \kappa + \frac{t}{KW} \sin \kappa - 1.
\]

For the Darrington Phyllite, the foliation thickness (\( t \)) was taken to be 0.1 cm based on thin section analyses (see Chapter 4). The plan width of the kink band can then be calculated by multiplying the calculated internal shortening by the kinked width. The initial length of the foliation is given by the sum of the kinked widths and spacing along a transect line, and the final length by the sum of the plan widths and spacing.

Shortening across each kink band ranges from less than 0.1% to 10% (Figure 2.25a), but is less than 3% for the majority of bands. There is no clear correlation between shortening and any other measured parameters (\( R^2 < 0.5 \) for spacing, kinked, and plan widths). Shortening across each outcrop is generally less than 5%, averaging 2%.

Kink band density (number of bands per measured length) ranges from 2 bands per meter to 46 bands per meter (Figure 2.25b). Kink band density within set B outcrops is very low (<10 bands per meter for all but one outcrop), while set A outcrops have much denser networks of kink bands overall.

**Interpretation of Outcrop Features**

The kink band geometries observed in the field and the statistical analyses of measured parameters have elements of both mobile- and fixed-hinge kinking models (see Figure 1.4). In the idealized models of kinking, the kink angles \( \alpha \) and \( \beta \) are closely
Figure 2.25. Histograms of shortening data for kink bands from Samish Island.  
(a) Distribution of shortening across 142 individual bands and separated by sets.  
(b) Distribution of kink band density (number of kink bands per meter of outcrop) for 30 outcrop transects, separated into sets.
linked to the kink model: $\alpha = \beta$ at all times for mobile-hinge kinking, but $\alpha$ is independent of $\beta$ in fixed-hinge kinking (Verbeek, 1978). However, Stewart and Alvarez (1991) determined that comparing $\alpha$ and $\beta$ was not an accurate test of the two models; as even experimental kink bands formed via mobile-hinge kinking have scatter in the angular relationships due to interlayer slip. Therefore it is unsurprising and indeterminate that kink bands from Samish Island have a range of $\alpha$ and $\beta$ relationships. Equal $\alpha$ and $\beta$ can occur in both kink models, as the initial and constant condition for mobile-hinge kinking, and as the final, “locked” condition for fixed-hinge kinking. $\beta > \alpha$ is the initial condition for fixed-hinge kinking, with $\beta$ decreasing to match $\alpha$. $\beta < \alpha$ should not occur in structure that conform to the idealized kinking models; however, rotation of the external foliation or shear along the kink band boundaries can increase $\alpha$ or decrease $\beta$, thereby complicating the simple models (Gay and Weiss, 1974; Verbeek, 1978). The angles $\alpha$ and $\beta$ cannot by themselves distinguish mobile- vs. fixed-hinge kinking here, but comparing these angles to other parameters can reveal other, more illuminating patterns.

The range of $\kappa$ suggests that rotation is a likely mode of kinking and can be associated with either mobile- or fixed-hinge kinking. If the kink bands were formed by mobile-hinge kinking and lateral migration only, the orientations (i.e. $\alpha$ and $\kappa$) should be similar for all bands forming in close proximity; however, large scatter in both $\alpha$ and $\kappa$ is seen in groups of adjacent kink bands. Similarly, $\alpha = \beta$ is not always true for groups of adjacent bands, and single outcrops have bands with $\beta$ greater than, equal to, and less than $\alpha$. The wide ranges of $\alpha$ and $\kappa$ suggest that rotation inside and outside the kink
bands occurred during deformation. The ratio of $\beta/\alpha$ is used in this study as a proxy for maturity, assuming rotation as part of the kinking mechanism. It is not possible to determine whether the external foliation has rotated in the field, but fractures and disaggregated kink band boundaries in several places (e.g. outcrops Q5, Q7, and B10) suggest that shearing along the kink band boundaries is likely.

The two modes of kinking should have different characteristic relationships between the angles $\alpha$, $\beta$, and $\kappa$ and other measured parameters. In mobile-hinge kinking, $\kappa$ should increase while both $\alpha$ and $\beta$ decrease at the same rate, and kinked width should increase (by adding new material) while plan width decreases slightly (due to shortening). In fixed-hinge kinking, $\kappa$ also increases, but $\beta$ and plan width should decrease significantly while kinked width and $\alpha$ (if no external rotation) remain unchanged. For kink bands on Samish Island, $\alpha$ and $\beta$ both change with maturity, but while $\beta$ decreases with increasing maturity, $\alpha$ increases (Figure 2.26a, b). Both $\alpha$ and $\beta$ decrease with increasing rotation ($\kappa$) (Figure 2.26c, d), which could suggest mobile-hinge kinking; however, the two angles do not decrease at the same rate, suggesting independence and therefore fixed-hinge kinking. $\kappa$ is lower for most immature bands, concentrated between 10° and 40° (Figure 2.21c), and higher for both mature and over-rotated bands, concentrated between 30° and 50°; the similar distribution of $\kappa$ for both mature and over-rotated bands suggests that once a kink band reaches maturity and locks at $\alpha = \beta$ the internal foliation may cease to rotate and only the external foliation continues to rotate to accommodate further shortening.

The range of widths and the relationships between angles and width do not clearly distinguish between the two models. The kinked width distribution (Figure 2.20a) shows
Figure 2.26. Scatter plots of angular parameters for 217 kink bands classified by \( \beta/\alpha \) ratios. (a) \( \alpha \) vs. \( \beta/\alpha \) for all three populations showing an increase in \( \alpha \) with increasing maturity. (b) \( \beta \) vs. \( \beta/\alpha \) showing a decrease in \( \beta \) with increasing maturity. (c) \( \alpha \) vs. \( \kappa \) showing decreasing \( \alpha \) with increasing \( \kappa \). (d) \( \beta \) vs. \( \kappa \) showing decreasing \( \beta \) with increasing \( \kappa \). N=52 for \( \beta>\alpha \); n=75 for \( \beta=\alpha \); n=60 for \( \beta<\alpha \).
similar ranges and patterns for all three maturity subsets, which suggests that the width of
the kinked limb is rather arbitrary and may be set from the initiation of the band. Kinked
width does increase slightly for over-rotated bands, which could suggest some migration
of kink band hinges. Decreasing plan width from immature to mature bands (Figure
2.20c) is consistent with rotation of a kinked limb with fixed width; however, over-
rotated bands have greater plan and kinked widths than immature bands, which suggests
that kink bands may widen once they lock. Thus, both fixed-hinge and mobile-hinge
kinking may operate: as a kink band accommodates shortening by rotation, the kinked
width remains constant but the plan width decreases until the band locks at $\beta = \alpha$ (fixed-
hinge kinking); further deformation is accommodated by lateral migration of the kink
band hinges (mobile-hinge kinking) which increases both the kink and plan widths of the
bands, and/or rotation of the unkinked foliation. The relationship between width and
maturity is not entirely clear because the initial widths of the bands are unknown.

Spacing between bands is poorly correlated with other parameters for the
complete population of bands, but some relationships are observed among subsets. The
ranges of spacing for the three maturity levels of bands are similar, though the average
spacing for immature bands is slightly higher than that for mature or over-rotated bands
(Table 2.2). For immature and mature bands, no clear correlations exist between spacing
and other measured parameters; for over-rotated bands, however, spacing positively
correlates with both kinked and plan widths ($R^2 = 0.83$ and 0.85, respectively). Hobson
(1973) observed that the spacing between bands correlated only to kinked width and
length of the kink bands (not measured here) in his study, and interpreted this to mean
that the initial frequency of kink bands is determined at initiation and no new bands are
nucleated once preexisting bands lock. This interpretation does not hold for Samish Island, as only a small percentage of bands match the conditions proposed by Hobson (1973). The closer spacing of mature bands and wider spacing of immature bands suggests that new bands may nucleate as preexisting bands lock, creating denser sets of kink bands. The bands of set A are generally more closely spaced (<10 cm for most bands), while those of set B have no clustered distribution and range widely with an average spacing of 12 cm. The wider spacing suggests that set B represents an immature set of bands, and set A may be a mature set with nucleation of new bands accommodating more deformation than expansion of existing kink bands.

In the ideal scenario proposed by Weiss (1980), volume inside a kink band remains constant as deformation progresses, and all deformation is accommodated by slip along the foliation surface. Weiss (1980) showed that volume is constant when $\alpha = \beta$, thus requiring that $\alpha = \beta$ for all stages of a kink band undergoing mobile-hinge growth. If $\alpha$ and $\beta$ are not equal, however, there must be a volume change inside the kinked zone that is related to both $\alpha$ and $\beta$. Ramsay (1967) stated that the internal dilation (normal to the foliation inside the kink band) can be calculated by:

$$\Delta = \frac{\delta t}{t} = \frac{\sin \beta}{\sin \alpha} - 1,$$

where $\delta t$ is the dilation across a single layer of thickness $t$ (Figure 2.27); this equation assumes two-dimensional plane strain within the kink band. From this equation it is clear that when $\alpha$ and $\beta$ are equal, dilation is zero, consistent with Weiss’ (1980) ideal scenario. However, many natural and experimental kink bands deviate from the ideal
Figure 2.27. Dilation spaces within kink bands. (a) Dilation $\delta t$ across a layer of thickness $t$ occurs when $\alpha$ and $\beta$ are not equal. (b) Dilation within the hinge zones occurs due to interlayer slip within the kink band, and is dependent on the rotation angle $\kappa$ and the ratio between the layer thickness and the kinked width (KW). Redrawn and modified from Ramsay (1967).
scenario (e.g. Donath, 1968; Hobson, 1973; Verbeek, 1978; Stewart and Alvarez, 1991; this thesis), requiring a volume change inside the kink band.

Calculating internal dilation from Eqn. 2.2 for a range of initial $\alpha$ (Figure 2.28) shows dilation is positive when $\beta$ is greater than $\alpha$, and negative when $\beta$ is less than $\alpha$. Maximum dilation is reached when $\beta = 90^\circ$, and is positive but decreasing as $\beta$ approaches $\alpha$. If $\beta$ is less than $\alpha$, there is contraction within the kink band, requiring removal of material via pressure solution. In fixed-hinge kinking, the angle $\alpha$ is set at initiation; therefore, the amount of dilation for a band with some internal thickness $t$ is dependent on the orientation of the bands as defined by $\alpha$. When $\alpha$ is low, $\beta$ is initially large ($>90^\circ$), allowing for more rotation and thus more dilation before locking; when $\alpha$ is high, $\beta$ is initially close to $90^\circ$ and less dilation is possible. Honea and Johnson (1976) showed that kink bands nucleate where irregularities in the foliation cause localized buckles that progress into kink bands; therefore, initial $\kappa$ will be close to $0^\circ$ in most cases, and $\beta$ will be larger than $\alpha$. Kink bands should not nucleate with $\alpha$ greater than $\beta$.

In kink bands from Samish Island, $\alpha$ ranges from $50^\circ$-$90^\circ$; however, very high values of $\alpha$ may be due to external rotation of the foliation during or after kinking, or shear along the kink band boundaries (Dewey, 1965; Verbeek, 1978). The average $\alpha$ for all measured bands with $\beta \geq \alpha$ is $71^\circ$; average $\beta$ is $77^\circ$ and average $\kappa$ is $32^\circ$. Using these average values and Eqn. 2.2, the average dilation per thickness $t$ for kink bands on Samish Island is $3\%$; the maximum dilation is $21\%$. It was not possible to measure dilation directly in the field, so dilation must be estimated using average values. The foliation spacing throughout most of Samish Island is roughly $1\ mm$, though the rock
Figure 2.28. Calculated dilation normal to the kinked foliation for a range of kink band geometries. When $\beta > 90^\circ$, dilation is positive and increases to a maximum at $\beta = 90^\circ$. As $\beta$ decreases below $90^\circ$, dilation is positive but decreasing until the kink band locks at $\alpha = \beta$ and dilation reaches 0. If $\beta$ is less than $\alpha$, contraction within the kink band occurs. If $\alpha$ is fixed at initiation and only $\beta$ and $\kappa$ change as deformation progresses, the amount of dilation is dependent on the initial orientation of the kink band as defined by $\alpha$. 

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becomes coarser and the fabric more widely spaced in the southwestern section.

Allowing dilation to vary with layer thickness using Eqn. 2.2 and assuming constant $\alpha = 71^\circ$ (the mean for bands with $\beta \geq \alpha$) shows that dilation perpendicular to the internal foliation increases as layer thickness increases (Figure 2.29). For kink bands with layer thicknesses of 1 mm (estimated from thin sections; see Chapter 4) and using Eqn. 2.2, the maximum possible separation normal to the internal foliation at $\beta = 90^\circ$ is 0.06 cm; 0.03 cm when $\alpha = 71^\circ$ and $\beta = 77^\circ$.

If deformation is being accommodated by interlayer slip, dilation is also possible within hinge zones (Ramsay 1967; Figure 2.27b). Dilation along the hinges is possible in both mobile- and fixed-hinge kinking but should be very small in mobile-hinge kinks (Stewart and Alvarez, 1991). As the layers slip past each other, small openings are possible in the hinges, akin to saddle reefs in the hinges of tight chevron folds (Ramsay, 1967). The dilation along the hinges can be calculated by:

$$\Delta = \frac{t}{KW} \left(2 \tan \left(\frac{\kappa}{2}\right) - \kappa\right), \hspace{1cm} (2.3)$$

where $KW$ is the kinked width (Ramsay, 1967). For a given foliation thickness, dilation in the hinges increases as the kinked width decreases and approaches the foliation thickness; dilation also increases as the internal foliation rotates to higher $\kappa$ (Figure 2.30). The magnitude of dilation has a small range when $\kappa$ is low ($<30^\circ$), but at higher $\kappa$ the dilation is very sensitive to the value of $t/KW$. The median kinked width for measured bands on Samish Island is 5.5 mm (range: 1 mm – 55 mm), which corresponds to a $t/KW$ ratio of ~0.2. The expected hinge dilation for a kink band with $\kappa = 32^\circ$ (mean for all bands) and a kinked width of 5 mm is 0.4%. The hinge dilation for the majority of bands
Figure 2.29. Variation in dilation normal to the kinked foliation as a function of the thickness of the foliation layers in mm. Dilation is greater when layers are thicker at a given $\alpha$ (here, $\alpha = 71^\circ$ for all curves). Each curve tracks dilation as $\kappa$ increases from $0^\circ$ at $\beta = 109^\circ$ to $60^\circ$ at $\beta = 49^\circ$. 

\[\alpha = \beta\] 

\[\alpha = 71^\circ\]
Figure 2.30. Variation in dilation along kink band hinges with kink band geometry. Each curve traces a different ratio of foliation layer thickness to kinked width (t/KW) as $\kappa$ increases from $0^\circ$ to $90^\circ$. Dilation increases at high $\kappa$ depending on the ratio of thickness to width.
(150 of 186 total) is less than 1%, and the dilation for all bands is less than 7% (Figure 2.31). There is no correlation between the two types of dilation ($R^2 = 0.14$), nor is there correlation between the kinked widths and either type of dilation ($R^2 = 0$ for internal dilation and $R^2 = 0.08$ for hinge dilation); however, bands with kinked widths less than 1 cm have a very wide range of calculated internal and hinge dilation (Figure 2.32a, b), while those with widths greater than 1 cm have close to zero calculated hinge dilation (Figure 2.32b).

Triangular deposits of quartz and/or calcite along kink band boundaries and in sigmoidal veins within the kink bands themselves are both consistent with dilation during fixed-hinge kinking. During rotation of the internal foliation of a fixed width, dilation must occur within the kink band, separating the foliation and creating triangular voids along the boundaries (see Figure 1.4). Precipitation of material during or after kinking fills in these gaps, creating a series of triangular deposits or veins that outline the kink band boundaries. As $\kappa$ increases, void spaces should grow as long as $\beta$ is greater than $\alpha$, reaching a maximum at $\beta = 90^\circ$ and then diminishing until $\beta = \alpha$ and the bands locks (Ramsay, 1967). Mineral fibers are too fine to observe in the field, but thin section analyses yield information on the growth of quartz and calcite within the triangular voids (see Chapter 4). Sigmoidal veins connecting the void spaces are also consistent with dilation during fixed-hinge rotation. In most cases, the connecting veins are not parallel to the kinked foliation but cross it at low angles (e.g. Figure 2.16). As rotation increases, mineral fibers within the dilation spaces inside the kink band would grow obliquely and trace the path of rotating points within the internal layers (Stewart and Alvarez, 1991); the final vein would be oriented perpendicular to the initial separation direction and not
Figure 2.31. Histogram of hinge dilation calculated for 183 kink bands. The majority of bands have dilation in the hinges of less than 1%; the maximum dilation for any individual band is 6.3%.
Figure 2.32. Variation in (a) internal dilation and (b) hinge dilation with kinked width for 186 kink bands. Dilation of both types is lower for bands with kinked widths greater than ~1 cm, and there is wide variation in bands with kinked widths less than 1 cm.
parallel to the final kinked foliation. The timing of kinking vs. the development of very large sigmoidal veins (e.g. those in outcrop Q5) is unclear; however, one hypothesis is that a wider kink band allowed for larger space to open in the initial vein, which then grew rapidly and contributed to the over-rotation of the foliation inside the kink band. Undeformed veins that cross-cut kink bands indicate that some vein precipitation must have occurred post-kinking.

Kink Bands and Applied Stress

Gay and Weiss (1974) determined from deformation experiments that there is a systematic relationship (angle \(\rho\)) between \(\alpha\) and the orientation of the principal compressive stress \((\sigma_1)\) (Figure 2.33). From the values given in Gay and Weiss (1974), best-fit lines that relate \(\rho\) to the measured angles \(\alpha\) and \(\beta\) are given by:

\[
\alpha = 0.567 \rho + 60^\circ, \quad \text{and} \\
\beta = 0.633 \rho + 71^\circ.
\] (2.4)

When \(\sigma_1\) is parallel to the foliation (\(\rho = 0^\circ\)), kink bands initiate at \(\alpha = 60^\circ\), commonly in conjugate form; as \(\rho\) increases, \(\alpha\) also increases, thereby lowering the maximum possible rotation and the amount of shortening for each kink band. The sign convention of \(\rho\) is such that negative \(\rho\) is possible, which would decrease \(\alpha\) below 60\(^\circ\); however, there must be some lower limit to \(\alpha\) and to \(\rho\). On Samish Island, the minimum observed \(\alpha\) is \(~50^\circ\), corresponding to \(\rho = -17^\circ\); if \(\rho = +17^\circ\), the expected \(\alpha\) is 70\(^\circ\), which matches the average values for bands with \(\beta \geq \alpha\). However, \(\alpha\) of 90\(^\circ\) were measured in the field, which would correspond with much higher values of \(\rho\) unless the high values of \(\alpha\) (>70\(^\circ\)) are a result of
Figure 2.33. Illustration defining the angles between the principal compressive stress ($\sigma_1$) and the kink band. The angle between $\sigma_1$ and the external foliation is $\rho$; the angle between $\sigma_1$ and the kink band boundary is $\theta$. Redrawn and modified from Gay and Weiss (1974).
external rotation during or after kinking. Using the maximum measured value of $\beta$ (92.5°) to calculate $\rho$ shows that the maximum possible $\rho$ is 34° on Samish Island. This corresponds to $\alpha = 79°$, which is a more inclusive upper limit for $\alpha$. The wide range of $\rho$ values is likely due to changes in the foliation orientation around Samish Island due to pre-kinking folding, resulting in localized stress fields that were more conducive to kinking in certain places due to the orientation of the foliation. The changes in orientation of the foliation with respect to the main compression direction may explain why kink bands are not evenly distributed around Samish Island, and there are large stretches of outcrop with no visible kink bands.

Summary

Kink bands occur throughout the exposures of the Darrington Phyllite on the northern point of Samish Island. Kink bands are concentrated in outcrops that are clearly foliated and may be slightly folded; however, regions with tight folding and high concentrations of veins are notably lacking in kink bands. In cross section, kink band boundaries are relatively straight and parallel, with some merging Y-type intersections present; rarely do kink bands cross or truncate in this plane. On the foliation surface, kink band trends are highly variable, with individual bands noticeably curved along strike and intersecting with other bands in X-, Y-, and T-type intersections. Y-type intersections are the most common, followed by T and X. The majority of bands are closely spaced (<10 cm) and less than 1 cm wide, though a small subset are very widely spaced (up to 52 cm) and can be very wide (>2 cm). There is a wide range of angular relationships between the kinked and uninked foliations, with internal kink angles ($\beta$)
concentrated between 55° and 90° and external kink angles (α) generally between 60° and 80°. Kink bands with β = α (mature) are most common, but a significant number of bands show β > α (immature) and β < α (over-rotated). Rotation angles (κ) range from 0-70° but are more commonly 20°-50°.

Correlations between measured parameters are generally lacking, though certain subsets of bands show internal relationships. For bands with β < α there is a positive correlation between spacing and width, suggesting that narrow bands at high angles to the external foliation are more closely spaced, possibly as a result of new bands nucleating as preexisting bands lock. Both α and β decrease with increasing rotation of the kinked limb, starting with β > α and progressing towards β = α and locking of the kink bands; however, the significant number of bands with β < α suggests that further deformation has taken place. As rotation increases, β decreases significantly more than α, suggesting that the two angles are independent, and consistent with fixed-hinge kinking. Increasing α with maturity suggests that external rotation may have taken place, with the long limbs of the kink bands rotating towards normal with the kink band boundaries; alternatively, shear along the kink band boundaries can decrease β significantly. The decrease in plan width and relatively constant kinked width for immature and mature bands are consistent with fixed-hinge kinking; however, many over-rotated bands have higher kinked and plan widths than immature or mature bands, suggesting lateral migration of kink band hinges may occur after rotation ceases. Triangular void spaces and sigmoidal veins within the kink bands are both consistent with dilation during fixed-hinge kinking.

Based on field observations alone, both mobile- and fixed-hinge models are possible, though the data are more consistent with fixed-hinge kinking with added
external rotation. Certain aspects of each model cannot be tested with field data alone, and other observations are necessary to better constrain the mechanisms of kinking.
CHAPTER 3: GEOMETRIC CURVATURE ANALYSES

The geometry of folded surfaces is commonly described qualitatively (see Chapter 1), but accurately describing the three-dimensional geometry of a folded surface quantitatively can be difficult. Differential geometry has been shown to be a powerful tool in quantifying the three-dimensional geometry of a surface and predicting areas of highest strain (e.g. Lisle, 1994; Bergbauer and Pollard, 2003; Pearce et al., 2006; Mynatt et al., 2007; Stecchi et al., 2009). Curvature analyses can uniquely describe the shape of a folded surface (Bergbauer and Pollard, 2003), relate the strain distribution within a fold to the location and orientation of fractures and joints (Bergbauer and Pollard, 2004), and determine the concentration of maximum 3D strain (e.g. Pearce et al., 2006). Quantifying the shape of a surface and calculating the unique parameters for each point on that surface can provide insight into the localization of strain in folded rocks and may aid in understanding the relationships among adjacent structures. This chapter describes the application of differential geometry to produce quantitative descriptions of kink band morphologies in hand sample and their relationships to one another and to other structures.

Theory of Geometric Curvature

Bergbauer and Pollard (2003) presented a method to accurately quantify the curvature of a folded surface with exact mathematical expressions independent of the coordinate system. The following description of curvature calculations is summarized from their work:
A curved surface can be described by a combination of tangent and normal vectors at any point along that surface. The curvature, \( k \), is defined by how the tangent vector changes spatially across the surface, \( \frac{dt}{ds} \), where \( t \) is the tangent vector at any point and \( ds \) is an incremental change along the surface in a given direction. The curvature vector varies in magnitude in all directions from a single point, but reaches maximum and minimum values in two orthogonal directions. These maximum and minimum values are called the principal surface curvatures and are used to quantitatively describe the shape of a surface. The principal surface curvatures and directions of curvature can be calculated from the First and Second Fundamental Forms of a surface, which together uniquely describe its shape in 3D space.

The First Fundamental Form describes the differential arc length of all curves through a point on a surface, and can be calculated from partial derivatives of a smooth surface with respect to an arbitrary coordinate system in 3D space. The elevation of points on a surface \( (z) \) can be described as a function of the independent location variables \( x \) and \( y \). Each point can be described by a position vector \( \mathbf{r} \), where
\[
\mathbf{r} = x \mathbf{e}_x + y \mathbf{e}_y + z(x, y) \mathbf{e}_z,
\] (3.1)
and \( \mathbf{e} \) is the unit base vector. The slope of the surface in two arbitrary orthogonal directions \( (dx \text{ and } dy) \) can be calculated by the partial derivatives \( \frac{\partial z}{\partial x} \) and \( \frac{\partial z}{\partial y} \) and is represented by two tangent vectors:
\[
\frac{\partial \mathbf{r}}{\partial x} = \mathbf{r}_x = \mathbf{e}_x + \left( \frac{\partial z}{\partial x} \right) \mathbf{e}_z,
\]
\[
\frac{\partial \mathbf{r}}{\partial y} = \mathbf{r}_y = \mathbf{e}_y + \left( \frac{\partial z}{\partial y} \right) \mathbf{e}_z,
\]
\[ d\mathbf{r} = \left( \frac{\partial \mathbf{r}}{\partial x} \right) dx + \left( \frac{\partial \mathbf{r}}{\partial y} \right) dy. \] (3.2)

The First Fundamental Form \((I)\) is the square of the differential arc length, \(d\mathbf{r}\), or:

\[
I = d\mathbf{r}^2 = \mathbf{r}_x \cdot \mathbf{r}_x + 2(\mathbf{r}_x \cdot \mathbf{r}_y) + \mathbf{r}_y \cdot \mathbf{r}_y,
\]

where \(\alpha_{xx}\), \(\alpha_{xy}\), and \(\alpha_{yy}\) are scalar quantities called the metric coefficients, defined as:

\[
\alpha_{xx} = 1 + \left( \frac{\partial z}{\partial x} \right)^2,
\]

\[
\alpha_{xy} = \left( \frac{\partial z}{\partial x} \right) \cdot \left( \frac{\partial z}{\partial y} \right),
\]

\[
\alpha_{yy} = 1 + \left( \frac{\partial z}{\partial y} \right)^2.
\] (3.3b)

For any surface, the values of the metric coefficients may change depending on the defined coordinate system, but the magnitude of \(I\) is invariant with respect to coordinate transformations; therefore, the description of the surface curvature using the First Fundamental Form is independent of an arbitrarily defined coordinate system \(x\) and \(y\).

The First Fundamental Form can be used to calculate distances, angles, and areas of a curved surface.

The Second Fundamental Form describes the shape of a curved surface at any point. Mathematically, it describes the spatial rate of change of the unit normal vector to a surface on a path along the surface. The unit normal vector \(\mathbf{n}\) can be calculated from two orthogonal tangent vectors, lying in the tangent plane of any point on the surface; these tangent vectors are the same as those used to calculate the First Fundamental Form.
in Eqn. 2, above. The unit normal vector is the normalized cross product of the tangent vectors, or:

\[
n = \frac{\mathbf{t}_x \times \mathbf{t}_y}{|\mathbf{t}_x \times \mathbf{t}_y|} = \frac{\mathbf{e}_z - \left(\frac{\partial z}{\partial x}\right)\mathbf{e}_x - \left(\frac{\partial z}{\partial y}\right)\mathbf{e}_y}{\sqrt{\alpha_{xx} \alpha_{yy} - \alpha_{xy}^2}}.
\]  

(3.4)

The Second Fundamental Form (\(II\)) is the dot product of the differential normal (\(d\mathbf{n}\)) and tangent (\(d\mathbf{r}\)) vectors at any point on the surface, written as:

\[
II = -d\mathbf{n} \cdot d\mathbf{r} = \beta_{xx} dx^2 + 2\beta_{xy} dxdy + \beta_{yy} dy^2,
\]  

(3.5a)

where \(\beta_{xx}\), \(\beta_{xy}\), and \(\beta_{yy}\) are the curvature coefficients, defined as:

\[
\beta_{xx} = \frac{\partial^2 z/\partial x^2}{\sqrt{\alpha_{xx} \alpha_{yy} - \alpha_{xy}^2}},
\]

\[
\beta_{xy} = \frac{\partial^2 z/\partial x \partial y}{\sqrt{\alpha_{xx} \alpha_{yy} - \alpha_{xy}^2}},
\]

\[
\beta_{yy} = \frac{\partial^2 z/\partial y^2}{\sqrt{\alpha_{xx} \alpha_{yy} - \alpha_{xy}^2}}.
\]  

(3.5b)

The curvature coefficients can be used to describe the shape of a surface as combinations of elliptical, parabolic, hyperbolic, or planar forms (Pollard and Fletcher, 2005).

The normal curvature of a surface is found using the two fundamental forms. The magnitude of the normal curvature, \(K_n\), can be found by dividing the Second Fundamental Form by the First, or:

\[
K_n = \frac{II}{I} = \frac{\beta_{xx} dx^2 + 2\beta_{xy} dxdy + \beta_{yy} dy^2}{\alpha_{xx} dx^2 + 2\alpha_{xy} dxdy + \alpha_{yy} dy^2}.
\]  

(3.6)

The magnitude of the normal curvature is directionally dependent and will have different values for 360° around a single point on a surface. The magnitude of the curvature at any
point on a cylindrical fold is equal to the inverse of the radius of the fold, and the units are inverse meters. The normal curvature will reach minimum and maximum values at two orthogonal directions, and these values are called the principal curvatures of the surface, $K_1$ and $K_2$. The directions of principal curvature ($\lambda_1$ and $\lambda_2$) are defined as the orientations of the corresponding tangent vectors, and can be calculated by:

$$\begin{align*}
\lambda_{1,2} &= -\frac{\alpha_{xx}\beta_{yy} - \alpha_{yy}\beta_{xx}}{2(\alpha_{xx}\beta_{yy} - \alpha_{yy}\beta_{xx})} \pm \sqrt{\frac{1}{4} (\alpha_{xx} \beta_{yy} - \alpha_{yy} \beta_{xx})^2 - (\alpha_{xx} \beta_{yy} - \alpha_{yy} \beta_{xx})(\alpha_{xx} \beta_{yy} - \alpha_{yy} \beta_{xx})} \\
&\quad \pm \frac{(\alpha_{xx} \beta_{yy} - \alpha_{yy} \beta_{xx})(\alpha_{xx} \beta_{yy} - \alpha_{yy} \beta_{xx})}{(\alpha_{xx} \beta_{yy} - \alpha_{yy} \beta_{xx})}. \quad (3.7)
\end{align*}$$

The principal directions can then be substituted into Eqn. 6 to find $k_1$ and $k_2$:

$$K_{1,2} = \frac{\beta_{xx} + 2\beta_{xy} \lambda + \beta_{yy} \lambda^2}{\alpha_{xx} + 2\alpha_{xy} \lambda + \alpha_{yy} \lambda^2}. \quad (3.8)$$

Alternatively, matrix algebra can be used to calculate the normal curvature, and the eigenvalues and eigenvectors of the resulting curvature matrix represent the principal curvature magnitude and the direction of curvature, respectively. The maximum principal curvature ($K_1 = K_{\text{max}}$) and its direction at every point can highlight areas of tightest folding, and paired with the directions of minimum principal curvature ($\lambda_2$) can highlight the locations of fold hinges (Pearce et al., 2006).

The Gaussian curvature and mean curvature together provide a quantitative description of the shape of a surface. The Gaussian curvature ($K_G$) is the product of the two principal curvatures:

$$K_G = K_1 \cdot K_2, \quad (3.9)$$

and the mean curvature ($K_{\text{mean}}$) is the average of $K_1$ and $K_2$:

$$K_{\text{mean}} = \frac{1}{2} (K_1 + K_2). \quad (3.10)$$
Maps of Gaussian curvature can be used to define inflection points along a surface (Pearce et al., 2006): where \( K_G = 0 \), the surface is changing from positive to negative curvature, and connecting areas where \( K_G = 0 \) can define lines of inflection. The shape of the surface can be classified based on the Gaussian and mean curvatures by a quantity called the geologic curvature (Mynatt et al., 2007; Figure 3.1). Geologic curvature differentiates between synformal and antiformal cylinders and saddles, domes and basins, and planar structures. True surfaces are rarely ideal or conform to cylindrical constraints; geological curvature can be used to describe any surface regardless of its irregularities or spatial variation.

Plotting the absolute value of mean curvature (\( |K_{\text{mean}}| \)) allows for comparison of the curvature values for adjacent folds of opposite senses (e.g. syncline/anticline) to confirm whether there are consistent curvature values for each pair. However, if the sum of the principal curvatures is close to zero, the mean curvature for those points will also be zero, masking the possibility of significant strain (Stewart and Podolski, 1998). To mitigate the muting effect of \( K_{\text{mean}} \), a different parameter is defined: \( K_{\text{total}} \), where

\[
K_{\text{total}} = |K_{\text{max}}| + |K_{\text{min}}|. \tag{3.11}
\]

Maps of \( K_{\text{total}} \) describe the shape of surfaces better than \( |K_{\text{mean}}| \) where strain is variable in a small area and surface curvature changes rapidly.

**Previous Applications**

Differential geometry and geometric curvature calculations have been shown to be versatile in application and to adequately describe and predict the shape, orientation, and location of deformation structures on complex, non-ideal surfaces. Gaussian
Figure 3.1. Geologic curvature classification defined by Mynatt et al. (2007). The eight classes of fold shapes are defined by combinations of mean curvature ($K_{\text{mean}}$) and Gaussian curvature ($K_G$). Colors in this classification grid are used in the maps of geologic curvature that follow. Figure reproduced from Mynatt et al. (2007).
Curvature analyses have been used previously to predict the location of faults and fractures within noncylindrical folds (Lisle, 1994; Bergbauer and Pollard, 2004; Stecchi et al., 2009) based on structural contour maps, seismic data sets, and GPS-derived data sets. Gaussian and geologic curvatures have also been used to constrain areas of highest 3D strain and describe complicated surfaces as combinations of simple fold shapes (Pearce et al., 2006; Mynatt et al., 2007; Stecchi et al., 2009). Maps of principal curvature magnitudes and directions highlight fold hinges, and allow for more accurate mapping of complicated structures when such detail is difficult to observe in the field (Pearce et al., 2006). For structures with multiple fold frequencies (e.g. a kilometer-scale anticline with meter-scale parasitic folds or fractures), application of a low-pass filter can subtract the noise from high frequency surface undulations and leave the low frequency, larger-scale structure intact (Bergbauer and Pollard, 2003); however, caution must be taken to not oversimplify the surface during data smoothing, and the filter must be set for the appropriate scale. Departure from an ideal surface can also be quantified and subtracted by using a curvature threshold filter (Mynatt et al., 2007), which identifies areas with overprinted structures for later filtering. Studies of geometric curvature show that complicated curvature calculations can easily be performed using widely available software (e.g. MATLAB) that can handle large data sets ($10^5$-$10^7$ points) acquired by GPS, LiDAR, or 3D scanning (e.g. Pearce et al., 2006; Mynatt et al., 2007; Stecchi et al., 2009).
Application to Kink Bands in the Darrington Phyllite

Kink bands are a distinct type of double-hinged fold that are traditionally viewed in simple two-dimensional cross section, but can have complex shapes and orientations in the plane of the foliation. The curving, anastomosing, and intersecting behavior of kink bands in the third dimension can be described qualitatively using outcrop/surface maps and written descriptions, but quantitative descriptions of the third dimension have not been previously presented. Geometric curvature analyses can quantify the magnitude of curvature of a kink band, outline inflection points and hinges for kink bands, and quantify the amount of shortening the rock has undergone. Curvature analysis also illuminates the characteristics of kink bands that intersect, merge or split, taper out, or end diffusely. Geometric curvature can also be used to distinguish between true kink bands and other features on a sample’s surface, such as lineation, fractures, or irregular foliation planes, though comparison to the actual sample is also needed for accurate interpretation.

Selected hand samples were scanned with a 3D laser scanner to produce a gridded surface and the techniques outlined above were used to calculate different measures of curvature for kink bands with a variety of spacing, widths, morphologies, and intersections.

Methods

Eight hand samples containing kink bands from Samish Island were selected for surface curvature modeling; the selected rocks came from two outcrops, B10 and B13 (see Figure 2.1) and the small beach just south of outcrop B10 (samples DFo21a and b). Samples were chosen that had roughly planar surfaces with ideal or intriguing kink band geometries on the surface of the foliation; most important was the presence of a single
foliation plane providing the kinked surface. Samples were scanned using the FARO arm 3D scanner in Western Washington University’s Electronics Engineering Technology department. The FARO arm uses a laser scanner to produce a point cloud containing x-y-z coordinates of points on the surface; the coordinate system is arbitrary and uses the flat table as its base. The point cloud was exported as a text file for further manipulation.

An interpolated gridded surface for each sample was produced using Golden Software Surfer software, version 8. The imported point clouds were cropped to exclude extraneous points produced during scanning (e.g. the table under the sample, edge effects, and irregular portions of the rocks) and gridded using a kriging method; the grid step size was roughly 0.5 mm in both directions (exact values depended on sample size). The surfaces were then filtered using a low-pass 9-node moving average filter to remove high-amplitude noise from the weathered lineations on the rock surfaces; each surface was filtered twice. The gradient of the surface was calculated using built-in functions of Surfer 8. The filtered, gridded surface and gradient data were exported for use as input files to MATLAB for further curvature calculations.

Several MATLAB scripts were written or modified to import the gridded data and calculate curvature parameters (Appendix B). First, a matrix Z was created representing the elevation of points on the surface, with the x and y coordinates defining each cell of the matrix (i.e. Z(1,1) represents the elevation at the top left corner of the sample). Similarly, a corresponding matrix was created with gradient values for each point in Z. Surface and contour plots were created in MATLAB from the matrices Z and gradient to confirm the data were imported correctly. The coordinate system defined by the scanner is such that all plots are an upward projection of the surface; all imported matrices were
rotated in order to achieve a downward projection. Second, the partial derivatives of the surface \( Z \) were calculated in \( d \) and \( y \) using the built-in gradient function in MATLAB. The outcrops represent \( \frac{\partial z}{\partial x} \) and \( \frac{\partial z}{\partial y} \) in two arbitrarily chosen directions corresponding to the gridded data coordinates; the incremental spacings \( dx \) and \( dy \) are the known spacing between adjacent points. The second derivatives of \( Z \) were calculated by taking the gradient of the first derivatives with respect to \( x \) and \( y \). For all derivative matrices the edge rows and columns on all four sides were deleted to minimize edge effects along the grid.

The metric and curvature coefficients were next calculated from the partial derivatives based on Eqns. 3.3b and 3.5b, above. Eqns. 3.7 through 3.10 were also scripted to calculate the principal directions and magnitudes of curvature as well as the Gaussian and mean curvatures (Appendix B); these scripts were modified from those published by Pollard and Fletcher (2005) and Mynatt et al. (2007). Multiple trial calculations at different threshold values of \( K_t = 0, 0.05, 0.08, \) and 0.1 were performed; \( K_t = 0.08 \) provided the optimal filtering without losing fidelity or resolution, and was used for all analyses. Once the calculations were complete, plotting tools in MATLAB were used to create filled contour maps and associated vector plots of the different curvature values for analysis and interpretation.

Elevation, gradient, and curvature data were extracted for each sample using multiple transects along each surface. Transect lines were drawn using a MATLAB script (Appendix B), drawn parallel to the lineation and approximately perpendicular to kink band hinges. A scaling factor was calculated for each line based on the numerical cross-section length vs. the actual length of the sample, and all distance and width data
were scaled to the sample length. Values were cross-checked to the first order by verifying numbers against the hand sample measured with a ruler.

Data extracted along each transect included surface elevation (relief), gradient (calculated by Surfer 8), mean curvature, the absolute value of mean curvature, and the absolute value of total curvature. Data for each kink band along a given transect were then manually extracted. Kink bands were identified on a graph of distance along the transect vs. gradient and curvature (Figure 3.2) and by comparing the transect to a map of the sample. Kink bands are distinguished in the transect lines by a steep gradient peak accompanied by sharp curvature peaks that directly coincide with the edges of the gradient peak; the curvature peaks always consistent of synclinal-anticlinal pairs that matched the step-sense of the sample (except at merged hinges). For each band, data extracted included the relief between hinges, average gradient and peak gradient, and width of each hinge curvature peak and its peak value (Figures 3.2 and 3.3). All values were entered into an Excel spreadsheet for statistical calculations (e.g. kinked width, rotation angle) to evaluate correlations among these attributes.

Results

Maps of surface topography, gradient, and curvature calculations for each sample indicate that the methods outlined above accurately capture the expression of kink bands in the plane of the foliation, and that these methods can be used to describe kink band quantitatively as well as qualitatively. Individual kink bands within samples are referred to by letter labels; see Appendix C for annotated photographs and curvature maps of each sample and accompanying descriptions. Streaking roughly perpendicular to the kink
Figure 3.2. Example transect line location and extracted data, sample B10-F4. (a) Zones of high gradient mark the kink bands. (b) Gradient peaks in the transect data corresponding to kink bands are well above background and are accompanied by a peak-trough pair in the mean curvature data. The order of the peak-trough set is dependent on the step-sense of the sample; in this sample, kink bands step up from left to right, so kink band peaks have synclinal (trough)-anticlinal (peak) hinges from left to right. Four bands are visible in this transect.
Figure 3.3. Schematic representation of measured geometric parameters. The top view shows a kinked surface with four kink bands, and the final and initial lengths of the surface needed for shortening calculations are found as shown. The kink band close-up defines the variables discussed in the text: relief (R), rotation angle (κ), kinked width (KW), plan or peak width (PW), and hinge width (HW). PW and HW are measured on transects of $K_{total}$ as shown on Figure 3.2b.
bands is visible on all maps for most samples; the streaks represent the weathered lineation on the sample surface that was not completely filtered during data processing.

**Kink Band Expression**

Kink bands are well expressed in contour plots of gradient values as well as all curvature parameters. In maps of gradient (Figure 3.4), extended zones of similarly steep slopes represent kink bands, surrounded by relatively flat surfaces. Gradients of kink bands range from ~0.2 up to 0.7-0.8, and most samples show a wide variety of gradients among the kink bands. The average gradient for kink bands in all samples is between 0.25 and 0.3. Kink band boundaries are evident by tightly spaced gradient contours, and tighter contours along the boundaries indicate sharper changes in slope (i.e. sharper hinges). Bands with steeper kinked planes (higher gradients) usually have well defined boundaries; gentler or very wide kink bands have wider or even diffuse boundaries, and can be difficult to distinguish from the generally flat background (e.g. bands E and F in B10-F3, Figure 3.4b). High slopes usually correspond to high relief, but while higher gradient bands tend to be narrow, tight, and high, not all narrow and high relief bands have extreme gradients. All samples from both outcrops have similar ranges of gradient values, and fractures and faults within the samples are clearly distinguished from kink bands by highly elevated gradient values (i.e. >1). Within individual bands, the gradient usually remains consistent throughout the band, except when bands split, merge, bend, or taper (see below). Sample B10-F4 has three straight bands and two that bend towards each other (Figure 3.4a); band B has straight and narrow boundaries and a consistently steep slope of ~0.6 along its length. In contrast, bands D and E have different gradient
Figure 3.4. Representative contour maps of surface gradient. (a) Sample B10-F4, and (b) sample B10-F3. Warmer colors correlate with slope steepness, and kink bands are clearly outlined by closely spaced contours bracketing zones of higher gradient. Tapering and bending bands are visible in both samples.
values at the nose of the bend (D increases from ~0.4 to ~0.5, and E decreases from ~0.45 to ~0.35), indicating that deviation from a straight trajectory influences the steepness of the band.

Contour plots of mean curvature ($K_{\text{mean}}$) show the hinge zones of each kink band (Figure 3.5), corresponding well to the zones of tightly spaced gradient contours. Zones of negative curvature identify synformal hinges, and zones of positive curvature identify antiformal hinges. Each pair of hinges bracket a planar (zero curvature) surface, consistent with the idealized form of a kink band as a planar surface bounded by two tight hinges. The separation between hinges, indicated by the width of the planar kinked limb, reflects the plan width of each kink band on the sample. Application of a curvature threshold value of $K_t = 0.08$ simplifies the overall surface pattern and amplifies the higher curvature of the hinges. Curvature of the hinges ranges from ±0.05 to ±0.3 m$^{-1}$ (negative for synclinal hinges and positive for anticlinal hinges), corresponding to curvature radii of 20 mm to 3.3 mm. Most bands have paired hinges of similar widths, with higher curvature values in the center of the hinge; rarely are paired hinges of significantly different widths. The higher curvature values (generally $|K_{\text{mean}}| > 0.15$ m$^{-1}$) at the center of the hinges mark the sharp bend of the foliation that is easily visible in hand sample; the lower curvature values (generally $|K_{\text{mean}}|$ between 0.05 and 0.15 m$^{-1}$) for the rest of the hinge zone suggest that kink band hinges are not single sharp lines but instead narrow strips of increased curvature. The mean curvature plots also indicate that all bands within a single sample have the same kink sense, with synformal (negative curvature values) and antiformal hinges (positive curvature values) in the same order for each band.
Figure 3.5. Representative contour maps of mean curvature. (a) B10-F4, and (b) B10-F3. Kink bands are shown by paired hinges of elevated curvature; negative curvature values correspond with synclinal hinges and positive curvature values with anticlinal hinges. In both samples kink bands step up to the right, indicated by negative magnitude (synclinal) hinges on the left and positive magnitude (anticlinal) hinges on the right. Streaking perpendicular to the kink bands is a residual lineation signal that was not completely filtered out.
Contour maps of $K_{\text{mean}}$ allow for quick identification of kink bands and recognition of the kinking sense (uphill vs. downhill) as well as general magnitude of curvature. Curvature values are generally consistent along the kink band hinges, again with the exception of band intersections or deviations from straight trajectories (e.g. sample B10-F4, Figure 3.5). Curvature values are also consistent for all samples from both outcrops (both with maximum curvatures of 0.3 m$^{-1}$), but hinges are slightly narrower for bands in sample B13-4 (Appendix C5); the bands themselves are also narrower in sample B13 vs. those in B10 samples (Appendix C), so hinge width may be a function of kinked or plan width.

Plotting the absolute value of mean curvature ($|K_{\text{mean}}|$) allows for comparison of the curvature values for each pair of hinges (Figure 3.6), confirming there are consistent curvature values for each pair. However, the curvature values are very low and the sharpness of the hinges that is so striking in hand sample is not readily apparent. Averaging the curvature values for each point subdues the curvature signal, broadening the sharp hinges into wider zones and losing some of the clarity of thinner bands in particular. Plots of total curvature (Figure 3.7) clearly show the sharp hinges of each bands as very narrow strips of elevated curvature (ranging from 0.1 to >0.35 m$^{-1}$), retaining the relative width and magnitude signal of each hinge pair. The broad signal of the hinge zone is muted here, with each hinge marked by concentrated high curvature values. The plotted hinges are also more continuous using total curvature, with many of the gaps left by $K_{\text{mean}}$ filled in. Finer bands (e.g. bands F, J, K3 of sample B13-4B; Appendix C6) are better defined, and the residual lineation signal is muted.
Figure 3.6. Representative contour maps of the absolute value of mean curvature. (a) B10-F4, and (b) B10-F3. Kink band hinges are visible but have very low curvature values, with matching values for each pair of hinges.
Figure 3.7. Representative contour maps of the total curvature. (a) B10-F4, and (b) B10-F3. The sharpness of the hinges and the similar magnitude of each hinge are clearly shown. Tight knots of elevated curvature along the hinges are likely due to interference of the weathered surfaces (i.e. weathered lineation crossing the hinges). The streaking lineation signal is less prominent in the total curvature maps than in the mean curvature maps.
Maps of geologic curvature (Figure 3.8) indicate that each kink band is indeed composed of a synform-plane-antiform set as indicated by the gradient and curvature maps discussed above. The stripes indicate the hinges are relatively continuous along each band and sharply contrast with the planar nature of the surface between and within kink bands. The successful simplification of the kink bands into these idealized fold shapes via the threshold curvature value \( K_t \) indicates that kink band hinges can indeed by approximated by cylindrical folds.

**Kink Band Intersections**

Chapters 1 and 2 describe three types of kink band intersections defined by Kirschner and Teixell (1996): crossing (X), merging/bifurcating (Y), and truncating (T) (see Figure 1.5). All three types of intersections are present in the scanned samples, and multiple intersections can occur within a single band group. Each intersection type has unique features present in the curvature data, and identification of these diagnostic features may aid in interpreting more complicated surfaces.

**X-type Intersections**

Three samples contain kink bands with crossing intersections: DFO21a, DFO21b, and the weathered top side of B13-4. In all three samples the sense of kink displacement is consistent for all bands within the same rock; thus, none of the crossing sets of bands can be considered conjugate kink bands. All three X intersections have acute angles of 25-38° and obtuse angles of 130-150°, and there is usually a ~5° difference for paired acute angles for a single intersection. Kink band boundaries are very well defined for bands in sample B13-4; both DFO21a and DFO21b have highly irregular surfaces, and the
Figure 3.8. Representative maps of geologic curvature. (a) B10-F4 and (b) B10-F3. The sequence of antiform (light blue) - plane (yellow) - synform (red) is consistent and apparent in both samples. The shape of the surface is easily recognizable and simply described. The colors used here correspond to the colors in Figure 3.1.
noise of the weathered surface obscures the kink band signal slightly. Despite the influence of the surface topography, distinct characteristics of X-type intersections can be observed. Where two bands cross, a distinct rhomb-shaped patch can be observed in hand sample (Figure 3.9a), clearly kinking at a different angle than either band external to the intersection. The gradient of the rhomboid patch is much higher, up to twice as steep, than that of either kink band; in sample DFo21a (Figure 3.9b), band B has an average gradient of ~0.55 compared to ~0.35 for band C, the sum of which is comparable to the very steep (>0.8) gradient within the rhomb intersection. DFo21b has two bands cut by a third band at about a 30° angle (Appendix C8); both X intersections show elevated slopes, but the intersection involving the narrower band has higher slopes than the other intersection. The bands in B13-4 are even thinner (Appendix C5, C6), and show even more extreme contrast at the intersection; band width appears to have an effect on the magnitude of slope change at a crossing intersection. Gradient contours appear to trace out one band’s continuity over the other in each crossing pair (e.g. B over C in DFo21a, Figure 3.9b); however, the curvature calculations and inspection of the hand sample often contradict the cross-cutting sense of the gradient contours.

Maps of mean curvature (Figure 3.9c) and total curvature (Figure 3.9d) show knots of elevated curvature where the hinges of one band cross the other. These knots of curvature correspond to the vertices of the rhomboid patch described above. The magnitude of each knot is dependent on the combination of hinges interacting at each point: antiformal-antiformal, synformal-synformal, or antiformal-synformal. Where two hinges of the same sense cross, curvature values reach extremes, up to twice as high as the hinges outside the intersection. An antiformal-synformal combination yields slightly
Figure 3.9. Example of an X-type intersection in sample DFO21a. (a) Photograph of the intersection on the sample, with bands labeled and the rhomb intersection outlined. The intersection rhomb is visible in plots of (b) gradient, (c) mean curvature, (d) total curvature, and (e) geologic curvature. Black arrows in (c) and (e) mark the clear crossing of a synformal-antiformal hinge pair, resulting in a saddle.
lower and sometimes almost negligible curvature values, and the opposing sense of folding may results in an apparent flattening of the hinge zone. Contour plots of $K_{\text{total}}$ outline the traces of the bands especially well (Figure 3.9d), clearly marking the rhomb of combined bands and highlighting the clusters of high curvature at the crossing of the hinges ($K_{\text{total}} > 0.3 \text{ m}^{-1}$ at the vertices vs. $<0.25 \text{ m}^{-1}$ outside).

Geologic curvature also highlights the unique geometry of the crossing intersection (Figure 3.9e), showing the continuous traces of the kink band hinges outside the cross and indicating the shape of the rhomboid patch itself. As expected by the theory of geologic curvature, two antiformal hinges crossing form a dome; similarly, a synformal pair forms a basin, and crossing hinges of opposing fold senses appear as saddles. The sense of the saddle (synformal or antiformal) is dependent on the shape of the dominant hinge; that is, the hinge that is most continuous and has higher overall curvature than the other. Samples DFO21a (Figure 3.9e) and DFO21b (Appendix C8) each have only one opposite-sense hinge crossing well illustrated, both showing antiformal saddles dominated by the antiformal hinge of the more continuous band; this is also visible in the mean curvature plots. The crossing intersections in B13-4 (Figure C5) show bands H and I crossing with saddles that are antiformal or synformal depending on the fold sense of the dominant band’s hinge shape.

Crossing intersections are easily recognized in hand sample, and have distinct curvature and surface shape behavior (Figure 3.10). A similar pattern is visible in the curvature data, however, for fractures that cut kink bands (e.g. bands B and C1 on the bottom of B13-4, Appendix C6). Elevated gradient, knots of curvature outlining a rhomb shape, and the basin/dome/saddle expression of geologic curvature are all present here,
Figure 3.10. Illustration of an idealized X-type intersection. (a) Geometry of the intersection, with rhomb-shaped patch identified with red dots at the vertexes. Anticlinal and synclinal hinges are labeled with “A” and “S,” respectively. Idealized expression of the intersection shown by: (b) gradient, (c) mean curvature, and (d) geologic curvature.
suggesting an X intersection; close inspection of the sample indicates that band B stops before reaching band C1, a fracture across band C1 trends similarly to band B, and no plane is visible between the two hinges in the geologic curvature data. Care must be taken to ensure that signals in the gradient and curvature data are correctly interpreted based on visual inspection of the sample surface.

**Y-type Intersections**

Two samples show clear Y-type intersections (DFo21a and both sides of B13-4). True Y intersections are fork-like, with a single parent band splitting completely into two separate new bands (Figure 3.11a); in two places (both in B13-4, one of either side, involving different bands) two Y intersections occur within a single band, splitting and rejoining to create a lens of unkinked material within the composite band (Appendix C5, C6). The angle between the forked bands is very low, usually around 10º; one ambiguous band split in sample B13-4 (bottom side, band J) has an interkink angle of 20º. For all fork-like intersection, the parent band is wider than the offshoot strands, usually widening slightly just before the fork. The offshoot bands are generally close to the same width as each other, but significantly thinner than the parents; however, the sum of the offshoot widths is approximately the width of the single parent band. The parent band has a steeper slope than the offshoots, with maximum gradient values usually obtained just before the point of the fork’s V (Figure 3.11b). The slopes of the offshoot strands are significantly lower than that of the parent, but similar between the two offshoots. A wedge of clearly lower slope (almost background) is visible between the divided strands.

Mean curvature (Figure 3.11c) and total curvature (Figure 3.11d) outline the behavior of the hinges at the intersection, delineating best the fork-like nature of the split.
Figure 3.11. Example of a Y-type intersection in sample B13-4 (top side). (a) Photograph of the intersection on the sample, with bands and Y intersection labeled; notice a $\lambda$-type intersection occurs near the top of the band. The fork-like nature of the splitting band is visible in plots of (b) gradient, (c) mean curvature, (d) total curvature, and (e) geologic curvature. The location of the new hinges nucleating is marked by arrows.
The original band’s hinges become the outer hinges of the two forked bands, and two new hinges nucleate between, forming the inner hinges. The outer hinges bow outwards and remain continuous; the inner hinges nucleate at a point as thin tapered zones but quickly widen to approach the width of the outer hinges. The outer hinges also retain similar curvature values from the parent band, and the inner hinges have lower (magnitude) curvature values at their start (barely above background) before tightening to match the outer hinges (except where surface topography obscures the magnitude of the hinge). Knots of elevated curvature are usually apparent on the outer hinges just as they begin to split and bow outwards from the parent band. Plots of both mean and total curvature show tapering of opposite-sense hinges of similar curvature nucleating at a point.

Geologic curvature indicates no distinct or unique shape to the point of bifurcation or to the nucleation of new hinges. The shape of the outer hinges remains constant, and the inner hinges nucleate as opposite-sense folds at a point in the planar kinked section of the parent band (Figure 3.11e). The nucleation of new hinges produces a triangular patch of planar kinked material in the peak of the fork, appearing to kink more material at this point than along the straight-edged band itself. However, no clear distortion effect is seen in the shape of the hinges on either side of the bifurcation point. Patchy saddles are visible in the outer hinges, corresponding to the points of high curvature seen in maps of $K_{\text{total}}$; however, the saddles are not always present or continuous across the band, nor do they fully interrupt the overall shape of the hinge. This may be due to surface noise or the filtering effect, and the presence of a slight saddle where the outer hinges begin to bend outwards is geometrically likely.
Y-type intersections occur when two bands merge or split at low angles, and have curvature and geometric properties that are clearly distinct from X-type intersections (Figure 3.12). It is unclear whether the dominant method of formation is merging of two bands into one or bifurcation of a parent band into two strands, and the control(s) on why and where Y-type intersections occur are similarly unknown. Y-type intersections can also be difficult to distinguish from the third type of intersection described below.

**T-type Intersections, or λ-type Intersections**

Kirschner and Teixell (1996) describe T-type intersections as the truncation of one band by another, inferring that the abutting band was younger and was stopped in its development by the older, truncating band. True truncation would require that the hinges of the abutting band would stop abruptly at the truncating band, with no visible connection to the truncating band’s hinges. The majority of merging band intersections in the samples from Samish Island do not show total truncation of the abutting band; instead, one hinge from the parent band splits itself and nucleates one new hinge while the other parent hinge remains continuous and straight, in a hybrid Y-T intersection that may more appropriately be termed a “λ-type” intersection (Figure 3.13a). This behavior is not always clearly visible in hand sample, and close examination of curvature plots illuminates the distinct behavior of the hinges.

λ-type intersections are the most abundant of all intersection types in the scanned samples, with at least 8 and possibly 12 examples in three rocks (B10-1a, B10-F3, and both sides of B13-4). λ intersections are characterized by a thin strand diverging from one hinge of a wider parent band (Figure 3.13a); the offshoots are much thinner and less pronounced than the parent band. Gradient plots confirm that the offshoots have much
Figure 3.12. Illustration of an idealized Y-type intersection. (a) Geometry of the fork-like intersection. Anticlinal and synclinal hinges are labeled with “A” and “S,” respectively. Idealized expression of the intersection shown by: (b) gradient, (c) mean curvature, and (d) geologic curvature.
Figure 3.13. Example of a $\lambda$-type intersection in sample B13-4 (top side). (a) Photograph of the intersection on the sample. The offshoot band is clearly subordinate to the main band but visible in plots of (b) gradient, (c) mean curvature, (d) total curvature, and (e) geologic curvature.
lower slopes than the parent bands, usually barely above background levels (Figure 3.13b). The parent band retains relatively consistent slopes along its length despite the small offshoot.

The true behavior of bands involved in λ intersections is more clearly shown in maps of mean and total curvature (Figure 3.13c, d). For all clear λ intersections, the parent band does not split as a whole, nor does the offshoot band fully truncate its hinges against the main band. Instead, one hinge of the parent band remains completely continuous and does not change its trend, unlike the Y intersections where both bands usually bow outwards in response to the bifurcation; the bowed nature of the Y intersections is not always clear, but the continuity of the hinges is distinct from that of λ-type intersections. The other parent hinge splits itself into two: one strand continuous as the parent hinge, usually retaining close to the same width and curvature values as the original hinge; the other strand veers off at an oblique angle (usually 20-30º) with slightly lower curvature values and a slightly smaller width before becoming subparallel to the parent band. Where the two hinges begin to split, the overall width of the joined hinge increases. The magnitudes of mean and total curvatures of the splitting hinge in the wider hinge zone are usually lower than the curvatures of the other parent hinge at that point (e.g. 0.1-0.15 m⁻¹ for the splitting hinge vs. >0.2 m⁻¹ for the continuous hinge, Figure 3.13d). The second hinge of the offshoot band nucleates in the wedge between the split hinges, not at the point of bifurcation itself. The new hinge tapers into existence, starting thin and with low mean and total curvature values (<0.1 m⁻¹ and <0.15 m⁻¹, respectively, Figure 3.13c, d), then increasing to match the other offshoot hinge. In some cases a knot of elevated curvature accompanies the split (e.g. near the nucleation point of
the new hinge in Figure 3.13c, d); however, these knots usually coincide with irregular
surface topography, so the association of high curvature knots with splitting hinges does
not appear to be diagnostic. Geologic curvature maps (Figure 3.13e) also outline the
wider shape in the splitting hinge, and nucleation of a new, thin, separate hinge in the
wedge between the split hinges. There is no clear pattern of basins, domes, or saddles
associated with the different hinges involved.

λ-type intersections are distinct from Y-type intersections in the widths of the two
bands involved and the behavior of the hinges at the point of intersection (Figure 3.14).
From the scanned samples, λ-type intersections appear to be the most common, but there
is no clear mechanism for why one hinge should split while the other remains continuous.
In the field it is difficult to distinguish Y from λ intersections, though reexamining
photographs and samples after curvature analyses suggests that the two intersections can
be distinguished if the behavior of the hinges and two strands are traced based on the
curvature results.

**Tapered Kink Bands**

Many kink bands in the scanned samples do not run the full width of the sample,
tapering out partway along strike. In some cases single bands appear to taper out (Figure
3.15a), and in others pairs of kink bands with similar trends taper towards each other
from either side of the sample (Figures 3.15b, 3.16a). In all cases the sense of kinking of
the tapered bands is consistent with the kink sense of all other bands in the sample. Both
paired and unpaired tapered kink bands have similar characteristics, but a clear
relationship exists between paired sets.
Figure 3.14. Illustration of an idealized \( \lambda \)-type intersection. (a) Geometry of the diverging intersection. Anticlinal and synclinal hinges are labeled with “A” and “S,” respectively. The offshoot band is expressed also by: (b) gradient, (c) mean curvature, and (d) geologic curvature.
Figure 3.15. Photographs of tapered kink bands in hand sample. (a) Unpaired tapered kink bands in sample B10-F3. Bands B and C taper and end halfway up the rock, but bands A and D arch upwards, flatten, and join into one band at the top. (b) Paired tapered kink bands in sample B10-1b. The bands enter from opposite ends and taper out together in the middle.
Figure 3.16. Paired tapered kink bands bracketing a continuous band in sample B10-F4. The behavior of the tapered bands photographed in (a) is shown by maps of (b) gradient, (c) mean curvature, (d) total curvature, and (e) geologic curvature. Bold dashed lines mark the end of each tapered band (where curvature of the hinges becomes less than $K_r$). See text for further descriptions.
Tapered kink bands generally have lower slopes than continuous kink bands in the same sample and, when unpaired, are only slightly elevated above background slopes. Distinct boundaries for the bands appear to taper and disappear quickly at the tips, and gradient maps show that bands effectively stop within a few millimeters of distinct slope change (Figure 3.16b). A subtle extension of slightly elevated slopes is visible in a few cases (e.g. band B in B10-F3, Figure 3.4b); these ghost bands may be premonitory extensions of the current kink bands. The end of a tapered band is defined to be where the hinges are no longer continuous in the curvature maps (e.g. curvature is below the $K_t$ value). Paired tapered bands tend to have widths consistent with the continuous bands in the same sample, but unpaired tapered bands tend to be much thinner than neighboring bands. In sample B10-F3, three of the four tapered bands (B, F1, I) have ghost extensions in the gradient map, and two (F1 and I) appear to flatten out and continue rather than truly taper to an end (Figure 3.4b and Appendix C3). Paired bands also have similar gradients and hinge curvatures, further suggesting a connection between the paired set.

All tapered bands have distinct hinges outlined by elevated curvature values that abruptly terminate where the gradient begins to significantly decrease (Figure 3.16c, d). Hinge curvatures are generally lower than those of neighboring bands, but in places (e.g. band B in B10-F3) can approach the curvature of a broader neighboring band. Paired tapered bands have approximately equal hinge curvatures that diminish into the background within a few millimeters of the change in gradient, though the outside hinges (i.e. the left hinge of band B and right hinge of band C in B10-F3) may extend a few millimeters further than the inner hinges. Geologic curvature maps (Figure 3.16e) also
indicate that tapered kink bands diminish quickly. Spotty extension of tapered bands can occur, but the rapid flattening of bands greatly reduces the ability to distinguish hinges from background.

The sets of paired tapered bands in samples B10-1a and B10-F4 suggest that paired bands may accommodate the same shortening as a single band of similar dimensions. The steepness and hinge curvature magnitudes are approximately equal for each member of a paired set, and both vales decrease slightly in the overlap zone of B10-1a (Appendix C1). Bands A and C in sample B10-F4 have ends separated by less than a centimeter along strike, though they are several centimeters apart and on either side of a steep narrow band (B); where C ends the gradient of band B decreases markedly (Figure 3.16b), but the end values of C and A are roughly equal. Bands AB and B in sample B10-1b have ends separated by about 2 cm with no intervening band; however, band C appears to respond to the tapered bands, with higher gradient and curvature values adjacent to the flatter band B and lower values adjacent to the more prominent band AB (Figure 3.17).

Other Geometries

Other features are noticeable in the scanned samples, including behavior of kink bands along their trajectories and interactions with other features (e.g. surface topography, small faults, and veins). In all samples kink bands rarely occur as perfectly parallel sets; even bands that do not visibly intersect may have trajectories that converge or diverge. The ideal view of kink bands is of straight parallel sets of bands; however, it is clear that in the third dimension bands converge and diverge and do not necessarily
Figure 3.17. Paired tapered kink bands in sample B10-1b. (a) Annotated photograph of the sample shows the two bands AB and B tapering out toward each other in the center of the rock, and continuous band C to the right. Maps of (b) gradient and (c) total curvature highlight the relationships between the three bands: band C appears to respond to changes in the tapered bands, becoming steeper and having tighter hinges next to the more subtle band B, and vice versa alongside the more prominent band AB. C abruptly changes gradient and curvature values along the gap between the tapered bands. The ends of bands AB and B are marked with dashed white lines.
have straight boundaries. Several samples (DFo21b, B10-F4, B13-4 both sides) have kink bands that bend and arc in the plane of the foliation. When the arcing bands are small strands of a larger band (e.g. in B13-4) they show little deviation along their length in terms of slopes as well as mean and total curvature values. In contrast, two major bands bend towards each other in sample B10-F4 (Figure 3.18a) and appear to interact along their lengths. Where the bands are closest, at the peak of the arc, the left band is narrowest and has high slopes while the right band is slightly wider and has lower slopes (Figure 3.18b). As the left band widens, the right narrows and the slopes respond accordingly. Similar patterns are seen in the curvature of the hinges (Figure 3.18c): where the bands are closest, the hinges are generally tightest, and values decrease as the bands diverge. The interaction of the two bands is greatest where they are closest, and decreases as they move apart (Figure 3.19). Two bands arc together in B10-F3 above two thin tapering bands (Figure 3.15a), but instead of tightening or joining clearly, the arcing bands flatten and widen, eventually joining in a very wide and shallow band that is too subtle for the calculations to distinguish from background (Figure 3.4).

Kink bands also interact with non-kink features in the samples, and features such as fractures and veins are also outlined by curvature calculations. Sample DFo21b has a faulted kink band, a vein associated with another kink, and very irregular surface topography (Figure 3.20a). Both the fault and the vein are outlined in gradient and curvature maps, but while the vein is distinguished from kink bands by its shape and trajectory, the fault is very closely associated with the anticlinal hinge of its band. The fault has very high curvature values and appears as an anticline with an apparent synclinal hinge to its right (Figure 3.20b); the syncline represents the base of the fault,
Figure 3.18. Bending kink bands in sample B10-F4. (a) Annotated photograph of the sample showing band D distinctly bending towards band E, which bends slightly towards D. (b) Gradient map of the bands showing elevated slopes in D at the nose of the arc (arrows) and slightly lowered slopes in E at the same point. Note how D’s gradient decreases along strike towards the bottom of the sample where the band flattens and widens. (c) Total curvature map shows elevated curvature in D at the nose of the arc and lower curvature for E at the same point.
Figure 3.19. Line plots showing the interaction of bending bands D and E along strike in sample B10-F4. Plotted is distance along strike by transect number vs. separation distance (black solid line on all plots) and (a) gradient, (b) relief, (c) plan width, and (d) total curvature. The two bands are closest at transect 2, where band D is steeper, higher, and more tightly curved than band E; as the bands separate, their characteristics become more equal. The noticeable dip in the gradient and relief at transect 4 is due to surface topography on the sample. Error on relief, separation, and width is 0.5 mm.
Figure 3.20. Example of a sample with kink band hinges associated with veins and a fault, sample DFo21b. (a) Annotated photograph of the sample; note that the upper part of the sample (greyed out and separated by dashed line) has a sharp surface break and topography, so curvature maps were cropped at the dashed line. The fault associated with band B and the vein associated with band C are marked on maps of (b) mean curvature and (c) geologic curvature. See text for further description.
and the fault’s signature clearly overprints the still-anticlinal nature of the hinge. There is a pronounced fabric of higher curvature and anticlines/synclines running perpendicular to the kink bands, and the bands curve slightly as they cross these stripes; the surface is irregularly weathered in a broad wave, and kink bands deflect slightly as they cross the inflection points of the topography. The deflection is most likely due to the angle of weathering cutting the foliation plane, but kink bands are clearly continuous and well outlined even across the irregular surface.

**Statistical Relationships and Shortening**

Numerical data for kink bands were extracted along four to six transects across each sample, parallel to the lineation (similar to transects measured in the field). Data extracted were: spacing between bands, plan width of each band, hinge curvature, mean gradient, and peak gradient; mean gradient is the average gradient between the two hinges, and peak gradient is the maximum gradient value for the kink band. As many kink bands as possible were measured on each transect, providing at least one and preferably five or six points of measurements for each band in a given sample.

The shortening \( e \) for each line (Table 3.1) was calculated using the transect data:

\[
e = \frac{|L_{\text{final}} - L_{\text{initial}}|}{L_{\text{initial}}}
\]  

(3.12)

where the final length was measured from the inner hinges of the outermost bands, and the initial length was the sum of the intervening spacings and kinked widths (Figure 3.3). Lines that cross more kink bands have more shortening, indicating that the magnitude of shortening is dependent on the number of kink bands along a line. To minimize this
Table 3.1. Transect shortening data for all six surfaces scanned.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Transect #</th>
<th># bands</th>
<th>Span</th>
<th>L_initial</th>
<th>L_final</th>
<th>- e</th>
<th>D_kb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full length of sample, maximum bands for each line</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B10-1a</td>
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<td>1</td>
<td></td>
<td>61.6</td>
<td>61.5</td>
<td>0.16%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-1a</td>
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<td>3</td>
<td></td>
<td>94.0</td>
<td>93.0</td>
<td>1.04%</td>
<td>0.03</td>
</tr>
<tr>
<td>B10-1a</td>
<td>3</td>
<td>4</td>
<td></td>
<td>118.0</td>
<td>116.5</td>
<td>1.23%</td>
<td>0.03</td>
</tr>
<tr>
<td>B10-1a</td>
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<td></td>
<td>117.2</td>
<td>116.2</td>
<td>0.89%</td>
<td>0.04</td>
</tr>
<tr>
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<td>4</td>
<td></td>
<td>91.8</td>
<td>90.7</td>
<td>1.17%</td>
<td>0.04</td>
</tr>
<tr>
<td>B10-1b</td>
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<td>110.3</td>
<td>0.45%</td>
<td>0.03</td>
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<td>0.03</td>
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<td>84.3</td>
<td>84.0</td>
<td>0.26%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-1b</td>
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<td></td>
<td>117.5</td>
<td>117.2</td>
<td>0.28%</td>
<td>0.03</td>
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<td>0.03</td>
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<td>95.8</td>
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<td>0.04</td>
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<td>0.04</td>
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<tr>
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<td></td>
<td>211.3</td>
<td>209.1</td>
<td>1.05%</td>
<td>0.04</td>
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<td>0.05</td>
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<td>0.05</td>
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<td>92.1</td>
<td>91.8</td>
<td>0.35%</td>
<td>0.02</td>
</tr>
<tr>
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<td>2</td>
<td></td>
<td>90.5</td>
<td>90.2</td>
<td>0.33%</td>
<td>0.02</td>
</tr>
<tr>
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<td>90.2</td>
<td>0.30%</td>
<td>0.02</td>
</tr>
<tr>
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<td>2</td>
<td></td>
<td>95.4</td>
<td>94.7</td>
<td>0.74%</td>
<td>0.02</td>
</tr>
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<td></td>
<td>97.5</td>
<td>96.9</td>
<td>0.67%</td>
<td>0.02</td>
</tr>
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<td>8</td>
<td></td>
<td>195.9</td>
<td>194.1</td>
<td>0.92%</td>
<td>0.04</td>
</tr>
<tr>
<td>B13-4T</td>
<td>2</td>
<td>11</td>
<td></td>
<td>312.4</td>
<td>310.6</td>
<td>0.58%</td>
<td>0.04</td>
</tr>
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<td>3</td>
<td>12</td>
<td></td>
<td>312.2</td>
<td>310.0</td>
<td>0.71%</td>
<td>0.04</td>
</tr>
<tr>
<td>B13-4T</td>
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<td>12</td>
<td></td>
<td>308.6</td>
<td>306.8</td>
<td>0.60%</td>
<td>0.04</td>
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<td>266.8</td>
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<td>0.03</td>
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<td>12</td>
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<td>294.3</td>
<td>0.58%</td>
<td>0.04</td>
</tr>
<tr>
<td>B13-4B</td>
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<td>12</td>
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<td>280.5</td>
<td>0.67%</td>
<td>0.04</td>
</tr>
<tr>
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<td>15</td>
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<td>0.05</td>
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<tr>
<td>B13-4B</td>
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<td>13</td>
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<td>332.3</td>
<td>330.1</td>
<td>0.68%</td>
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<td>B13-4B</td>
<td>5</td>
<td>12</td>
<td></td>
<td>308.6</td>
<td>306.5</td>
<td>0.70%</td>
<td>0.04</td>
</tr>
<tr>
<td>B13-4B</td>
<td>6</td>
<td>10</td>
<td></td>
<td>314.7</td>
<td>312.3</td>
<td>0.77%</td>
<td>0.03</td>
</tr>
<tr>
<td>Average</td>
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<td></td>
<td></td>
<td>0.70%</td>
<td>0.03</td>
</tr>
<tr>
<td>B10 only</td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.69%</td>
<td>0.03</td>
</tr>
<tr>
<td>B13 only</td>
<td>11.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.71%</td>
<td>0.04</td>
</tr>
<tr>
<td>Sample</td>
<td>Transect #</td>
<td>Transect</td>
<td># bands</td>
<td>Span</td>
<td>L_{initial}</td>
<td>L_{final}</td>
<td>- e</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>----------</td>
<td>---------</td>
<td>---------------</td>
<td>-------------</td>
<td>-----------</td>
<td>-----</td>
</tr>
<tr>
<td>B10-1a</td>
<td>2</td>
<td>3</td>
<td>End B/start E</td>
<td>89.3</td>
<td>88.2</td>
<td>1.19%</td>
<td>0.03</td>
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<tr>
<td>B10-1a</td>
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<td>3</td>
<td>End B/start E</td>
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<td>80.5</td>
<td>1.22%</td>
<td>0.04</td>
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<td>B10-1a</td>
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<td>End B/start E</td>
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<td>74.2</td>
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<td>0.04</td>
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<td>End B/start E</td>
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</tr>
<tr>
<td>B10-1b</td>
<td>1</td>
<td>2</td>
<td>End C1/start E2</td>
<td>81.4</td>
<td>81.3</td>
<td>0.20%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-1b</td>
<td>2</td>
<td>2</td>
<td>End C1/start E2</td>
<td>81.9</td>
<td>81.8</td>
<td>0.20%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-1b</td>
<td>3</td>
<td>2</td>
<td>End C1/start E2</td>
<td>84.3</td>
<td>84.0</td>
<td>0.26%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-1b</td>
<td>4</td>
<td>2</td>
<td>End C1/start E2</td>
<td>83.9</td>
<td>83.7</td>
<td>0.21%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-1b</td>
<td>5</td>
<td>2</td>
<td>End C1/start E2</td>
<td>82.5</td>
<td>82.2</td>
<td>0.29%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-F3</td>
<td>1</td>
<td>3</td>
<td>End E/start H</td>
<td>60.4</td>
<td>59.9</td>
<td>0.81%</td>
<td>0.05</td>
</tr>
<tr>
<td>B10-F3</td>
<td>2</td>
<td>3</td>
<td>End E/start H</td>
<td>65.7</td>
<td>65.1</td>
<td>0.95%</td>
<td>0.05</td>
</tr>
<tr>
<td>B10-F3</td>
<td>3</td>
<td>2</td>
<td>End E/start H</td>
<td>60.1</td>
<td>59.5</td>
<td>0.99%</td>
<td>0.03</td>
</tr>
<tr>
<td>B10-F3</td>
<td>4</td>
<td>3</td>
<td>End E/start H</td>
<td>60.0</td>
<td>59.4</td>
<td>0.97%</td>
<td>0.05</td>
</tr>
<tr>
<td>B10-F3</td>
<td>5</td>
<td>3</td>
<td>End E/start H</td>
<td>63.4</td>
<td>62.9</td>
<td>0.83%</td>
<td>0.05</td>
</tr>
<tr>
<td>B10-F3</td>
<td>6</td>
<td>4</td>
<td>End E/start H</td>
<td>60.5</td>
<td>59.9</td>
<td>1.00%</td>
<td>0.07</td>
</tr>
<tr>
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<td>1</td>
<td>2</td>
<td>End B/start E</td>
<td>92.1</td>
<td>91.8</td>
<td>0.35%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-F4</td>
<td>2</td>
<td>2</td>
<td>End B/start E</td>
<td>90.5</td>
<td>90.2</td>
<td>0.33%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-F4</td>
<td>3</td>
<td>2</td>
<td>End B/start E</td>
<td>90.5</td>
<td>90.2</td>
<td>0.30%</td>
<td>0.02</td>
</tr>
<tr>
<td>B10-F4</td>
<td>4</td>
<td>1</td>
<td>End B/start E</td>
<td>83.5</td>
<td>83.3</td>
<td>0.28%</td>
<td>0.01</td>
</tr>
<tr>
<td>B10-F4</td>
<td>5</td>
<td>1</td>
<td>End B/start E</td>
<td>84.1</td>
<td>83.9</td>
<td>0.21%</td>
<td>0.01</td>
</tr>
<tr>
<td>B13-4T</td>
<td>1</td>
<td>8</td>
<td>End D/start L</td>
<td>195.9</td>
<td>194.1</td>
<td>0.92%</td>
<td>0.04</td>
</tr>
<tr>
<td>B13-4T</td>
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<td>8</td>
<td>End D/start L</td>
<td>202.8</td>
<td>201.5</td>
<td>0.62%</td>
<td>0.04</td>
</tr>
<tr>
<td>B13-4T</td>
<td>3</td>
<td>8</td>
<td>End D/start L</td>
<td>203.1</td>
<td>201.6</td>
<td>0.77%</td>
<td>0.04</td>
</tr>
<tr>
<td>B13-4T</td>
<td>4</td>
<td>8</td>
<td>End D/start L</td>
<td>202.3</td>
<td>201.0</td>
<td>0.67%</td>
<td>0.04</td>
</tr>
<tr>
<td>B13-4T</td>
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<td>8</td>
<td>End D/start L</td>
<td>203.3</td>
<td>201.6</td>
<td>0.84%</td>
<td>0.04</td>
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<td>End D/start L</td>
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<td>0.56%</td>
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<td>B13-4B</td>
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<td>End D/start L</td>
<td>203.9</td>
<td>202.5</td>
<td>0.65%</td>
<td>0.05</td>
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<td>10</td>
<td>End D/start L</td>
<td>216.0</td>
<td>214.6</td>
<td>0.65%</td>
<td>0.05</td>
</tr>
<tr>
<td>B13-4B</td>
<td>5</td>
<td>9</td>
<td>End D/start L</td>
<td>197.8</td>
<td>196.5</td>
<td>0.64%</td>
<td>0.05</td>
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<tr>
<td>B13-4B</td>
<td>6</td>
<td>7</td>
<td>End D/start L</td>
<td>197.5</td>
<td>196.3</td>
<td>0.63%</td>
<td>0.04</td>
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</table>

**Average**: 4.8, 0.67%, 0.04

**B10 only**: 2.4, 0.64%, 0.03

**B13 only**: 8.8, 0.71%, 0.04

Note: e is shortening (positive meaning contraction); D_{kb} is kink band density, calculated by dividing the number of kink bands per final length.
effect and to better compare values between samples with different numbers of kink bands, a kink band density ($D_{kb}$) was calculated for each line:

$$D_{kb} = \frac{N}{L_{final}}$$

(3.13)

where $N$ is the number of kink bands along the line. Shortening values were also normalized to the number of bands measured to give an estimate of accommodated strain per kink band. Correlation coefficients ($R$ and $R^2$) for multiple variables were computed using MATLAB to look for meaningful relationships between measured and calculated parameters (Tables 3.2 and 3.3); calculations were performed on individual bands as well as all transect averages, and for all bands together as well as separated by outcrop (B10 and B13). The small data set precludes strong correlations (i.e. $R^2 > 0.9$); however, meaningful relationships can still be drawn from weaker correlations, recognizing the limitations of the data set. A threshold of $R^2 > 0.5$ was used to identify correlations in the curvature data, and the results were compared to those from the much larger field data set.

Shortening perpendicular to the kink bands across a sample is very small, averaging 0.14% for all samples (maximum 0.37%, both values normalized by number of bands; Table 3.1). Samples from outcrop B10 have significantly more shortening than those from outcrop B13, averaging 0.18% vs. 0.07%, respectively. Individual samples generally have consistent shortening along the kink band trends, with more variation in samples from outcrop B10, which has larger tapered or intersecting bands. Interestingly, there is a distinct change in shortening between samples B10-1a and B10-1b, two
Table 3.2. Correlation coefficient (R) matrix for 33 transects on 6 samples across the full length of the sample.

<table>
<thead>
<tr>
<th></th>
<th>KB density per Lfinal</th>
<th>Relief (max)</th>
<th>Relief (avg)</th>
<th>Plan width (max)</th>
<th>Plan width (avg)</th>
<th>Kmean (max)</th>
<th>Kmean (avg)</th>
<th>Kinked width* (max)</th>
<th>Kinked width* (avg)</th>
<th>Hinge width (max)</th>
<th>Hinge width (avg)</th>
<th>Spacing (max)</th>
<th>Spacing (avg)</th>
<th>Gradient (max)</th>
<th>Gradient (avg)</th>
<th>Rotation angle** (max)</th>
<th>Rotation angle** (avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KB density per Lfinal</td>
<td>0.734</td>
<td>0.800</td>
<td>0.621</td>
<td>0.690</td>
<td>0.523</td>
<td>0.179</td>
<td>0.100</td>
<td>0.081</td>
<td>0.503</td>
<td>0.462</td>
<td>0.081</td>
<td>0.503</td>
<td>0.462</td>
<td>0.179</td>
<td>0.100</td>
<td>0.081</td>
<td>0.503</td>
</tr>
<tr>
<td>Relief (max)</td>
<td></td>
<td>0.890</td>
<td>0.523</td>
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<td>0.374</td>
<td>0.369</td>
<td>0.233</td>
<td>0.295</td>
<td>-0.150</td>
<td>0.621</td>
<td>0.621</td>
<td>0.350</td>
<td>0.586</td>
<td>0.419</td>
<td>0.654</td>
<td>0.374</td>
<td>-0.150</td>
</tr>
<tr>
<td>Relief (avg)</td>
<td>0.080</td>
<td>0.119</td>
<td>0.131</td>
<td>0.530</td>
<td>0.586</td>
<td>0.369</td>
<td>0.233</td>
<td>0.295</td>
<td>-0.150</td>
<td>0.621</td>
<td>0.621</td>
<td>0.350</td>
<td>0.586</td>
<td>0.419</td>
<td>0.654</td>
<td>0.374</td>
<td>-0.150</td>
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<td>Plan width (max)</td>
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<td>0.081</td>
<td>0.503</td>
<td>0.081</td>
<td>0.503</td>
<td>0.462</td>
<td>0.179</td>
<td>0.100</td>
<td>0.081</td>
<td>0.503</td>
<td>0.081</td>
<td>0.503</td>
<td>0.462</td>
<td>0.179</td>
<td>0.100</td>
<td>0.081</td>
<td>0.503</td>
</tr>
<tr>
<td>Plan width (avg)</td>
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<td>0.131</td>
<td>0.523</td>
<td>0.654</td>
<td>0.374</td>
<td>0.369</td>
<td>0.233</td>
<td>0.295</td>
<td>-0.150</td>
<td>0.621</td>
<td>0.621</td>
<td>0.350</td>
<td>0.586</td>
<td>0.419</td>
<td>0.654</td>
<td>0.374</td>
<td>-0.150</td>
</tr>
<tr>
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<td>0.374</td>
<td>0.369</td>
<td>0.223</td>
<td>0.295</td>
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<td>0.100</td>
<td>0.081</td>
<td>0.503</td>
<td>-0.037</td>
<td>0.133</td>
<td>-0.162</td>
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<td>0.187</td>
<td>-0.183</td>
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<td>-0.037</td>
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<td>-0.037</td>
<td>0.133</td>
<td>-0.037</td>
<td>0.133</td>
<td>0.100</td>
<td>0.081</td>
<td>0.503</td>
<td>-0.037</td>
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<td>-0.037</td>
<td>0.133</td>
<td>-0.037</td>
<td>0.133</td>
<td>-0.037</td>
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<tr>
<td>Kinked width* (max)</td>
<td>0.465</td>
<td>0.669</td>
<td>0.091</td>
<td>0.215</td>
<td>0.257</td>
<td>0.238</td>
<td>0.110</td>
<td>0.086</td>
<td>0.095</td>
<td>0.425</td>
<td>0.328</td>
<td>0.386</td>
<td>0.513</td>
<td>0.465</td>
<td>0.669</td>
<td>0.091</td>
<td>0.215</td>
</tr>
<tr>
<td>Kinked width* (avg)</td>
<td>0.238</td>
<td>0.081</td>
<td>0.503</td>
<td>0.081</td>
<td>0.503</td>
<td>0.462</td>
<td>0.179</td>
<td>0.100</td>
<td>0.081</td>
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<td>0.081</td>
<td>0.503</td>
<td>0.462</td>
<td>0.179</td>
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<td>0.081</td>
<td>0.503</td>
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<tr>
<td>Hinge width (max)</td>
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<td>0.503</td>
<td>0.462</td>
<td>0.179</td>
<td>0.100</td>
<td>0.081</td>
<td>0.503</td>
<td>0.081</td>
<td>0.503</td>
<td>0.462</td>
<td>0.179</td>
<td>0.100</td>
<td>0.081</td>
<td>0.503</td>
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<tr>
<td>Hinge width (avg)</td>
<td>-0.509</td>
<td>0.036</td>
<td>0.119</td>
<td>0.117</td>
<td>-0.152</td>
<td>-0.404</td>
<td>-0.122</td>
<td>-0.367</td>
<td>0.166</td>
<td>-0.022</td>
<td>0.157</td>
<td>0.026</td>
<td>0.573</td>
<td>0.235</td>
<td>0.035</td>
<td>0.119</td>
<td>-0.152</td>
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<td>0.233</td>
<td>0.324</td>
<td>0.369</td>
<td>0.126</td>
<td>0.187</td>
<td>0.187</td>
<td>-0.220</td>
<td>0.317</td>
<td>0.187</td>
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<td>0.126</td>
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<td>0.187</td>
<td>0.187</td>
</tr>
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<td>-0.913</td>
<td>0.350</td>
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<td>-0.656</td>
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<td>-0.269</td>
<td>-0.668</td>
<td>-0.186</td>
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<td>0.416</td>
<td>0.072</td>
<td>0.213</td>
<td>0.126</td>
<td>0.049</td>
<td>0.350</td>
<td>-0.189</td>
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<tr>
<td>Gradient (max)</td>
<td>0.719</td>
<td>0.586</td>
<td>0.350</td>
<td>0.049</td>
<td>-0.656</td>
<td>-0.189</td>
<td>-0.269</td>
<td>-0.668</td>
<td>-0.186</td>
<td>-0.044</td>
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<td>0.126</td>
<td>0.049</td>
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<tr>
<td>Gradient (avg)</td>
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<td>0.117</td>
<td>0.117</td>
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<td>0.187</td>
<td>0.126</td>
<td>0.049</td>
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<td>-0.189</td>
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<tr>
<td>Rotation angle** (max)</td>
<td>0.812</td>
<td>0.594</td>
<td>0.584</td>
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<td>0.187</td>
<td>0.187</td>
<td>0.126</td>
<td>0.049</td>
<td>0.350</td>
<td>-0.189</td>
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</table>

Notes: Correlations with R^2 > 0.5 are indicated in bold and highlighted. Light grey values are not correlatable (same variable or directly calculated).

*Calculated from relief and plan width.

**Calculated from kinked and plan widths.
<table>
<thead>
<tr>
<th></th>
<th>KB density per Lfinal</th>
<th>Relief (max)</th>
<th>Relief (avg)</th>
<th>Plan width (max)</th>
<th>Plan width (avg)</th>
<th>Kmean (max)</th>
<th>Kmean (avg)</th>
<th>Kinked width* (max)</th>
<th>Kinked width* (avg)</th>
<th>Hinge width (max)</th>
<th>Hinge width (avg)</th>
<th>Spacing (max)</th>
<th>Spacing (avg)</th>
<th>Gradient (max)</th>
<th>Gradient (avg)</th>
<th>Rotation angle** (max)</th>
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<td>0.822</td>
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<td>0.581</td>
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<td>0.634</td>
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<td>0.341</td>
<td>-0.601</td>
<td>-0.640</td>
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<td>0.385</td>
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N = 21 transects on 4 samples.
Notes: Correlations with $R^2 > 0.5$ are indicated in bold and highlighted. Light grey values are not correlatable (same variable or directly calculated).
*Calculated from relief and plan width.
**Calculated from kinked and plan widths.

<table>
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<th>Relief (max)</th>
<th>Relief (avg)</th>
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<th>Plan width (avg)</th>
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N = 12 transects on 1 sample (2 sides scanned).
Notes: Correlations with $R^2 > 0.5$ are indicated in bold and highlighted. Light grey values are not correlatable (same variable or directly calculated).
*Calculated from relief and plan width.
**Calculated from kinked and plan widths.
sections of the same slab; shortening in the updip sample (B10-1a) is up to twice that of the downdip sample (B10-1b) (Table 3.1).

Shortening is positively correlated with kink band density ($R = 0.73$; Table 3.2), and with maximum relief, gradient, and rotation angle (all $R$ between 0.71 and 0.81; see Figure 3.3 for definitions). The steepening of the bands is also accompanied by a moderate increase in the curvature of the hinges ($R = 0.76$). There is no significant correlation between spacing of kink bands and any other measured variables (e.g. width, relief, curvature).

Separating out the samples from the two different outcrops (B10 and B13) shows a distinct difference in the relationships between kink bands in the two outcrops (Table 3.3). Kink bands in samples from outcrop B10 suggest more relationships between the variables, though as before, few show $R > 0.9$. The same correlations for all samples as discussed above are also true for B10 samples alone, with marginally higher $R$ values. Kink band density is also positively correlated with maximum relief, plan width, and kinked width, but negatively correlated with average hinge width ($R = -0.80$). Unique to samples from outcrop B10 are correlations between mean curvature of the kink band hinges and gradient ($R = 0.73$) as well as rotation angle ($R = 0.81$). Spacing is negatively correlated with width ($R = -0.80$ for plan width and $R = -0.71-0.81$ for kinked width), so narrower bands are more widely spaced.

Samples from outcrop B13 show very few correlations, and none of the same as outcrop B10 samples. Maximum spacing is negatively correlated with normalized shortening ($R = -0.76$), but no other relationships exist between spacing and other parameters. Average relief is positively correlated with average plan width ($R = 0.82$).
but negatively correlated with kink band density ($R = -0.75$). Hinge widths are also positively correlated with plan width and kinked width; however, hinge widths are on the order of 1-2 mm, and the precision of measurement was roughly 0.5 mm, so any relationships with hinge widths are suspect. Interestingly, samples from the two different outcrops have opposite relationships between kink band density and relief: kink bands from B10 have positive correlations and those from B13 have negative correlations, despite having similar kink band densities.

Geometric variables and measured curvature values can be correlated for individual bands. Curvature of kink band hinges is positively correlated with gradient ($R = 0.73$) and rotation angle ($R = 0.72$). Relief and plan width are also positively correlated ($R = 0.73$). No other significant relationships are indicated by the correlation coefficients, and relationships among spacing, width, or relief are noticeably lacking. Bands from B10 samples have strong correlations between curvature of hinges and gradient and rotation angle ($R$ between 0.72 and 0.82), but little else; bands from outcrop B13 show only correlations between relief and gradient ($R = 0.71$).

**Interpretation of Curvature Analyses and Comparison to Field Data**

The curvature analyses presented here provide important insights on both the geometric models of kinking and the behavior of kink bands in the third dimension. The observations from curvature scans provide a more detailed and precise characterization of kink bands than is possible in the field, though in this study the number of samples scanned is very small. The ability to quantify the tightness of kink band hinges and to
obtain more accurate measurements of relief and width provides important information to help constrain the mechanism(s) of kinking.

Kink band measurements derived from the curvature analyses show relationships that are consistent with those seen in the field data, and add several new parameters that are not measureable in the field. The strong correlation between maximum relief and shortening, and maximum rotation angle (κ) and shortening, both support rotation as a mechanism for kinking: as bands rotate, they increase in relief and accommodate more shortening. Hinge curvature also increases as κ increases, but is weakly negatively correlated with plan width; decreasing plan width with increasing rotation and hinge curvature is consistent with progressive rotation of the kinked limb and tightening of the hinges. The correlations between hinge curvature and both kinked and plan width are weak, most likely due to a mix of band maturity levels within each sample and the small sample size. There is limited evidence for mobile-hinge kinking: a weak positive correlation between relief and plan width in samples from outcrop B13 suggests that bands increase in relief as well as expand laterally; however, this correlation is not true for the majority of samples.

Both the curvature and field data sets have evidence for nucleation of new bands as deformation progresses. Positive correlations between kink band density and shortening in the curvature data suggest that more bands are needed to take up more shortening, and spacing decreases as shortening increases. In the field data, over-rotated bands are more closely spaced, also consistent with nucleation of new bands once preexisting bands lock and can no longer rotate. The negative correlation between kink band density and relief suggests that the more bands there are, the less each band has to
rotate to take up shortening; conversely, fewer or more widely spaced bands in a given area rotate more (i.e. increase in relief) to accommodate the same amount of shortening. The lack of correlations between spacing and other variables is consistent with the field data, but inconsistent with the observation that kink bands interact along their lengths. A correlation between curvature of a hinge and the adjacent spacing (i.e. the left hinge of a band and the uninked length to that band’s left) could be an important point in understanding the nucleation of new bands within a sample (e.g. a tight hinge indicates a locked band, so a closely spaced band nearby could be a new nucleation with more open hinges); however, no meaningful correlation exists between these variables.

The behavior of kink bands in the third dimension is described more completely by using geometric curvature. The combination of gradient, total curvature, and geologic curvature maps allow for more precise mapping of kink band trends and behavior of individual bands or strands at complicated intersections than is possible in the field. However, the mechanisms by which kink bands intersect or split are still not well understood. The variability of kink band trends on the foliation surface make it likely that two bands trending at high angles to each other will cross in an X-type intersection, with one band kinking the other. The fork-like behavior of bands involved in Y-type intersections suggests that splitting of one band as it propagates is a likely sequence for the formation of such geometries; however, there is no visible control on the location or orientation of the intersections. The behavior of bands in $\lambda$-type intersections is even more puzzling, and no clear mechanism exists to explain how one hinge may split while the other remains constant. Understanding the mechanisms or behavior of intersecting bands as they propagate requires further study, and deformation experiments that allow
The direct observation of bands in the third dimension could provide valuable information on the controls on complicated band geometries.

Summary

Kink bands are microtopographic features that are adequately represented and described by curvature calculations on a scanned surface. Surface slope and curvature are quantitative descriptors of the shape of a surface, and the sharp hinges and steep slopes of kinked material are clearly defined within the larger sample. Calculations of different curvature parameters allow for quantitative comparison of kink bands within a single sample as well as between samples, and coupled with qualitative descriptions of kink band behavior can give a more complete picture of kink band expression. Complicated intersections of kink bands in the third dimension are also captured by maps of mean, total, and geologic curvature values, better illuminating the true geometry of kink band hinges as they intersect.

Curvature analysis of kink bands indicates that even small topographic features can be successfully characterized by differential geometry, and that deformation features such as kink bands and small folds can be distinguished from faults and fractures of the same scale. Curvature analysis allows for rapid identification of the surface shape via mean, total, and geologic curvature as well as easy comparison between different samples. The application of a curvature threshold filters out noisy surface topography and promotes the kink band signal well; however, more subtle kink bands or small features can also be suppressed during this step, and care must be taken to select the most appropriate threshold value. Careful interpretation is required in order to correctly
identify the true deformation features, as irregular surface shapes can imitate the fold signals. Geometric curvature analyses are a valuable tool for understanding the curving and intersecting behavior of kink bands in the plane of the foliation, but detailed mapping and field measurements are necessary to characterize a kink band set more completely and to identify locations where geometric curvature analyses would be most instructive. The techniques outlined here can be applied to broader scans of outcrops containing kink bands in order to more accurately map the expression of kink bands on the foliation surface. In future work, care should be taken to sample a range of locations, orientations, and geometries of kink bands and host lithologies to obtain a more complete picture.

The curvature data are consistent with the field data from Samish Island, and both data sets support rotation as a mechanism for kinking. The curvature analyses provide new data in the form of hinge curvatures and more accurate relief and width measurements, and relationships between hinge tightness (i.e. curvature) and other geometric variables are consistent with progressive rotation. The curvature data cannot distinguish clearly between mobile- and fixed-hinge kinking, but when compared to other observations at different scales using different techniques add to the overall picture of the kinematics of kinking.
CHAPTER 4: THIN SECTION ANALYSES

The geometry of kink bands has been found to be highly dependent on the composition and spacing of the anisotropy in the host rock, with more micaceous rocks hosting sharper-hinged kink bands and more quartz-rich rocks producing kink bands with curved hinges (Paterson and Weiss, 1966). Thin sections of naturally deformed phyllite analyzed by Paterson and Weiss (1966) showed clear deflection of the foliation within the kink bands and a qualitative relationship between composition and kink band geometry, but the descriptions focused mainly on the orientations of the kink bands to the applied stress field. Stewart and Alvarez (1991) reported pressure solution, vein development, and calcite twinning in thin sections of kinked rocks, but no evidence for interlayer slip or internal shearing within kink bands. Thin sections of kink bands from the Darrington Phyllite illuminate the mineral-scale structure of the folds and provide evidence for dilation and pressure solution within the kink bands themselves.

Methods

Seven samples were selected for thin sections, from the quarry and both sides of the beach (Figure 4.1); all seven samples were float rocks that had curving or intersecting kink bands on the foliation surface. Rocks were first cut perpendicular to the foliation and perpendicular to the main kink band trend on the foliation surface to best expose the trace of the foliation and the geometry of the kink bands. An arbitrary top and right was selected for each rock slice in order to compare multiple thin sections from the same rock; one thin section per kink band was made for all samples except B13-F2, which had
Figure 4.1. Sample locations for thin section analyses.
two thin sections along strike for one kink band. Individual chips containing kink bands were cut for petrographic thin sections; 11 chips were standard size (26 x 46 mm) and one chip was 2”x3”.

**Lithology and Fabric**

The dominant mineral phases in thin section are quartz, feldspar, white mica, and actinolite, with minor calcite, chlorite, and opaques. Lamb (2000) also identified pumpellyite and epidote, and based on the occurrence of actinolite and pumpellyite determined metamorphic conditions of 200-350º C and 2 to 7 kbar. Grain size is generally very fine, with coarsest grains in the southernmost sample (B1-1) and finer grains in samples from the northern end of the beach (B10-F1, MGB2, B13-F1, F2, and F3). The coarser rocks are also more quartz-rich, and the proportion of mica increases from south to north. The main foliation in thin section is defined by alternating horizons of recrystallized quartz with a grain shape or aggregate shape preferred orientation and concentrations of aligned mica and weakly aligned actinolite laths (Figure 4.2a). The foliation is weakest in the coarse-grained southern sample (B1-1), defined by wispy mica and anastomosing pressure solution seams around large quartz grains (Figure 4.2b); as the proportion of mica increases, the foliation is better developed, more clearly defined by a ~2:1 ratio of thicker quartz (1-2 mm) to thinner mica (0.5 mm) layers.

Quartz in all samples but B1-1 is recrystallized. Quartz grains are commonly very fine (<0.2 mm) with lobate boundaries; larger (~1 mm) unstrained quartz porphyroblasts overprint the foliation in many samples. Relict feldspar grains are also present in many samples, with recrystallized quartz rims and mica tails aligned parallel to the main
Figure 4.2. Photomicrograph of phyllitic foliation in thin section. (a) In sample B10-F1, the well developed foliation (F) is defined by a grain shape preferred orientation of quartz grains and aggregates (Q) and aligned mica (M) (crossed polars); some samples also show weakly aligned actinolite laths associated with micaceous horizons. (b) A poorly defined foliation (F) in sample B1-1 consists of pressure solution seams (PS) anastomosing around quartz and feldspar grains (plane light).
foliation. The grain shape preferred orientation (GSPO) of quartz defining the foliation is very strong in samples Q5-2, B10-F1, and B13-F2; an aggregate shape preferred orientation (ASPO) is dominant in MGB2 and B13-F3, and poorly developed in B13-F1; no clear grain fabric is visible in B1-1.

Pressure solution within the bulk rock is clearly seen in most samples. Dark pressure solution seams are roughly parallel to the foliation in most rocks, associated with the mica-rich horizons; this orientation and association is consistent with Lamb’s (2000) S2 foliation, parallel to the main (S1) mineral foliation. In samples B1-1, MGB2, and B13-F3, a discontinuous set of seams oriented about 30° from the foliation anastomose around quartz grains (Figure 4.3); this orientation and expression corresponds to Lamb’s (2000) S3 foliation. Both series of pressure solution seams consist mainly of dark insoluble residues and minor mica.

Sample Q5-2 from the quarry has a very well-developed fabric that is distinct from that of the foliated beach samples. In outcrop, the rock is tightly folded with crenulations on the foliation surface trending parallel to the major fold hinges. In thin section, the rock is much more micaceous than the beach rocks, with very thick (2-4 mm) horizons of micas/opaques and fine quartz bounding 1-2 mm thick bands of recrystallized quartz (Figure 4.4). The recrystallized quartz zones have a strong grain shape preferred orientation parallel to the main foliation direction and most likely represent original bedding. Several of the quartz bands have been folded, with axial planes parallel to the main foliation, and are most likely F1 folds (Figure 4.4).
Figure 4.3. Pressure solution seams (PS) create a spaced cleavage (Lamb’s (2000) S3) that cuts the main foliation (F) at about 30° in sample B13-F3. Plane light, field of view is 2.2 mm x 2.9 mm.
Figure 4.4. Photomicrograph of well-developed cleavage in recrystallized and very mica-rich sample Q5-2. The quartz and mica horizons are well segregated, and mica laths are larger and have stronger alignment than in other samples. A quartz layer is folded in the upper right (axial plane shown in green) in a probable first generation (F1) fold. Crossed polars; field of view 2.2 mm x 2.9 mm.
Kink Bands

Twelve kink bands, ranging in widths from <1 mm up to 1 cm, were analyzed in thin section. Observations included kink angles (α, β, and κ), width of the kinked limb and perpendicular width of the kink band, thickness of the foliation inside and outside the kink band (taken as the spacing between mica layers), geometry and shape of the hinges, and presence of voids, gashes, or veins associated with the bands (Figure 4.5; Table 4.1). Kink bands are clearly delineated in most samples by a relatively sharp change in mica orientations at the boundary: micas have uniform extinction within the kink band that is rotated from that of external micas (Figure 4.6). Kink band boundaries are generally better defined in more micaceous samples (e.g. B10-F1, B13-F1, F2, F3), and tend to be sharper (Figure 4.7a); rounded, diffuse kink band hinges are more common in more quartz-rich and/or coarser-grained samples (e.g. B1-1, MGB2; Figure 4.7b). The thickness of foliation layers is similar inside and outside of kink bands, though in some cases isolated horizons expand or thin in the hinge zone with no systematic pattern. Changes in foliation spacing and thickness are most noticeable at the hinges but are difficult to measure due to the discontinuity of quartz and mica zones that define the foliation both inside and outside of kink bands. Observations were made on all kink bands, and based on these observations bands were separated into groups based on the angular relationship between β and α, which can be used as a proxy for kink band maturity (see Chapter 2).

Kink bands in four samples (Q5-2, B10-F1, B13-F1, B13-F3) had β > α for both hinges, with α ranging from 60° to 75° (average: 65°) and β ranging from 70° to 97° (average: 83°). The rotation angle κ for the kink bands ranged from 8° to 50°
The angles $\alpha$, $\beta$, and $\kappa$, kinked width (KW), and plan width (PW) are the same variables measured in the field. The spacing of the foliation is measured as the average thickness of quartz-rich layers (Q) bounded by thin mica horizons (M).
Table 4.1. Kink band parameters measured in thin section.

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<tr>
<th>Sample</th>
<th>Thin section</th>
<th>Band</th>
<th>α</th>
<th>β</th>
<th>κ</th>
<th>Kinked width (mm)</th>
<th>⊥ width (mm)</th>
<th>Mica/qtz ratio</th>
<th>Foliation spacing</th>
<th>Hinge type</th>
<th>Other</th>
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<tbody>
<tr>
<td>Q5-2</td>
<td>A1</td>
<td>1</td>
<td>75</td>
<td>97</td>
<td>8</td>
<td>17</td>
<td>10</td>
<td>M&gt;&gt;Q</td>
<td>0.4 mm Q/M</td>
<td>Fractured, sharp</td>
<td>Triangular voids in hinges</td>
</tr>
<tr>
<td>B1-1</td>
<td>A1</td>
<td>1</td>
<td>63</td>
<td>65</td>
<td>52</td>
<td>8</td>
<td>6</td>
<td>Q&gt;&gt;&gt;M</td>
<td>Pressure solution bounds ~1 mm Q grains</td>
<td>Very rounded and diffuse</td>
<td>Pressure solution within band, 34º from boundaries; some Q precipitation along hinge line</td>
</tr>
<tr>
<td>MGB2</td>
<td>A1</td>
<td>1</td>
<td>88</td>
<td>68</td>
<td>24</td>
<td>4</td>
<td>3.5</td>
<td>Q&gt;M</td>
<td>0.5-1 mm Q, 0.2 mm M</td>
<td>Rounded</td>
<td>Q-filled gashes along hinges, oriented 45º-55º from unkinked foliation</td>
</tr>
<tr>
<td>B10-F1</td>
<td>A1</td>
<td>1</td>
<td>65</td>
<td>81</td>
<td>34</td>
<td>4-5</td>
<td>4-5</td>
<td>Q=M</td>
<td>0.2-0.5 mm M, 0.5-1 mm Q</td>
<td>Slightly rounded</td>
<td>Gashes on one hinge only, 75º from unkinked foliation</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>1</td>
<td>72</td>
<td>91</td>
<td>17</td>
<td>7</td>
<td>6</td>
<td>Q=M</td>
<td>0.5 mm M/Q, then 1 mm pure Q</td>
<td>Rounded</td>
<td>M increases/Q decreases in hinges; gashes on both hinges ~60º from u.k. foliation</td>
</tr>
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</table>
Table 4.1. continued

<table>
<thead>
<tr>
<th>B13-F1</th>
<th>A1</th>
<th>1</th>
<th>81</th>
<th>67</th>
<th>32</th>
<th>2</th>
<th>2</th>
<th>Q&gt;M</th>
<th>Ranges, 1 mm Q to 0.2 mm M</th>
<th>Sharp</th>
<th>Widest near thick (2 mm) Q vein, rounder hinges where more Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>1</td>
<td>60</td>
<td>70</td>
<td>50</td>
<td>2</td>
<td>2</td>
<td>Q&gt;M</td>
<td>Ranges, 1 mm Q to 0.2 mm M</td>
<td>Sharp</td>
<td>Widest near thick (2 mm) Q vein, rounder hinges where more Q</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>1?</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>Bands are sheared and disaggregated</td>
<td></td>
</tr>
<tr>
<td>B13-F2</td>
<td>A1</td>
<td>1</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>5.5</td>
<td>4.5</td>
<td>Q~M</td>
<td>0.5 mm alternating Q/M</td>
<td>Subrounded</td>
<td>Pressure solution within band, 10º from boundary</td>
</tr>
<tr>
<td>A3</td>
<td>1</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>4</td>
<td>4</td>
<td>Q~M</td>
<td>0.5 mm alternating Q/M</td>
<td>Subrounded</td>
<td>Pressure solution within band, 10º from boundary</td>
<td></td>
</tr>
<tr>
<td>B13-F3</td>
<td>A1</td>
<td>1</td>
<td>60</td>
<td>74</td>
<td>46</td>
<td>1</td>
<td>1</td>
<td>Q&gt;M</td>
<td>0.4 mm M, 1-2 mm Q</td>
<td>One sharp, one rounder</td>
<td>Truncates against thick quartz layer at bottom</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>60</td>
<td>85</td>
<td>35</td>
<td>10</td>
<td>8</td>
<td>Q&gt;M</td>
<td>0.4 mm M, 1-2 mm Q</td>
<td>One sharp, one rounder</td>
<td>Gashes/voids filled with calcite along boundaries; some shearing within and along kink band in places</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.6. Photomicrograph of a kink band in sample B13-F3 showing the difference in extinction angles for mica inside and outside the kink band. Mica grains inside the kink band show higher order colors, while mica outside the kink band is close to extinction. Bent quartz grains or aggregates of grains (arrow) are seen at the tight kink hinge (dashed lines); the pressure solution component of the foliation (dark seams labeled PS) are also kinked. Crossed polars; field of view 2.2 mm x 2.9 mm.
Figure 4.7. Photomicrograph of kink band hinges (dashed lines) in thin section. (a) Sharp kink band hinge in sample B10-F1, with clearly defined foliation layers of alternating quartz and mica changing orientation sharply; crossed polars. (b) Rounded kink band hinge in sample MGB2 with associated triangular gashes filled with quartz; plane light. Both images field of view 2.2 mm x 2.9 mm.
(average: 32º). All four samples have significant mica content and generally fine, equigranular, recrystallized quartz segregated into alternating layers, but quartz vs. mica content has wide variation, and spacing of mica layers ranges from 0.5 to almost 2 mm. This group of kink bands has the largest widths (both plan and kinked) observed, averaging ~7 mm but up to 17 mm in Q5-2. Well-developed triangular voids are present along the boundaries of the kink bands in Q5-2 and B13-F3 (Figure 4.8a), and smaller gashes are seen along the boundaries of bands in B10-F1 (Figure 4.8b); no clear voids are seen in B13-F1. The voids are filled with large (>1 mm) polygonal quartz crystals or very large (>3 mm) irregularly shaped calcite crystals that are controlled by the shape of the void and not the foliation. In Q5-2 especially, unrecrystallized quartz veins extend from the tip of the triangular voids across the kink band, following the trace of the foliation (Figure 4.8a). In the large voids of Q5-2, quartz fibers adjacent to the external foliation are small and elongate parallel to the external foliation (Figure 4.9a); grains become larger and more polygonal in the center of the void space, and quartz fibers on the inside of the voids are rare. The edges of the large voids in sample Q5-2 are ragged due to very small-scale interfingering of mica grains with the fine-grained quartz at the rims (Figure 4.9b); similar interfingering is visible along the edges of calcite-filled voids in B13-F3. Details of the quartz fiber orientations or possible interfingering of mica with the quartz are not discernable in the much smaller voids in B10-F1.

Two samples (B13-F2 and B1-1) have kink bands with $\beta = \alpha$, resulting in rotation angles of 60º. The band in B13-F2 is well defined by clearly kinked mica/quartz horizons across the boundaries, with similar fabric to the other samples from B13. The kink band in B1-1 is difficult to see in thin section due to the coarse grain size, elasic
Figure 4.8. Photomicrograph of triangular voids along kink band hinges. (a) Large triangular void filled with unrecrystallized quartz in sample Q5-2. Larger grains fill the center of the triangular void, and smaller grains rim the triangle; a vein of similar quartz extends into the kink band, parallel to the kinked foliation (k; unkinked = uk). (b) Small semi-triangular gashes (dashed outlines) along the hinge filled with quartz in sample B10-F1. Both images crossed polars, field of view 2.2 mm x 2.9 mm.
Figure 4.9. Photomicrographs of quartz-filled voids in sample Q5-2 and evidence for multi-stage opening segments and interlayer slip. (a) Quartz fibers on the outside of the void are elongate and parallel to the unkinked foliation (UK); the inside of the void is filled with larger, polygonal quartz grains. The dashed line separates the two types of grains. The two shapes and orientations of quartz grains suggest multiple opening segments. (b) Mica grains along the kinked foliation (K) interfinger with the quartz grains in the void space, suggesting interlayer slip inside the kink band; also visible in photo (a).
texture, and lack of a continuous foliation. The boundaries are vaguely visible as thin zones of equigranular quartz weakly aligned perpendicular to the pressure solution cleavage of the unkinked rock, but the trace of the kinked limb is not discernable.

Unique to these two bands is clear evidence of pressure solution within the kink bands themselves that does not extend into the unkinked rock (Figure 4.10). Pressure solution seams trend subparallel to the kink boundaries in B13-F2 and persist through the full width of the band; where the seams coincide with the boundaries, the hinges are sharper than just the kinked foliation alone. Clear offsets are seen in the kinked mica layers across the seams, but displacement is variable and difficult to measure. In B1-1, the pressure solution seams make a larger angle with the kink band boundaries (34º here, vs. 10º in B13-F2) and are better defined than the actual kinked limb. In both samples, the hinge zones are very rounded except where affected by pressure solution.

Two kink bands (in samples MGB2 and B13-F1) have $\beta < \alpha$, with the highest observed $\alpha$ values (81º, 88º) but not abnormally low $\beta$ (68º, 67º) or rotation angles (24º, 32º). The fabric of both rocks is similar to that of nearby samples (B10-F1 for MGB2 and B13-F2, B13-F3 for B13-F1), with similar grain sizes and mica/quartz spacing. MGB 2 has a higher quartz/mica ratio and its kink band has rounded hinges that are difficult to trace in some places. Small but closely spaced gashes filled with quartz are associated with the hinges, making an angle of ~50º with the unkinked foliation. The band in B13-F1 is very narrow, less than 1 mm wide at one end and widening along its length up to 2 mm across. The wider portion of the kink band occurs where a thick (2 mm) quartz vein runs parallel to the foliation. The kink band hinges are sharper where the band is thinner and in a more micaceous zone; as the band hits the quartz vein the
Figure 4.10. Crenulation cleavage within kink bands. Solid lines trace the kinked foliation; dashed lines trace the pressure solution seams within the kink bands. (a) Scan of a thin section from B1-1 showing quartz precipitation along the kink band boundaries and pressure solution within the kink band. (b) Pressure solution seams within a kink band in B13-F2 are subparallel to the kink band boundaries (dotted line); reflected light.
hinges become very rounded and less defined. The quartz in the vein is much larger than that of the matrix, and has lobate to serrated boundaries.

One sample (B13-F3) has two kink bands of opposite kink senses trending towards each other (Figure 4.11). The thinner band (1 mm kinked width) has relatively sharp hinges and truncates against a quartz/opaque-rich zone near the bottom of the sample. The wider band (10 mm kinked width) maintains its width along its length but has many filled voids and gashes along its hinges, as well as evidence for shear along the boundaries. The kink is clearly defined within the quartz/opaque-rich layers at the bottom of the sample, with few boundary gashes present. As the band continues into the more micaceous zone, large and elongate triangular voids appear along the hinges, filled with large calcite crystals (Figure 4.12a). In some places the hinge is defined by very fine-grained quartz aligned along the hinge rather than with the foliation (Figure 4.12b); in others, truncation and translation of foliation layers is evidence for shearing (Figure 4.13a). Even more intense shearing is seen in thin section B13-F1-A3, where the kink bands are too deformed for accurate measurements (Figure 4.13b).

**Interpretation of Kink Bands in Thin Section**

Common elements among the majority of thin sections include: relatively equal spacing of foliation layers inside and outside kink bands; uniform extinction of micas inside kink bands; sharp to rounded hinges across which the foliation is continuous; and quartz- or calcite-filled voids along the kink band boundaries. The composition and grain size of the foliation inside kink bands is similar to that outside kink bands, though quartz-rich layers sometimes thicken in the hinges and small fractures or pressure solution seams
Figure 4.11. Scan of thin section B13-F3 showing two kink bands of opposite kink sense trending towards each other. The thinner band (1) appears to truncate against the quartz/opaque-rich layers (Q/O) at the bottom. The wider band (2) has large calcite-filled voids along its hinges as well as throughout the band; the band appears to disaggregate in the central portion, shearing along void-filled zones (approximated by dotted lines).
Figure 4.12. Photomicrographs of kink band hinges in sample B13-F3. (a) In many places, large calcite crystals fill elongated triangular voids along the kink band hinge; kinked (k) and unkinked (uk) foliation are labeled. (b) In some places, recrystallized quartz grains are aligned with the hinge rather than the main foliation, with associated calcite. Both images crossed polars, field of view 2.2 mm x 2.9 mm.
Figure 4.13. Evidence for shear inside and along kink bands in thin section. (a) Sample B13-F3, and (b) B13-F2-A3. Shear planes are marked by dotted lines; it is difficult to determine kinked rock from sheared/rotated rock, though both are distinct from the unkinked foliation (uk). Reflected light; field of view 7 mm x 9 mm.
along kink band hinges obscure the traces of individual layers as they cross the kink band boundaries. There is no evidence for broken grains inside kink bands that would indicate outward migration of hinges as kinking progressed, nor are there adequate strain markers to test whether the internal foliation has been strained or merely rotated. The uniform extinction of mica grains suggests rotation of the kinked limb as one unit, a feature common to kink bands with very different rotation angles (κ). The interfingering of mica grains with quartz in the hinges suggests slip along mica-rich horizons both inside and outside the kink band; interlayer slip is a necessary mechanism for rotational kinking.

Voids along kink band hinges as well as veins parallel to the kinked foliation are indicative of dilation within the kink band during deformation. The largest voids are seen in sample Q5-2, where β is much greater than α and is greater than 90°; previous workers (e.g. Ramsay, 1967; Verbeek, 1978) have shown that dilation is at a maximum when β = 90° and is greater than α. The voids in Q5-2 show evidence for multiple opening events, with small quartz fibers on the outer edge parallel to the external foliation, and larger polygonal grains in the main part of the void (Figure 4.9a). The first opening segment may have been very small, promoting fibrous growth; as rotation increased, the space widened rapidly and larger, polygonal grains precipitated. The quartz veins extending from the triangular hinge voids into the kink band also indicate dilation normal to the kinked foliation. Internal dilation is a diagnostic characteristic of fixed-hinge rigid rotation (mode IV) kinking, and violates the assumptions made for mobile-hinge kinking. Small quartz-filled tension gashes along kink band hinges in most samples also indicate that dilation is a common feature on Samish Island.
There is some evidence for shear along kink band boundaries in samples B13-F1 and B13-F3, but is unclear whether the shearing occurred during or after kinking. In B13-F1, shearing and faulting affect the rock both inside and outside the kink band, and are not confined to the kink band hinges; therefore, some if not all of the shearing is unrelated to kink band development. In B13-F3, shearing along the boundaries of the larger kink band is confined to the band itself but disaggregates it into discrete sections. One possibility is that the kink band could no longer accommodate shortening purely by rotation and localized strain along the boundaries, leading to shearing (mode III kinking) instead of only rotation; this may have opened new space inside the kink band and allowed voids to develop, further disaggregating the foliation. Increased shortening near outcrop B13 is also indicated by the development of pressure solution within a kink band from sample B13-F2. Pressure solution seams run subparallel to the kink band hinges and are clearly controlled by the kink itself, suggesting that kinking could not take up all the shortening in this area and pressure solution began to operate.

The evidence for dilation inside the kink bands, interlayer slip along the mica-rich horizons of the foliation, and lack of migration structures inside kink bands all support rigid rotation of the internal foliation between fixed hinges (mode IV kinking). Dilation within the kink bands is clearly present in samples with $\beta > \alpha$, which is predicted by previous descriptions of fixed-hinge kinking (e.g. Verbeek, 1978; Stewart and Alvarez, 1991). Dilation spaces along the hinges are also present in bands with $\beta < \alpha$, which is inconsistent with expected contraction when $\beta$ is less than $\alpha$; one explanation is that the external foliation may have rotated during or after kinking, increasing $\alpha$ and modifying the angular relationship. Bands with $\alpha = \beta$ show clear evidence for pressure solution.
inside the kink band. If the bands developed by mode IV kinking, rotation ceased once\n$\alpha = \beta$ and any further shortening had to be accommodated by pressure solution. The\nevidence from thin sections strongly support fixed-hinge rigid rotation as the dominant\nkinking mechanism, and there is little evidence for internal simple shear or hinge\nmigration (modes I and/or II). The very fine grain size precludes the use of strain\nmarkers to quantify any strain in the kinked foliation; magnetic fabric analyses (Chapter\n5) provide more information on strain inside the kink bands.
CHAPTER 5: MAGNETIC FABRIC ANALYSES

Mineral fabrics in metamorphic rocks are commonly used to interpret the deformation history of the rock units, comparing structural elements such as foliation, lineation, and folding to determine the conditions and stress regime of deformation. For many rocks, strain markers can be used to determine the strain state of the rock as well, though such markers can be difficult to find or accurately measure. For fine-grained or weakly deformed rocks especially, the anisotropy of magnetic susceptibility (AMS) can be used to qualitatively and even quantitatively describe the amount of deformation a rock has undergone (e.g. Hrouda, 1978; Averbuch et al., 1992; Parés and van der Pluijm, 2002; Debacker et al., 2004). Small-scale structures such as kink bands and crenulation cleavage can also be analyzed using AMS and other magnetic techniques to determine the relationship between the mineral and magnetic fabrics and the mechanisms responsible for deformation (Kirker and McClelland, 1997; Anderson and Morris, 2004; Martín-Hernández et al., 2005). Here, AMS is used to estimate variations of strain in centimeter-scale kink bands in the Darrington Phyllite of Samish Island.

Theory and Previous Applications

Magnetic anisotropy is controlled by the crystallographic orientation and shape of minerals within a rock; in foliated rocks, the phyllosilicates defining the foliation typically carry a large part of the susceptibility signal, accompanied by other tabular or elongate minerals or ferrimagnetic grains such as magnetite (Parés and van der Pluijm, 2002). All of the minerals in a rock contribute to its bulk susceptibility (Tarling and
Hrouda, 1993), and understanding the distribution and crystallographic orientations of such minerals is important to interpreting the AMS ellipsoid. AMS of a sample can be described by a 3x3 matrix whose eigenvalues provide the magnitudes of the three principle susceptibility axes (where $k_1 = k_{\text{max}}$ and $k_3 = k_{\text{min}}$), and the eigenvectors the orientation of these axes (Tarling and Hrouda, 1993; Figure 5.1a). This representation allows the AMS ellipsoid to be presented and evaluated using the same geometric method as strain analyses: the shape of the AMS ellipsoid can be described using ratios of the principal susceptibilities representing structural fabric elements of a rock: the lineation (L) parameter, or $k_{\text{max}}/k_{\text{int}}$, and the foliation (F) parameter, or $k_{\text{int}}/k_{\text{min}}$ (Tarling and Hrouda, 1993). These two variables can be plotted on a Flinn diagram (Figure 5.1b) to describe the shape of the ellipsoid and therefore the dominant fabric of the rock as prolate (elongate), oblate (flattened), or spherical (uniform deformation or no deformation). Comparing the orientation of the ellipsoid with structural data on a stereoplot can associate a mineral fabric with a deformation fabric (e.g. Hrouda, 1978; Parés and van der Pluijm, 2002).

The application of AMS to folded and deformed rocks has yielded several important conclusions. The orientation and shape of the ellipsoid can be directly correlated with the structural, mineralogic, or intersection fabrics within deformed rocks (e.g. Hrouda, 1978; Parés and van der Pluijm, 2002; Anderson and Morris, 2004; Debacker et al., 2004), and a fabric produced during early deformation can persist through subsequent events (Anderson and Morris, 2004). In order to properly interpret the AMS of (multiply) deformed rocks, however, a clear understanding of the deformation history and the structural fabrics is needed. Comparing AMS results across
Figure 5.1. The AMS ellipsoid and representative plots. (a) The susceptibility ellipsoid, with the magnitudes of the principal susceptibilities \((k_{\text{max}}, k_{\text{int}}, k_{\text{min}})\) defining the lengths of the three axes and the orientations plotted on a stereonet using standard symbols. (b) Flinn plot describing the shape of the ellipsoid using the foliation \((F)\) and lineation \((L)\) parameters. Fields of prolate and oblate ellipsoids are separated by neutral (or spherical) ellipsoids where \(k_{\text{max}} = k_{\text{int}} = k_{\text{min}}\). Redrawn and modified from Tarling and Hrouda (1993).
a fold or a deformed region can yield information on the intensity of deformation and the orientation of principal stresses that modified original fabrics or produced new fabrics (Parés and van der Pluijm, 2002).

The magnetic fabric of kink bands in particular has been poorly studied; two studies analyzed magnetic fabrics inside and outside kink bands in order to quantify finite strain within the bands. Kirker and McClelland (1997) showed that small-scale processes such as pressure solution or crenulation cleavage development within kink bands can affect the rotated magnetic fabric by changing the orientation of primary magnetic particles and therefore the AMS ellipsoid within the band (Figure 5.2). Comparing the observed deflection of the susceptibility axes inside the kink band with the expected deflection from rotation alone yields information on micro-scale processes that may not be readily observable in the mineral fabric. Martín-Hernández et al. (2005) showed that the width and wavelength of the kink bands are also influences on the susceptibility signal, as are heterogeneities within the rock itself. The heterogeneity of the mineral fabric and the variation in mineral composition complicate the association of the AMS with finite strain. However, if kinking can be shown to be the final deformation stage, both the kinked and unkinked rocks should have similar initial fabrics, and differences between the two can yield information on strain associated with kink folding.

**AMS and Kink Bands in the Darrington Phyllite**

Kink bands in the Darrington Phyllite are similar in size to those measured by Kirker and McClelland (1997) and Martín-Hernández et al. (2005), and occur in deformed, low-grade rocks similar to those of Anderson and Morris (2004) and Martín-
Figure 5.2. Illustration showing the effect of kinking and pressure solution on $k_{\text{min}}$. Two magnetic components—that of the bedding plane and that of the pressure solution plane, at high angles to each other—combine to form an intermediate resultant that is steeper than the kink angle ($\kappa$). Redrawn from Kirker and McClelland (1997).
The mineral fabric and structural elements of the bands have been investigated in the field (see Chapter 2) and in thin section (see Chapter 4); the phyllitic foliation is well-developed in thin section and is defined by alternating layers of recrystallized quartz with minor feldspar and white mica layers. A pronounced mineral lineation is also visible on the foliation surface. Centimeter-scale kink bands clearly deflect the mineral fabric in thin section, accompanied by quartz void fill along many kink band hinges and, in a few samples, crenulation/pressure solution cleavage within the kinks themselves. The mineralogy observed in thin section suggests a paramagnetic signal that may be modified by small ferromagnetic grains; magnetic hysteresis can be used to define the carriers of the magnetic fabric.

AMS results are compared to the observed fabric in hand sample to determine how the magnetic fabric deflection relates to the mineral fabric deflection. Rigid rotation of the kink limb should result in rotation of the AMS directions by the angle $\kappa$ (Figure 5.2), and the ellipsoid shapes should be similar inside and outside the kink band. If the rock inside the kink band has been strained, the orientation and shape of the ellipsoid for the kinked rock will reflect this, and the deviation can be quantified to evaluate strain due to kinking.

**Methods**

Four block samples, each containing at least one kink band, were collected from quarry outcrops on Samish Island (see Figure 2.3); three samples were oriented and one was float. Two rocks were drilled perpendicular to the oriented foliation surface and the other two were drilled parallel to the foliation; this was done to separate kinked and
unkinked material more completely in the cores depending on the samples and to compare the magnetic fabric in multiple directions. For the unoriented sample, the foliation was given an orientation similar to the nearest outcrop from which it was taken; this assigned orientation is for comparison in geographic coordinates, and does not affect the internal rotation sense of the isolated kink bands. Small cores measuring 1.6 cm in diameter and 1 cm in length were cut from material both inside and outside major kink bands; care was taken to include as little as possible unkinked material on the edge of the kink band cores, though in all but one case bands were too thin to isolate completely. One sample (QX-1) produced unusable cores due to a high density of internal fractures; the remaining three rocks yielded 4 to 11 useable cores each.

All magnetic analyses were performed in the Pacific Northwest Paleomagnetism Lab at Western Washington University. The anisotropy of magnetic susceptibility of each core was measured using a KLY3-S Kappabridge. Magnetic hysteresis of each sample was measured on small chips using a Princeton Measurements vibrating sample magnetometer. AMS directions for each sample were plotted on a lower hemisphere projection and compared to structural data collected in the field. The magnitudes of the three principal susceptibilities were graphed to evaluate the shape and ellipticity of the AMS ellipsoids inside and outside the kink bands. The minimum susceptibility directions for kinked and unkinked specimens for each sample were input into the program StereoWin (Allmendinger, 2002) and the angle between the kinked and unkinked directions was calculated using built-in tools. The rotation angle ($\kappa$) was measured directly on the sample with a protractor.
Results

All three useable samples produced clear AMS results for both unkinked and kinked specimens. For all three rocks, $k_{\text{max}}$ and $k_{\text{int}}$ for the unkinked specimens lie in the plane of the foliation, with $k_{\text{min}}$ close to the pole of the foliation (Figure 5.3, 5.4, 5.5). The shape of the ellipsoid, however, is prolate, which indicates that the magnetic fabric is not controlled solely by the foliation; instead, the mineral lineation coincides closely with $k_{\text{max}}$, suggesting the fabric is associated with the shearing event that produced the lineation. The alignment of magnetic with structural fabrics is not perfect, due to variability of the orientations in outcrop and difficulty in coring perfectly perpendicular to the foliation, and the association is weakest for sample Q4-2 for which the orientation was estimated. However, the consistency between all three samples suggests that the magnetic fabric is indeed controlled primarily by the mineral lineation.

Both kinked and unkinked specimens had very weak magnetic moments, resulting in noisy hysteresis loops despite multiple runs and large sample volumes (Figures 5.6, 5.7). The raw hysteresis loop (Figure 5.6) shows a single line with a positive slope, indicating that the bulk sample magnetic signal is paramagnetic; thus, the AMS is measuring the orientation and degree of alignment of the paramagnetic matrix phases. Correction of the raw data for the high field slope (Figure 5.7) indicates that there may be a small contribution from ferromagnetic phases; however, the openness of the loop, lack of saturation at high fields, and noisy data preclude any definitive interpretations on the ferromagnetic minerals within the phyllite. Based on petrological analyses (Lamb, 2000), pyrite and/or pyrrhotite are minor phases within the bulk rock. Demagnetization curves for small chips of the bulk rock suggest a remanent phase (e.g. pyrrhotite), but the data
Figure 5.3. Magnetic fabric data for sample Q4a-1. (a) AMS directions plotted on a lower hemisphere projection for unkinked specimens (dark symbols) and one kink band (shaded grey, labeled); the unkinked foliation (line), pole to foliation (o), and mineral lineation (x) orientations are also shown. Kink bands are clearly distinct from the unkinked rock. (b) Confidence (error) ellipsoids for AMS directions. (c) Flinn plot of AMS ellipsoid shapes and (d) ellipticity plot for kinked and unkinked specimens. Both kinked and unkinked specimens contain prolate magnetic fabrics, but the kinked specimen has clearly been modified. Error bars for plots (c) and (d) are smaller than the symbols used.
Figure 5.4. Magnetic fabric data for sample Q4-2. (a) AMS directions plotted on a lower hemisphere projection for unkinked specimens (dark symbols) and three kink bands (shaded grey, labeled); the unkinked foliation (line), pole to foliation (o), and mineral lineation (x) orientations are also shown. Kink bands 1 and 4 are clearly different from the unkinked rock, but band 3 is similar. (b) Confidence (error) ellipsoids for AMS directions. (c) Flinn plot of AMS ellipsoid shapes and (d) ellipticity of the AMS ellipsoid for kinked and unkinked samples. Ellipsoids are prolate to triaxial, and kink band ellipsoids are clearly more triaxial than the unkinked rock fabric. Kink band 3 has a purely triaxial ellipsoid but has rotated least from the unkinked rock. Error bars for plots (c) and (d) are smaller than the symbols used.
Figure 5.5. Magnetic fabric data for sample Q4-4. (a) AMS directions plotted on a lower hemisphere projection for unkinked specimens (dark symbols) and two kink bands (shaded grey, labeled); the unkinked foliation (line), pole to foliation (○), and mineral lineation (x) orientations are also shown. Both kink bands deflect similarly from the unkinked rock. (b) Confidence (error) ellipsoids for AMS directions. (c) Flinn plot of AMS ellipsoid shapes and (d) ellipticity of the AMS ellipsoid for kinked and unkinked samples. Both kink bands are similarly more triaxial than the prolate fabric in the unkinked rock. Error bars for plots (c) and (d) are smaller than the symbols used.
Figure 5.6. Example uncorrected hysteresis curves for sample Q4a-1. (a) Unkinked specimen, and (b) kinked specimen from the same rock. Both specimens produce a single line with positive slope, indicating that the AMS of the rock is controlled by a paramagnetic fabric. The difference in the magnitude of the magnetization between the specimens is due to a much smaller volume of rock measured for the kinked specimen. There is no appreciable difference between the kinked and unkinked rock.
Figure 5.7. Example corrected hysteresis curves for sample Q4a-1. (a) Unkinked specimen, and (b) kinked specimen from the same rock. Both curves show open curves without a clear loop, and the separation of the curves at high fields suggests that the magnetic signal is weak. The shape of the curves (narrow loop, weak saturation at high field) suggests that both paramagnetic and superparamagnetic components are possible; the specific components are undetermined. There may also be a small ferrimagnetic component; however, the concentration of these particles is very low. The similarity of the two curves suggests that the magnetic fabric is similar both inside and outside the kink band; the lower magnetization values for the kinked sample are due to a smaller volume of rock analyzed.
are not definitive. The very narrow hysteresis loop and high saturation suggest a superparamagnetic component is also possible. Both kinked and unkinked specimens produce similar high-field loops (Figure 5.7), suggesting that there is no appreciable difference in the magnetic carriers inside and outside the kink bands, with little contribution from ferromagnetic phases, and the AMS directions can be compared directly with the assumption that there is no mineralogic difference between the two zones.

The AMS directions within the kink bands are clearly rotated from the unkinked foliations. The AMS ellipsoids within the kinked specimens are also modified from the prolate ellipsoids of the unkinked specimens; the kinked specimens are close to triaxial in Q4a-1 (Figure 5.3) and Q4-4 (Figure 5.5), though only one band is triaxial in Q4-2 (Figure 5.4). The three measured bands in Q4-2 show a range of modifications and rotations from the unkinked foliation, with bands 1 and 4 rotating furthest but with little change in the ellipsoid shape; band 3, however, plots close to the unkinked foliation in its orientation but has the most changed ellipsoid shape. This band may have been strained more than bands 1 and 4 in this rock despite its smaller rotation angle.

Comparing the rotation angle on the sample ($\kappa$) to the angle between $k_{\text{min}}$ for kinked/unkinked specimens yields a clear deviation (Table 5.1). For all kink bands the $k_{\text{min}}$ deflection is clearly less than the expected deflection due to the change in foliation orientation within the kink band. Samples Q4a-1 and Q4-4 have kink bands with similar rotation angles, and the deviation ($\delta$) of the magnetic fabric from the expected angle is also similar in these two rocks, ranging from 11.7° to 16.3°. The range of deviation in sample Q4-2 is very wide, from 4.7° to 17.1°, though the range in rotation angles is not
Table 5.1. $k_{\text{min}}$ orientations and deflections determined via AMS.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unkinked $k_{\text{min}}$ (mean)</th>
<th>Kink band</th>
<th>Kinked $k_{\text{min}}$ (mean)</th>
<th>Measured $\kappa$ (error)</th>
<th>Rotation angle (calc)</th>
<th>Deviation $\delta$</th>
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</thead>
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<tr>
<td>Q4a1</td>
<td>13.2</td>
<td>36.2</td>
<td>KB1</td>
<td>13.8</td>
<td>58.6</td>
<td>38 (3)</td>
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<tr>
<td>Q4-2</td>
<td>33.5</td>
<td>25.9</td>
<td>KB1</td>
<td>64</td>
<td>6</td>
<td>31.5 (8.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>KB3</td>
<td>43.4</td>
<td>31.5</td>
<td>27.5 (2.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>KB4</td>
<td>67</td>
<td>14.5</td>
<td>40 (2)</td>
</tr>
<tr>
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<td>KB1</td>
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<td></td>
<td></td>
<td>KB2</td>
<td>58.5</td>
<td>41</td>
<td>35 (2)</td>
</tr>
</tbody>
</table>

Note: Error ellipses for kinked and unkinked $k_{\text{min}}$ orientations are shown in Figures 5.3-5.5.
that high (27.5° to 40°). The deviation for samples Q4a-1 and Q4-4 is outside the margin of error for the measurements, suggesting that the magnetic fabric is indeed shallower than expected. For sample Q4-2, the error bars are very large and it is unclear whether the shallowed $k_{\text{min}}$ directions are actually significantly changed. In almost all core specimens, some unkinked material was included in the core due to the thinness of the kink bands, and so some of the error or deflection of $k_{\text{min}}$ could be due to the mixing of two AMS directions (kinked and unkinked); however, the clear difference in the shape of the AMS ellipsoid between the kinked and unkinked specimens strongly suggests internal strain associated with kinking.

The shallowing of $k_{\text{min}}$ inside the kink bands does not match the results reported by Kirker and McClelland (1997) for kink bands that showed a steepening of $k_{\text{min}}$. In that study, the authors proposed that crenulation cleavage inside the kink bands could rotate individual magnetic particles within the rock, effectively steepening the fabric. For the kink bands studied here, two possible scenarios are proposed, based on models of kink band development and thin section analyses of other kink bands. One scenario modifies the model of Kirker and McClelland (1997), using pressure solution inside the kink bands to produce a secondary $k_{\text{min}}$ that dips opposite the expected $k_{\text{min}}$ direction (Figure 5.8a); the resultant vector would be shallower than expected. Pressure solution and crenulation cleavage within kink bands has been observed in thin sections from Samish Island (see Chapter 4), but it is not ubiquitous. It is also unlikely that the small amount of pressure solution would significantly rotate $k_{\text{min}}$ to produce such a large deflections. The second scenario proposes that interlayer slip within the kink band creates internal shear that rotates and flattens the AMS ellipsoid (Figure 5.8b). This scenario is more likely, as
Figure 5.8. Possible scenarios for shallowing of $k_{\text{min}}$ inside the kinked zone.
(a) Pressure solution inside the kink bands (dashed lines), oriented obliquely to the kink band boundaries (heavy dotted lines), produces a secondary fabric with a different $k_{\text{min}}$; the resultant vector (R) is deflected through angle $\delta$ from the expected angle $\kappa$. (b) Interlayer slip inside the kink band induces internal strain and shear along the foliation that effectively shallows $k_{\text{min}}$ to $\kappa - \delta$. 
interlayer slip is considered a fundamental mechanism of kinking and would easily be accommodated by the micaceous layers within the rock.

**Summary**

AMS is used to evaluate the magnetic fabric in a rock and quantify strain in deformed rocks. The Darrington Phyllite has a measureable magnetic fabric that is associated with both the mineral lineation and the well-defined foliation. For unknked portions of the rock, the AMS ellipsoid is prolate, k\(_{\text{max}}\) is roughly parallel with the lineation direction, and k\(_{\text{min}}\) clusters near the pole to foliation. Within the kink bands, the ellipsoid is rotated significantly from the unknked directions and is more triaxial; however, the amount of rotation for the AMS axes is consistently shallower than expected when compared to the foliation dip across the kink band boundaries. Two scenarios are proposed to explain the change of shape and shallowed orientation: crenulation cleavage within the kink bands produces a secondary magnetic fabric, and the resultant vector is less steep than the kinked fabric; or shear strain due to interlayer slip along the foliation during kinking sheared the AMS ellipsoid, modifying the rotational fabric. The infrequency of pressure solution inside kink bands on Samish Island and the lack of a significant change in the magnetic properties inside and outside the kink bands suggest the second scenario is more likely, and interlayer slip played an important role in kink band development.
CHAPTER 6: DISCUSSION AND CONCLUSIONS

This thesis investigates kink bands on Samish Island that are analyzed at several scales and with a number of different tools, providing a large dataset with which to evaluate the four major kinematic models of kinking. In addition, these data may be used to evaluate the relationship between kink bands and the regional structural and tectonic setting. Observations on each scale—field mapping and measurements at the outcrops, curvature analyses on hand samples, thin section and magnetic fabric analyses at the microscale—provide unique insights into kink band geometry and development, and together are used to determine which model(s) of kinking best fits the kink band network of Samish Island.

Mobile-Hinge vs. Fixed-Hinge Kinking

Each of the four kinking models (Figure 1.4) represents a hypothesis about the development of kink bands. Accordingly, each predicts relationships and characteristics (Table 6.1) that can be deduced from previous descriptions of deformation experiments (e.g. Paterson and Weiss, 1966; Gay and Weiss, 1974; Stewart and Alvarez, 1991), kinematic studies (e.g. Weiss, 1980), and field studies (e.g. Verbeek, 1978; Stewart and Alvarez, 1991). The model predictions can therefore be tested by observations. Geometric relationships (e.g. spacing, widths, angles, relief) can be measured directly in the field, in hand sample, or in thin section; hinge curvature can be described qualitatively in thin section analyses or quantitatively by geometric curvature; evidence for migrating hinges, interlayer slip, and volume changes can be observed in thin section,
Table 6.1  Summary of predictions from each of the four kinematic models of kink band development.

<table>
<thead>
<tr>
<th>Deformation mechanism(s)</th>
<th>Mobile-hinge models</th>
<th>Fixed-hinge models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mode I</td>
<td>Mode II</td>
</tr>
<tr>
<td>Deformation mechanism(s)</td>
<td>Rotation and migration of hinges</td>
<td>Lateral migration of hinges</td>
</tr>
<tr>
<td>α and β</td>
<td>α = β ≠ constant; decrease with increasing rotation to maintain α = β = 90°-κ/2</td>
<td>α = β = constant, dependent on initial κ</td>
</tr>
<tr>
<td>κ</td>
<td>Increases to 90°</td>
<td>Constant</td>
</tr>
<tr>
<td>Kinked width</td>
<td>Increases due to incorporation of new material</td>
<td>Increases due to incorporation of new material</td>
</tr>
<tr>
<td>Plan width</td>
<td>Decreases to 0 at κ = 90°</td>
<td>Increases</td>
</tr>
<tr>
<td>Relief</td>
<td>Increases</td>
<td>Increases but less drastically than by other modes</td>
</tr>
<tr>
<td>Hinges</td>
<td>Rotate and migrate</td>
<td>Migrate laterally</td>
</tr>
<tr>
<td></td>
<td>Sharpen with increasing rotation and migration</td>
<td>Constant curvature; variable and dependent on initial angles</td>
</tr>
<tr>
<td>Foliation continuous</td>
<td>Foliation continuous</td>
<td>Foliation continuous</td>
</tr>
<tr>
<td>Migration structures (if strain is high enough)</td>
<td>Migration structures (if strain is high enough)</td>
<td>None</td>
</tr>
<tr>
<td>Interlayer slip</td>
<td>Yes</td>
<td>Yes?</td>
</tr>
<tr>
<td>Volume change inside kink band</td>
<td>No (Stewart and Alvarez 1991 say possible)</td>
<td>No (Stewart and Alvarez 1991 say possible)</td>
</tr>
<tr>
<td>Confining pressure</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Angular controls</td>
<td>Dominates when κ &lt; 60°</td>
<td>Dominates when κ ≥ 60°</td>
</tr>
</tbody>
</table>
in the magnetic fabric, and sometimes in the field. Here, the characteristics (predictions) of each model are briefly described in order to test the mode(s) of kinking against observations from the Darrington Phyllite.

**Mode I (Mobile-Hinge, Rotation and Migration)**

Mode I kinking accommodates shortening by rotation of the internal foliation and the kink band boundaries as those boundaries migrate outwards into the undeformed material (Weiss, 1980). In the ideal case, the kink angles $\alpha$ and $\beta$ are equal at all times but decrease as the internal foliation rotates to higher $\kappa$ to maintain $\alpha + \beta = 90^\circ - \kappa/2$ (Weiss, 1980). As rotation increases, kinked width increases due to incorporation of new material, while plan width decreases. The hinges tighten with increased rotation, increasing strain within the hinge zones (Stewart and Alvarez, 1991). As the boundaries migrate, mineral grains are bent and then straightened, leaving fractured migration structures within the kink band that can be observed in thin section (Paterson and Weiss, 1966); however, if migration is slow or strain is low, migration structures may be poorly developed (Stewart and Alvarez, 1991). Rotation is allowed by slip along the foliation, and even small amounts of slip inside the kink band can change the relationship between $\alpha$ and $\beta$; therefore, $\alpha \neq \beta$ does not automatically rule out mode I kinking (Stewart and Alvarez, 1991). There should be no dilation within the kink band; however, small dilation spaces, may open in the hinge zones during migration (Stewart and Alvarez, 1991). Deformation experiments (Gay and Weiss, 1974; Stewart and Alvarez, 1991) and subsequent calculations involving mechanical work (Weiss, 1980) suggest that mode I kinking dominates when $\kappa$ is less than $60^\circ$ and the confining pressure is high.
Mode II (Mobile-Hinge, Lateral Migration)

Mode II kinking is characterized by lateral migration of kink band hinges at a fixed rotation angle $\kappa$ and constant $\alpha = \beta$ (Weiss, 1980). New material is incorporated as hinges migrate outward, deforming once to become part of the kink band with no further rotation or deformation (Weiss, 1980). The kinked width and plan width both increase as deformation progresses; this is the only mode for which plan width should increase. Relief also increases, though less significantly than in other modes. Similar to mode I, migration structures should be seen within the kink band as grains are assimilated, but the curvature of the hinges should remains constant as the width changes, and dilation should be small and confined to the hinges alone (Stewart and Alvarez, 1991). Mode II kinking becomes dominant when $\kappa$ approaches 60° and confining pressure is high (Weiss, 1980; Stewart and Alvarez, 1991).

Mode III (Fixed-Hinge, Shear Along Boundaries)

Mode III kinking deforms the internal foliation by continuous simple shear along fixed boundaries. The kink angles are independent of each other: $\alpha$ is set at nucleation and remains constant, and $\beta$ decreases as $\kappa$ increases. The boundaries are shear planes that accommodate all slip; there is no slip along the foliation inside the kink band (Verbeek, 1978). Foliation planes are discontinuous at the margins. The kinked width first decreases as the internal foliation undergoes simple shear and thickens, and then increases as the layers thin and continue to rotate (Twiss and Moores, 1992). Shear along the boundaries allows $\beta$ to decrease past the “locking” point of $\alpha = \beta$, and both dilation
and contraction are possible depending on the relationship between $\beta$ and $\alpha$ (Srivastava et al., 1998). If the foliation remains continuous, as the edges of the internal foliation are dragged along the kink band boundaries, strain is concentrated in the center of the band, resulting in more thinning of the foliation in the center and less at the margins; the resulting curved zone would not be a true kink band (Dewey, 1965; Verbeek, 1978).

**Mode IV (Fixed-Hinge, Rigid Rotation)**

Mode IV kinking operates via rigid rotation of the internal foliation between fixed hinges that initiate at some angle $\alpha$ to the external foliation. The angle $\alpha$ remains constant as $\kappa$ increases, and $\beta$ decreases from $\beta > \alpha$ until the band locks at $\alpha = \beta$ (Verbeek, 1978). The kinked width remains constant while plan width decreases, relief increases, and the hinges sharpen (Stewart and Alvarez, 1991). Unique to mode IV kinking is dilation within the kink band in order to maintain continuity across the boundaries (Verbeek, 1978; Stewart and Alvarez, 1991). Dilation is positive when $\beta > \alpha$, reaching a maximum when $\beta = 90^\circ$ and then still positive but decreases to 0 when the band locks (Verbeek, 1978; Stewart and Alvarez, 1991). Dilation spaces occur between the internal foliation planes as well as along the kink boundaries, where the void spaces are roughly triangular or elongate; dilation within the hinges can also form saddle reef-like openings that are oblique to the boundaries and extend into the undeformed rock (Ramsay, 1967). Deformation experiments indicate that mode IV kinking operates in narrow, small kink bands in very thinly layered rocks at low to moderate confining pressures; as confining pressure increases or layers become wider it takes less work to allow the hinges to migrate and fixed-hinge kinking ceases (Stewart and Alvarez, 1991).
Kinking Modes in the Darrington Phyllite

Elements of both mobile- and fixed-hinge kinking are represented in the observations presented in this thesis. Many of the characteristics of Samish Island kink bands are possible in several modes of kinking; however, certain diagnostic features and relationships suggest that fixed-hinge (mode IV) kinking was the dominant mode of kink band development. Migration of kink band hinges may have occurred in later stages of kinking, but there is little evidence of hinge migration in the observed kink bands.

The variability and distribution of rotation angles ($\kappa$) throughout the island strongly suggest that rotation was a mechanism of kinking for most bands. $\kappa$ is generally less than $60^\circ$ and shows a wide range of values even within individual outcrops; for example, three adjacent bands of equal widths in outcrop B1 have $\kappa$ values of $22^\circ$, $64^\circ$, and $30.5^\circ$. If mode II kinking were operative under a locally uniform stress field (e.g. several meters, the width of most outcrops), most kink bands within an outcrop should initiate at similar orientations, and the spread of $\alpha$, $\beta$, and $\kappa$ would be small. The positive correlations between $\kappa$ and shortening in the field data and between $\kappa$ and hinge curvature in hand sample are consistent with progressive rotation. There are no clear migration structures visible inside kink bands in the field or in thin section.

Rotation can occur during both mobile- and fixed-hinge kinking, so other observations are necessary to further distinguish the mode of kink development. The angular relationship $\alpha = \beta$ is most common but not ubiquitous on Samish Island, and the significant number of bands with $\beta > \alpha$ suggests that fixed-hinge kinking was operative; however, Stewart and Alvarez (1991) observed in deformation experiments that even small amounts of interlayer slip within mobile-hinge kink bands can cause significant
deviation from $\alpha = \beta$. AMS analyses indicate a shallowing of the minimum magnetic susceptibility axes inside the kink band that is interpreted to be due to shear strain along the foliation due to interlayer slip (Figures 6.3-6.5); slip is also evident in thin section from small mica grains protruding into dilation spaces along kink band hinges (Figure 4.9a). Therefore, the deviation of $\alpha$ and $\beta$ can either be due to fixed-hinge kinking or non-ideal mobile-hinge kinking. A better constraint is to compare the correlations between $\alpha$, $\beta$, and $\kappa$ to determine whether both $\alpha$ and $\beta$ decrease with increasing $\kappa$ (for mobile-hinge kinking) or whether only $\beta$ is correlated with $\kappa$ and $\alpha$ is independent (for fixed-hinge kinking). Using $\beta/\alpha$ as a proxy for maturity, the field data show that $\alpha$ and $\beta$ both change with increasing maturity (Figure 2.26a, b); however, $\alpha$ increases with increasing maturity as determined by $\beta/\alpha$ but decreases as the rotation angle increases (Figure 2.26a, c). The conflicting relationships between $\alpha$, $\kappa$, and maturity suggest multiple processes may have operated. The $\kappa$ values are similar for both mature and over-rotated bands (Figure 2.21c), suggesting that locking of kink bands did occur; thus, bands with $\beta/\alpha < 1$ are not truly over-rotated ($\kappa > \text{locking}$) but may have had $\alpha$ increased by rotation of the external foliation after the band locked. External rotation modifies the angular conditions produced by kinking alone and thus precludes bands with $\alpha > \beta$ from being diagnostic of any one kinking process.

Increasing kinked width with increasing maturity and/or rotation is indicative of mobile-hinge kinking; however, recognition of this relationship is contingent upon knowing the initial width of the band. In the case of Samish Island, the initial widths of the bands are unknown, so using any correlations between kinked or plan width and other parameters cannot be used to test any kinking mode. The distribution of widths,
however, suggests that kinked widths are independent of rotation or shortening (Figure 2.20b, c): the kinked width distributions are similar for immature, mature, and over-rotated bands and are likely defined at nucleation. Kinked widths for over-rotated bands are slightly higher, which may indicate that the kinking mechanism transitioned from mode IV to mode I or II after the kink bands locked; however, there is little other evidence for migration in over-rotated bands.

There is clear evidence for dilation inside kink bands in a majority of outcrops on Samish Island, which strongly supports mode IV kinking. Triangular voids filled with quartz and/or calcite are clearly visible in multiple outcrops (Figure 2.16a, Figure 2.17b), and smaller veins or tension gashes are also associated with many kink bands. Filled voids are also seen in thin section (Figure 4.8), and the orientations of mineral fibers inside the larger voids suggest multiple opening segments at different orientations (Figure 4.9), as would be expected by progressive rotation. In some cases, veins extend parallel to the internal foliation from the hinge voids, indicating layer-normal dilation during kinking (Figure 4.8a). Thin sigmoidal veins run at low angles to the kinked foliation in several locations in the quarry (Figure 2.16a), which is consistent with progressive rotation during mode IV kinking (Stewart and Alvarez, 1991). Many of the larger bands are disaggregated and sheared along their boundaries where dilation spaces are especially large, suggesting that deformation may transition to mode III if dilation is very large and the foliation becomes discontinuous.

Mode IV fixed-hinge kinking is consistent with the evidence for progressive rotation, independence of the kink angles $\alpha$ and $\beta$, variable kinked width, and dilation associated with kink bands. Stewart and Alvarez (1991) determined from deformation
experiments that widening of kink bands is uncommon at less than 10% shortening, and nucleation of new bands accommodates most of the shortening; at greater than 10% shortening, lateral migration of hinges becomes more important. Shortening accommodated by kink bands on Samish Island is generally less than 5%, and the amount of shortening in a given area increases as the number of kink bands increase, suggesting nucleation of new bands indeed occurred. Fixed-hinge kinking and nucleation of new bands are both more prevalent at low to moderate confining pressures (Weiss, 1980; Stewart and Alvarez, 1991).

3D Geometry of Kink Bands

The Darrington Phyllite on Samish Island exposes intricate patterns of kink bands on the foliation surface. Kink bands are curved on the foliation surface, despite having relatively straight and parallel axial planes in cross section, and interact in crossing, merging, and truncating intersections. The most common intersections are $\lambda$-type, where a thin band splits from a continuous parent band at an oblique angle; this type of intersection was called a T-type intersection by Kirschner and Teixell (1996) but geometric curvature analyses presented in this study show that the offshoot band is not truncated by the parent but instead grows out of one parent hinge (Figure 3.14). Y-type intersections are also common, where one band splits into two smaller but comparable bands (Figure 3.12); however, the control on the initiation of such intersections is unknown. True crossing (X) intersections appear to be rare, and are most likely controlled by the initial trend of the kink band; as most bands are roughly parallel, intersecting trends should be rare. All three types of intersections were previously
observed by Kirschner and Teixell (1996) in kink bands in the Somport Slates of the Pyrenees, which also formed via fixed-hinge kinking (Verbeek, 1978). The anastomosing and curving kink band trends on the foliation surface and three types of intersections common to both locations suggest that similar processes may have operated at both places to produce similar patterns. Kirschner and Teixell (1996) proposed that curving monoclinal kink bands form during bulk coaxial, non-plane-strain deformation where the principal stress directions are inclined to the foliation; local reorientation of the stress field near kink band tips as they propagate causes the bands to curve towards each other, resulting in curving and intersecting bands. This model is potentially applicable to the kink bands of Samish Island; however, further work is needed to investigate the effects of non-plane-strain deformation on kink band development.

Timing of Kink Band Development

The observations presented in this study provide some insight into the relationship between the kink bands and tectonic and structural history of Samish Island. Kink bands deform preexisting foliations from at least three different deformation events, termed by Lamb (2000) as D1, D2, and D3. The main foliations on the island are S1 and S2, both of which are visibly kinked in the field and in thin section. S2 is axial planar to meter-scale folds, and kink bands are notably absent where folding is most intense, suggesting that tightly folded foliation inhibited kink band nucleation. Crenulation along F2 folds is also kinked in the quarry (outcrops Q5 and QX), indicating post-folding kinking. S3 and F3 folds are poorly developed in kink band outcrops, and S3 has no clear relationship to kink bands. There is a wide spread in kink band orientations (Figure 2.5); this may be
due to gentle F4 folding post-kinking as suggested previously by Lamb (2000). However, it is more likely that the spread is due to natural variation in kink band orientation due to the anastomosing and curving nature of the kink band sets. The data presented here are consistent with Lamb’s (2000) interpretation of the relationships between folding events and kinking.

This study better constrains the relationships between veins and kink bands on Samish Island. V1 veins parallel to the foliation are kinked, consistent with V1 development pre-F2 folding. V2 veins are parasitically folded within F2 folds, also pre-kinking. Lamb (2000) interpreted undeformed, en echelon veins to comprise V3, pre-kinking but post-F3 folding; in many places such veins may be pre-kinking, but there are clearly syn- and post-kinking veins present on Samish Island. Dilation spaces within kink bands are filled with quartz and minor calcite that precipitated during kinking; pressure solution within kink bands in outcrop B13 also suggests migration of fluid and material during kinking. In several places, both in the quarry (e.g. outcrops Q1 and Q2) and on the beach (B13) undeformed quartz veins cross-cut kink bands and in places (e.g. B13) offset kink band boundaries, suggesting post-kinking vein development

Regional Tectonic Setting

Gay and Weiss (1974) reported a systematic relationship between the orientation of the kink band axes and the principal compressive stress (angle $\theta$; see Figure 2.33). Using their reported data and best-fit lines for trends of $\theta$ vs. $\rho$ and $\rho$ vs. $\alpha$, the following relationships can be deduced:

$$\alpha = 0.567 \rho + 60^{\circ};$$  \hspace{1cm} (6.1a)
\[ \theta = -0.433 \rho + 60^\circ. \]  
(6.1b)

By substitution of Eqn. 6.1a into 6.1b for the term \( \rho \), the angle \( \theta \) can be calculated from \( \alpha \) (measured directly in the field) by:

\[ \theta = -0.764^\circ(\alpha - 60^\circ) + 60^\circ. \]  
(6.2)

The orientation of the principal compressive stress during kinking can be found by using a stereonet and plotting the line \( \theta \) degrees from the measured kink axial plane (Figure 6.1). There are slight differences between the stress axes for kink bands from sets A and B (Figure 6.1), with the principal compressive stress slightly steeper for bands of set B. However, the clusters of stress axes for both sets indicate that both kink band sets were produced by shallow NE/SW compression and subvertical extension; this stress field is kinematically consistent with that found by Lamb (2000) to operate late in the deformation history of Samish Island. Subvertical extension and the inferred moderately low confining pressure that allowed rotational kinking to occur are consistent with uplift or unroofing during late-stage deformation.

**Conclusions**

Kink bands in the Darrington Phyllite are well exposed on Samish Island in cross section and on the foliation surface, providing a three-dimensional view of a complicated kink band system. In cross section, kink bands have relatively straight boundaries and are monoclinal; conjugate kink bands are rare. There is wide variation in the geometries of kink bands, even within single outcrops, and a significant number of bands deviate from the ideal condition of equal internal and external kink angles. The angle \( \kappa \) through which the internal foliation has been rotated is highly variable in all outcrops, and
Figure 6.1. Stereoplot showing principal stress axes for both sets of kink bands on Samish Island. Set A axial planes and principal stresses $\sigma_1$ and $\sigma_3$ are in blue; set B in red. Filled circles represent $\sigma_1$ orientations; open circles represent $\sigma_3$ orientations.
generally is less than 60°; the wide range of κ values suggests progressive rotation as a mechanism of kinking. Protruding mica grains into kink band hinges and modification of the magnetic susceptibility ellipsoid within the kink bands suggest interlayer slip accompanied the rotation. Evidence for kink band hinge migration is lacking both in the field and in thin section; uniform extinction of micas inside kink bands and sheared and broken kink band boundaries in places both suggest fixed-hinge kinking. Dilation spaces in the form of quartz- and/or calcite-filled voids in the hinges and sigmoidal veins across the kinked foliation also support fixed-hinge rigid rotation as the dominant kinking mechanism.

Geometric curvature quantifies strain in the hinges and produces more accurate measurements of relief and width than are possible in the field. The curvature data show that tighter hinges are associated with steeper bands with high relief, which also supports a rotation model. Shortening is positively correlated with kink band density; when coupled with the field observations that over-rotated bands are more closely spaced, the relationship between shortening and kink band density supports the hypothesis that new kink bands nucleate to accommodate further deformation once preexisting bands lock.

On the foliation surface, kink band hinges are curved and produce anastomosing and intersecting patterns. Crossing intersections are relatively rare; bifurcation (Y) and oblique truncation (λ) of kink bands is more common. Geometric curvature illuminates the behavior of kink bands in each type of intersection, indicating increased curvature (i.e. increased strain) where kink band hinges cross in X intersections or bifurcate in Y intersections. Previous workers had identified T-type intersection where one band is fully truncated by another; curvature analysis showed that true truncation is rare, but
instead one hinge of a parent band may split and form a thin offshoot while the paired
parent hinge continues unchanged in what is called her a $\lambda$-type intersection. There is no
clear mechanism to explain the curving and intersecting patterns of kink bands in the
third dimension; further work including deformation experiments must be done in order
to understand the factors that cause kink bands to bend and interact.
References


from the Anglo-Brabant Deformation belt (Belgium) and the North Dobrogea Orogen (Romania). Journal of Structural Geology, vol. 30, pp. 1047-1059.


APPENDICES

Appendix material that is directly cited in the text is included as part of this pdf. The complete appendices can be found on the CD included in the print version of this thesis.

Appendix A – Field Maps

Appendix A consists of digital photographs of kink band outcrops and accompanying maps of those outcrops that outline the trends of the kink bands. The digital archive for each measured outcrop contains raw photographs, mapped photographs, and traces of the kink bands separate from the photographic image for especially complicated outcrops.

On the mapped photographs, black is used to outline and label kink bands. Blue is used to mark intersection types, with X, Y, λ, and D (see chapters 3 and 4 for explanations), as well as locations of transect lines along which measurements were taken. Prominent veins are mapped in red.

Appendix B – MATLAB scripts for curvature analyses

Appendix B consists of annotated MATLAB scripts (saved as .m files) used to import, analyze, and plot 3D scan data on hand samples.

Appendix C – Curvature analysis maps

Appendix C includes annotated photographs and accompanying curvature plots for 8 scanned surfaces on 6 different samples.
APPENDIX B: MATLAB SCRIPTS

The following MATLAB scripts were used to import and manipulate surface scan data for hand samples to produce curvature maps. Several scripts were modified from previously written code; credit is given at the beginning of the appropriate code(s) below. These scripts can be found as .m files on the included CD.

Script 1 – Import scanned data
Input files are pre-gridded data files exported from Surfer v. 8. The values dx and dy are the known spacing between points used to grid the data in Surfer and must be re-entered for each data file. This script was written with help from Jackie Caplan-Auerbach.

% Import data from Surfer grid into MATLAB-ready file %
A = load('filename.dat'); % enter .dat file of grid from Surfer
G = load('filename_gradient.dat'); % enter .dat file of gradient grid
dx=0.5; dy=0.5; % grid spacing values taken from
% gridding report (different for
% each sample)
% calculate size of matrix for sample
a=round((max(A(:,1))-min(A(:,1)))/dx)+1;
b=round((max(A(:,2))-min(A(:,2)))/dy)+1;

Z = zeros(b,a); % creates matrix of zeros to fill in
X = zeros(b,a);
Y = zeros(b,a);
grad= zeros(b,a);

% sequentially fill in sample matrix from loaded .dat file
for i = 1:b;
    Z(i,:) = A(
        [(a*(i-1)+1):(a*i)],
        3);
    X(i,:) = A(
        [(a*(i-1)+1):(a*i)],
        1);
    Y(i,:) = A(
        [(a*(i-1)+1):(a*i)],
        2);
    grad(i,:) = G(
        [(a*(i-1)+1):(a*i)],
        3);
end
Z(find(Z==max(max(Z))))=nan; % replace blanked cells with NaNs
grad(find(grad==max(max(grad))))=nan;

save('file.mat', 'X', 'Y', 'Z','dx','dy'); % enter filename to save
clear A i a b;
Script 2 – Calculate curvature values

Modified from scripts written by Stephan Bergbauer, Ian Mynatt, and David Pollard, which can be found at:
http://pangea.stanford.edu/projects/structural_geology/chapters/chapter03/scripts/curvature.m

% Load base data file and enter curvature threshold value

clear

load file.mat; % replace with filename saved from script 1
Kt=input('Enter Kt value: '); % enter value at prompt
warning off

% Calculate partials based on arbitrary coordinate system
[n,l] = size(Z);
[dZx,dZy] = gradient(Z,dx,dy);
[dZxx,dZxy] = gradient(dZx,dx,dy);
[dZxy,dZyy] = gradient(dZy,dx,dy);
dZx=dZx(2:n-1,2:l-1); % cut the outer rows/columns from each matrix to elimination
end

dZy=dZy(2:n-1,2:l-1);
dZxx=dZxx(2:n-1,2:l-1);
dZxy=dZxy(2:n-1,2:l-1);
dZyy=dZyy(2:n-1,2:l-1);
Z = Z(2:n-1,2:l-1);
X = X(2:n-1,2:l-1);
Y = Y(2:n-1,2:l-1);
grad = grad(2:n-1,2:l-1);

clear i k l n;

% calculate First Fundamental Form
alpha11=ones(size(dZx))+(dZx).^2;
alpha12=(dZx).*(dZy);
alpha22=ones(size(dZx))+(dZy).^2;

% calculate Second Fundamental Form
alpha3=1./(sqrt(alpha11.*alpha22-alpha12.^2));
beta11=alpha3.*dZxx;
beta12=alpha3.*dZxy;
beta22=alpha3.*dZyy;

% convert to PF/Mynatt notation
E=alpha11; F=alpha12; G=alpha22;
L=beta11; M=beta12; N=beta22;

% Calculate Principal Curvature Directions and Magnitudes
% (Kminx, Kminy, Kminz, Kmin; Kmaxx, Kmaxy, Kmaxz, Kmax)
[n,h]=size(dZx); % modified by RD for cropped matrix
K11=zeros(n,h);
K22=zeros(n,h);
K12=zeros(n,h);
K11=K11(2:n-1,2:l-1);
K22=K22(2:n-1,2:l-1);
K12=K12(2:n-1,2:l-1);
Kmin=zeros(n,h);
Kmax=zeros(n,h);
Kmin=Kmin(2:n-1,2:l-1);
Kmax=Kmax(2:n-1,2:l-1);

K2x=zeros(n,h);
K2y=zeros(n,h);

for i=1:n
    for j=1:h
        I=[E(i,j) F(i,j);F(i,j) G(i,j)];
        II=[L(i,j) M(i,j);M(i,j) N(i,j)];
        SO=inv(I)*II;
        A=max(max(isnan(SO)));
        if A==0
            [Kd,Km]=eig(SO);
        elseif A==1
            Kd=[NaN NaN;NaN NaN];
            Km=[NaN NaN;NaN NaN];
        end
    end

% Principal Curvature A
    KmA(i,j)=-Km(1,1); KdA1(i,j)=Kd(1,1); KdA2(i,j)=Kd(2,1);
% Principal Curvature B
    KmB(i,j)=-Km(2,2); KdB1(i,j)=Kd(1,2); KdB2(i,j)=Kd(2,2);

end

% Convert Principal Directions to Tangent Space (3D)
    KAx=KdA1;
    KAy=KdA2;
    KAz=KdA1.*dZx+KdA2.*dZy;
    normA = sqrt(KAx.^2+KAy.^2+KAz.^2);
    KAx = KAx./normA;
    KAy = KAy./normA;
    KAz = KAz./normA;

    KBx=KdB1;
    KBy=KdB2;
    KBz=KdB1.*dZx+KdB2.*dZy;
    normB = sqrt(KBx.^2+KBy.^2+KBz.^2);
    KBx = KBx./normB;
    KBy = KBy./normB;
    KBz = KBz./normB;

% Sort to Kmax and Kmin
    i=find(KmB>KmA);
    Kmax=KmA;
    Kmin=KmB;
    Kmaxx=KAx; Kmaxy=KAy; Kmaxz=KAz;
    Kminx=KBx; Kminy=KBy; Kminz=KBz;

    Kmax(i)=KmB(i);
    Kmin(i)=KmA(i);
    Kmaxx(i)=KBx(i); Kmaxy(i)=KBy(i); Kmaxz(i)=KBz(i);
    Kminx(i)=KAx(i); Kminy(i)=KAy(i); Kminz(i)=KAz(i);

% Apply Curvature Threshold
    i=find(abs(Kmin)<Kt);
    Kmin(i)=0;
    i=find(abs(Kmax)<Kt);
    Kmax(i)=0;
% Calculate Gaussian Curvature
Kg=Kmax.*Kmin;
Kgaus=Kg;
i=find(Kg<0);
j=find(Kg>0);
Kg(i)=-1.*ones(size(i));
Kg(j)=ones(size(j));

% Calculate Mean Curvature
Km=0.5.*(Kmax+Kmin);
Kmean=Km;
i=find(Km<0);
j=find(Km>0);
Km(i)=-1.*ones(size(i));
Km(j)=ones(size(j));

% Calculate Total Curvature from mean curvature
Kmabs=abs(Kmean);
absKtot=abs(Kmin)+abs(Kmax);

% Find Saddles
Kst=Km*2;
i=find(abs(Kst)<Kt);

% Calculate Geologic Curvature (GC)
% -4=perfect saddle -2.5=dome -1.5=antiform -0.5 antiformal-saddle
% 0.2=plane 0.75= synformal saddle 2= synform 3= basin
GC=Kg;
% Synformal Saddle (0.75)
i=find(Kg<0 & Km<0);
GC(i)=0.75.*ones(size(i));
% Saddle (-4)
i=find(Kg<0 & abs(Kmax+Kmin)<Kt);
GC(i)=-4.*ones(size(i));
% Antiformal Saddle (-0.5)
i=find(Kg<0 & Km>0);
GC(i)=-0.5.*ones(size(i));
% Dome (-2.5)
i=find(Kg>0 & Km>0);
GC(i)=-2.5.*ones(size(i));
% Plane (0.20)
i=find(Kg==0 & Km==0);
GC(i)=0.20.*ones(size(i));
% Synform (2)
i=find(Kg==0 & Km<0);
GC(i)=2.*ones(size(i));
% Antiform (-1.5)
i=find(Kg==0 & Km>0);
GC(i)=-1.5.*ones(size(i));
% Basin (3)
i=find(Kg>0 & Km<0);
GC(i)=3.*ones(size(i));

warning on
clear i j KmA KmB KBx KBy KBz KAx KAy KAz Km1 Km2 Klx Kly K2x K2y normN I II A SO Kd KdA1 KdA2 KdB1 KdB2;
Script 3 – Plot curvature maps

Plots curvature matrices produced by script 2 as filled contour maps. The order of plotting (X and Y coordinates) is dependent on the arbitrary coordinate system orientation assigned by the scanner; in order to plot the data correctly, reversing X and Y were sometimes necessary, and different orders are necessary for samples scanned at different times. Syntax for geologic curvature plot from Bergbauer, Mynatt, and Pollard script referenced in script 2.

% This script is intended to run while the data from script 2 are still
% loaded in MATLAB.

Xplot=X-min(min(X)); % convert X, Y, Z coordinates from arbitrary
Yplot=Y-min(min(Y)); % values into millimeter scale beginning at 0
Zplot=Z-min(min(Z));

% most samples will plot as: Yplot,-Xplot,Zplot
% B10-F4 plots as Xplot,Yplot,Zplot
% DFo21a and DFo21b plot as -Yplot,Xplot,Zplot

sample=input('Enter sample name: ','s');

% surface topography
figure
contourf(Yplot,-Xplot,Zplot,80) % adjust contour interval as needed
axis image
colorbar
caxis([0 10]) % adjust max contour level as needed
xlabel('mm'); ylabel('mm')
title(['Surface topography, ', sample]);

% gradient
figure
contourf(Yplot,-Xplot,grad,40) % adjust contour interval as needed
axis image
xlabel('mm'); ylabel('mm');
colorbar
caxis([0 0.7])
title(['Gradient, ', sample]);

% geologic curvature
figure
contourf(Yplot,-Xplot,GC) % do not need to enter a contour interval
axis image
xlabel('mm'); ylabel('mm');
view(2);
caxis([-4 3]);
colormap(jet(8));
colorbar('YTickLabel',
{'Perfect saddle','Dome','Antiform',
'Antiformal saddle','Plane','Synformal saddle','Synform','Basin'});
title(['Geologic curvature, ' sample, '  (Kt = ', num2str(Kt), ')']);

% absolute curvature
figure
contourf(Yplot,-Xplot,absKtot,20) % adjust contour interval as needed
axis image
xlabel('mm'); ylabel('mm');
% mean curvature
figure
contourf(Yplot,-Xplot,Kmean,20) % adjust contour interval as needed
axis image
xlabel('mm'); ylabel('mm')
colorbar
caxis([-0.3 0.3])
title(['Mean curvature, ' sample, ' (Kt = ', num2str(Kt), ')']);

% transect 1
% plot data (absolute curvature) to choose transect line
contourf(Kmabs,40)
axis equal
caxis([0 0.3])
grid minor
[x1,y1]=ginput(1); % pick starting point of line
[x2,y2]=ginput(1); % pick ending point of line
A=[x1,y1]; B=[x2,y2];
ABx=[x1,x2]; ABy=[y1 y2];
hold on
line('Xdata',ABx,'Ydata',ABy,'Color','k','LineWidth',2); % plot line
hold on
dy=B(2)-A(2); dx=B(1)-A(1); % calc components of slope of line
if isequal(dy,0),dy=eps;end;
if isequal(dx,0),dx=eps;end;
slope=dy/dx; % Slope of transect line
if x1>x2
    xx=round(x2:x1);
    yf=y2;
else
    xx=round(x1:x2);
    yf=y1;
end
k=length(xx);

Script 4 – Extract curvature transect data
Extracts curvature data based on a transect line chosen by clicking the endpoints of the desired line on a map of absolute curvature. Modified from a script written by Mustafa Deniz, posted on the MATLAB help website: http://www.mathworks.nl/matlabcentral/fileexchange/23873-get-cross-section.
For multiple transects, copy this segment and re-number files as needed.
yy = round(slope.*(xx-xx(1))+yf);

% extract data from topography, gradient, and curvature files
for ii=1:k;
    yt(ii)=Z(yy(ii),xx(ii));
    yg(ii)=grad(yy(ii),xx(ii));
    ykm(ii)=Kmean(yy(ii),xx(ii));
    yak(ii)=absKtot(yy(ii),xx(ii));
end
relief=(yt)'; % create a vector of relief values along the transect
steep=(yg)'; % create a vector of gradient values
meanabs=(ykm)'; % vector of absolute mean curvature
meank=(yak)'; % vector of mean curvature
absk=(yak)'; % vector of absolute total curvature

d=sqrt(((max(xx))-min(xx))^2+(max(yy)-min(yy))^2);
dst=0:d/(k-1):d; % calculate distance along the transect
relief1=relief; steep1=steep; meanabs1=meanabs; meank1=meank; ...
    absk1=absk; dst1=dst; ABx1=ABx; ABy1=ABy; A1=A; B1=B;
save('XS1.mat','relief1','steep1','meanabs1','meank1',...
    'absk1','dst1','ABx1','ABy1','A1','B1');
clearvars -except Kmabs Kmean Kt Z absKtot grad;
% copy above segment as many times as desired for multiple lines on the
% same sample; change saving file name and components, if necessary.
Appendix C1. Curvature analysis output for sample B10-1a. (a) Annotated photograph of sample, followed by contour maps of (b) topography (mm), (c) gradient, (d) mean curvature (1/m), (e) total curvature (1/m), and (f) geologic curvature (see Figure 3.1 for key to colors).
Appendix C2. Curvature analysis output for sample B10-1b. (a) Annotated photograph of sample, followed by contour maps of (b) topography (mm), (c) gradient, (d) mean curvature (1/m), (e) total curvature (1/m), and (f) geologic curvature (see Figure 3.1 for key to colors).
Appendix C3. Curvature analysis output for sample B10-F3. (a) Annotated photograph of sample, followed by contour maps of (b) topography (mm), (c) gradient, (d) mean curvature (1/m), (e) total curvature (1/m), and (f) geologic curvature (see Figure 3.1 for key to colors).
Appendix C4. Curvature analysis output for sample B10-F4. (a) Annotated photograph of sample, followed by contour maps of (b) topography (mm), (c) gradient, (d) mean curvature (1/m), (e) total curvature (1/m), and (f) geologic curvature (see Figure 3.1 for key to colors).
Appendix C5. Curvature analysis output for sample B13-4T (top side). (a) Annotated photograph of sample, followed by contour maps of (b) topography (mm), (c) gradient, (d) mean curvature (1/m), (e) total curvature (1/m), and (f) geologic curvature (see Figure 3.1 for key to colors); (d)-(f) on the following page.
Appendix C5, continued.
Appendix C6. Curvature analysis output for sample B13-4B (bottom side). (a) Annotated photograph of sample, followed by contour maps of (b) topography (mm), (c) gradient, (d) mean curvature (1/m), (e) total curvature (1/m), and (f) geologic curvature (see Figure 3.1 for key to colors); (d)-(f) on the following page.
Appendix C6, continued.
Appendix C7. Curvature analysis output for sample DFo21a. (a) Annotated photograph of sample, followed by contour maps of (b) topography (mm), (c) gradient, (d) mean curvature (1/m), (e) total curvature (1/m), and (f) geologic curvature (see Figure 3.1 for key to colors).
Appendix C8. Curvature analysis output for sample DFo21b. Contour maps are cropped at the break in the sample marked by a solid black line in the photograph. (a) Annotated photograph of sample, followed by contour maps of (b) topography (mm), (c) gradient, (d) mean curvature (1/m), (e) total curvature (1/m), and (f) geologic curvature (see Figure 3.1 for key to colors).