Depositional and Structural Evolution of Cretaceous Strata, St. Croix

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ABSTRACT

A tectonic complex of Cretaceous sedimentary rocks underlies St. Croix, possibly to substantial depth. The sedimentary rocks are almost entirely volcaniclastic derived from contemporaneous arc volcanoes during Cenomanian or Turonian, through Maastrichtian time. Minor pelagic beds (chert) also occur. All the volcanigenic sedimentary rocks are deep marine and can be assigned to turbidite facies from an outer to inner-fan setting. The depositional site was a basin floor near the slope base of a Late Cretaceous island arc whose duration of activity was at least 14 ma and perhaps greater than 30 ma. The tectonic complex in which all the Cretaceous strata occur is an assembly of thrust sheets (i.e. nappes). Beds in all the sheets were folded and cleaved to varied degrees and in varied sequences before a short episode of late Maastrichtian igneous intrusion. Early deformations are S-to SW-verging. The tectonic complex is interpreted as a product of accretion during Late Cretaceous convergence in which the downgoing plate had a component of N to NE transport in today's coordinates.

INTRODUCTION

Cretaceous sedimentary and intrusive igneous rocks underlie all of St. Croix's surface except for a central region of unconformable Miocene and younger cover (Fig. 1). The depositional realms and pre-Miocene structural evolution of the largely volcanigenic Cretaceous strata are the focus of this paper with the aim of understanding the early tectonics of St. Croix (note: unless otherwise stated, sites mentioned in the text are located on either Figure 1 or 3). Our field work in St. Croix was conducted in the middle seventies and, more recently, 1988. Some results are summarized in Speed (1974), Joyce (1979), and Speed *et al.* (1979). Earlier publications providing data on the Cretaceous rocks include Quin (1907), Cedarstrom (1950), and Whetten (1966), and later ones by Stanley (1988; this volume). Our studies focused more closely on outcrop-scale structural analysis, structural synthesis, and dating, and had the benefits of advances in turbidite-facies analysis not available to earlier workers.

The magmatic character of St. Croix's Cretaceous intrusions and the metamorphism of Cretaceous sedimentary rocks are important facets of St. Croix's early evolution not dealt with in this paper. Whetten (1966) provides discussions on these subjects.

ARCHITECTURE OF ST. CROIX

The island of St. Croix is a peak on the submarine St. Croix platform which is a bathymetric ridge and probable extensional fault block in the southeasternmost Greater Antilles. At the surface, St. Croix is underlain by Cretaceous sedimentary rocks that occupy a Cretaceous tectonic complex, Cretaceous igneous intrusions, and Cenozoic strata (Fig. 1).

The central region of St. Croix is underlain by little-deformed Cenozoic sedimentary cover (Fig. 1; Gill *et al.*, this volume). The cover occupies a deep basin that may be a SSE-tilted halfgraben as shown on Figure 1. Cenozoic strata that lie unconformably on Cretaceous rocks at the basin flank are as old as middle or early Miocene (Multer *et al.,* 1977) but could be pre-Miocene in the deeper reaches of the graben (Whetten, 1966; Lidz, 1988). The Miocene and Pliocene normal faulting associated with subsidence of the graben is probably related to regional extension that has developed the St. Croix platform and adjacent basins (Speed, this volume).

CRETACEOUS LAYERED ROCKS

Introduction

The Cretaceous layered rocks of St. Croix are almost entirely volcanigenic sediments together with minor pelagic sediment that accumulated below wave base, probably at deep-marine sites. There are no lavas or proven pyroclastic deposits, contrary to claims by Whetten (1966) and Lidz (1988).

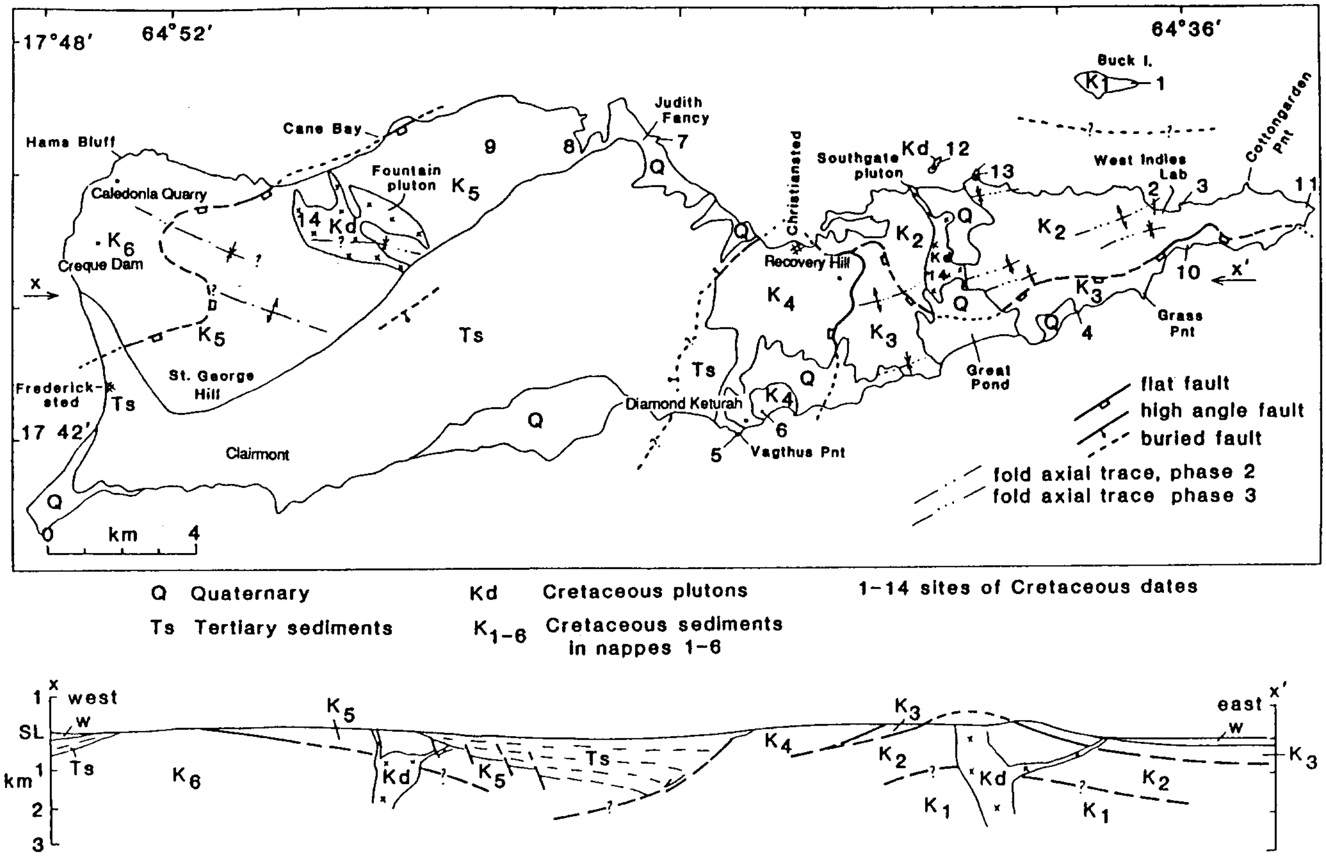

Figure 1. *Map of St. Croix showing outcrop areas of Cretaceous and Cenozoic rocks, nappes KI-K6 of Cretaceous rocks, diagrammatic cross section. axial traces to some macroscopic folds, and sites of samples dated by fossils or K-Ar (Table 2).*

Each of the nappes of the Cretaceous tectonic complex probably or possibly contains a coherent stratigraphy (K2, K4, K5 are probable, others are possible), but correlations cannot be made between adjacent nappes. There is thus no established islandwide stratigraphy of Cretaceous strata. Moreover, because the Cretaceous rocks in different nappes did not necessarily come from a single original stratigraphic sequence, there can be no valid estimate of composite thickness (such as given by Lidz, 1988). Whetten's (1966) proposal of an islandwide stratigraphy showed great complexity, which he attributed to facies changes related to what he correctly perceived as a turbidite realm of deposition. Our observation of fault boundaries between parcels of strata with mainly different characteristics (Table 1), however, implies that the abrupt juxtapositions are tectonic, and not generally depositional. Whetten's (1966) formational names, not used here, are still convenient for discussion of stratal types (i.e., Caledonia for thin-bedded sandy-muddy turbidite and Judith Fancy for thick, coarse lithic-rich beds), but should not be used to convey stratigraphic position. Correlations of bed sequences within non-adjacent nappes may ultimately be valid, given new dating; suggestions for such correlation by general lithic look-alikes were aptly made by Whetten (1966; e.g. parts of nappes K2 and K6).

Depositional Ages

Fossil evidence for ages of deposition now exists from ten samples at eight sites, and a radiometric age exists for an igneous clast found in sandstone at a ninth site (Table 2). Of these, only two of the eleven samples can be taken as a probable age of deposition. The two are ammonites, one found as an isolated individual at the top of a distal turbidite *(Perinoceras)* and the other as float on a hilltop in similar beds *(Tarrantoceras)*. Neither is associated with other fossils, and each is much larger than any associated grains. The ammonites are therefore probably pelagic. The other dated samples are resedimented and give only a maximum age of deposition. The planktic forams at sites 4 and 6 (Table 2) are considered resedimented because of their association with resedimented megafossils. The time span represented by dates of the Cretaceous strata is about 28 ma at maximum (base Cenomanian to 69 ma) and about 15 ma at minimum (mid-Turonian to base Maastrichtian), using the correlations of Kent and Gradstein (1985). A minimum age of deposition of the Cretaceous strata is probably

Table 1. *Characteristics of Nappes in the Cretaceous tectonic complex*

Nappe	Lithotypes	Known Depositional Ages	Structures
K1	thin-bedded, graded, sandy turbidite and nongraded ss, both with local calcarenite; massive mdst; minor pebbly ss with nonvolcanic + volcanic lithoclasts; ss are fsp > lith > skel > pyrx	Campanian or Maastrichtian	subvertical homoclinal bedding and S 1 cleavage + steep Fl fold axes; steep and flat shear zones with F2 folds, S2 cleavage, and quartz veins; late kinks
K2	thin and med.-bedded sandy-muddy turbidite with cherty tops; intervals of thick graded volcanic ss ± debris flowup to 20 m thick; bedded chert; ss are fsp >> lith > pyrx = skel	Cenomanian or Turonian and Coniacian	4 phases: 1) local zones of isoclines; 2) pervasive SW-verging close major and minor folds + cleavage; 3) upright macrofolds of beds + cleavage; 4) steep and flat faults + related folds and kinks
K3	massive and laminated mdst, local cherty and muddy turbidite; thick-bedded, graded, massive, or pebbly ss; skeletal debris flow; ss are fsp > lith > pyrx > skel	late Campanian or Maastrichtian	similar to K2 phases 2-4
K4	thick-bedded massive or graded coarse wacke, mainly pebbly, and sed. breccia; thin-bedded sandy turbidite; ss are lith > fsp = pyrx; locally skel.-rich	late Campanian and Maastrichtian	major and minor SW-verging open or closed folds with local cleavage; later faults and related local folds
K5	thick-bedded graded and massive ss and sandy turbidite alternate with intervals of thin-med.-bedded, sandy-muddy turbidite; also massive mdst and debris flow; ss are lith > fsp > pyrx > skel	Campanian or Maastrichtian	major upright or S-overturned folds with local cleavage; late faulting
K6	thin-bedded muddy-sandy turbidite, locally with cherty tops; intervals thick graded-lam. or massive ss ± pebbly ss ± debris flow; ss are fsp > lith > skel > pyrx	undated	early minor folds and pervasive cleavage with SW vergence plus flattened cgls; late minor folds of bedding and cleavage

given by dates of the intrusive rocks (Table 2) which cut all the nappes. The similarity in petrography and of radiometric dates from seven sites makes a compelling argument for nearly synchronous emplacement of the igneous bodies throughout St. Croix. No dates exist, however, for dikes in nappes K1, K4, and K6, and we must assume that such dikes are also Maastrichtian. The average value for all igneous dates is about 69 ma (late Maastrichtian according to Kent and Gradstein, 1985), and the oldest mean value is 71.8 ma (early Maastrichtian). These dates on igneous hornblende can be regarded as accurate because of the fresh nature of mineral separates and the absence of postemplacement heating or burial (Speed *et al.,* 1979).

Dating (Table 1) indicates that nappes K1, K3, K4, and K5 contain beds of Campanian and/or Maastrichtian age, and K2 contains substantially older beds (Cenomanian or Turonian and Coniacian). K6 is undated and can only be assumed to be Maastrichtian or older. It is important to note that each nappe probably contains a thick stratal sequence, and current dating does not sample the full sequence of any nappe. The dated sites in K2 are probably low in its sequence, and because K2 is mainly thin bedded and probably not rapidly deposited, it may continue well up into the Late Cretaceous.

Volcanigenic Lithotypes

Nearly all (>99%) of the Cretaceous sediments of St. Croix have generally related compositions: arc volcanigenic with varied minor proportions of skeletal and intraclastic debris (Table 3). Clast types outside this realm are very rare, and in particular, no sediment derived from continental or high-grade metamorphic terranes has been recognized. The volcanigenic particles were probably

Table 2. *Depositional ages of Cretaceous sedimentary and igneous rocks*

Site[1]	Fault Packet	Basis	Age[2]	Reference
1. Buck Island	Kl	coral	Campanian or Maastrichtian*	Whetten (1966)
2. Tague Bay	K2	ammonite, *Tarrantoceras (?)*	probably Cenomanian, possibly early to middle Turonian	Speed *et al.* (1979)
3. Romney Point	K2	ammonite, *Perinoceras*[3]	Coniacian	this paper
4. Robin Bay	K3	hbl K-Ar on igneous clasts in pebbly sand-stone	75.2±4.3 ma, Maastrichtian or late Campanian*	Speed *et al.* (1979)
5. Vagthus point	K4	planktic forams	Campanian or Maastrichtian*	Whetten (1966)
		rudist, *Titanosarcolites*	Maastrichtian*	Whetten (1966)
		"benthic microfauna"	Maastrichtian*	Andreieff *et al.* (1986)
6. Diamond Keturah	K4	planktic forams	late Campanian*	Whetten (1966)
7. Judith Fancy	K5	rudist, *Barrettia* sp.	Campanian*	Wheuen (1966)
8. Sugar Bay	K5	rudist, *Barrettia* sp.	Campanian*	Whetten (1966)
9. Clairmont	K5	benthic forams	Campanian*	Whetten (1966)
10. Grapetree Pnt.	—	mafic porphyry dike; hbl K-Ar	70.1 ± 3.9 ma, Maastrichtian	Speed *et al.* (1979)
11. East Point	—	mafic porphyry dike; hbl K-Ar	71.8 ± 2.2 ma, Maastrichtian	Speed *et al.* (1979)
12. Green Cay	—	mafic porphyry dike; hbl K-Ar	66.1 ± 1.8 ma, Maastrichtian to early Paleocene	Speed *et al.* (1979)
13. Pull Point	—	Southgate pluton hbl K-Ar	66.0 ± 3.2 ma, Maastrichtian to early Paleocene	Speed *et al.* (1979)
14. plutons; sites uncertain	—	3 hbl K-Ar dates, presumably from Fountain and Southgate plutons (Fig. 1)	mean values 69 to 71 ma	Lidz (1988)

[1]numbered sites on Figure 1
[2]radiometric-geologic time scale correlations from Kent and Gradstein (1985)
[3]identified by W.A. Cobban, written commun., 1988
*maximum age

Table 3. Lithic properties of Cretaceous strata.

	constituent grains	granulometry	matrix-cement	rock types
SEDIMENTARY BRECCIA	**volcanic fragments:** chiefly porphyritic, occasionally equigranular basalt, pyrox. andesite, hbl-pyrox. andesite, dacite, pyrox. dacite, plag.-pyrox-chlorite rock, and altered equivalents; scoria **skeletal fragments:** rudist, bivalve, gastropod, coral **sedimentary rock fragments:** lithic-feldspar wacke and arenite, mudstone, chert; limeclasts, locally stromatolitic **mineral fragments:** framework components in microbreccia; same as in sandstone	granule to cobble size; chiefly angular; local accumulations of sub-rounded coarse fragments.	matrix is variable mixture of sand-sized particles (of types in sandstones) in coarse-grained breccia and chlorite, 10A mica, zeolite, and hydrocalcsilicate minerals; locally dominant CO_3 cement.	lithic breccia lithic-feldspar microbreccia lithic-skeletal breccia/ microbreccia megabreccia (partly brecciated slump masses)
SANDSTONE	feldspar (plagioclase) pyroxene quartz lithic clasts: very fine-grained andesite, dacite chloritic rocks, chert skeletal particles hornblende	very fine-grained to coarse-grained sand; generally angular; subrounded coarse-grained sand at places	wacke: chlorite, 10A mica arenite:carbonate cement, minor clay, zeolite, prehnite	fine-grained feldspar-lithic wacke medium- to coarse-grained feldspar-pyroxene-quartz-lithic wacke ditto: arenite
MUDSTONE	variable proportions of silt- to very fine-grained sand size feldspar-quartz-skeletal particles and finer-grained chlorite, 10A mica, carbonate, and cherty quartz; abundant silica microveinlets; gradations in proportion of SiO_2 between mudstone and chert.			laminated siltstone-mudstone silty (sandy) mudstone homogeneous mudstone porcellainite
CHERT	microcrystalline quartz; veinlets of calcite and quartz abundant; frequent sprinkling of silt-sized quartz (no indications they are biogenic); smears of opaque substance.			chert silty chert

all derived from a region of contemporaneous volcanism, not from an ancient terrane. Whetten's (1966) distinction of pyroclastic vs epiclastic volcanigenic debris is not supported by our observations; the sediments he called epiclastic are at higher grades of in situ metamorphism, which may account for perceived mineralogical differences. A radiometrically dated volcanic clast in K3, a pyroxene-hornblende porphyry, provided a date of 75.3 ± 4.3 ma (Table 2), indicating that the maximum duration of extrusion, transport, deposition, and deformation before the late Maastrichtian intrusion, was about 6 ma. It would be more logical to consider that extrusion and deposition were concurrent at 75 ma and to assume that the tectonic complex took 5 or 6 ma to build up. Further, the only clast type suggestive of an unroofed source region is rare diorite, but these may have emerged from the volcano as inclusions in extrusions.

Most volcanic lithoclasts are angular but some are subrounded, indicating that residence times in the littoral or subaerial environments at the source volcanoes were generally short. The skeletal debris is widely distributed as broken fragments in trace amounts in medium and in coarse-grained sandstone. However, they are locally concentrated as unbroken fossils in some grain- and debris flows. Such particles (Table 1) are resedimented from neritic and/or littoral environments.

The volcanic rock fragments in Cretaceous sediments throughout St. Croix are variable in their color index, phenocryst/matrix ratio, pyroxene/hornblende ratio, presence of quartz, and vesicularity. Such properties may vary greatly in a given bed, but the ranges are not conspicuously different among the six nappes.

The principal lithic distinctions among the six nappes are of general particle size distribution and the non-independent parameters of sand composition and mean layer thickness (Table 1). Nappes K2 and K6 ("Caledonia") are relatively fine grained (sand/mud ~1), rich in feldspar relative to other sand particles, and thinner bedded. Sandstones of these nappes contain, however, minor but evenly distributed pyroxene and/or hornblende, and volcanic rock fragments, as well as local intervals of very thick sandstone and debris flows. In contrast, K4 and K5 are relatively coarse grained as a whole (sand/mud >3), have more equal proportions of dark minerals and lithics to feldspar, and have greater proportions of thick beds. In nappe K3 sediments are bimodal, characterized by massive mudstone and channel-filling coarse and pebbly sandstone, with rarer beds of intermediate size grade. Nappe K1 has high proportions of fine sandstone and detrital carbonate compared to other nappes. It also has a some pebbly sandstone beds that are distinctive in their content of nonvolcanic lithoclasts (i.e. rounded radiolarite, chert, and siliceous carbonate, not seen in other nappes).

Layer Styles and Transport Mechanisms

The Cretaceous volcanigenic sediments of St. Croix occur in a vast range of depositional unit thicknesses, from 1 cm to greater than 30 m. Commonly related variables are grain-size distribution, sand composition (discussed above), and the existence of channeled bases. All layers are sediment-gravity flows, except perhaps for certain thick massive mudstones which might be hemipelagic. Of the sediment-gravity flows, both turbidites and nonturbidites occur in varied proportions in each nappe. Turbidites are here defined as being generally tabular, upward fining, and having two or more consecutive Bouma zonations.

Turbidites of St. Croix are of three general types:

1. *muddy:* thin-bedded mud-rich (ss/mdst 0.1 to 1), base absent and top present, non-channelized, sand rarely coarser than fine-grained; examples: Lamb Point to East End section, east Butzberg.
2. *thin sandy:* thin and medium-bedded, sand-rich (ss/mdst >1), generally base absent, top present or absent, mainly nonchannelized, have sand rarely coarser than medium-grained; examples: northern St. George quarry, Point Cudejarre, Buck Island, Allendale.
3. *thick sandy:* layers 0.5 to 3 m thick, commonly in upward-thickening sequences, ss/mdst >5, base present and commonly have pebbly (lithoclastic) basal zones and scoured bases; such beds may have full Bouma zonation or be top-absent; intraclasts are commonly concentrated in the Tb zone; interesting Tbcbc... repetition occurs within some individual turbidites; examples: Grapetree Point, Tague Point, Hams Bluff, Creque Dam.

Nonturbidites are of widely varying types: thick mudstone, thin ungraded sandstone, thick massive sandstone, and sedimentary breccia. Thick mudstone is either massive or vaguely laminated and may or may not include laminae of thin, ungraded sandstone or chert. The mudstone is commonly organic-rich (black). We have not investigated the microstructure of such rocks and are uncertain whether they are very muddy turbidites, perhaps locally or widely homogenized by bioturbation, or are due to hemipelagic deposition. Examples can be found at Hughes Point, Grass Point, Cane Bay, and Mt. Fancy.

Thin, ungraded sandstones are well-sorted, fine to coarse-grained, tabular, and plane-bottomed. They commonly occur in sections with muddy or thin sandy turbidites, and have higher proportions of cement (carbonate, calcsilicate) and less matrix than turbiditic sand. They are generally massive except in coarser layers where they are conspicuously cross-laminated. These were interpreted by Speed (1974) as either a product of reworking of turbidites by bottom currents, or for the coarser beds as grain flows. Stanley (1988) subscribes to the first explanation. Examples occur along the south shore of Buck Island and East End Point on St. Croix.

Thick massive sandstones are channelized deposits associated with slumps and debris flows. They are coarse grained, commonly pebbly, and may have a crude planar lamination. Nonequant particles are well-aligned, indicating a fully turbulent flow. The top few percent of the layer, if present, is commonly upward-fining. Examples can be seen at Tague Point, Isaac Point, Robin Bay, Recovery Hill, and Creque Dam.

Sedimentary breccia consists partly of thick fragment-touching piles of angular lithoclasts and poorly-sorted, muddy-sandy matrix. These deposits are debris flows, and although locally plane or concordantly bottomed, they can occur in lenticular, channelized, coarse-grained sedimentary sequences. Their moderate to good clast alignment and locally graded tops indicate generally fluidized flows. Slumps form a second type of sedimentary breccia. These consist of slabs and folded masses of intraclastic turbidites and other layer types together with lithoclasts; these occur in association with debris flows and/or massive sandstone. Examples occur at Grass Point, Shoy Point, Tague Point, Hams Bluff, Judith Fancy, and Vagthus Point.

Chert and Pelagic Rocks

Aside from sediment-gravity flows of volcanigenic particles, pelagic deposits probably form the remaining, but tiny, fraction of the Cretaceous strata. These are mainly found in sections of thin-bedded volcanigenic rocks. The evidence for pelagic constituents is inferred from the existence of bedded chert (Speed, 1974) which is the result of thorough diagenetic transformation. Chert occurs both as a layered vitreous type and as grainy rock in the top few centimeters of muddy and sandy turbidites. Vitreous chert almost certainly arose from *in situ* biogenic particles, although no tests have been recognized in dissolution residues (D.L. Jones, written comm., 1980) or by microscopic study. The grainy cherts are an evident replacement product that occurs as pore fillings at bedding tops, implying that soluble biogenic particles of pelagic origin accumulated between successive turbidites.

Evidence for early chert diagenesis in the history of the Cretaceous sediments includes: 1) chert is cut by sandstone dikes, 2) it occurs in intraclasts in channelized deposits, and 3) chert-rich zones took up displacements by buckling in the first deformation whereas other stratal types deformed without flexing, probably by pore-volume loss. Examples of chert are found at Cramer Park apd Buck Island.

Layer Sequences

Upward thickening and coarsening sequences can be recognized on two scales. Gradual thickening over 100's of meters occurs at East End to Point Cudejarre, indicating progressive progradation, probably over a broad outer fan.

More abrupt thickening sequences over 10's of meters, commonly culminating in channelized deposits, can be seen at Grass Point, Grapetree Bay, Cramer Park, and Creque Dam. Upward thinning sequences are less evident.

Sand Load Casts

The Cretaceous rocks of nappes K2, K3, and K6 contain remarkable loading features, called linear load casts by Speed (1974) and Speed *et al.* (1979), and abundant sandstone intrusions occur throughout. Linear load casts are highly elongate features at the bases of sandstone layers and protrude into subjacent mudstone usually in association with flame structures of mudstone. They differ from standard loads which are equant in the bedding plane by their axiality and parallelism (Fig. 2). They are postdepositional (i.e. not flutes) as they deform laminations in subjacent layers. Moreover, they are related to tectonic deformation because axial plane cleavage and tectonic fold axes parallel the bisecting plane of the linear loads and flames (Fig. 2). These are interpreted (Speed, 1974) to have arisen during layer-parallel tectonic compression when sands were incompressible but incohesive, and cleavage development and pore collapse could affect the underlying muds. The vertical exchange of sand and mud in planes normal to maximum compression permitted the sand layers to shorten without detachment from subjacent mudstones. The upshot of this is that tectonism and cleavage development began in nappes K2, K3, and K6 before lithification of at least the basal parts of many sandstones. Examples of linear load casts occur at Coakley Bay, Romney Point, Grapetree Point, and Caledonia Quarry.

Sand Intrusions

Sandstone dikes and irregular intrusions occur widely in St. Croix. Such bodies transferred coarse sand fractions up or down from a sand source bed. Sandstone dikes intruded before, during, and after cleavage development, but there is no evident dike alignment relative to strain axes. Interesting sandstone phacoliths occur in folds at places where sand intruded hingeward during folding. As with linear load casts, sand intrusions indicate that some sands remained unlithified through at least early tectonism. Examples can be seen at Cramer Park, Vagthus Point, and Judith Fancy.

Depositional Realm

Because all the Cretaceous nappes of St. Croix contain turbidites with marine skeletal particles, a general environment of deposition can be established as deep-marine, below wave base. The absence of planktic calcareous fossils, except at Vagthus Point and Diamond Keturah (Whetten, 1966), suggests that the depth was below the carbonate compensation depth, assuming that cherts came from siliceous plankton and that diagenesis is not the cause for the near-absence of calcareous tests. Moreover, the planktic forams at the two exceptional sites are probably resedimented, as discussed earlier, and thus were buried too rapidly for dissolution in deep ocean water. The occurrence of intraclasts and slumps of turbiditic and other layers in channel-filling beds and turbidites above channel fills implies that the channels formed in the same deep-water environment.

It is generally convenient and useful to relate such layer sequences to model turbidite fan facies (for example, Walker, 1984). We do not infer, however, that the Cretaceous rocks of St. Croix occupied any particular original fan geometry, and it is possible they may never have occupied a single initial stratigraphic succession.

The turbidite layers occur with varying abundance in all nappes. These are probably outer fan or fan fringe facies because of their tabularity and lateral continuity (where observable, such as at East End) and intervals of upward thickening that imply source progradation without erosion. The variations about the outer-fan theme differ among nappes. Nappes K2 and K6 ("Caledonia") are principally outer fan deposits that include sporadic, but thick channel fills (10->50 m) which were emplaced and covered by thin turbidites. This indicates that the channeling was not due to a systematic migration or reconfiguration of the fan system.

In nappe K1, discrete layers of fine sand and mud are abundant, and may represent either bottom-current reworking, interchannel plus crevasse-splay deposits, or both. The fineness of grain and paucity of sedimentary structures in such rocks may suggest the former, and the association with channelized pebbly sandstone carbonate grain flows, the latter.

In nappe K3, the abundant nonturbidite (?) mudstone and thick channel filling sequences suggest either an upper fan, interchannel regime or fan-abandonment facies with sudden reactivation. Nappe K4 may contain midfan and upper-fan, channel-mouth deposits together with outer fan intervals (Whetten's [1966] Recovery Hill member). Nappe K5 contains outer midfan facies in western outcrops and upper-fan channel deposits at Clairmont and Judith Fancy.

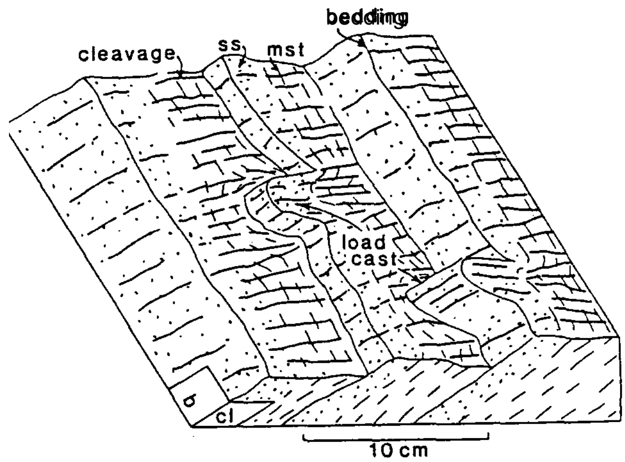

***Figure 2.** Three-dimensional illustration of relations among linear load casts, bedding, and cleavage.*

The provenance of sediment in the sediment-gravity flow deposits was an active, emergent island arc with volcanic edifices emitting magmas of varied composition, from basalt to dacite, and with neritic and/or littoral carbonate banks that flanked parts of the volcanic edifices. The source terrane is known to have supplied sediment for at least 14 ma and perhaps 30 ma or longer.

Whetten's (1966) interpreted flow directions in St. Croix turbidites as southerly. Our measurements, corrected for tectonic rotation, however, indicate varied directions and dispute claims to any preferred direction. All such measurements must take into account steeply plunging fold axes (to 60°) whose axial trends vary with position (Speed, 1974). Thus, the sedimentology of the Cretaceous rocks does not indicate the source-basin direction.

The fan facies of the Cretaceous strata suggest a basin floor rather than a slope as the general depositional site because of the overall preponderance of turbidites and rarity of rocks typical of slopes such as mudslumps, pebbly mudstones, and channelized fine-grained sandstones. The basinal site was probably close to the base of slope as implied by innerfan and fan-channel facies.

The basinal site may have been on the fore or backside of the active Late Cretaceous island arc. The width of a forearc was probably narrow because there is no continent-derived sediment involved, and arc-derived sediment probably funneled directly to the slope base, as in modem Pacific arcs. The forearc slope base was likely to have been an unfilled bathymetric trench because the island arc was the only sediment source, with a single exception, i.e. the clast population in pebbly sandstones of nappe K1 (Buck Island). This indicates unroofed pelagic rocks, perhaps resedimented within the forearc. In a trench, fan facies would have developed a complex pattern as a result of flow parallel to and across the trench axis (for example, Graham *et al.*, 1975; Schweller and Kulm, 1978). Further, most sediments deposited in a trench would have probably accreted within a few million years of their accumulation. Therefore, accretion (imbrication and folding) and sedimentation were continuing and contemporaneous phenomena, and strata in adjacent imbricate sheets would not generally have occurred in a single initial stratigraphic succession.

A backarc basin site, on the other hand, would probably have been relatively stable tectonically during sediment accumulation. A vertical succession of radial fans (Walker, 1984) would be predicted. Then, the onset of a phase of tectonic activity, not specifically predicted by plate-tectonic theory, is required to have imbricated the succession. Such activity can be envisioned as a Maastrichtian subduction of backarc basin lithosphere below the arc, in which case the arc-trench system would have been N or NE facing in today's coordinates.

We feel that a forearc site is more likely for the following reasons. First, the imbricate sheets do not repeat an evident stratigraphic succession. Second, the imbrication and deformation of Cretaceous strata in nappes K1, K3, K4, and K5 occurred shortly after their deposition (0-10 ma) and the sand mobility in all nappes indicates undercompaction before imbrication. Therefore, we interpret that the Late Cretaceous island arc system was S to SW facing (in today's coordinates).

STRUCTURES OF CRETACEOUS STRATA

All the Cretaceous strata of St. Croix are deformed. The structures and their sequence of development differ from nappe to nappe, but certain common elements exist among nappes. Each nappe underwent at least one phase of deformation before islandwide igneous intrusion in the Maastrichtian (66-72 mybp). The timing of some later phases of deformation relative to intrusion is uncertain. Table 4 summarizes principal structures in sequence for nappes K1-6. In Table 4 and the following sections, standard structural notations are used. Fl and F2 indicate two sequences of folding. S l and S2 refer to axial-plane cleavages. Di-D4 refer to successive episodes of deformation. It is important to note that each sequence of deformation (e.g. D-1 and D-2 in nappe Kl; D-1 through D-4 in nappe D-4) is applicable only to a single nappe, and a given deformational designator does not necessarily correlate between nappes (i.e. D-1 in K1 need not correlate with D-1 in other nappes).

Major Features

Beds in all the nappes are folded with harmonic content that varies with layer thickness. The number of fold superpositions (D in Table 4) varies among nappes; most have two, but K2 has four. Axial planes and related cleavage(s) all had initial strikes between E and NE and northerly dips. Vergences of major folds are southerly in all nappes. Axes of all folds plunge easterly, generally between 30° and 70°; except for some reoriented early folds.

Cleavage occurs in all nappes, but its development varies. It is strongly developed in the structurally lower nappes (K1, K2, K3, K6) which are generally more muddy. In these nappes, cleavage is closely spaced and pervasive, and at least partly a product of pressure solution. Its occurrence is more sporadic in higher nappes (K4, K5), even in muddier intervals. This seems to reflect initial development rather than degree of contact metamorphic obscuration. Structural depth may have been the controlling parameter to cleavage development.

No penetrative tectonic lineations have been recognized in St. Croix, implying strains were flattening rather than constrictional. This is supported by clast shapes in strained sedimentary breccias where X/Y = 1 to 3 within the cleavage plane. Late major folds have been superposed on earlier fold sets in at least four nappes (K2, K3, K5, K6). These have approximately E-striking axial planes with steep dips. These are discussed further below.

Late brittle faults and related folds and kinks in their walls affect all the nappes. Their orientations and slip

***Table 4**. Structures in sequence* in *Cretaceous nappes. Sequence numbers are not necessarily correlative from nappe to nappe*

K1	D1: subvertical to overturned homocline, E striking and S facing; foliation (Sl) steeply N dipping; tight minor folds (Fl) with axial planes in foliation plane and N verging; homocline probably a flank of a S verging major fold.
	D2: flat and steep fault zones with central shear zones with foliation and Quartz veins; open to tight folds of bedding and S 1 in shear zone walls; folds are mainly flat, some doubly hinged.
K2	Dl: local isoclines in chert-rich sections, folded nearly homoaxially by F2 folds; detached from adjacent strata
	D2: pervasive close S verging major folds (F2) with axial plane cleavage (S2) and trains of harmonics with vergence appropriate to limb position; axial planes dip between N and W (folded in D3); F2 axes plunge steeply in S dipping great circle.
	D3: major folds of D2 elements; D3 axial traces defined mainly by formlines of D2 cleavage (Fig. 4); D3 axial planes strike ENE, dip 70°S to 90° (Fig. 4); rotation of F2 axes in D3 suggests horizontal maximum elongation.
	D4: late fault-related folds and kinks. note: orientation data for K2 in Speed (1974).
K3	D1: isoclinal folds in pelitic rocks with strong axial plane cleavage, dipping betwen N and W, and major S verging folds of thick layer sequences.
	D2 and D3: same as D3 and D4 of nappe K2.
K4	D 1: sporadic close major and macroscopic folds with S vergence or overturning; local S 1 axial plane cleavage in muddy beds, poorly developed; cleavage and folds with varied orientation suggest D2 event and rotation of cleavage about a N plunging axis.
K5	D1: sporadic cleavage in muddy rock; dips between N and E, modally NE.
	D2: major close folds (Fig. 1) with WNW striking, steeply N dipping axial planes, and S overturning; F2 axes plunge steeply E.
K6	Dl: minor folds with axial plane cleavage (S 1) dipping NNE to NE; Fl axes plunge ENE; sedimentary breccia flattened in cleavage plane (NE dip) and X/Y = 1 to 3, X (max. elongation) N plunging.
	D2a: minor chevron and kink folds of bedding and cleavage; S2 axial planes conjugate, dip N and S; F2 axes steeply E plunging.
	D2b: major gentle syncline with WNW axial trace (Fig. 1), probably continuous with D2 syncline of K5.

sense are highly varied: normal-oblique, reverse, thrust, and horizontal. They probably formed in several stages and almost certainly are not all synchronous. Some normal faults were clearly contemporaneous with Maastrichtian diking, and are followed by dike tips and diatremes. At the East End, such faults indicate ENE-WSW horizontal extension during diking. It is probable that some sets of late faults are related to the central graben of Cenozoic age (Fig. 1).

East End Structures

Figure 3 includes a map of bedding and cross sections for eastern St. Croix. The principal features are the south to west vergent folds of nappes K2 (F2) and K3 (Fl) where exposures permit them to be identified. Because both nappes possess the same fold train, they were either 1) juxtaposed before this folding event or 2) folded at different sites under the same kinematic regime and then juxtaposed without rotation. At the three places where the

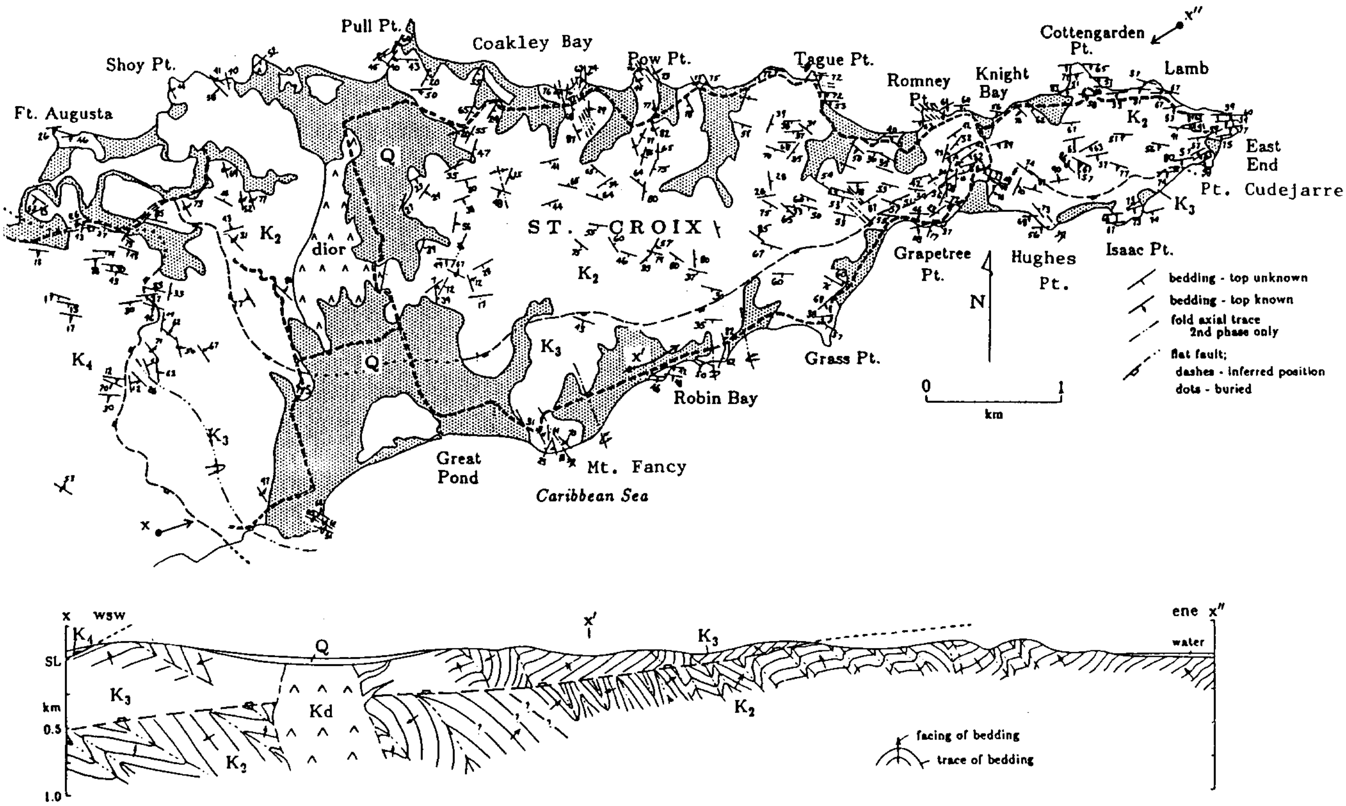

Figure 3. *Map and section of eastern St. Croix showing distribution of bedding attitudes, approximate nappe boundaries, and axial traces of folds of most intense deformation phase (phase 2 in K2, phase 1 K3).*

K2-K3 boundary is exposed, the fault cuts cleavage, implying that it is younger than this fold train. This supports the second explanation.

Figure 4 shows the orientations of cleavage related to the principal folding of K2 (S2) and K3 (Si), together with form lines to assess axial trace orientation of late major folds that cause the 90° variation in cleavage strike. Equal-area nets (lower hemisphere) show that poles to cleavage form a girdle with an easterly plunging axis and that the constructed axial plane for the late major fold strikes ENE and dips steeply.

The emplacement of nappe K4 on K3 and K2 occurred after the early deformations of the lower nappes (D2 in K2, Dl in K3) because the boundary cuts their cleavage. It is unclear whether or not the late major folds affect K4.

West End Structures

Figure 5 shows structural data and interpretation for a part of western St. Croix from our field studies, chiefly by J. Joyce, together with some information on bedding attitudes from Whetten (1966). The position of the K5-K6 fault boundary is interpolated among exposures at Cane Bay, the trail to Annaly Bay and a site near Oxford.

The lower nappe, K6, contains two deformation phases (Table 4). The first includes minor folds, F1, and axial plane cleavage, S1, from the northern coast to Sprat Hall (Fig. 5). S1 occupies a short girdle whose maximum verges SW. The F1 maximum of fold axes is steeply ENE. South of Sprat Hall, K6 may include the vertical or overturned limb of a major Fl fold (see section, Fig. 5). F2 folds in K6 have E striking axial planes; these are not included on the section of Figure 5 because their occurrence is sporadic and of small amplitude.

The upper nappe, K5, contains major folded beds and sporadic local cleavage (Table 4). Because the axial planes of the major folds (WNW strike, steep NNE dip) are not apparently coplanar with cleavage (NW strikes, moderate NE dip; Fig. 5), the two structures are provisionally considered to be sequential. Although the data are sparse, owing to limited exposure, cleavage seems not to be folded; hence, the major folds are interpreted as part of event D1, and cleavage as D2.

The K5-K6 boundary was an active fault during and/or after D1 of K6 because S 1 cleavage is deflected at the boundary. The nappe boundary was also active during D1 of K5 because it partly cuts out the major fold limbs (Fig. 5). The nappe boundary and homoclinal bedding of K6, however, are in low-amplitude folds with axial traces approximately coincident with those of D1 folds in K5. This implies that K5 and K6 locked together before the

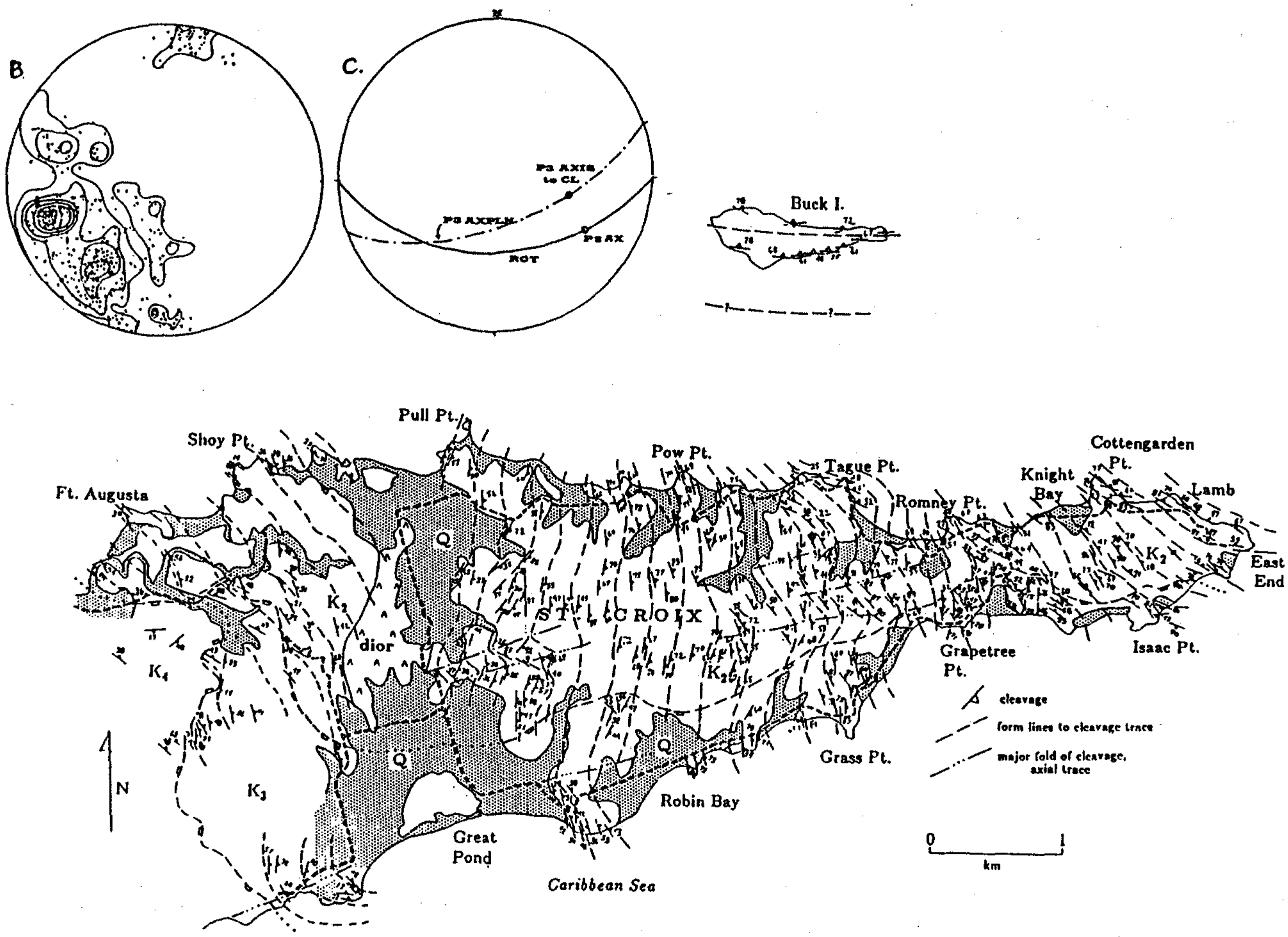

Figure 4. *Map of eastern St. Croix showing distribution of cleavage attitudes and axial traces of some late stage macroscopic folds of cleavage (phase 3 in K2, phase 2 in K3). Orientation diagrams (equal area, lower hemisphere): B) poles to cleavage (x) and axial planes (dots) that are phase 2* in K2 *and phase 1 in K3; C) calculated axial plane (dash-dot line) for late stage (phase 3) macrofolds from average axial trace (map) and axis to elements in B; solid great circle is rotation path of phase 2 fold axes.*

cessation of folding in K5. Perhaps D2 deformations in both nappes are a further response to contraction after nappe locking.

Timing of Structures

In eastern St. Croix, the juxtaposition of nappes K2 and K3 as well as deformations Dl and D2 in K2 and Dl in K3 occurred before Maastrichtian intrusion. Evidence includes cutting of structures by undeformed dikes and contiguity of the area of strong contact metamorphism by the Southgate pluton (Fig. 1) across the nappe boundary. The age of late major folding (D3 in K2, D2 in K3), however, is unknown within the range of Maastrichtian to early Miocene. This range is constrained by D1 in K3 and earliest known ages of little deformed cover to the Cretaceous of St. Croix. The intrusions do not date the late folding because such folds have large wavelengths and the dikes had no uniform initial attitude.

The age of juxtaposition of nappe K4 is unconstrained after rock deposition in the Maastrichtian. Until disputed by new evidence, we assume juxtapositioning to have occurred during the Cretaceous as with K2 and K3. A plausible alternative, however, is that the base of K4 is a Cenozoic low-angle normal fault related to tectonics that caused the central graben of St. Croix.

In western St. Croix, D2 cleavage of K5, and Dl of K6 related to juxtaposition of K5 and K6, preceded intrusion and are probably of Maastrichtian age. The key evidence is that metamorphism in dike walls is post-cleavage in both nappes. However, use of this to date the cessation of relative movement of the nappes pivots on the argument that cleavage of K5 is contemporaneous with, or later than, cessation. The age of D2 in K5 is unconstrained.

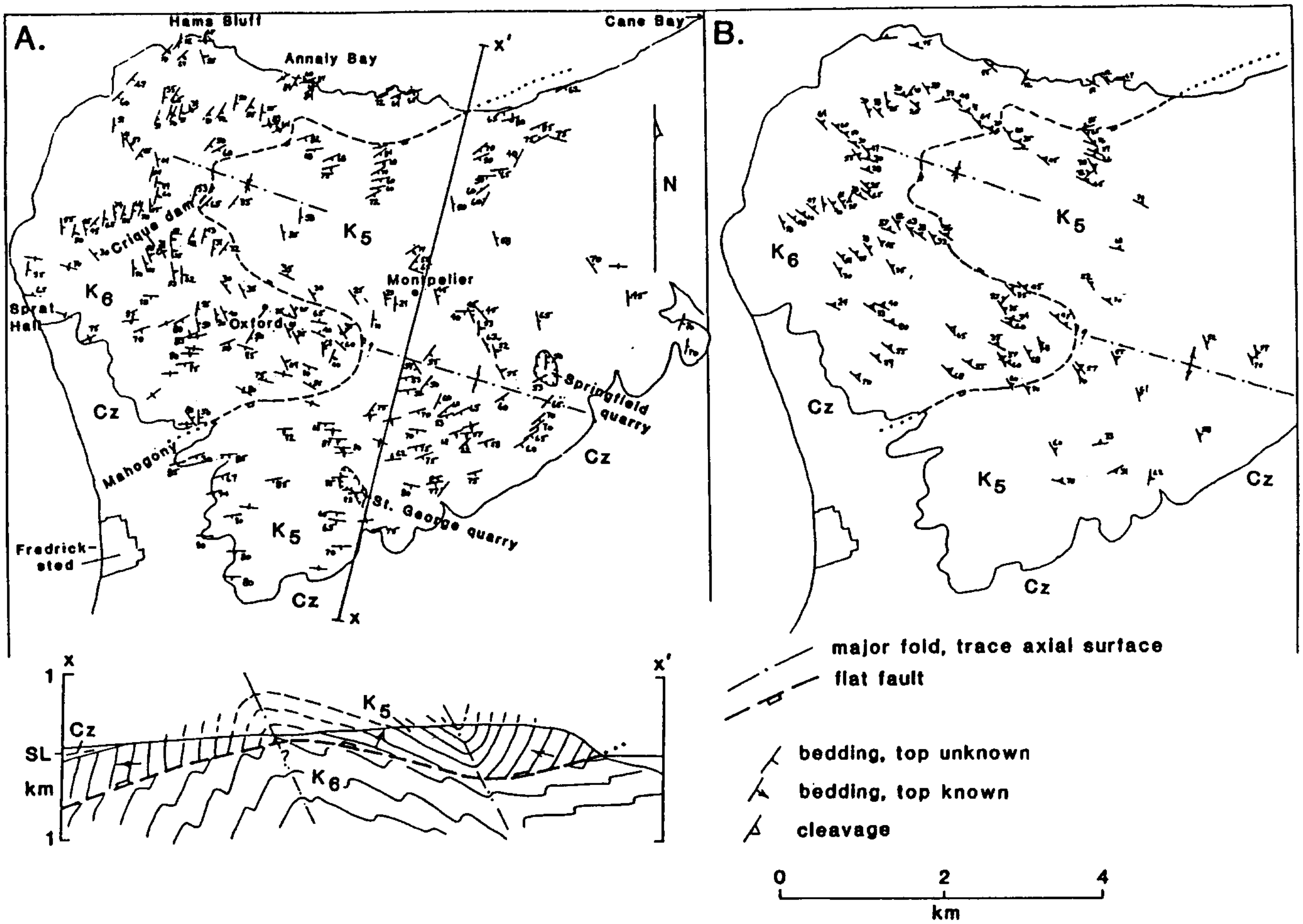

Figure 5. Maps of Northside Range, western St. Croix; A) bedding and phase 1 macroscopic fold axial traces; shows trace of cross section xx'; B) same map showing cleavage that is probably second phase.

Structural Evolution

The principal structures of the Cretaceous strata of St. Croix nappes, early folds, and foliation provide evidence for contraction and imbrication in Late Cretaceous time, probably mainly or entirely Maastrichtian. Such deformation can be interpreted as a product of thrust imbrication even though the ages across nappe boundaries are unknown.

Because the imbrication took place at or near the base of slope of an island arc, the displacement zone was almost certainly a convergent plate boundary. The thrust stacking accreted sediment sheets to the front of an overriding plate from a downgoing one. The pervasive SW to S vergence and/or overturning of structures within the imbricated sheets implies the downgoing plate had a component of Late Cretaceous relative motion between N and NE in today's coordinates. The late folding in nappes K2 and K3 can be interpreted as representing progressive NS shortening of the imbricated sediments after accretion.

The relationships of Cretaceous strata before imbrication are unclear. The lack of stratigraphic correlations among adjacent nappes indicates that either 1) the strata were sequentially deposited and accreted, as in a trench wedge, or 2) that both emergent thrusting and duplexing occurred in a continuous incoming stratigraphic sequence.

CONCLUSIONS

1. The exposed sub-Cenozoic rocks of St. Croix are deep-marine volcanigenic sedimentary rocks with minor pelagic interbeds. Their depositional ages range from Cenomanian or Turonian to Maastrichtian. There are no magmatic rocks, but the volcanigenic constituents came from an active island arc throughout this duration.
2. The Cretaceous strata occupy a tectonic complex of thrust-bounded sheets (nappes). No island-wide stratigraphic succession exists.
3. The Cretaceous strata occur in outer to inner fan facies. They were deposited at or near the base of slope of a Late Cretaceous island arc. The basin was probably a trench adjacent to the convergent boundary of the island arc system.

4. Island arc magmatism at the sediment source was ongoing for at least 14 ma and perhaps, more than 30 ma.
5. Imbrication of the Cretaceous strata was accompanied by folding and cleaving with vergence or overturning between S and SW in today's coordinates. The imbrication was followed by later NS horizontal contraction.
6. Imbrication was completed in Maastrichtian time. It is interpreted as representing the accretion of sediment to the forearc toe above a downgoing plate with a component of N to NE transport relative to the island arc.
7. The Cretaceous tectonic complex was invaded briefly by arc magmas late in Maastrichtian time.

ACKNOWLEDGEMENTS

This study resulted in part from research sponsored by NSF Grant EAR-8803633.

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