THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

A PETROGRAPHIC INVESTIGATION OF THE WINDSOR FORMATION, ST. ANN'S BASIN: IMPLICATIONS CONCERNING THE CRETACEOUS TECTONIC HISTORY OF NORTHERN JAMAICA

A THESIS

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By

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ABSTRACT

The Windsor Formation, in north-central Jamaica, crops out as a 1000ft (380m) sequence of terrigenous sandstones, shales, and micritic limestones extending into the subsurface for over 290m. The Windsor Formation represents deposition of a deep sea fan into the St. Ann's Basin during the late Cretaceous formation of the island of Jamaica. Deposition occurred in cycles. Each cycle is composed of a basal conglomerate layer containing cobble-sized clasts, which fines upward into sandstone, then shales and micritic limestones. These cycles may represent the avulsion of submarine fan channels. Paleocurrent analysis reveals the direction of sediment transport to be to the northeast.

Compositionally, the Windsor Formation is rich in volcanic rock fragments and zoned plagioclase feldspars, both indicators of derivation from volcanic highlands. Serpentine, chert, deep water micritic limestones, rock fragments, and scarce quartz present in the Windsor sediments indicate an ophiolite provenance. Cement types present in the sediments include clays, albite, calcite, and

phyllosilicates. From the cement mineralogies, the depth of burial of the sediments is inferred to be 3000 to 4000ft (1000 to 1200m).

An analysis of the heat flow data calculated from information supplied by PetroJamaica's Windsor #1 indicates a present-day heat flow of 0.96HFU. Compared regionally with other Caribbean basins, this value is quite low and indicates the Windsor Formation to be located in a cool tectonic basin, the *St.* Ann's Basin. Vitrinite refectance values from Rodrigues (1982) and PetroJamaica also indicate the Windsor sediments to have had a cool thermal history.

The petrographic findings, heat flow data, depositional systems analysis, paired metamorphic belt (of Draper et al, 1976), are consistent with the hypothesis that the *St.* Ann's Basin represents a Cretaceous fore-arc basin with a subduction zone dipping *South* or *Southwest*, and support to the regional models kinematically proposed by Perfit and Heezen (1978).

ACKNOWLEDGEMENTS

Special thanks go to Dr. John Pigott for suggesting the thesis topic and his guidance throughout its research and completion. I would like to acknowledge PetroJamaica, especially Donald Poulton, for making available heat flow information, maps, and core samples. Kaiser-Bauxite kindly provided transportation for the samples from Jamaica to the U.S. Thanks to Dr. John Wickham and Dr. Doug Elmore for their critical review of the manuscript. The AAPG Grants-in-Aid Scholarship and OU graduate student funding provided the necessary funds for the study. Special thanks go to Dale, my field partner from Discovery Bay who provided invaluable assistance. Finally, thanks to Ken Caldwell who assisted with laboratory work, reviewed the manuscript, helped type the manuscript, and provided moral support these past three years in graduate school.

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STATEMENT OF THE PROBLEM

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INTRODUCTION

STATEMENT OF THE PROBLEM

The purpose of this study is two-fold. First, it will describe the lithostratigraphy and sedimentary petrology of the Windsor Formation, St. Ann's, Jamaica. Secondly, this information will be used to interpret aspects of the tectonic evolutionary history of the St. Ann's Basin and thus further define the Cretaceous tectonic history of northern Jamaica.

Jamaica, today, lies on the crest of the Nicaraguan Rise, (Figure 1) a suboceanic ridge that forms the western extension of the Greater Antilles Arc (Arden, 1974). The Cretaceous rocks of Jamaica, their compositions, and their environments of deposition are a product of the tectonic activity during the time of Jamaica's formation as an island.

The Windsor Formation, a late Cretaceous terrigenous deposit, was chosen for study. The Windsor is located on the northern coast of Jamaica and forms part of the St. Ann's Inlier (Figure 2). The St. Ann's Inlier is one of several isolated surface occurrences of clastic Cretaceous rocks on Jamaica whose surface geology is largely Eocene and Miocene carbonate rocks.

The Windsor Formation represents the lower 1000 feet (300 meters) of the St. Ann's Sequence, and it represents the earliest observed deposition of sediments into a tectonic basin, herein named the St. Ann's Basin (Fig. 3). It will be shown that sediment deposition consists of several major high energy influxes of coarse clastic materials into the basin followed by periods of quiessance in which lower energy, quiet water deposition predominated. The high energy pulses are represented by the coarse conglomerate units found in the Windsor Formation. The quieter, low energy deposition is represented by thick shale

Figure 1. Location map illustrating Jamaica's present-day position and plate boundaries in the Caribbean (from Sykes _et_ _al._, 1982).

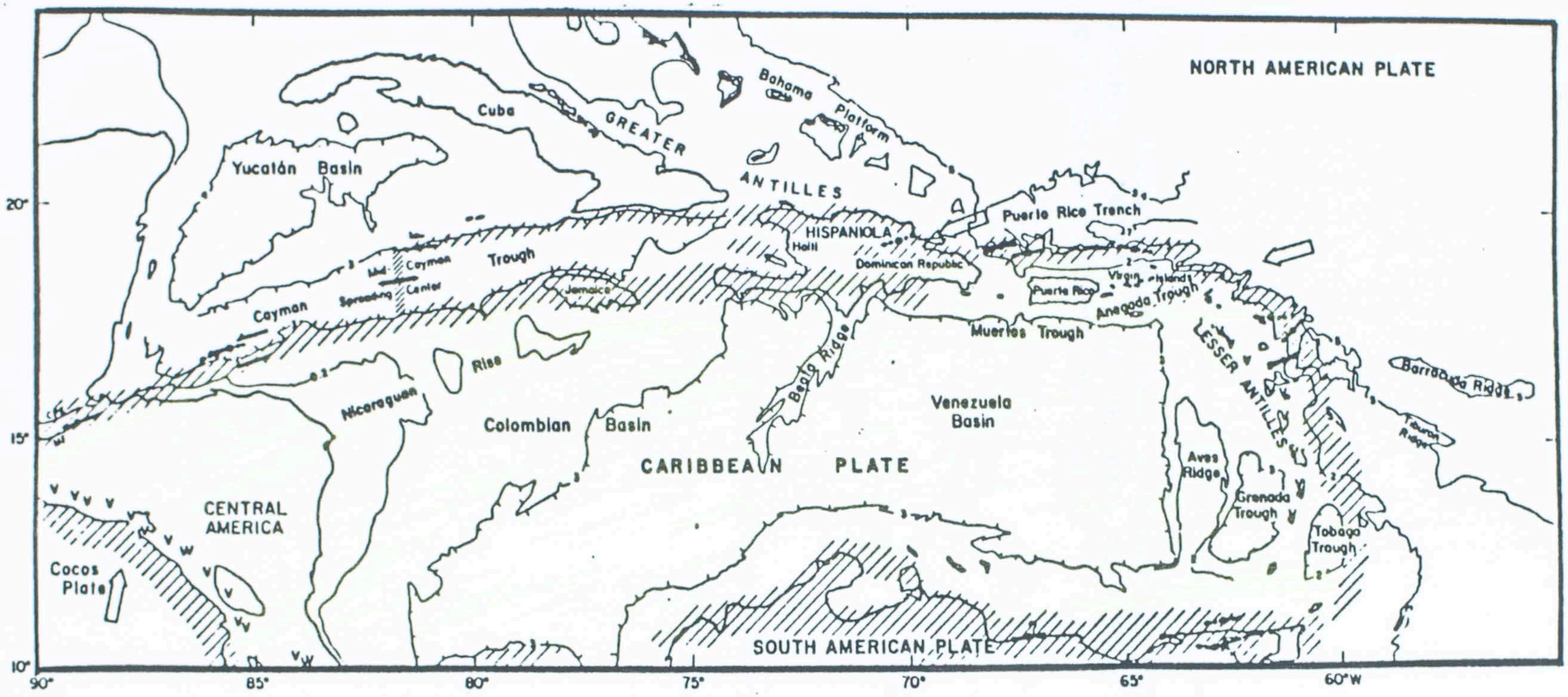
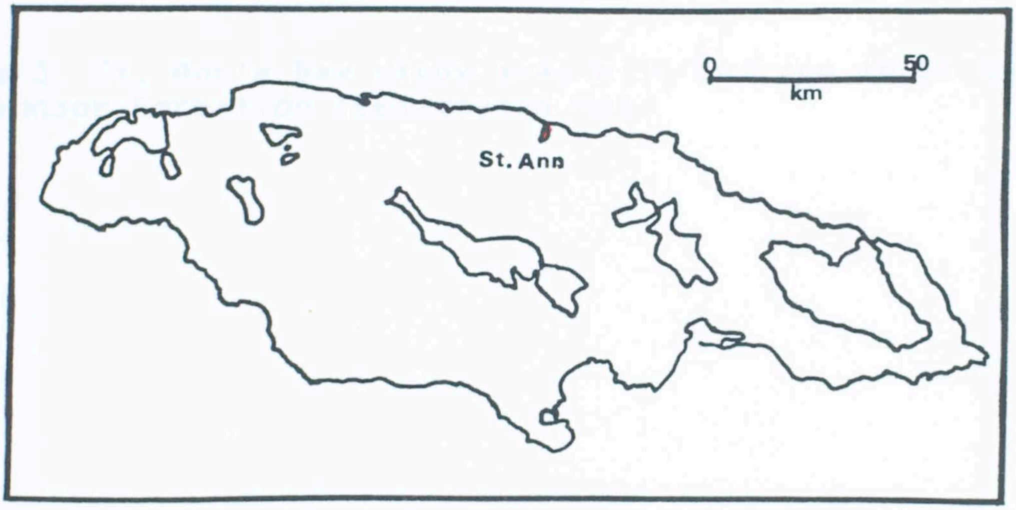
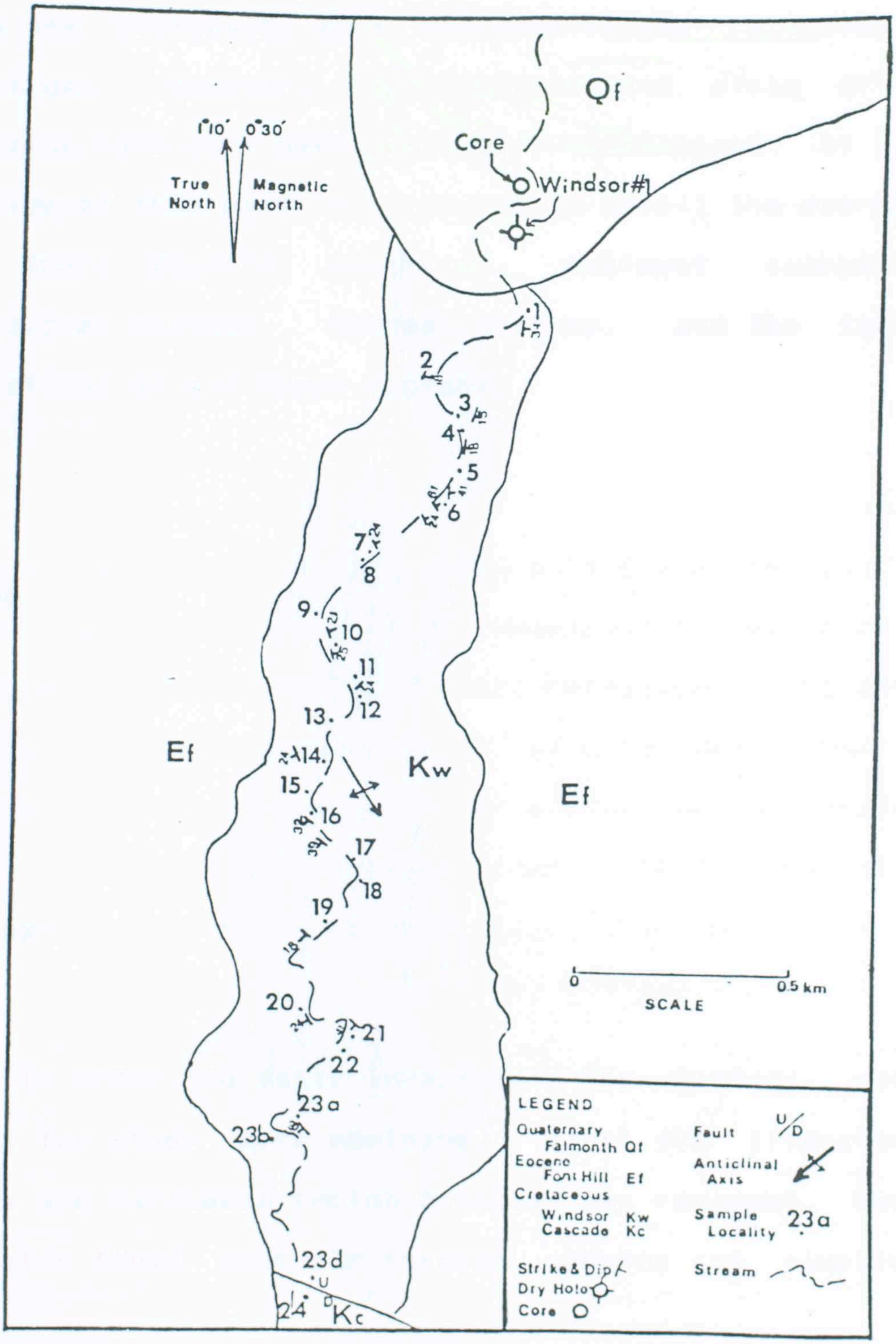

NORTH AMERICAN PLATE
Yucatán Basin
Cuba
GREATER ANTILLES
Bahama Platform
Puerto Rico Trench
HISPANIOLA
Haiti
Dominican Republic
Cayman Trough
Mid-Cayman Spreading Center
Cayman
Jamaica
Puerto Rico
Virgin Islands
Anegada Trough
Muertos Trough
LESSER ANTILLES
Barracuda Ridge
Tiburon Ridge
Rise
Nicaraguan
Colombian Basin
Beata Ridge
Venezuela Basin
CARIBBEAN PLATE
Aves Ridge
Grenada Trough
Tobago Trough
CENTRAL AMERICA
Cocos Plate
SOUTH AMERICAN PLATE
20°
15°
10°
90°
85°
80°
75°
70°
65°
60°W

Figure 2. Location of the Cretaceous Inliers of Jamaica (after Chubb, 1959). Note the position of the St. Ann's Inlier on the north-central coast.



0
50
km
St. Ann

Figure 3. St. Ann's Bay study area with outcrop locations of the Windsor Formation (designated Kw).


1°10'
0°30'
True North
Magnetic North
Qf
Core
Windsor#1
Ef
Kw
Ef
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23a
23b
23d
24
U
D
Kc
0
0.5 km
SCALE
LEGEND
Quaternary
Falmonth Qf
Eocene
Font Hill Ef
Cretaceous
Windsor Kw
Cascade Kc
Strike & Dip
Dry Hole
Core
Fault U/D
Anticlinal Axis
Sample Locality 23a
Stream

deposition with thin lenses of deep water carbonates.

I propose the sediments of the St. Ann's Basin can provide insight into the tectonics of Jamaica during the Cretaceous. Previous workers have suggested Jamaica formed during the Cretaceous as a volcanic island resulting from subduction. However, the polarity and style of this subduction have only been previously generalized. It is the objective of this paper to examine in detail the pre-Eocene St. Ann's Basin's evolution, sediment composition, depositional systems, thermal history, and the tectonic implications of all these factors.

METHODS

Strategy

In order to fully investigate the Windsor, various methods for study were employed. First the literature on Jamaica and Caribbean tectonic models was reviewed. Next, a systematic field analysis through mapping and sampling in

Jamaica was completed. In addition to the outcrop samples, core samples from PetroJamaica's Windsor #1 well were obtained from PetroJamaica to complete the study. The samples were examined petrographically to determine compositional trends. Heat flow data from the Windsor #1 provided information for a thermal analysis of the basin. Finally all of the findings were synthesized and applied to the tectonic history.

Field Analysis

A comprehensive field study of the area was conducted in the summer of 1982. This investigation entailed both mapping and sampling of the Windsor Formation. The area of study was restricted to outcrops of excellent exposure on and near the St. Ann's River since jungle vegetation covered the rocks in all other areas. This study area is approximately one-half mile (0.8km) wide and three miles (4.8km) long (Fig. 3). Outcrop evaluation was made of lateral and vertical variations of lithology, bedding, sedimentary structures, nature of contact with both horizontally and vertically adjacent units, paleocurrent directions, weathering patterns, structural features, and facies geometries. Outcrop descriptions of the Windsor are included in Appendix I.

In addition to outcrop data, a core, provided by the Petroleum Corporation of Jamaica, was described and sampled (Appendix II). The core was recovered from a preliminary drill site (Fig. 3) prior to the February 1982 spudding of the Windsor #1. Samples from the core extended the analysis into the subsurface.

Petrographic Analysis

Selected representative clastic rocks were slabbed, thin sectioned, described, and point-counted in thin sections for a minimum of 100 points (over 90% were counted for over 150) to determine quantitative mineralogical percentages and textural characteristics (Appendix III). A point count for 100 points has 4% to 9% error and 150 points has an error ranging from 3% to 7% (Van der Plas and Tobi, 1965) for the compositional percentages in the Windsor Formation. The carbonate rocks from the Windsor were named using both Folk (1959) and Dunham (1962) classifications, while the clastics were classified according to the Folk system (1980). Using the mineralogical percentages from the clastic rocks, a variety of compositional triangles were constructed to define and characterize the range of compositions.

Relative roundness of grains was measured by visual estimate using Power's (1953) chart. Grain sizes were measured by use of a calibrated micrometer. Average grain size measurements (phi 50) for each mineral in the thin section were made. The degree of sorting (σ) was estimated using Folk's method (1980) of measuring phi 16 and phi 84 and computing:

$$\frac{\text{phi } 16 - \text{phi } 84}{2}$$

Folk (1955) found the error in estimating grain sizes is 0.02, the error in roundness estimation is 0.35, and the error in estimating sorting to be 0.03. These values are noted from individual grain measures. Thin sections may not yield totally accurate nor precise sorting and roundness measures, but may be used as an approximation.

Thermal Analysis

An analysis of the heat flow of the area was made using thermal data provided by PetroJamaica from the Windsor #1. A bottom hole temperature, corrected for down-hole circulation times, and a present-day heat flow value were made available. This heat flow value was then compared with other Caribbean heat flow measures. Also included in the study are vitrinite reflectance values (Rodrigues, 1982) from the shales of the Windsor Formation which together provide important constraints upon the thermal history of the basin.

TECTONIC SETTING, A REVIEW OF THE PREVIOUS LITERATURE

INTRODUCTION: SEDIMENT COMPOSITION AS A TECTONIC RECORD

An interpretation of the Cretaceous tectonics of Jamaica must include a discussion of plate tectonics. The Caribbean region is presently made up of a series of plates and microplates: the North American plate, the South American plate, and the Caribbean microplate (Fig. 1). The Caribbean geology of today, as in the past, is largely governed by the movements of these plates. In the following section, the various theories proposed for Caribbean tectonics during the Cretaceous will be reviewed.

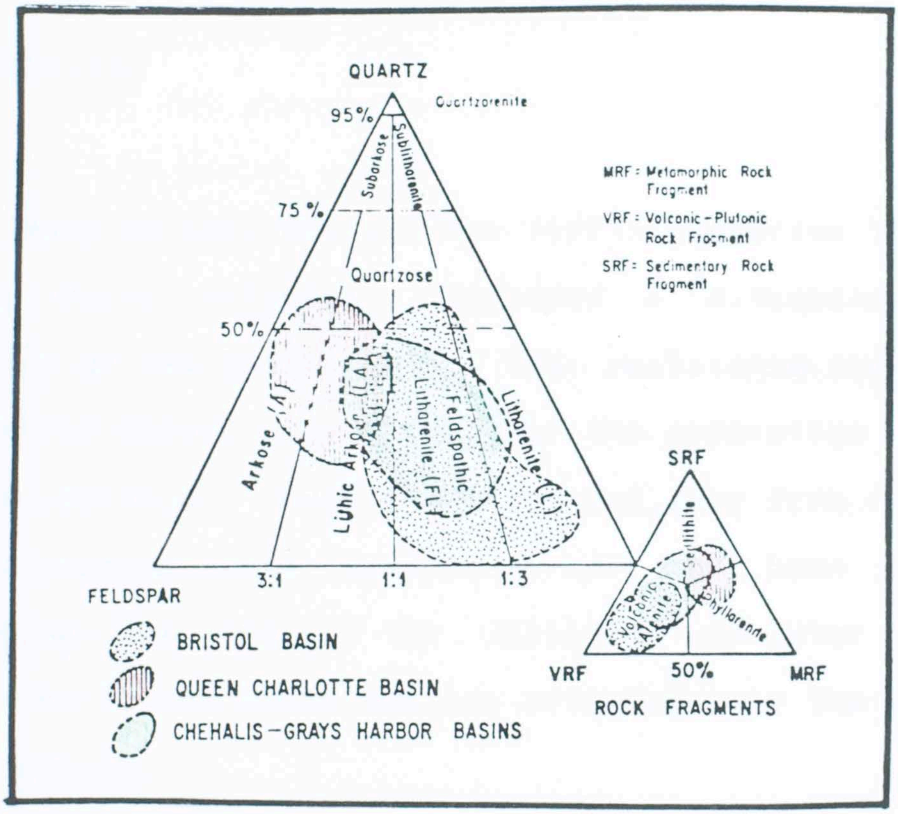
The regional tectonics of Jamaica during the Cretaceous are of importance in deciphering the setting of the Windsor Formation sediments. The petrology of these rocks should provide insight into the types of sediments deposited in the St. Ann's basin and additionally constrain the tectonic setting, i.e. polarity of subduction.

Krynine (1948) first proposed the concept of sandstone composition and its relationship to tectonics. He proposed that tectonic activity was ultimately responsible for exposing rocks at the surface. Krynine postulated a relationship between intensity of tectonic activity and original depth of the rocks exposed at the surface: the greater the tectonic activity, the greater the original depth of the exposed rock. He postulated that under quiet tectonic conditions, sedimentary rocks would provide the debris for sandstones resulting in the sedimentation of orthoquartzites (quartzarenites). Compressional tectonics such as folding and thrusting would create low-grade metamorphic rocks such as slates and phyllites. Erosion of these rocks would result in rocks rich in metamorphic rock fragments (called phyllarenites today). Vertical tectonics provided granite and gneiss as sources for arkoses. Although this theory is highly simplified, it marks the first significant attempt at relating tectonics to sedimentation.

Various authors have since noted sandstone compositions may be diagnostic of tectonic settings. Dickinson and Suzeck (1979) studied provenance types of sandstones, dividing them into three general groups: the continental block, the magmatic arc, and the recycled orogen. Using data from other authors, in addition to their own, they were able to suggest provenance types dictated sandstone composition. Dickinson (1982) later studied sandstone compositions of fore-arc sediments in the circum-Pacific area. He classified the sandstones on the basis of mineralogical compositional trends. Using these compositional trends he was able to cite particular compositions as indicative of fore-arc sedimentation. Galloway, (1974) working with rocks from the Pacific Northwest, noted mineralogical differences between fore-arc and back-arc basins (Fig. 4). Ingersoll (1977) studied the variation in mineralogical compositions of the Great Valley Sequence, in California. His study of the difference in sediment compositions also utilized compositional diagrams. He found that provenance changes induced sandstone composition changes in the Great Valley Sequence.

It is the Dickinson and Suczek (1979) and Dickinson (1982) studies which are significant to this study in their approach and method of data analysis. These authors utilized a variety of triangular diagrams in order to graphically illustrate mineralogical variations influenced by different tectonic settings, a tool of data presentation adapted here.

Figure 4. Triangular diagram illustrating the mineralogical differences between fore-arc and back-arc basins in the Pacific Northwest (from Galloway, 1974).


QUARTZ
Quartzarenite
95%
Subarkose
Sublitharenite
75%
Quartzose
50%
Arkose (A)
Lithic Arkose (LA)
Feldspathic Litharenite (FL)
Litharenite (L)
FELDSPAR
3:1
1:1
1:3
MRF = Metamorphic Rock Fragment
VRF = Volcanic-Plutonic Rock Fragment
SRF = Sedimentary Rock Fragment
SRF
Sedlithite
Volcanic Arenite
Phyllarenite
VRF
50%
MRF
ROCK FRAGMENTS
BRISTOL BASIN
QUEEN CHARLOTTE BASIN
CHEHALIS-GRAYS HARBOR BASINS

SUMMARY OF PREVIOUS WORKS

Plate Motions

Work by LePichon and Fox (1971), modeling the opening of the North Atlantic, included a discussion of the formation of the Caribbean. They postulated the Caribbean and Gulf of Mexico were formed by the generation of oceanic crust as North and South America moved away from each other. They suggested this oceanic crust had been completely created by the end of the Jurassic and later movements between North and South America affected only the margins of the Caribbean.

The LePichon and Fox model incorporated plate movements from only the North and South American plates in their model. Ladd (1976), however, believed that Caribbean geology cannot be explained by the simple plate movements of only North and South America. He stressed the need for additional plate interaction. According to his model, during the early Cretaceous (Valanginin to Coniacian), South America split away from Africa, producing a left-lateral strike-slip component of movement in the Caribbean. The

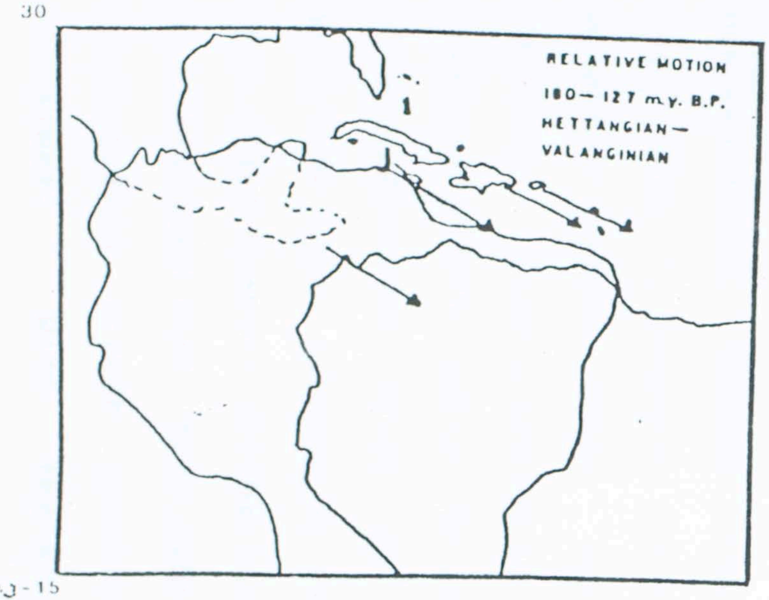
Greater Antilles experienced pre-Aptian andesite volcanism which Ladd attributed to a possible subduction zone. He believed all of the plate movement at this time could not be explained purely by simple strike-slip movement between two plates. Instead, Ladd interpreted his plate motion data to indicate subduction of the northern margin of the Caribbean plate beneath the Greater Antilles from the Coniacian until the end of the Eocene (Fig. 5).

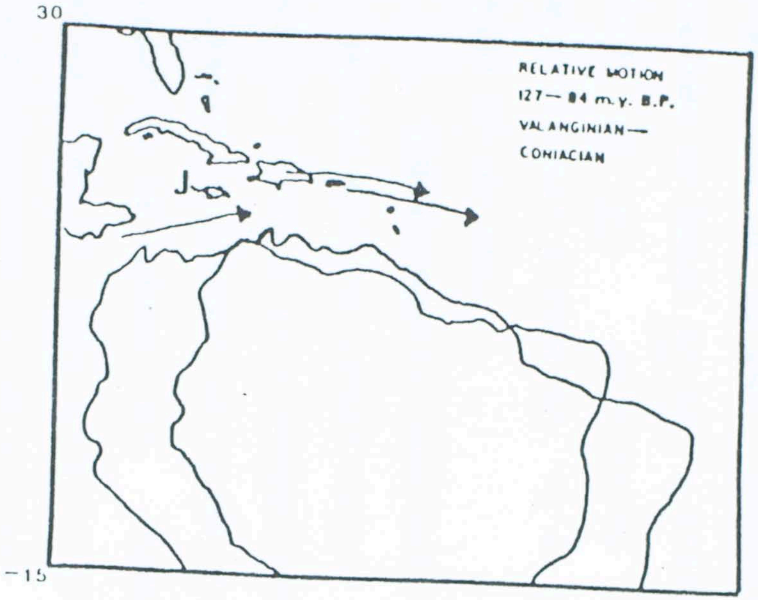
MacDonald and Opdyke (1972) attempted to interpret the plate movements about Jamaica from paleomagnetic sites in North and South America. From this information, they suggested Jamaica's Cretaceous paleolatitude was less than 10° N, and that since the Cretaceous Jamaica has moved northward to a latitude of 18°N.

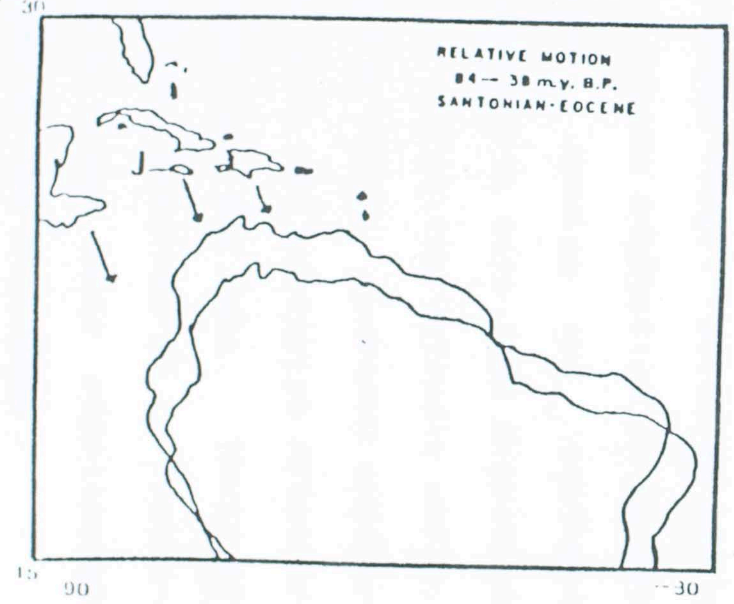
Crustal Character

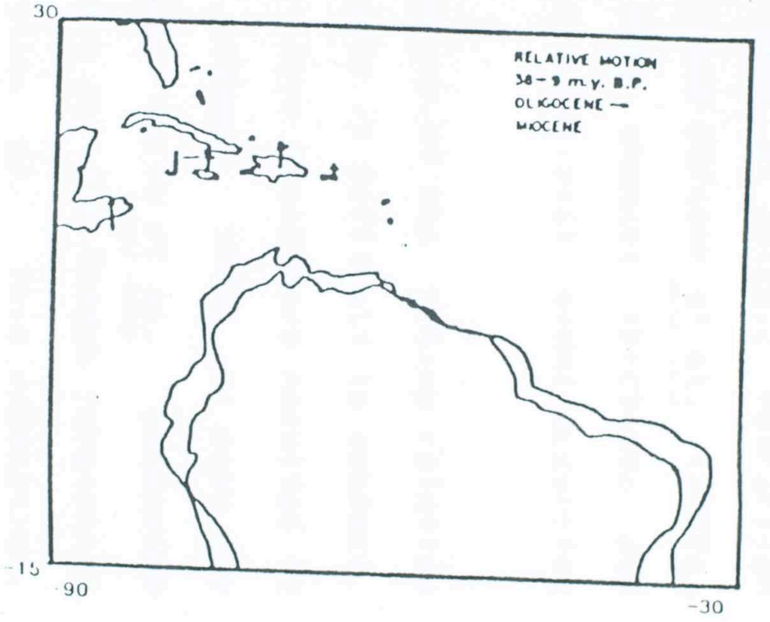
Burke *et al.* (1978) studied the unusually "buoyant" nature of the Caribbean crust. They proposed that if South America was attached to Africa during the opening of the Central Atlantic in the Jurassic, the Caribbean oceanic crust must have been produced between North America and South America. Burke *et al.* also noted the Caribbean ocean floor is presently at a depth of 1 to 2km, however, from

Figure 5. Ladd's reconstruction (1976) of relative plate motion in the Caribbean. "J" represents Jamaica.


30
-15
RELATIVE MOTION
180— 127 m.y. B.P.
HETTANGIAN—
VALANGINIAN
J


30
-15
RELATIVE MOTION
127— 84 m.y. B.P.
VALANGINIAN—
CONIACIAN
J


30
15
90
-30
RELATIVE MOTION
84— 38 m.y. B.P.
SANTONIAN-EOCENE
J


30
-15
90
-30
RELATIVE MOTION
38—9 m.y. B.P.
OLIGOCENE —
MIOCENE
J

thermal cooling considerations, a basaltic Cretaceous sea floor should have subsided to 5 or 6km (Sclater et al., 1971). They also noted the thicker than normal oceanic crust (15 to 20 km) demonstrated by seismic refraction studies by Edgar et al. (1971) and Officer et al. (1959). Burke et al. attributed this unusual thickness and "artificial" elevation to a basaltic sill event occurring about 80 my ago.

The unusually buoyant nature of the region relative to normal oceanic crust would make it difficult to subduct, and its arrival at a subduction zone could have resulted in a change of subduction polarity (Dewey, 1977) or even the cessation of subduction. Indeed, Burke et al. suggested the arrival of this altered crust at the trench terminated the convergence in the Eocene (Fig. 6). This subduction, they postulate, involved normal ocean floor. Burke et al.'s theory (Fig. 7) proposes the pre-Eocene subduction of normal Caribbean ocean floor beneath Jamaica and southern Hispanola. From a review of petrologic data from Hispanola by Wassal (1957), ophiolite ages, andesitic volcanic units, and granodiorites, Grippi and Burke (1978) proposed another subduction zone, dipping to the south and consuming Atlantic ocean crust beneath northern Hispanola and Cuba. Burke et al. postulated that this subduction occurred at a trench-trench-trench triple junction or some more complicated equivalent. With the arrival of the thickened

Figure 6. Burke *et al.*'s reconstruction (1978) of the unusually buoyant nature of Caribbean oceanic crust.

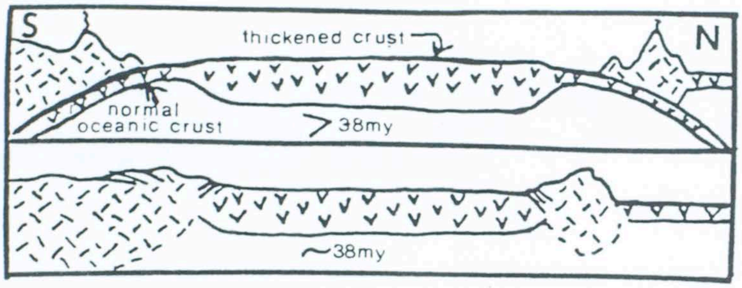
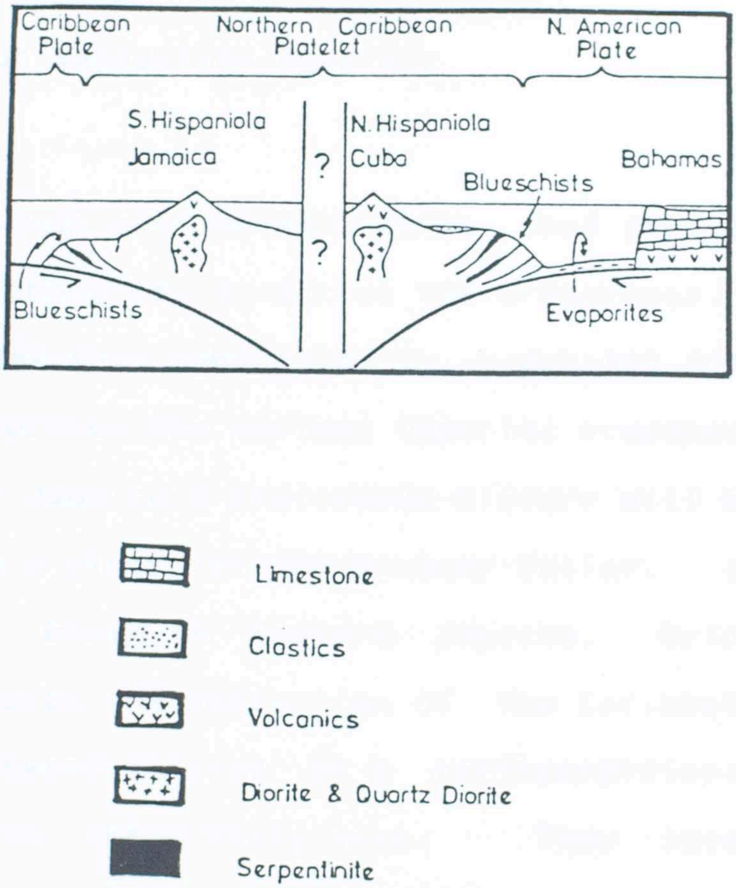

S
thickened crust
N
normal
oceanic crust
> 38my
~38my

Figure 7. Model proposed by Burke *et al.* (1978) for Late Cretaceous subduction. Note the northward-dipping subduction zone beneath Jamaica.


Caribbean Plate
Northern Caribbean Platelet
N. American Plate
S. Hispaniola
Jamaica
?
?
N. Hispaniola
Cuba
Blueschists
Bahamas
Blueschists
Evaporites
Limestone
Clastics
Volcanics
Diorite & Quartz Diorite
Serpentinite

Caribbean crust, a change in motion from pure convergence to left-lateral transform motion occurred.

Theories for Subduction Polarity

Although most workers agree that subduction occurred in the Caribbean region during the Cretaceous, the polarity and style of this subduction is a debated topic. In the following section the various theories proposed by different authors for Jamaica's Cretaceous history will be reviewed.

From a study of the Hanover Inlier, an outcropping sedimentary basin in Western Jamaica, Grippi and Burke (1978) modeled the subduction of the Caribbean region as a either southward-dipping or a northward-dipping subduction zone during the Cretaceous. They interpreted the depositional systems of the inlier as a submarine fan complex in an upper slope basin setting with an inferred dominant paleocurrent direction to the Northwest. In contrast to findings from the St. Ann's study, neither detrital quartz nor in situ volcanic rocks (ash) were reported in their analysis.

Malfait and Dinkleman (1972) advocated a northward dipping subduction zone as the mechanism for the Cretaceous formation of Jamaica. These authors envisioned the

Caribbean plate as part of the East Pacific plate that broke off from the main Pacific plate. The authors postulate Jamaica as having originated in southern Mexico and was later rafted into its present position by transform motion beginning in the Paleocene (Fig. 8).

Walper and Rowett (1974) support Malfait and Dinkleman's theory in that they too proposed a northward-dipping subduction zone (Fig. 9). They suggested that as the North American plate rotated clockwise and separated from the South American plate, part of the East Pacific plate was squeezed between the two plates and into the present Caribbean area. As the East Pacific plate moved into the Caribbean region, pressure from this movement forced the penisula of Central America eastward into its present arc configuration.

Sykes _et_ _al._ (1982) concluded that subduction occurred in the Caribbean during the Cretaceous as the North American plate was subducted until late Eocene when buoyant oceanic crust halted the subduction. They also proposed the Caribbean ocean crust to have originated as part of the Pacific plate and not from the Atlantic or the Gulf of Mexico. This is inferred from the easterly movement of the Caribbean at a moderately high velocity relative to the Americas.

Perfit and Heezen (1978) proposed an alternate direction of subduction from kinematic considerations.

Figure 8. Malfait and Dinkelman's model (1974) of Caribbean plate movements in the Cretaceous.

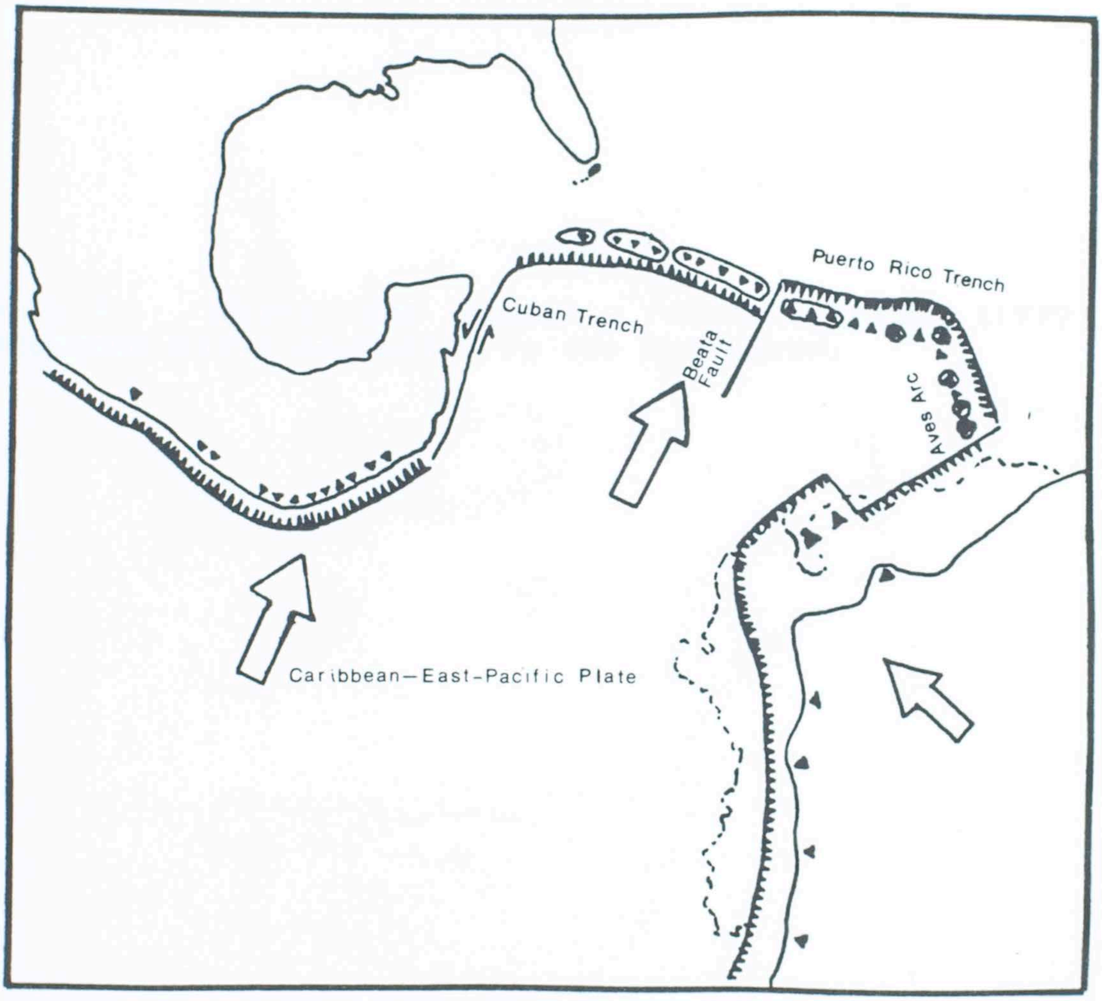
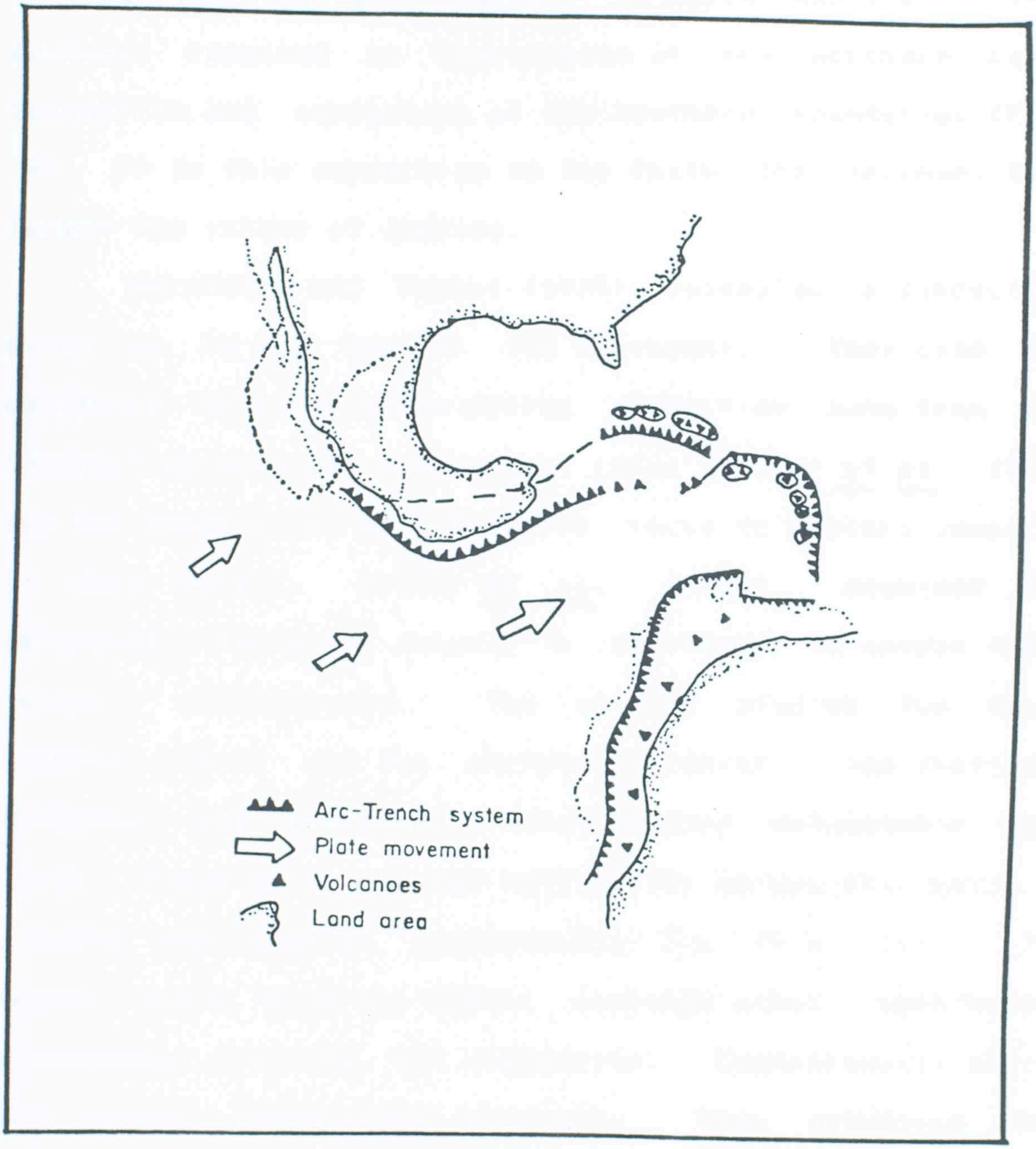

Puerto Rico Trench
Cuban Trench
Beata Fault
Aves Arc
Caribbean—East-Pacific Plate

Figure 9. Walper and Rowett's reconstruction (1972) of Cretaceous plate movements in the Caribbean.


Arc-Trench system
Plate movement
Volcanoes
Land area

Their theoretical model begins with the clockwise rotation of South America with respect to North America. This movement resulted in compression at the northern plate boundaries and subduction at the southern boundaries (Fig. 10). It is this subduction to the South, they believe, that formed the island of Jamaica.

Horsfield and Roobol (1974) suggested a subduction direction to the West or the Southwest. They cite the existence of a possible paired subduction zone from two contrasting belts of metamorphic rocks (Draper _et al_, 1976) and the restriction of ultramafic rocks to eastern Jamaica. In more detail, Draper _et al._ (1976) examined the metamorphic facies of Jamaica in an attempt to assess their tectonic significance. The authors studied the Mount Hibernia Schist and the Westphalia Schist, two spatially different but genetically inter-related metamorphic rock units. These units are two contrasting metamorphic belts in Jamaica separated by approximately 2km (Fig. 11). The eastern Mount Hibernia Schist contains alkali amphiboles, stilphnome, crossite, and riebeckite. Conspicuously absent are higher temperature minerals. They interpret this mineralogy as characteristic of a low temperature, high pressure metamorphic facies. To the West, Westphalia Schist, on the other hand, contains quartzo-feldspathic and rocks representative of a higher grade epidote-amphibolite facies and amphibolite facies mineralogy (Kemp, 1971). These

Figure 10. Perfit and Heezen's model (1978) of Late Cretaceous Caribbean subduction. "J" represents Jamaica's location.

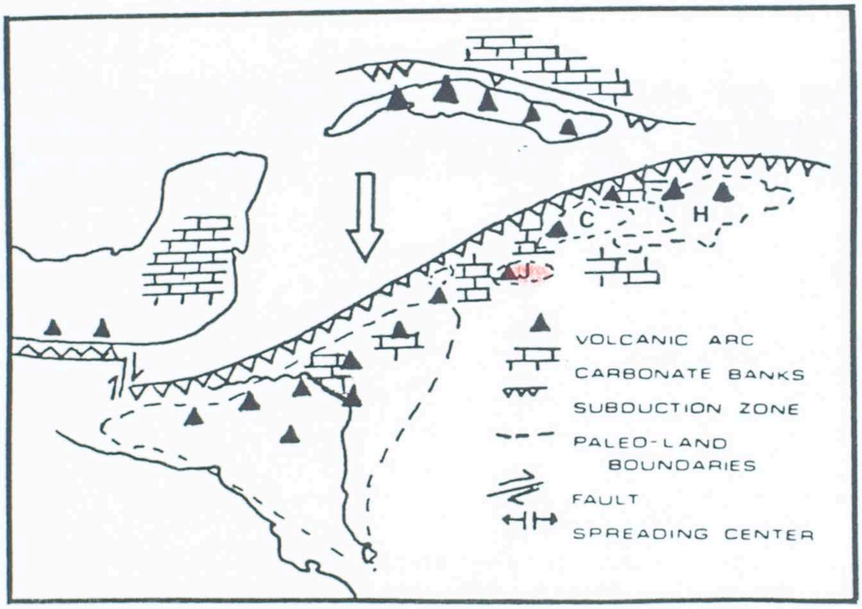
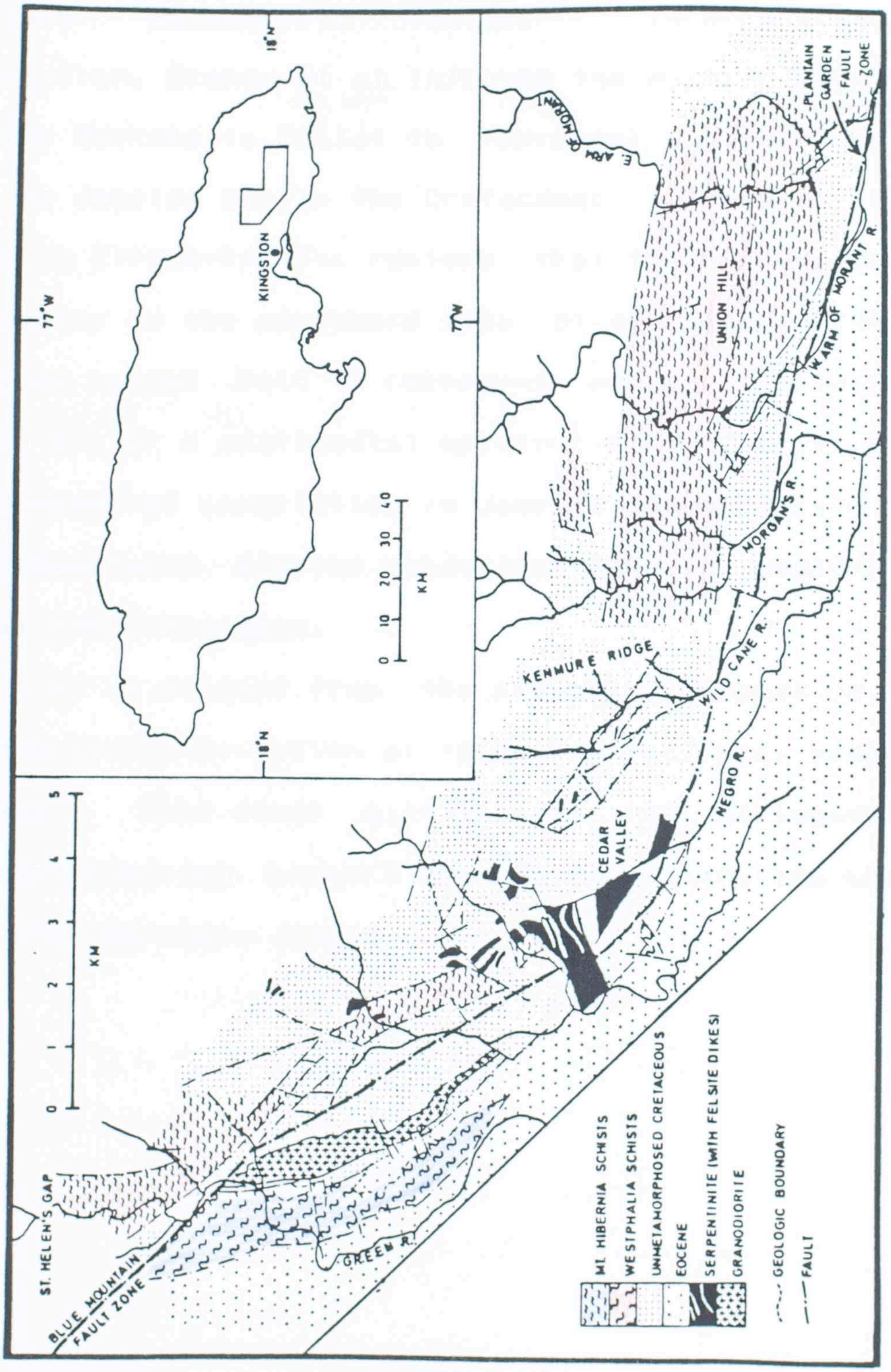

C
H
J
VOLCANIC ARC
CARBONATE BANKS
SUBDUCTION ZONE
PALEO-LAND BOUNDARIES
FAULT
SPREADING CENTER

Figure 11. Location map illustrating the two constrasting high-temperature and low-temperature metamorphic belts in southwestern Jamaica (from Draper *et al.*, 1976).


ST. HELEN'S GAP
BLUE MOUNTAIN FAULT ZONE
GREEN R.
KENMURE RIDGE
CEDAR VALLEY
NEGRO R.
WILD CANE R.
MORGAN'S R.
UNION HILL
W ARM OF MORANT R.
E. ARM OF MORANT
PLANTAIN GARDEN FAULT ZONE
KINGSTON
77°W
18°N
0 1 2 3 4 5
KM
0 10 20 30 40
KM
MT. HIBERNIA SCHISTS
WESTPHALIA SCHISTS
UNMETAMORPHOSED CRETACEOUS
EOCENE
SERPENTINITE (WITH FELSITE DIKES)
GRANODIORITE
GEOLOGIC BOUNDARY
FAULT

facies are representative of a high temperature, high pressure metamorphic facies. Incorporating this information, Draper et al. inferred the Mount Hibernia Schist and the Westphalia Schist to represent a paired metamorphic belt in Jamaica during the Cretaceous. Myashiro (1973) has noted in Circum-Pacific regions that the high-pressure belt is usually on the oceanward side of subduction with the low pressure paired belt to represent volcanic activity in an island arc or a continental margin. Consequently, Draper et al.'s observed association in Jamaica geometrically suggests a southwestward dipping subduction zone in eastern Jamaica during the Cretaceous.

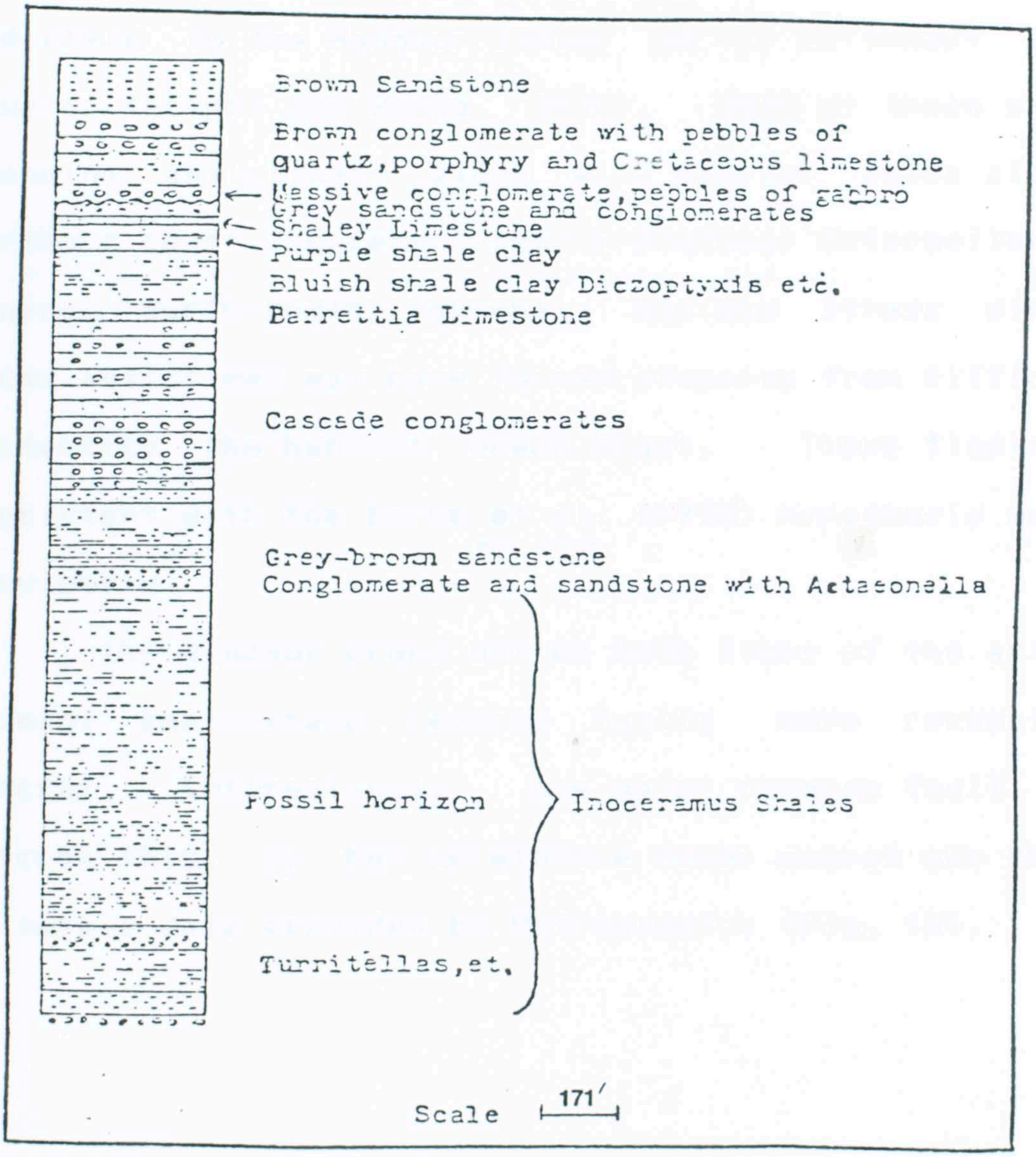
As is evident from the preceding discussion, almost every possible direction of subduction has been proposed for Jamaica. This study will examine the sediments of the Windsor Formation, perhaps the key to solving the problem at least for Northern Jamaica.

FIELD ANALYSIS

INTRODUCTION: GENERAL STRATIGRAPHY

The Windsor Formation consists of a series of alternating conglomerates, sandstones, siltstones, shales, and micritic limestones. These sediments represent deposition into the St. Ann's Basin during the late Cretaceous. Previous studies (Chubb, 1959; Cowan, 1980; Meyerhoff and Krieg, 1977) have generalized the depositional systems and constructed a schematic stratigraphic column (Fig. 12). One major purpose of this study is to define in greater detail the depositional systems of the Windsor Formation based on an intensive field study. The field observations are recorded in the following section. Petrologic data will be included in the description of the stratigraphic column.

Figure 12. Generalized stratigraphic section (from Chubb, 1959) of the *St. Ann's Sequence*. The Windsor Formation forms the lower portion of the section.


Brown Sandstone
Brown conglomerate with pebbles of quartz,porphyry and Cretaceous limestone
Massive conglomerate,pebbles of gabbro
Grey sandstone and conglomerates
Shaley Limestone
Purple shale clay
Bluish shale clay Diczoptyxis etc.
Barrettia Limestone
Cascade conglomerates
Grey-brown sandstone
Conglomerate and sandstone with Actaeonella
Fossil horizon
Inoceramus Shales
Turritellas,et.
Scale
171′

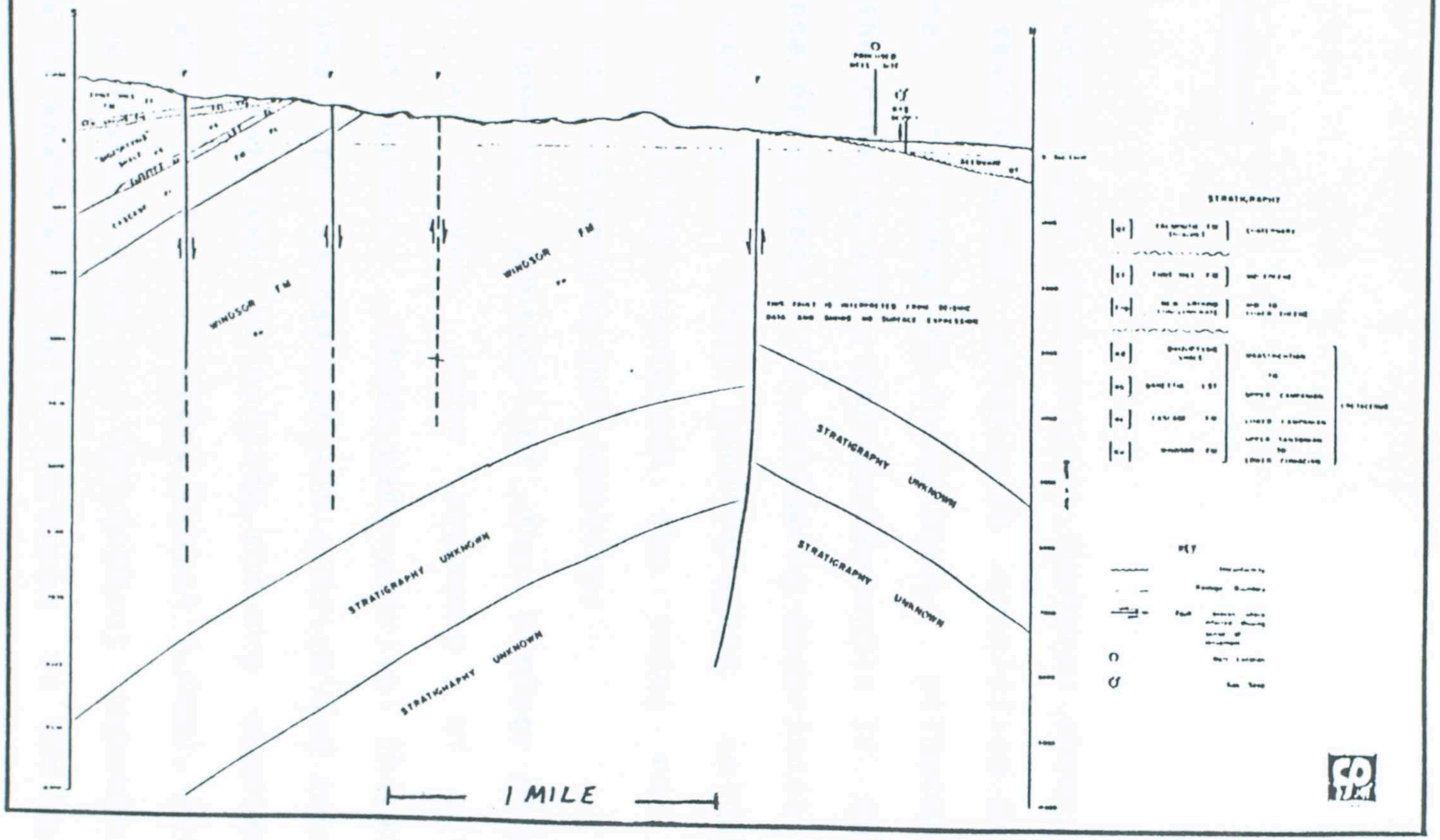
STRUCTURAL SETTING

The St. Ann's Basin has undergone post-Cretaceous folding into an anticline (Fig. 3), similar in orientation and style to the Hanover Inlier on the northwest coast of Jamaica (Grippi and Burke, 1978). Both of these east-west trending anticlines, along with similar folds along the northern coast, represent post-Cretaceous deformation with a general north-south regional maximum stress direction. These anticlines may have formed stemming from difficulty in subducting the buoyant ocean crust. These findings are consistent with the Burke *et al.* (1978) hypothesis mentioned previously.

The Windsor crops out on both limbs of the anticline. Several small-scale reverse faults were recognized in outcrop. Interestingly, one major reverse fault seen in outcrop (Fig. 3) but heretofore never mapped was confirmed on seimic data provided by PetroJamaica (Fig. 13).

Figure 13. Crossectional view of seismic data interpretation by PetroJamaica. The locations of the reverse faults are marked.

CROSS SECTION OF THE ST. ANN'S GREAT RIVER INLIER (N-S)



LITHOSTRATIGRAPHY

Outcrop Lithology

The predominant depositional features observed in the field are several major units each consisting of a basal conglomerate, followed by sandstones, siltstones, and shales. The stratigraphic column (Appendix I) details the rock sequence described. The following description of units will be made from this stratigraphic column. The percentages indicated represent the total per cent of constituent for the entire thin section.

The lowermost portion of the Windsor observed in outcrop is an eleven meter sequence of alternating sandstones and shales. These beds vary in thickness from 0.55m to 0.05m. The sandstones are massive and exhibit many fracture veins infilled by calcite and are weathered gray. The shales are very thinly bedded (about 1.0mm), fissle, and weather to a blueish-gray. The contact between the two lithologies is sharp with scour surfaces at the base of the sandstones. Several of the sand bodies display 0.5m by 1.2m channel profiles with lateral pinchout on the margins

(Fig.14). These sands are laterally discontinuous, extending only about one meter, appear well sorted, and are massive.

Sample W-12-1a, a coarse silt: micritic mature volcanic arenite from one of the sand-sized beds, is predominately volcanic rock fragments with minor quartz and feldspars. The feldspars are generally too altered to determine specific variety. The sample is well-sorted (=0.4) and fine-grained. The rock is cemented by a micritic calcite cement. Other sandstones in this same sequence show greater amounts of feldspar (W-12-2c, fine sandstone: immature feldspar-bearing lithic arenite). The shales in the sequence also contain volcanic rock fragment and are plagioclase rich with a clay matrix. They have a similar mineralogic composition to the sandstones, the only distinction being the finer grain size. Some of the sandstones are calcite cemented while others have a clay matrix.

This alternating sandstone-shale sequence is capped by a 0.8m carbonate. This rock is a medium calcarenite: feldspar-volcanic rock fragment-bearing foram biomicrite (feldspar-VRF fossiliferous mudstone). The rock contains 7% foraminiferal fossils and minor amounts of VRFs, but a large amount of feldspar (36%).

A fairly thick shale sequence overlies this bed. The shale is blue-gray, fissile, thinly bedded, and highly

Figure 14. Prounced channel geometry in sandstone beds (locality W-12).

Figure 15. Calcite infilling fracture in shale (locality W-13).

fractured with calcite infilling the fractures (Fig. 15). The uppermost portion of the shale contains cobble-sized clasts supported by the shale. The pebbles are disorganized with an open framework and no grading indicating the upper part of the shale to be a debris flow (Fig. 16). Petrographically, the aforementioned unit is a fine sandstone: micritic mature arkose and is in the fine silt category. The rock examined, (W-13-1d), contains about 52% feldspar with minor opaques. The other percentage of the rock is a micrite cement, clay, and vein calcite. The feldspars are very fine-grained and often altered to calcite. The rock is very well sorted ($\sigma = 0.2$). Stratigraphically equivalent to this shale is an ash flow that occurred in the northern part of the basin. This ash flow is now completely altered to clay. Volcanic bombs can be seen in outcrop (Fig. 17).

A petrographic analysis of the debris flow clasts reveals them to be volcanic rock fragments. The composition of W-13-1c2 is 30% unaltered plagioclase, 11% MRF, one per cent opaques and 25% altered groundmass. This is a porphyritic igneous rock with plagioclase and mafic mineral phenocrysts in a formerly volcanic glass groundmass that is now clay. The plagioclases have some alteration to calcite, and many display pronounced zonation. The phenocrysts which are not feldspar were once amphibole or pyroxene that has now altered to biotite or chlorite.

Figure 16. Rounded volcanic cobble-sized clasts in the upper portion of the shale unit (locality W-13).

Figure 17. Ash flow with volcanic bombs now totally altered to clay (locality W-10).

Overlying the shale is the first conglomerate unit, 9.75m thick. The pebbles found in this conglomerate are similar to those in the underlying shale. At the lower contact, the shale appears to have undergone soft sediment deformation (Fig.18). The conglomerate consists of cobbles boulders of variable size surrounded by a clay matrix. The pebbles are poorly sorted but fairly well rounded. Weathering has removed much of the clay, leaving the conglomerate very loosely cemented.

The petrology of the overlying litharenite conglomerate is similar to the clasts in the shale, the clasts being composed entirely of volcanic rock fragments. Sample W-14-1a2, a clast, has about 25% feldspar plus 21% alteration of feldspar to bauxite, both calichite and gibbsite. The rest of the rock is clay groundmass giving it a porphyritic texture. The bauxite alteration takes on the shape of the feldspar grain. Sample W-14-1a1, too, consists mainly of plagioclase microlites and a clay groundmass. The feldspars have minor gibbsite alteration. Pericline twinning angles of feldspars indicate compositions of An17 and An11 (Kerr, 1972). Only about three per cent of the feldspar is altered to calcite in this thin section. Because of the variation in size of the coarse clasts, the unit is very poorly sorted.

The conglomerate bed is overlain by a thin sequence (0.4m) of sandstone- pebble conglomerate-sandstone. The

Figure 18. *Soft* sediment deformation of shale during deposition of the overlying cobble-sized conglomerate (locality W-13).

lowermost sandstone is laminated, 0.1m thick, and well-sorted. A pebbly conglomerate follows that is about 0.2m thick, and is noticably finer than the coarse conglomerate. Farther up in section a 0.1m nonlaminated sandstone outcrops.

The next depositional unit is another coarse conglomerate bed 3.4m in thickness with channel geometry and a scoured surface. The conglomerate is similar in lithology and bedding characteristics to the first volcanic litharenite. W-14-1c is a sample from the second conglomerate bed. Although not as coarse as the preceding conglomerate, it still has an average grain size of 2.38mm. The deposit is very poorly sorted with VRFs as the most commonly occurring constituents (70%) with 7% feldspar and 2% MRFs. The rock has a clay matrix (19%). One of the VRFs has a great deal of calichite alteration (9% of thin section). The calichite probably represents alteration of the feldspars phenocrysts.

The uppermost conglomerate is overlain by a sandstone bed (0.3m thick) which exhibits laminated bedding and soft sediment deformation. The sandstone bed is deformed probably from the post-depositional weight of the overlying conglomerate bed, the third coarse conglomerate. At the base of this overlying conglomerate bed (litharenite) are mud clasts (Fig. 19), perhaps rip-up clasts from some unpreserved shale unit. These conglomerate beds, similar in

Figure 19.   Weathered mudclasts and sandstone clasts at the base of the conglomerate (locality W-14).

lithology, represent the similar pulses of coarse clastic material into the basin.

Following is another sandstone-shale sequence (8.5m thick). These sandstone beds stand out as small resistant ridges in the non-resistant shale (Fig 20). The sandstone beds are fine to medium grained, massive, and commonly less than 0.5 meters thick. The shales are fissile, gray-blue, and have several calcite veins running throughout. A fracture (or small-scale fault) runs through the shale. These sandstones tend to fine upwards to shale.

Petrographically, a medium sandstone: immature feldspathic litharenite unit, W-16-1b, has 36% feldspar, 39% Volcanic rock fragments, and a clay matrix. The sample is moderately sorted with a σ=1.0. Eight percent of the rock is serpentine and it also contains minor chert (1%). Sample W-9-2b, a very fine sand: mature microspar- cemented arkose has constituents of 74% feldspar, one per cent quartz, three per cent serpentine, three per cent opaque minerals, and is cemented by microspar (18%). The sample contains calichite alteration and has at least one fossil fragment (1%). The sample is moderately sorted (σ=0.75).

The remainder of Windsor consists of very thick shale units with occasional micritic limestone and thin (less than 0.5m) sandstone beds fining to shale. These shales are non-resistant, fissile, and similar to those seen in lower sections. These limestones and sandstones are fine-grained

Figure 20. Resistant sandstone beds forming thin ledges in the non-resitant shale (locality W-16).

and form small resistant ridges in the shale. The thick shale sequence of deposition continues until about the upper 10m of the shale when coarse cobble and boulder size clasts appear in the shale. This shale unit is terminated when the Cascade Formation, a coarse conglomerate unit begins.

Sample W-18-1d is representative of this thick shale deposition. The rock contains 8% quartz, 28% feldspar, 8% VRFs, 2% serpentine, 5% opaques, and 1% MRFs (chlorite). The medium silt: immature opaque-bearing arkose is relatively uncemented with a matrix of clay. Throughout this shale sequence are biomicrite (mudstone) beds. W-18-1c is a sample from one of these beds. The sample is classified as a plagioclase and VRF-bearing micrite (plagioclase-VRF mudstone), containing about 5% relatively unaltered feldspar and 24% highly altered VRFs with the remaining 71% micrite cement and clay.

Higher up in the section, isolated sandstone beds begin to occur. W-19-2c, a fine-grained immature arkose, is a representative sample of these beds. The sample contains about 39% feldspar, with subequal amounts of plagioclase and orthoclase, minor opaques, and a clay matrix. W-19-2g2 is a coarse siltstone: immature chlorite-cemented lithic arenite slightly higher up in the section that also occurs as an isolated bed within the shale. This sample has a mineralogy of 48% feldspar, 16% VRFs, 5% MRFs (mostly serpentine), 6% clay, and 3% calichite alteration. One interesting aspect of this sample is what appears to be the beginning of phyllosilicate cement.

Following is a long sequence of shales and biomicrites (mudstones) with occasional siltstone beds. W-20-1h is one of the thin beds. The sample is classified as a medium siltstone: calcitic immature MRF-bearing felspathic litharenite. The sample has 15% feldspar and 26% VRFs with 5% MRFs (altered-to-chlorite-and-biotite pyroxenes, amphiboles, and olivines). There are about 30% clay grains which are probably alteration of VRFs. Sample W-21-1a is a coarse siltstone sample that has a slightly different mineralogy (arkose) about 69% feldspar (too altered to determine variety). 21% micrite cement, 7% clay, and 3% opaques. The sample is very well sorted also. These two siltstones represent the slightly coarser deposition into the basin.

Samples W-22-1b and W-23-3a are representative of the deposition in the upper part of the Windsor. Sample W-22-1b is a feldspar MRF-bearing foraminifera biomicrite (feldspar -MRF-foraminifera mudstone) with 22% feldspar, 4% MRF, and the rest calcite (micrite cement). Minor foraminifera fossils occur thoughout the thin section. About half of the feldspars are altered completely to calcite. Sample W-23-3a is a fine grained sandstone: immature foraminifera-bearing arkose containing 49% feldspar, 6% quartz, 35% clay, 6% opaques, and 4% fossils (foraminifera). Its grain size is

0.03 (fine-grained). The clay occurs as a matrix. At the top of the section, coarse clasts which are completely VRFs begin to appear until the Cascade Formation is reached, the overlying conglomerate unit.

Core Lithology

A core provided from a preliminary drill site of the Windsor #1 enables the extension of the Windsor Formation into the subsurface. The core samples and petrographic samples will be described in the following section. A complete stratigraphic section of the core with sample locations is compiled in Appendix II.

Deposition of the Windsor began with two cycles of pebble conglomerates fining to sandstones, then shales, and coarsening to sandstones and pebble conglomerates. The pebble conglomerate beds are typically 0.5m and 0.6m thick. This type deposition continues for 7.9m where the pebble conglomerate is absent and instead deposition consists of coarse, medium, and fine sandstones, and shales.

Sample C-148 is taken from one of the fine sandstone beds which is 0.19mm in grain size and moderately sorted. Compositionally the unit is composed primarily of volcanic rock fragments and thus classified as a fine sandstone:

metamorphic rock fragment-bearing volcanic arenite. The sample is composed of 1% quartz, 62% volcanic rock fragments, 11% metamorphic rock fragments, 11% feldspar (all plagioclase), 2% chert, and 14% albite cement.

After 10.8m the coarse sandstone is no longer present and alternating medium sandstones and shales predominate. These sandstone beds are 0.3m thick with the shale beds about 0.7 to 0.8m thick. The sandstones are brownish with calcite veins running throughout. The shales do not recover well in this section.

At -238m a 0.5m bed of mudclasts which are fairly undeformed in a clay matrix are present. The rip up clasts may be derived from shale units since the original bedding on these rip up clasts is preserved. This sequence grades into 0.6m of alternating sandstone and shale deposition ending with another 0.3m thick mudclast conglomerate at -233m. The sequence described above of alternating sandstones and shales continues for 63m. Lithologically, the units remain similar to those described previously.

At -199m a pebble conglomerate with mudclasts 0.8m thick grades into alternating coarse to medium sandstones and shales. Pebble conglomerates occur again at -178m, and -169m. After -169m deposition fines with no more pebble conglomerates until -147m.

Sample C-65 represents a fine sandstone in the above described sequence. Petrographically it is composed of 2%

quartz, 51% volcanic rock fragments, 12% metamorphic rock fragments, 15% calcite cement, 9% plagioclase, and 1% orthoclase. About 15% of the volcanic rock fragments are altered totally to clay. Calcite occurs as both a cement and as a crack fill. The sample is moderately sorted and classified as fine sandstone: calcitic metamorphic rock bearing volcanic arenite.

At -129m the first cobble-sized conglomerate bed appears. This conglomerate is correlative with the lowermost cobble-sized conglomerate bed seen in outcrop. This is overlain by a shale (0.9m thick) in which cobble-sized clasts are found throughout.

Next a coarser sandstone cuts into the shale and grades into a conglomerate. At 131m a siltstone cuts through the conglomerate. This siltstone bed is only 0.4m thick as conglomerate deposition resumes immediately. The conglomerate, like the others, contains cobble-sized, rounded clasts, with a clay matrix. Angular mudclasts are seen in the uppermost part of the unit.

The cobble-sized conglomerate fines to a pebble conglomerate at -95m after which alternating sandstones and shales predominate from -90m to -80m until another coarse conglomerate begins. This cobble-sized bed contains rounded clasts and some mudclasts.

Sample C-36 was taken from the -76m to -63.8m sequence. It contains 6% quartz, 24% feldspar, 59% volcanic rock fragments, and 10% calcite cement. A trace of serpentine is also seen. The sample is moderately sorted and has an average grain size of 0.24mm. The sample is classified as a medium sandstone: calcitic feldspathic litharenite.

Deposition of the conglomerate continues for 11.0m at which it grades into a series of coarse sandstones with alternating siltstones and shales. Sample C-5 is a sample from one of the shale units. C-5 is a medium silt: immature MRF-bearing lithic arenite. Throughout the thin section are sparry calcite veins (15%). The sample is 0.03mm in size and moderately well sorted. Major constituents are 35% feldspar, 14% MRFs (mainly serpentine), 36% clay (both grain alteration and matrix), and the calcite vein. This deposition is broken by a 3m bed of conglomerate at -45.6m and then resumes until the end of the core. This conglomerate is cobble-sized with rounded clasts but no mudclasts are indentified within.

Paleocurrent Directions

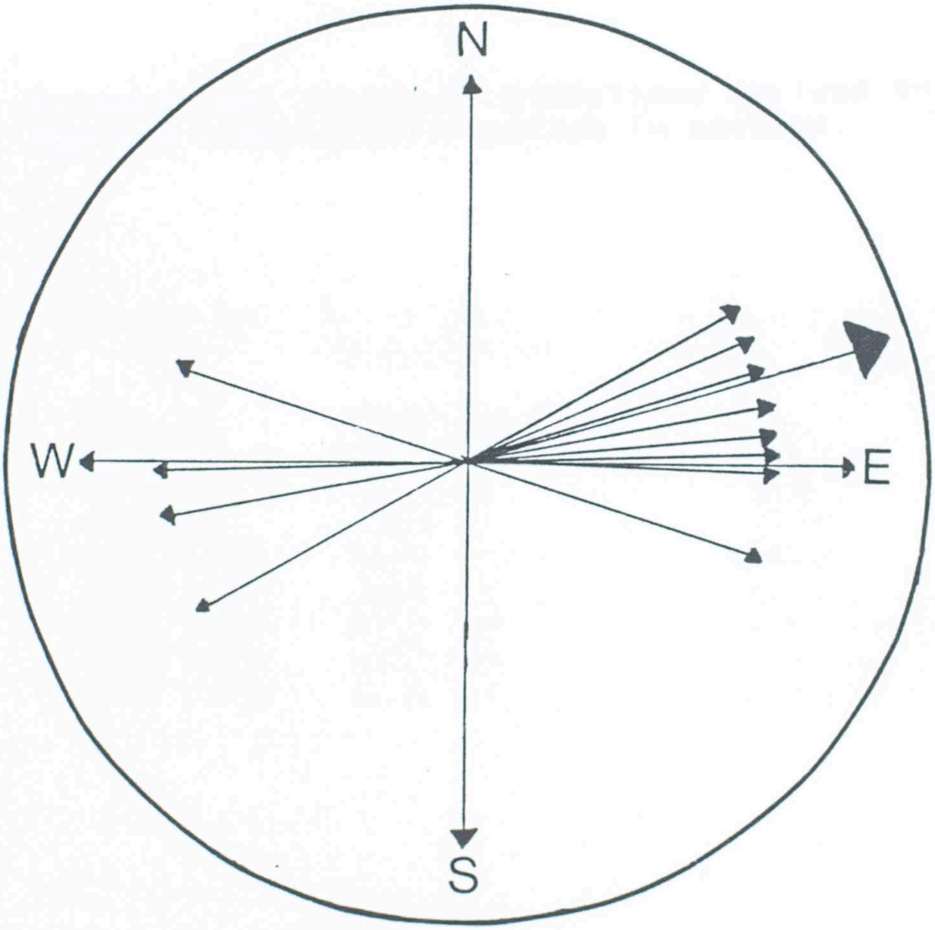
Paleocurrent direction was reconstructed from the orientation of cross-stratification on sandstone beds throughout the Windsor. Due to post-depositional deformation, it was necessary to rotate the beds back to original horizontality by the use of steronet projections (Table I). On a few of the beds, the exact direction of transport could not be determined since only a cross-sectional view was exposed. In these cases, two different directions, 180° apart, were recorded. An average paleocurrent direction of N75°E was obtained (Fig. 21). Although these paleocurrent directions are not many, their relative variation is small and it is felt that the measurements do give a general idea of the dominant paleocurrent direction. Supportingly, Grippi and Burke (1978) obtained an inferred paleocurrent direction to the Northwest in the Cretaceous Hanover Inlier to the west.

SYNTHESIS: PALEOENVIRONMENTAL RECONSTRUCTION

In this section the preceding field observations will be summarized and interpreted using a depositional systems approach.

The conglomerate beds did not display any discernible internal structures, except normal grading probably due to the coarseness of the deposit. These conglomerate beds, however, definitely have a limited lateral extent and truncated beds with a scoured surface, possibly

Figure 21. Rose diagram with paleocurrent direction measures from the Windsor Formation. Note the dominant palecurrent direction to the Northeast.



N
W
E
S

Table I. Paleocurrent transport directions derived from festoon cross-stratification in outcrop.

Location	Strike and Dip	Orientation of Cross-beds	Transport Direction (after rotation)
1a	N4°E 34°E	N26°E 11°	N66°E
1b	N4°E 34°E	N72°E 6°	N84°E
2	N24°E 18°E	N81°E 15°	N60°E
4	N9°E 18°E	N88°W 8°	N72°E
10	N50°E 15°SE	N40°W 15°	S88°E
12	N40°E 24°SE	N68°W 13°	N72°W or S72°E
20	N34°W 46°SW	N28°E 33°	N88°E or S88°W
21a	N35°W 34°SW	N45°W 10°	N62°E or S62°W
21b	N35°W 34°SW	N73°E 15°	N79°E or S79°W

indicative of a channel facies. The energy of the current that deposited these sediments must have been relatively high because of the conglomerate beds's coarse nature.

The alternating sandstone and shale sequence contains sandstones with a distinct channel geometry. The sandstones are well-sorted, cut into the shales with sharp boundaries, and tend to fine upwards. The shales in between the sands are thinly bedded, very dark, with no visible internal structures except for their thin beds.

The lateral geometries of the observed sand bodies indicate deposition in a series of channels. The areal extent of the conglomerate channels is greater than 10m. The interbedded sandstone and shales are of limited extent (2 to 3m).

Esker's foraminiferal study (1969) of the St. Ann's area establishes the Windsor as marine during the Cretaceous. The study, however, used planktonic forams and does not provide any information about water depth. Nonetheless, with the preceding observation, we may attempt a depositional systems interpretation.

The clastic sequences described above have many features that may be either a submarine fan or delta deposit. To some degree, both may have similar sedimentary structures, fossils, and associated facies. In order to make the proper distinction, it is necessary to closely examine the associated facies and their characteristics.

The method of sediment transport differs between a submarine fan and a delta. A submarine fan may be deposited by gravity flow mechanisms (Reineck and Singh, 1980). These mechanisms are turbidity currents, fluidized flow, grain flow, and debris flow. Deltas do not commonly transport sediment in this way. In the Windsor, the pebbles that begin to appear in the shale underlying the first conglomerate unit may mark the beginning of a gravity flow deposit. These cobble-sized clasts are petrographically similar to the clasts in the conglomerate bed stratigraphically higher and are probably derived from the same source.

An important associated facies of submarine fan deposition are levee deposits. The type of deposition expected is a combination of thin beds of fine sandstones, siltstones, and shales. A delta levee should display rootlets, tracks, and no primary sedimentary structures because of root mottling (Fisher and Brown, 1972).

The vast majority of fauna associated with the Windsor are marine planktonic foraminifera (predominately globogernid). In minor percentages (less than 3%) inoceramus, bivalves, echinoids, and crinoids are present, but not in definite living position, suggesting post-mortem transport.

Five main associated facies indicative of deep-water clastic submarine fans have been recognized by Walker

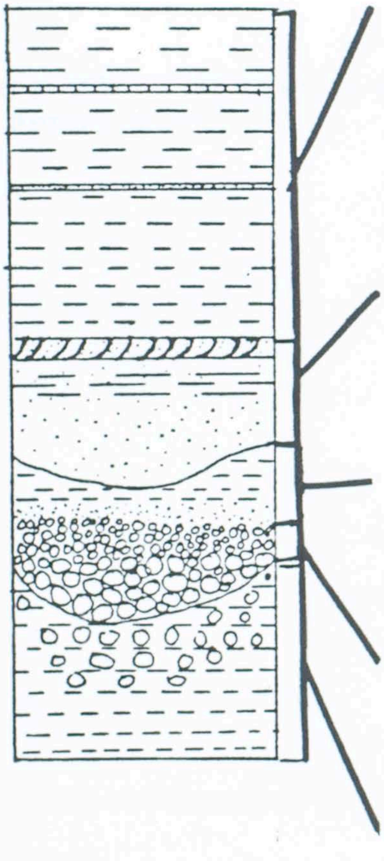
(1978): turbidites, massive sandstones, pebbly sandstones, conglomerates, and debris flows. The Windsor sediments contain at least part of each of these facies.

The Windsor formation is characterized by cycles of cobble-sized conglomerates, fining upwards to sandstones and shales (Fig. 22). At the base of the cobble-sized conglomerates are matrix-supported clasts interpreted as a drbris flow. Overlying the debris flow the conglomerate becomes grain supported with a channel geometry. These conglomerates are graded and have a scoured base. Within the conglomerate beds are a few thin sandstone or siltstone beds which fine upwards to shale. The debris flow and channeled conglomerates are interpreted as feeder channel deposits from the upper fan (Fig. 23). The fine-grained sandstones and siltstones overlain by shales are interpreted as levee deposits on the sides of the upper fan channel.

The cobble-sized conglomerates fine upwards to a pebble conglomerate (Walker's pebbly sandstone and then to a massive sandstone. Less commonly, an overlying sequence of sandstones with cross-stratification and planar laminations (ABC Bouma sequence) are present. These beds are interpreted to represent upper to midfan abandoned channels.

Capping the entire sequence is a very thick shale unit with occasional thin beds of fine-grained sandstone, siltstone, or carbonate. The carbonate rocks of the Windsor are not of a reefal or mound nature. The rocks are

Figure 22. Diagramatic vertical sequence through one major Windsor submarine fan cycle. See Appendix I and II for a complete description.



Distal facies with occasional thin, fine-grained sandstone, siltstone, or micritic limestone beds (Bouma D and E).

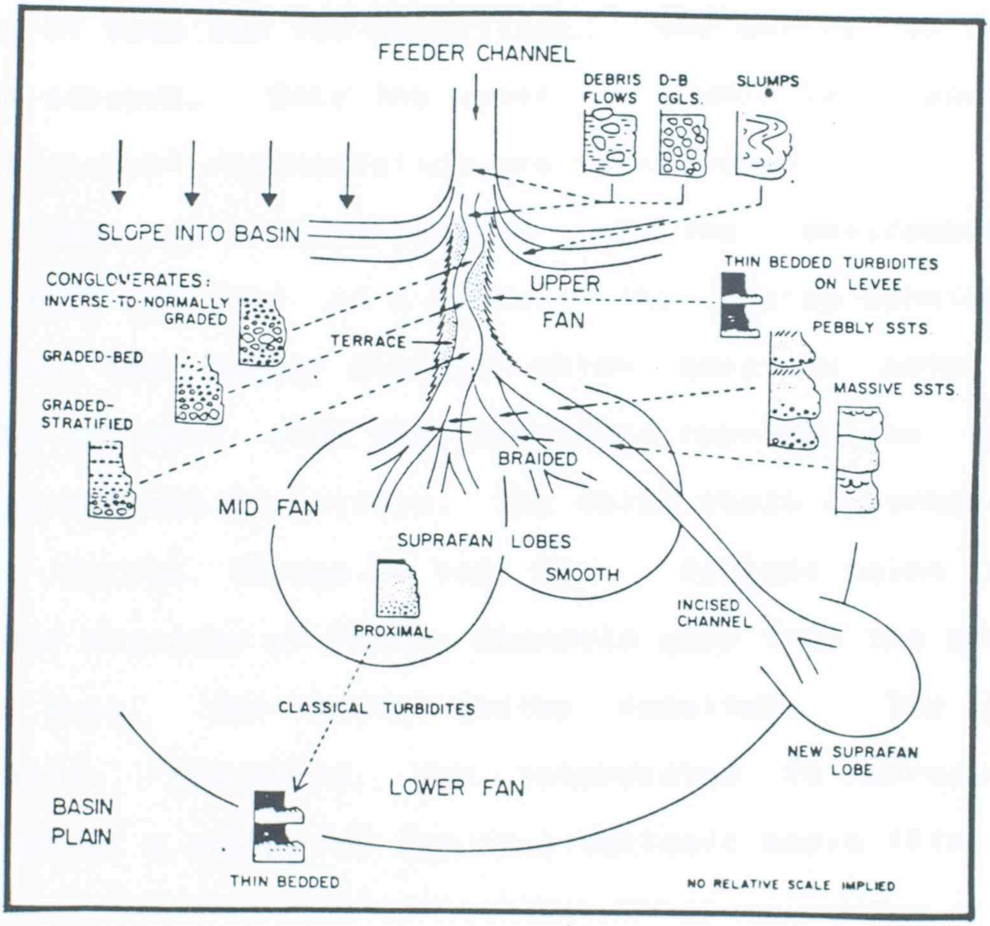
Middle to upper fan channels. Lower sandstone are massive with channel geometry. Overlying sandstones have planar laminations and festoon cross-stratification (A,B,C of Bouma sequence).

Levee deposits of fine-grained sandstones and siltstone fining to shale.

Upper fan channel deposits with scoured bottom surfaces, channel geometry, and grading.

Debris flow deposits with clay matrix-supported rounded clasts and slumping.

Figure 23. Walker's depositional model (1978) of submarine fan deposition.

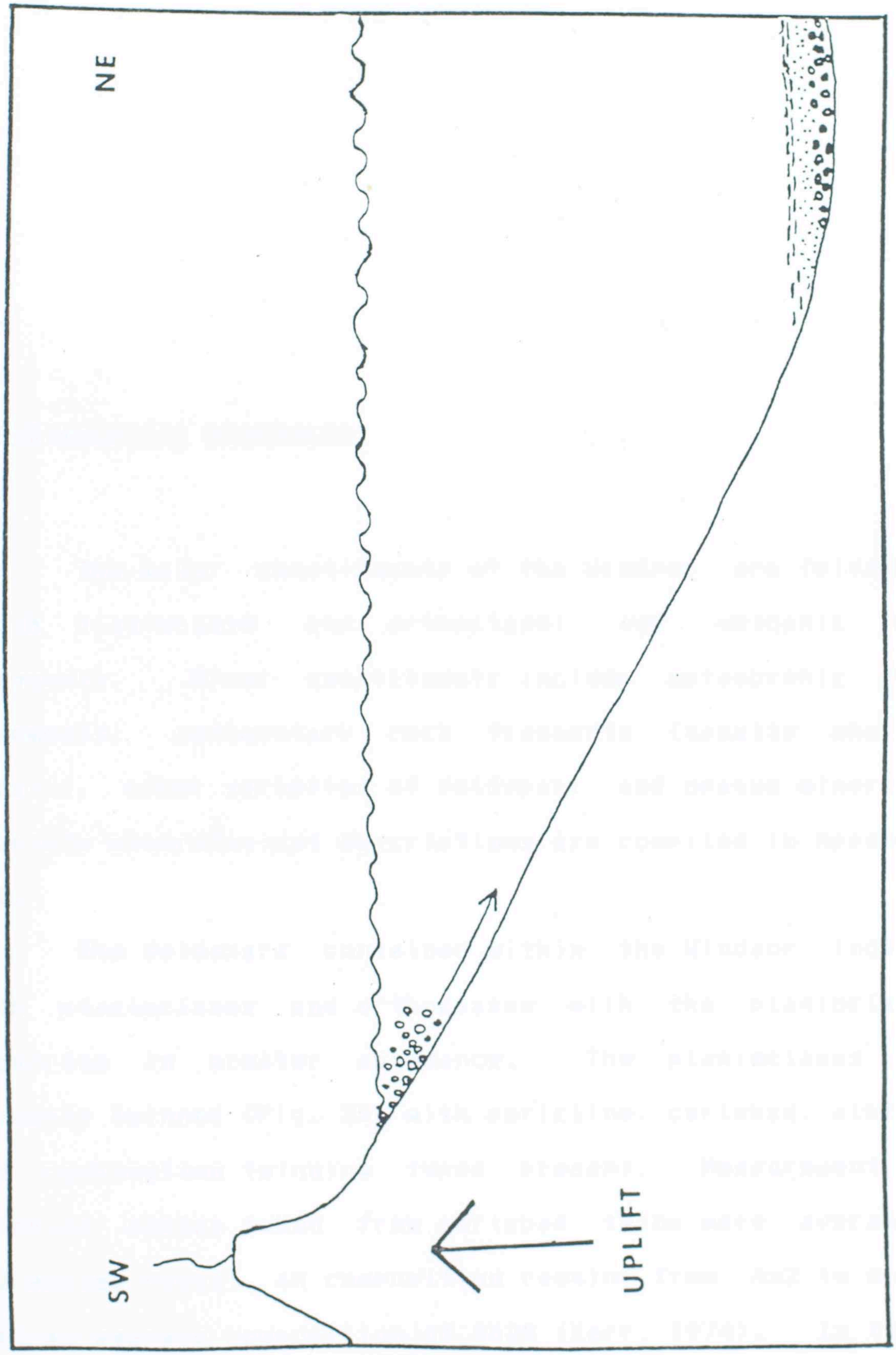

FEEDER CHANNEL
DEBRIS FLOWS
D-B CGLS.
SLUMPS
SLOPE INTO BASIN
CONGLOMERATES:
INVERSE-TO-NORMALLY GRADED
GRADED-BED
GRADED-STRATIFIED
TERRACE
UPPER FAN
THIN BEDDED TURBIDITES ON LEVEE
PEBBLY SSTS.
MASSIVE SSTS.
BRAIDED
MID FAN
SUPRAFAN LOBES
SMOOTH
PROXIMAL
INCISED CHANNEL
CLASSICAL TURBIDITES
NEW SUPRAFAN LOBE
LOWER FAN
BASIN PLAIN
THIN BEDDED
NO RELATIVE SCALE IMPLIED

micritic, rhythmically bedded, and commonly have up to 25% terrigeneous rock fragments. The predominant fossils are foraminifera. The carbonates' location in the thick shale sequences may be indicative of deep basinal conditions.

In summary the Windsor sediments represent several cycles of deep sea fan deposition. The entire fan sequence is not exposed. Only the upper to middle fan channels and distal channel sedimentation are represented.

The paleogeomorphology of the environment of deposition was that of a slope. The coarse conglomerates represent the feeder channels which were the point source for the sediment with the sandstones representing upper to mid fan channel deposition. The thick shale sequence is the distal facies (Bouma D and E). Perhaps owing to the episodic avulsion of feeder channels away from the preserved study area, the distal facies resulted. The Windsor sediments, therefore, are interpreted to represent the avulsion of a submarine fan in a tectonic basin (Fig. 24).

Figure 24. Model for Windsor deposition. Jamaica is represented by the volcanics to the southwest.


NE
SW
UPLIFT

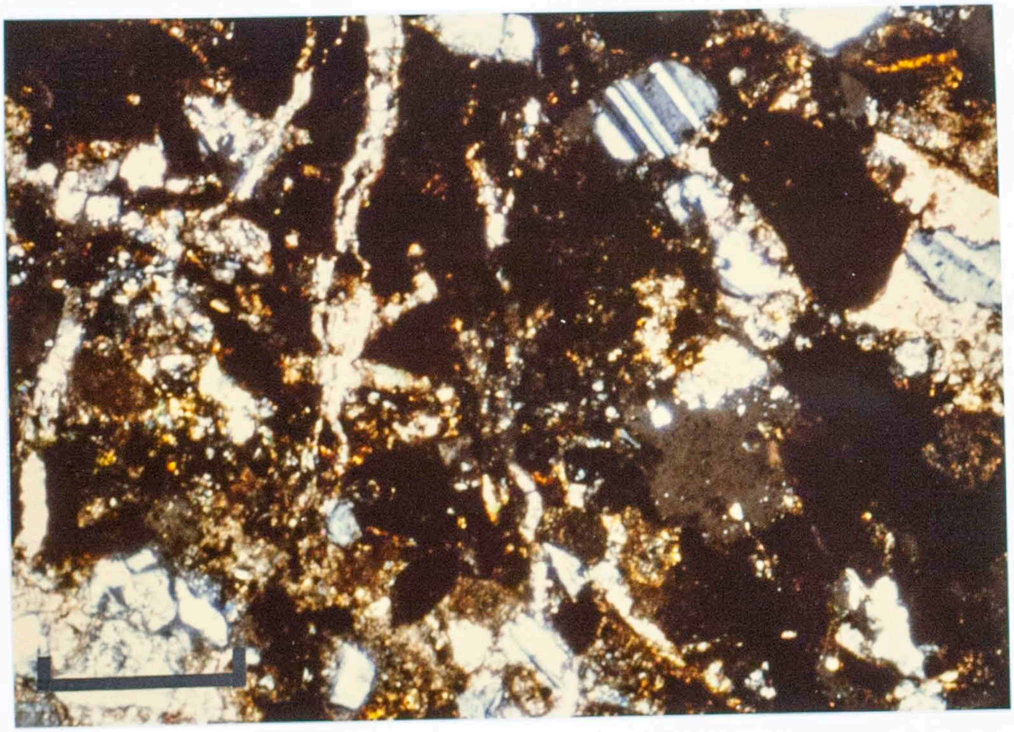
SEDIMENTARY PETROLOGY

PRE-DIAGENETIC MINERALOGY

The major constituents of the Windsor are feldspars (both plagioclase and orthoclase) and volcanic rock fragments. Minor constituents include metamorphic rock fragments, sedimentary rock fragments (usually chert), fossils, other varieties of feldspar, and opaque minerals. Complete mineralogical descriptions are compiled in Appendix III.

The feldspars contained within the Windsor include both plagioclases and orthoclases with the plagioclases occurring in greater abundance. The plagioclases are commonly twinned (Fig. 25) with pericline, carlsbad, albite, and combination twinning types present. Measurement of twinning angles taken from carlsbad twins were averaged. The angles reveal an composition ranging from An2 to An34, with an average composition of An20 (Kerr, 1974). In thin

Figure 25. Combined carlsbad-albite twins in plagioclase (crossed nicols). Bar represents 0.5mm at 40X magnification.



section the orthoclases resemble quartz but were easily distinguishable by the sericite alteration on the grains and the biaxial optic axis figure.

The volcanic rock fragments, or VRFs, have a variable mineralogy of phenocrysts, but are consistently prophyritic in texture. Minerals present as phenocrysts are plagioclase, clinopyroxene, orthopyroxene, olivine, and amphibole. Plagioclase occurs most frequently as a phenocryst, with many VRFs containing only plagioclase phenocrysts. The mafic minerals listed above may also occur as phenocrysts with plagioclase (Fig. 26). These mafic minerals never occur as more than 50% of the phenocrysts and are usually less than 10%. These mafic minerals are commonly altered to biotite or chlorite (Fig. 26) but in some cases the original mineral may be preserved.

The metamorphic rock fragments, or MRFs, are limited primarily to serpentine. Serpentine is defined as altered mafic minerals, especially olivine. The serpentine may occur as either of two varieties, antigorite or chysolite (Kerr, 1974). Due to the similarity between the two varieties, no distinction was made between them. The serpentine is commonly altered to chlorite (Fig. 27) and forms less than 5% of most thin sections. Other metamorphic rock fragments are altered-to biotite-or-chlorite pyroxenes and amphiboles, when these mineral do not occur as phenocrysts of volcanic rock fragments (mentioned above).

Figure 26. Plagioclase and altered mafic mineral phenocrysts in a volcanic rock fragment (crossed necols). Bar represents 0.5mm at 40X magnification.

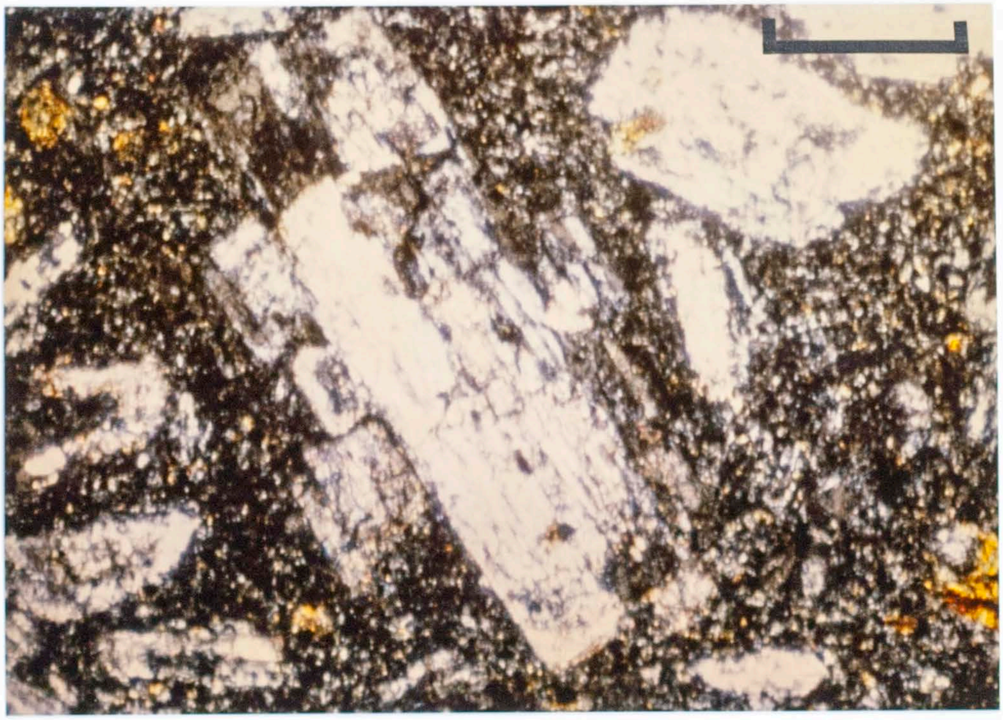
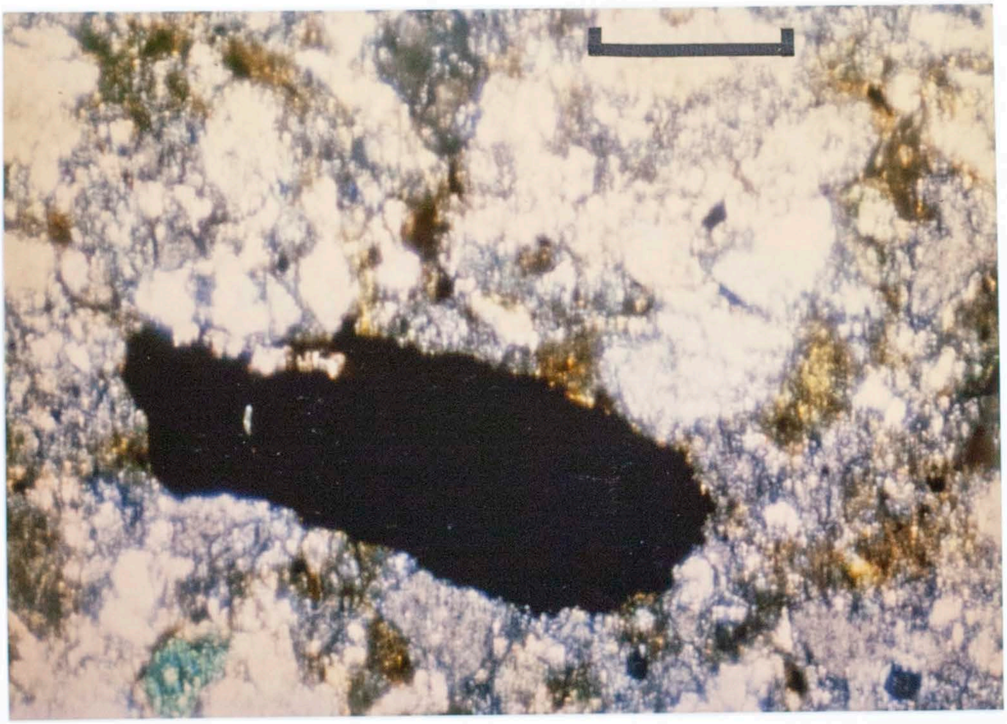


Figure 27. Serpentine rock fragments in a litharenite. The serpentine is commonly seen as the chlorite-altered green fragments. Note the large opaque pore fill (uncrossed nicols). Bar represents 0.5mm at 40X magnification.



Sedimentary rock fragments include both chert and mudclasts. Chert is quite abundant throughout the Windsor and usually occurs as 1 to 2% of samples (Fig. 28). Mudclasts are identified in only two samples. These clasts were probably lithified before deposition because of their minor deformation.

Quartz occurs as a relatively minor constituent in the Windsor Formation. It averages only 1 to 2% per thin section, and many sections do not contain any quartz. The quartz occurs as detrital grains and shows undulose extinction in some crystals (Fig. 29).

Fossils are present in both clastic and carbonate beds in the Windsor. Foraminifera (mainly globergernid) are the most common fossil in the carbonate rocks and may be infilled by opaque material (Fig. 30). Esker used these forams in his age study of the Windsor.

Fossils occur less often in the clastic rocks and are present in only eighteen samples. Fauna includes bryozoans, echinoderms, crinoids (Fig. 31), inoceramus (Fig. 29), and forams.

Opaques occur as two different forms in the Windsor: pore fill (Fig. 31) and parallel laminations (Fig. 32). The pore fill opaques are typically low percentages (1 to 5% of the sample). The linear opaques appear as wavy lines, possibly marking bedding planes. The linear opaques make up a higher percentage of the samples in which they occur (15

Figure 28. Chert rock fragment with opaque mineral as pore fill. Note the inoceramus fossil in the upper portion of the picture (crossed nicols). Bar represents 0.5mm at 40X magnification.

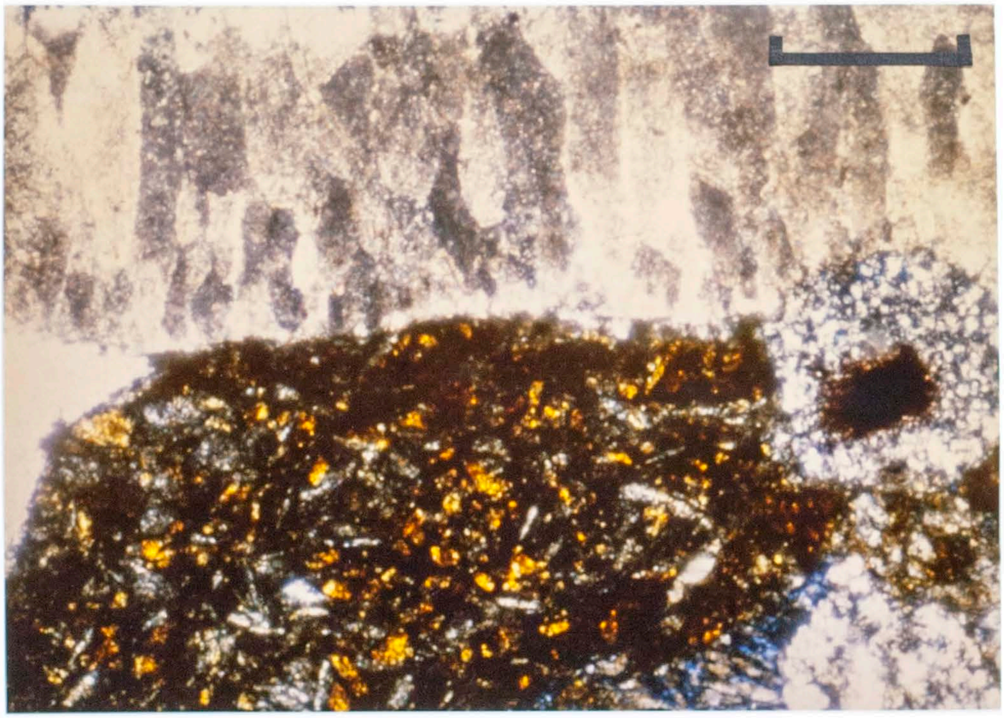


Figure 29. Undulose extinction in quartz grains (crossed nicols). Bar represents 0.5mm at 40X magnification.

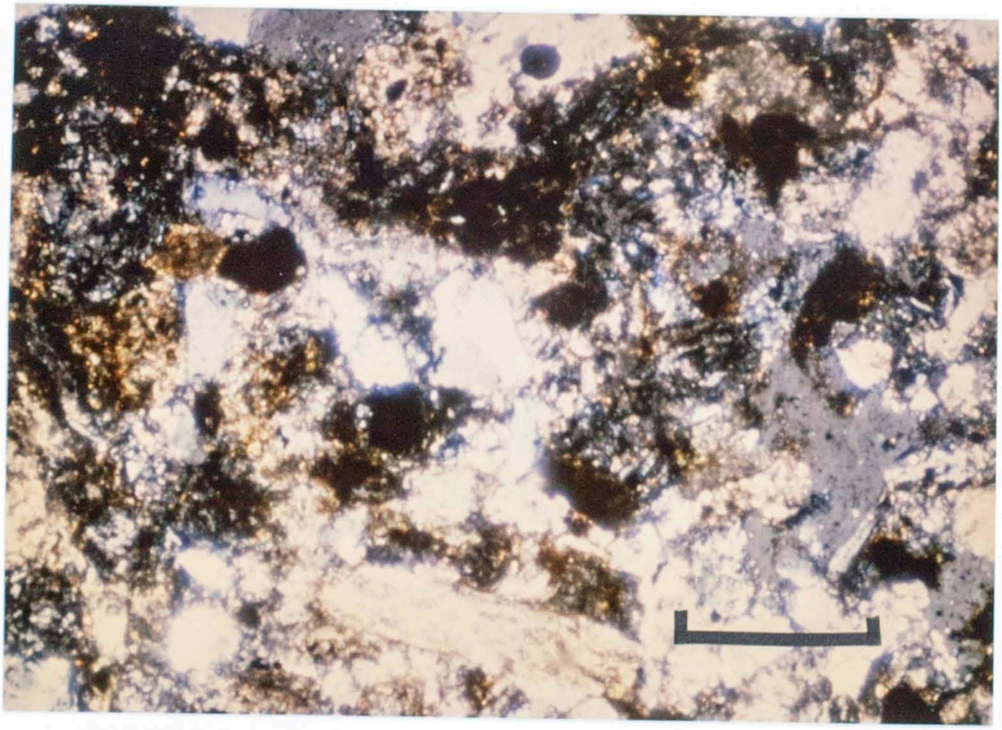


Figure 30. Globogerinid forams with opaque pore fill in a micritic cement. Note the large percentage of feldspar in this biomicrite (crossed nicols). Bar represents 0.5mm at 40X magnification.

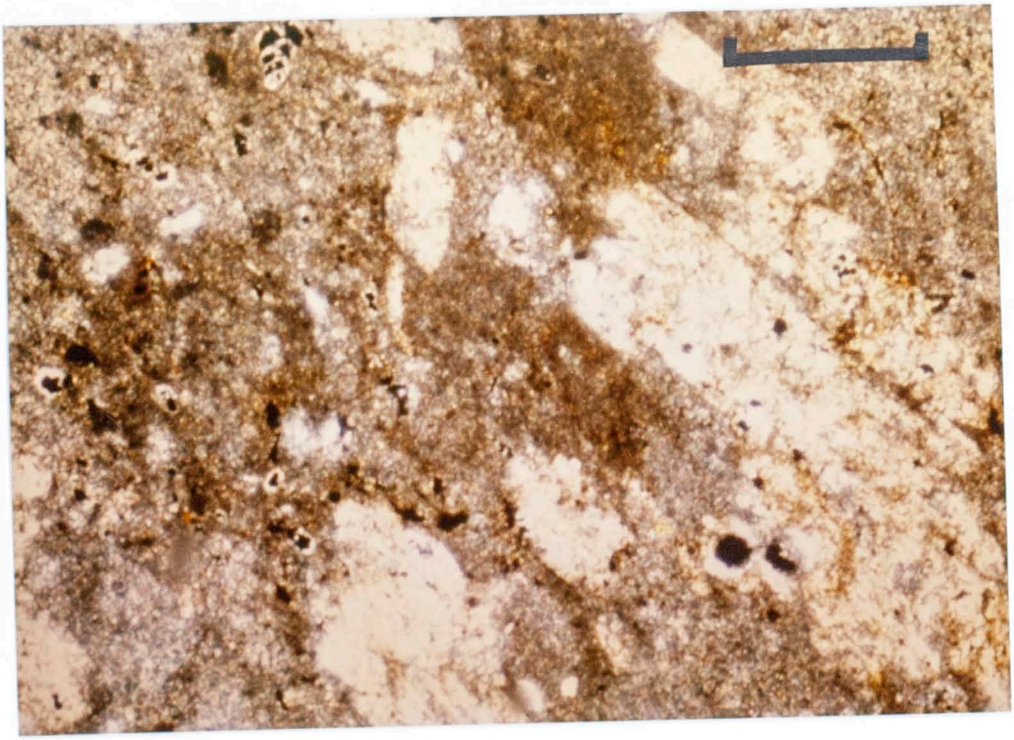


Figure 31. Bryozoan (upper left) and crinoid (lower left) fossils in the Windsor Formation (crossed nicols). Bar represents 0.5mm at 40X magnification.

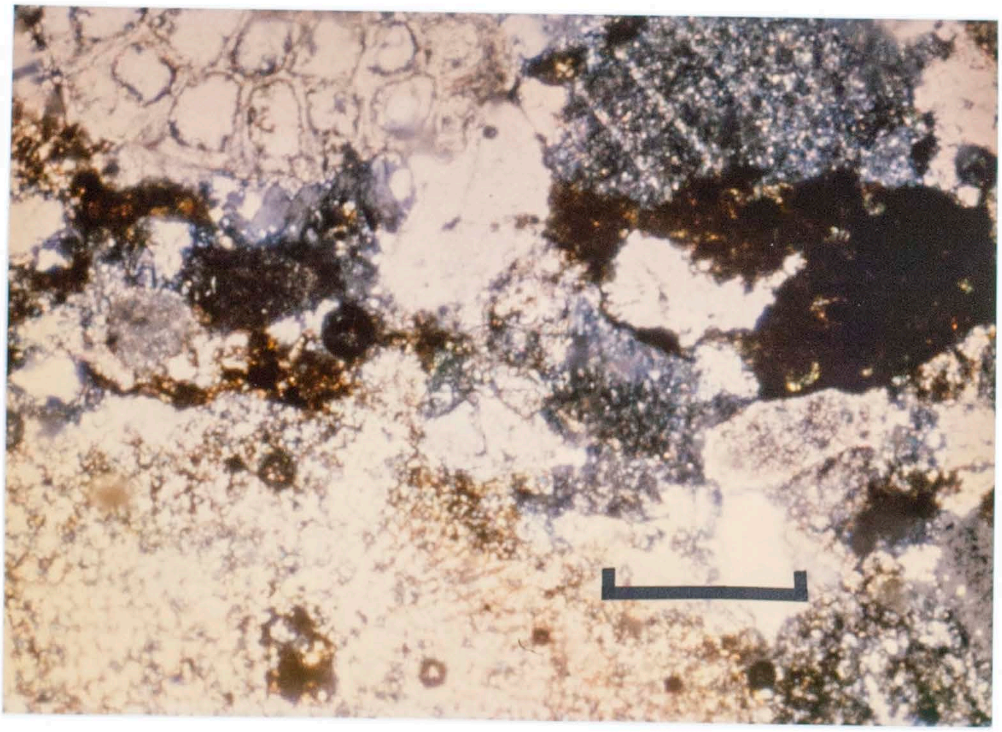
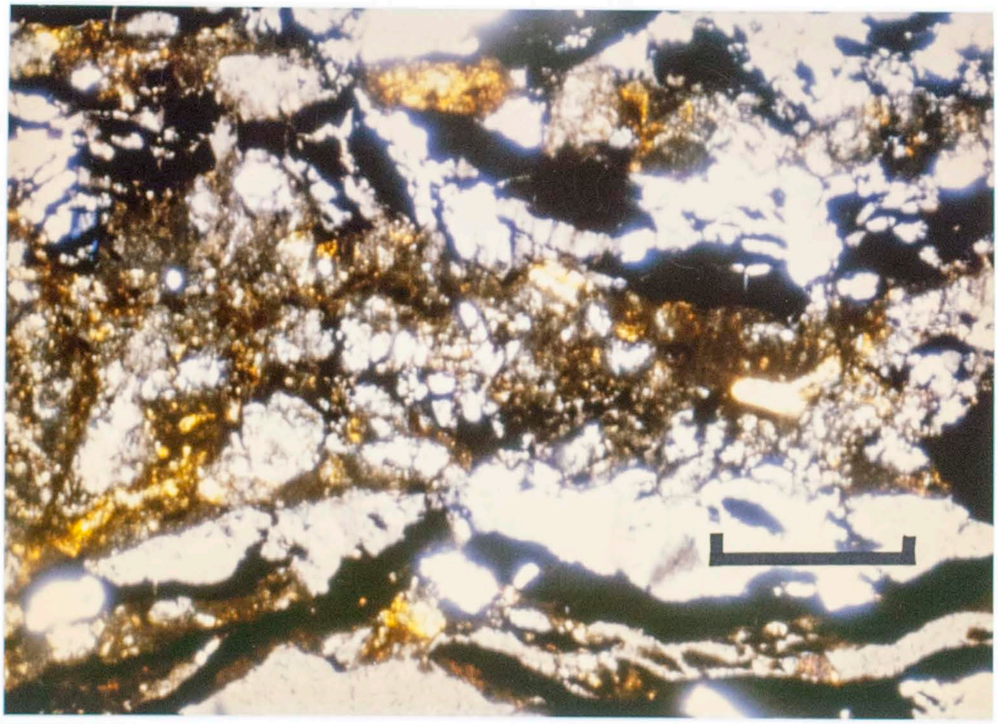


Figure 32. Parallel alignment of opaques along paleobedding planes (uncrossed nicols). Bar represents 0.5mm at 40X magnification.



to 27%), but are not as common as pore fill opaques. Use of reflected light identifies this opaque material as pyrite from its yellow-gold tint.

Diagenetic Products

Feldspar, because of its relative instability in these tropical formation waters, was the most altered mineral with the alteration taking the form of sericite, calcite, and bauxite. Sericite commonly occurs in small flakes as an alteration of silicates, usually feldspars (Kerr, 1977). The sericite is found on almost all of the feldspar grains of the Windsor.

The alteration of feldspar to calcite also occurs in the Windsor rocks. Because of the calcium-richness of the feldspars, they appear zoned with the more calcium-rich layers being altered to calcite and the more sodium-rich layers remaining as feldspar (Fig. 36).

Another alteration product of feldspar which forms in the Windsor rocks is bauxite. Two observed varieties occur, gibbsite (Fig. 33) and calichite (Fig. 34), with gibbsite being far more common. Calichite is observed only two samples of the Windsor. Bauxite is a weathering by product derived from the chemical breakdown of aluminosilicate

Figure 33. Complete gibbsite alteration of a volcanic rock fragment (crossed nicols). Bar represents 0.5mm at 40X magnification.

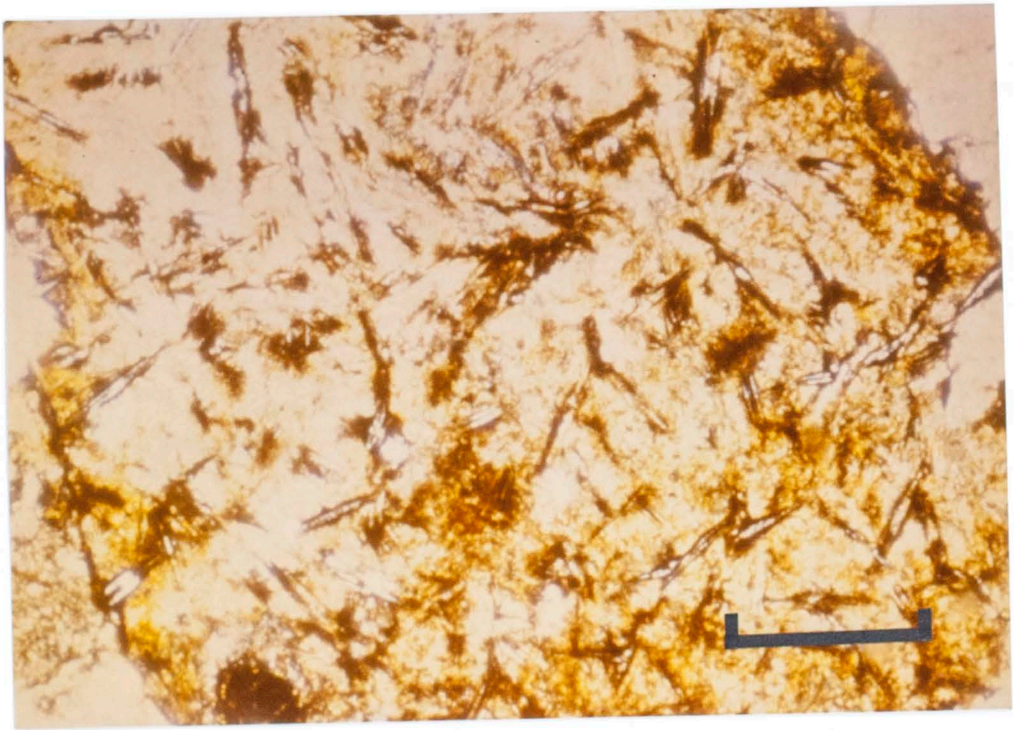
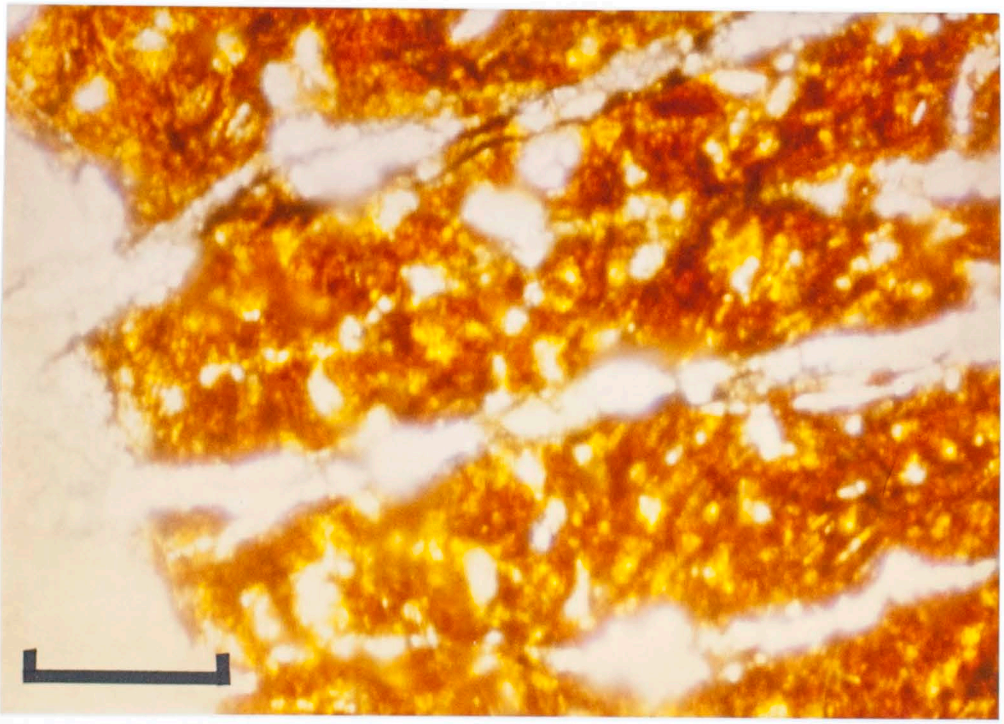


Figure 34. Calichite alteration on a volcanic rock fragment (uncrossed nicols). Bar represents 0.5mm at 40X magnification.



minerals (Kerr, 1977). The bauxite alteration occurs most frequently by weathering in warm, humid regions where the necessary organic acids can be easily derived from the decay of the dead jungle vegetation. However, most of the bauxite found in Jamaica is found in carbonate rocks and not the clastic deposits (Comer, 1974) such as the Windsor.

Cementation

It has been recognized by Galloway (1974), in a study of sandstones from a northeastern Pacific tectonic basin, cements may be related to the depth of burial of the sediments. This qualitative application will be attempted here with the Windsor sediments. However, this application must be used with caution since the geothermal gradients may differ between areas resulting in a variation of temperatures with depth. The Windsor's geothermal gradient does lie within the range of geothermal gradients in Galloway's study area. Also the original mineralogy may differ. The Windsor rocks contain calcite, albite, and clay matrix as the "cements". The depths at which these cements occur will be correlated with the rocks. Galloway established the following sequence for cement type with increasing burial:

early calcite facies (locally)→to clay rim and (or) clay facies to→laumonite-phyllosilicate facies to→prehnite-pumpellyite facies to→albite epidote facies.

In his study, at very shallow depths (less than 1000ft or 300m) and early in the burial history, calcite forms as a cement. As the sediments become buried deeper, at depths ranging from 1000 to 4000 feet (300 to 1200m), the chemical alteration of unstable grains produces authigenic clays (mainly chlorite, montmorillonite, illite, and kaolinite (Galloway, 1974). Many times the overburden pressure which causes the mineralogical changes may deform the grains. When rocks are subjected to greater depths of burial (3000 to 10000ft or 900 to 3000m), the remaining pore spaces will be infilled by either zeolite or phyllosillicate. The most common zeolite is laumonite, and the most common phyllosilicate is chlorite or montmorillonite. He found the clay coat from the previous stage is preserved. The phyllosillicates take the form of either irregular masses or pore space infilling. The zeolite occurs only as pore space infilling.

Continued burial of the sediments often results in further increase in the overburden pressure and temperature which produces a type of higher grade of diagenesis. Prehnite, pumpellyite, and epidote become the "cements" of this zone.

The Windsor Formation contains both 32% calcite (Fig. 35) and 3% albite (Fig. 36) cements as indicators of shallow burial. Albite and calcite may both form from anorthite by:

$$2H^{+} + Na^{+} + CO_2 + SiO_2 + \underset{\text{anorthite}}{CaAl_2Si_2O_8} = \underset{\text{albite}}{NaAlSi_3O_8} + \underset{\text{calcite}}{CaCO_3} + Al^{+3} + H_2O$$

Although the water chemistry is not known, formation of albite should be favored over the formation of calcite whenever the water is undersaturated with respect to calcite, thereby dissolving the calcite. Possible controlling factors are the pH and PCO .

The most common type of cement present in the Windsor is clay (Fig. 37). It occurs in 65% of petrographic samples as cement. Samples with calcite or albite cement often have the beginnings of clay coating on grains. The presence of these clays is indicative of depths of burial of 1000 to 4000ft or 300 to1200m.

Another cement, chlorite phyllosilicate cement, indicates even greater depth of burial (3000 to 10000ft or 900 to 3000m). The samples observed have only the beginnings of phyllosilicate cement (Fig. 38) and retain the clay coating. This cement occurs in only 3% of the samples.

Using the above, information, the depth to which the Windsor rocks have been buried can be approximated. Because

Figure 35. Calcite-cemented sample. Note the zoned plagioclase in the center (crossed nicols). Bar represents 0.5mm at 40X magnification.

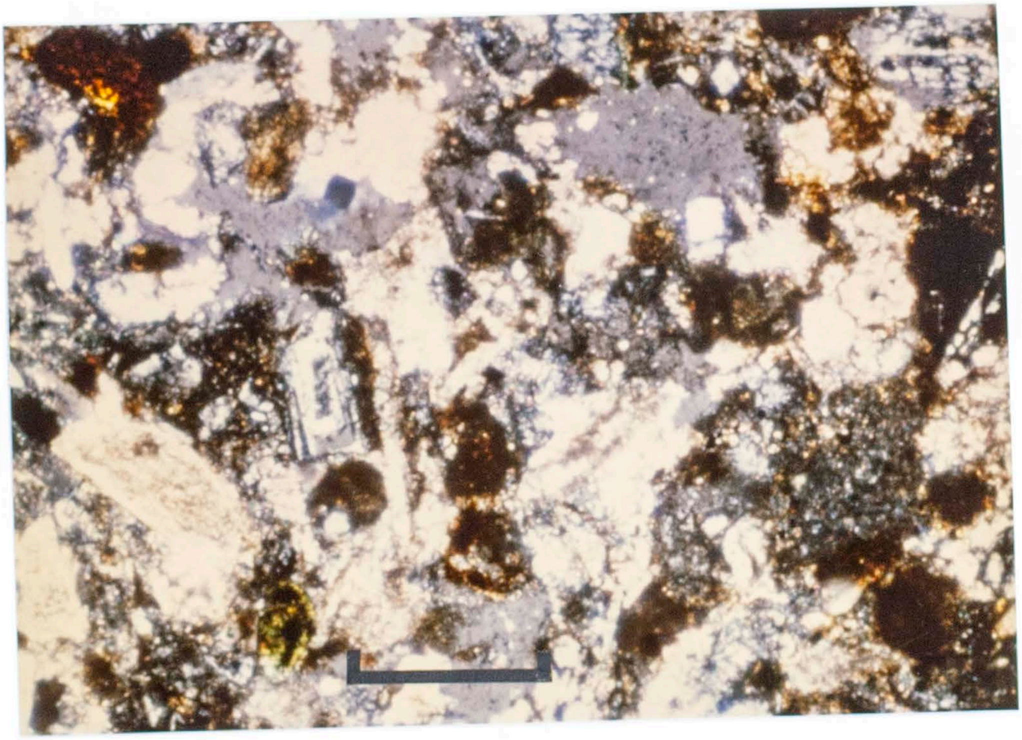


Figure 36. Albite-cemented sample. Note the pericline twinning of the plagioclase in lower left (crossed nicols). Bar represents 0.5mm at 40X magnification.

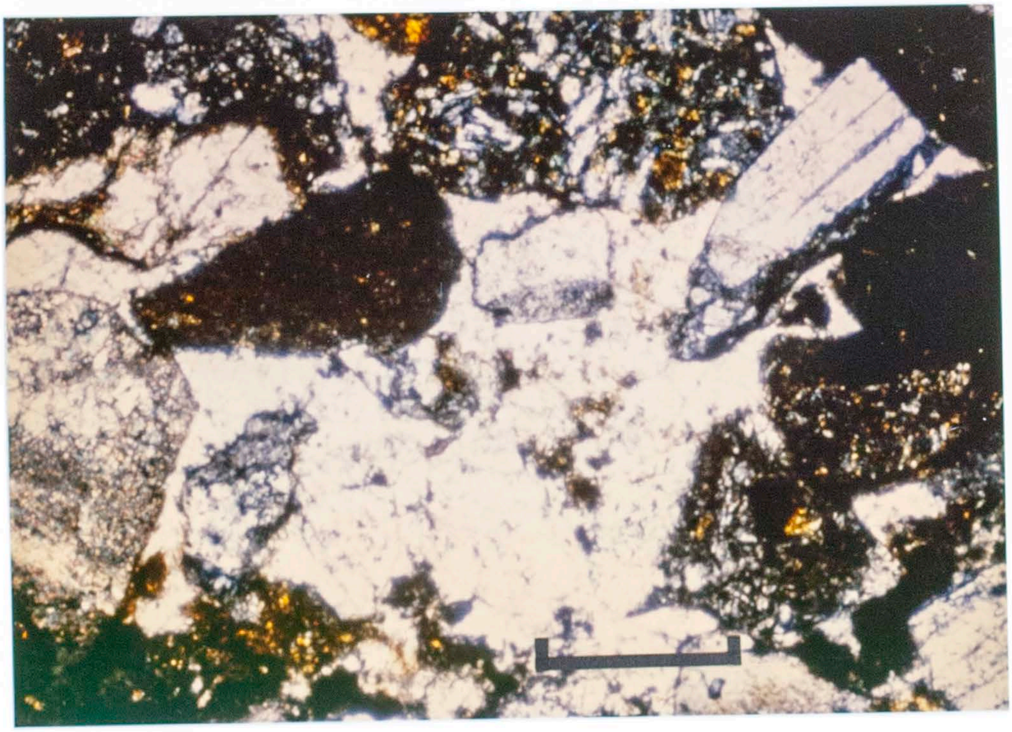


Figure 37. Clay matrix forms "cement" for this sample (crossed nicols). Bar represents 0.5mm at 40X magnification.

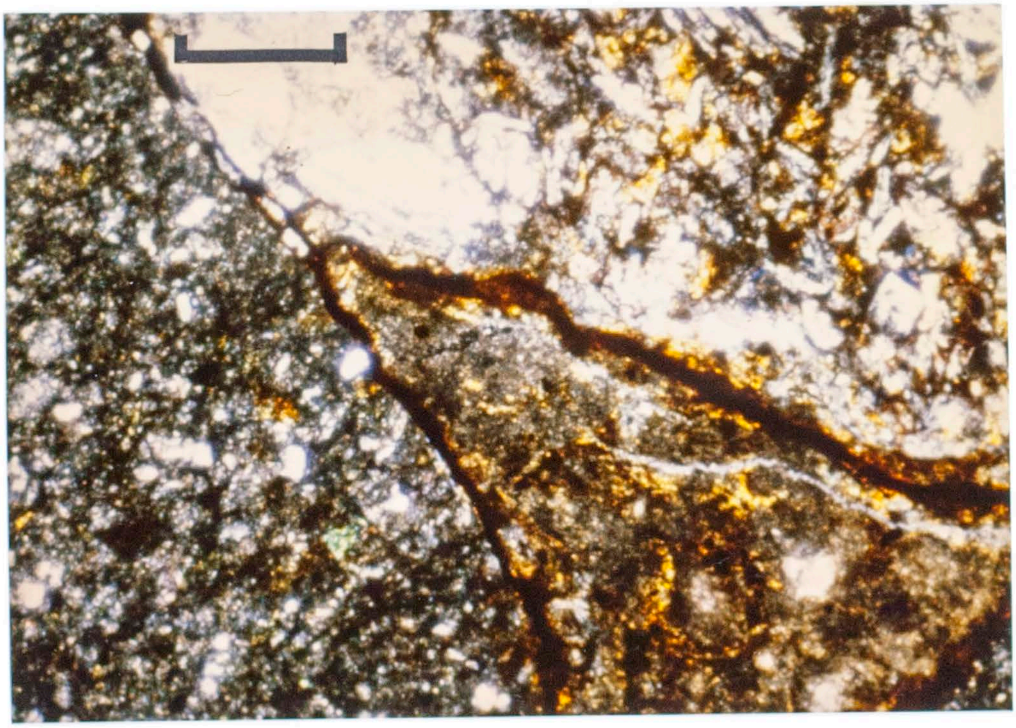
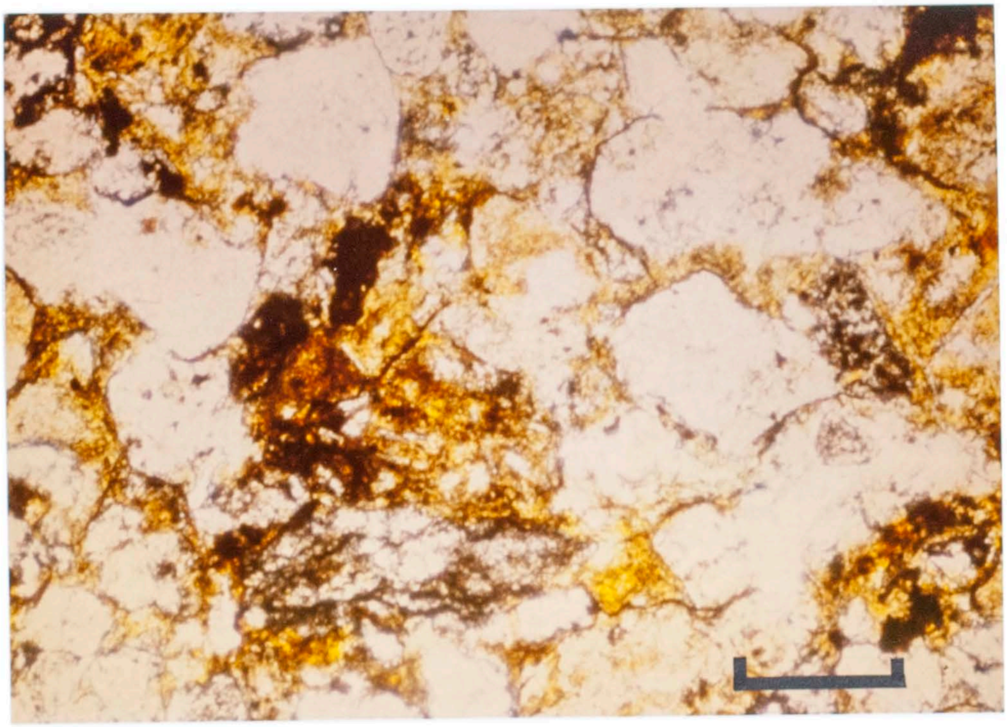


Figure 38. The beginnings of phyllosilicate cement. Note the cement forms rims around the grains (uncrossed nicols). Bar represents 0.5mm at 40X magnification.



of the presence of clays (i.e. montmorillinite, kaolinite, and illite) it can be assumed that the Windsor rocks were buried to at least 1000 to 4000 feet (300 to 1200m). The beginnings of phyllosilicate cement were found in a few thin sections indicative of burial to 3000 to 10000 feet (900m to 3000m); however because of its relative scarity (4%), it is inferred the rocks were buried to about 3000 to 4000 feet. This depth would allow sufficient pressure for the formation of phyllosillicates in some samples but would not totally transform the clays to phyllosilicates. As mentioned before, these depths are only approximate due to possible geothermal gradient variations.

Compositional Diagrams

Compositional diagrams have been utilized in sedimentologic data presentation by Dickinson (1982) and Galloway (1974) and in igneous data by Myashiro (1973). The usefulness of this method has been demonstrated previously. In the following section, several triangular diagrams will be presented and their mineralogical trends discussed. The mineralogical parameters for the triangular diagrams are catalogued in Table II.

The Quartz-Feldspar-Lithic Rock Fragment diagram from

Table II. Compositional End Members for Triangular Diagrams.

Triangular Diagram	Uppermost Pole	Lower Left Pole	Lower Right Pole
QFRF	Quartzose grains (Q)	Feldspar grains (F)	Unstable aphanitic lithic fragments (RF)
QmFRFt	Monocrystalline quartz grains (Qm)	same as above	Total aphanitic lithic fragments (RFt)
QmPO	Monocrystalline quartz grains (Qm)	Plagioclase grains (P)	Orthoclase grains (O)
SRF-VRF-MRF	Sedimentary rock fragments (SRF)	Volcanic rock fragments (VRF)	Metamorphic rock fragments (MRF)

the Windsor rocks (Fig. 39) reveals a very low quartz content (less than 5%). The rock fragments and feldspars are distributed along the bottom axes with nine samples containing only feldspar (relative to the other two constituents) and 14 samples containing only rock fragments. The compositions are gradational between feldspar and rock fragments and do not tend to cluster at either end member. Comparison with Dickinson's (1982) findings of the compositions of the Hokonui Assembledge of New Zealand, the Windsor sediments are more feldspar rich and tend to have more gradational compositions between rock fragments and feldspars. Compared with the Great Valley Sequence from California, the Windsor has considerably lower quartz values. This low quartz content is not surprising considering the great distance to the nearest continent.

Quartz (monocrystalline)-Feldspar-Lithic Rock Fragment diagram or Qm-F-L (Fig. 40) is similar to the QFL diagram. The only distinction between the two graphs is the inclusion of chert as a lithic rock fragment (sedimentary) and its exclusion as part of quartz. The diagram has a slightly lower quartz content but the other points remain clustered along the line between feldspar and lithic rock fragments. The number of rocks with only rock fragments as constituents increases from 14 to 16. Compared with Dickinson's data for the Honokui and the Great Valley Sequence, the Windsor again exhibits the same trends of more

Figure 39. Triangular diagram illustrating the relationship of quartz, feldspar, and rock fragments. Dotted lines represent findings by Dickinson (1982) of characteristic sedimentation of the Hokonui assembladge of New Zealand fore-arc sedimentation.

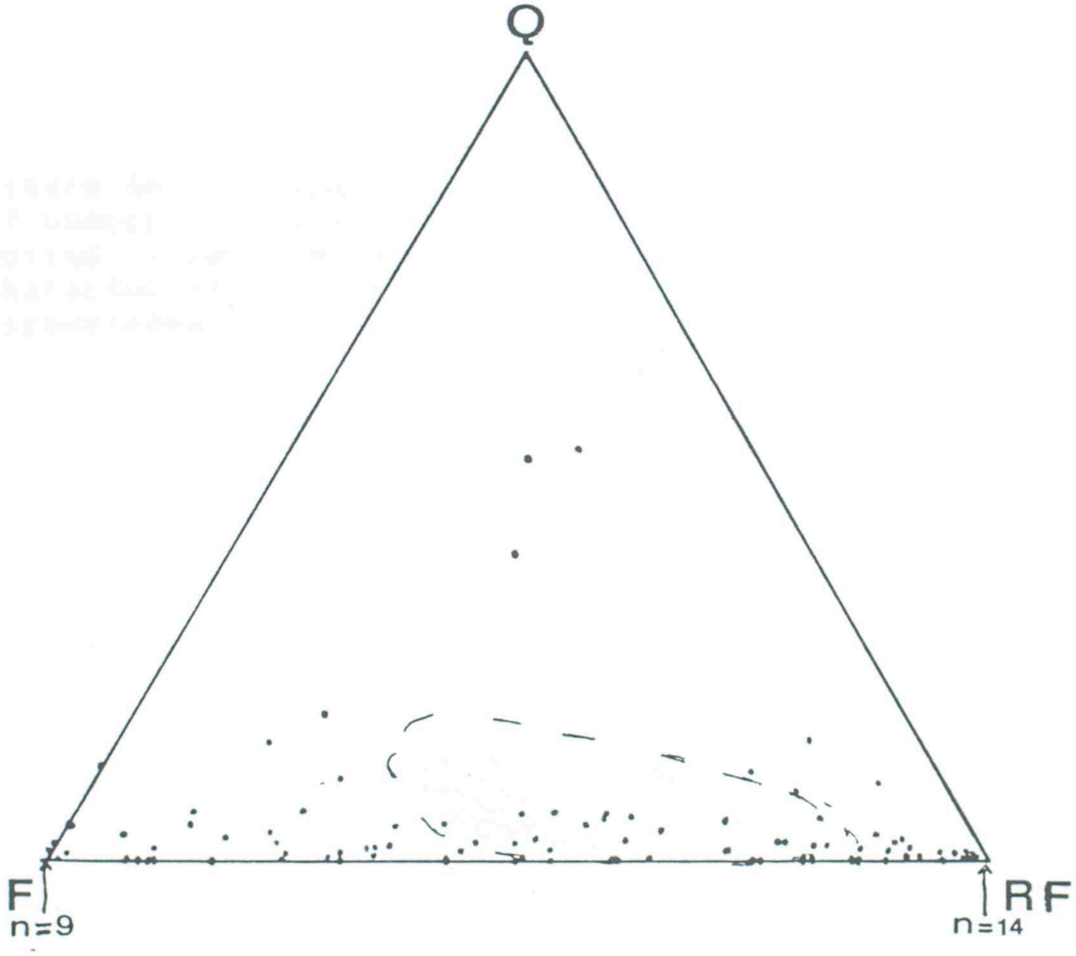
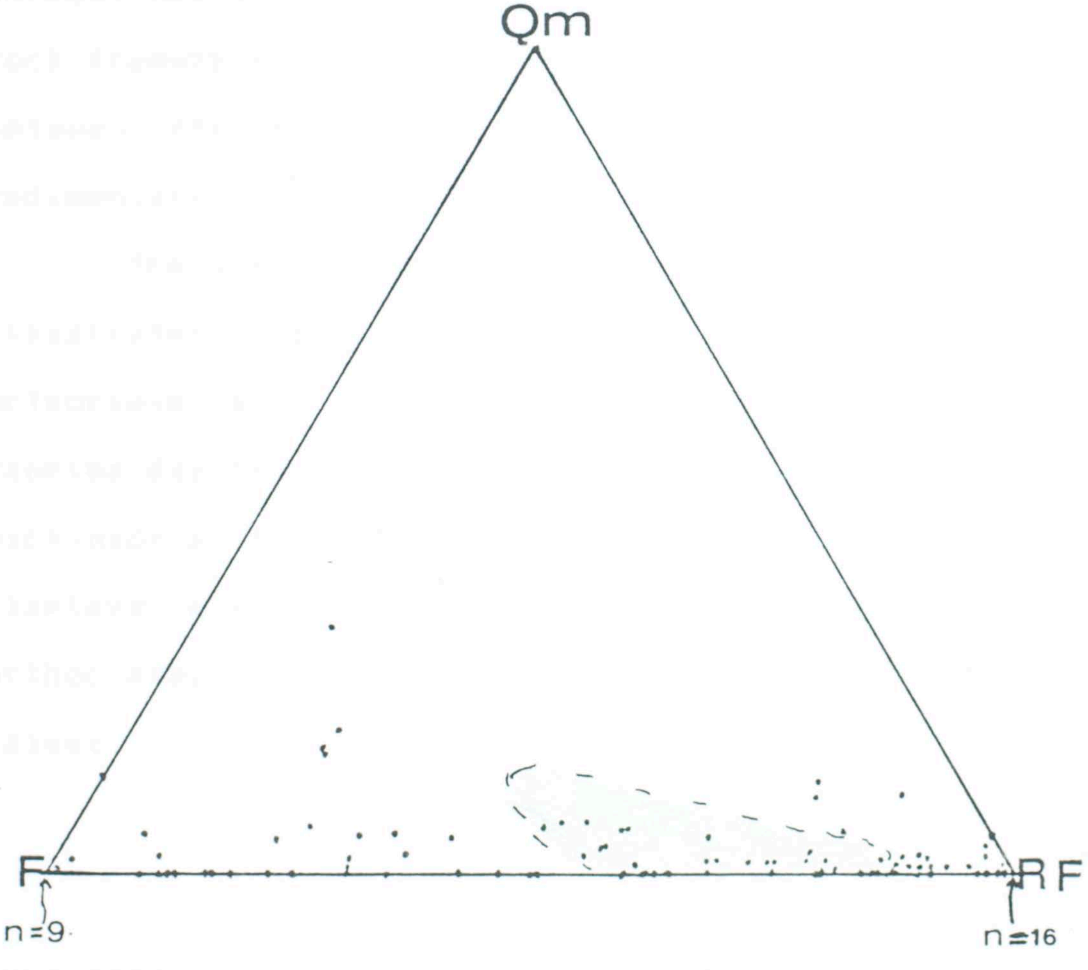

Q
F
n=9
RF
n=14

Figure 40. Triangular diagram illustrating the relationship of monocrystalline quartz, feldspar, and rock fragments. Dotted lines represent Dickinson's (1982) findings of characteristic fore-arc sedimentation of the Hokonui assemblage.


Qm
F
RF
n=9
n=16

gradation betweem rock fragments and feldspar and lower quartz contents.

Rock fragments may be subdivided into volcanic (VRF), metamorphic (MRF), or sedimentary (SRF). A triangular diagram illustrating the character of the rock fragments of the Windsor is shown in Figure 41. The rock fragments are predominately volcanic. Thirty-three samples contain only volcanic rock fragments. Metamorphic rock fragments, serpentines and altered mafic minerals, account for total rock fragments in six samples. The points tend to cluster between the volcanic and metamorphic fragments with low sedimentary rock fragments values.

The graph of Quartz-Plagioclase-Orthoclase (Fig. 42) illustrates the predominance of plagioclase over both orthoclase and quartz. The graph does not include all samples due to feldspar alteration which masks composition. Dickinson's findings (1982) for three fore-arc basins displays a similar abundance of plagioclase compared to orthoclase. However, again his data contained higher quartz values.

SYNTHESIS: PROVENANCE, CLIMATE, AND DIAGENESIS

The occurrence of such a large amount of volcanic

Figure 41. Triangular diagram illustrating the relationship of sedimentary, volcanic and metamorphic rock fragments.

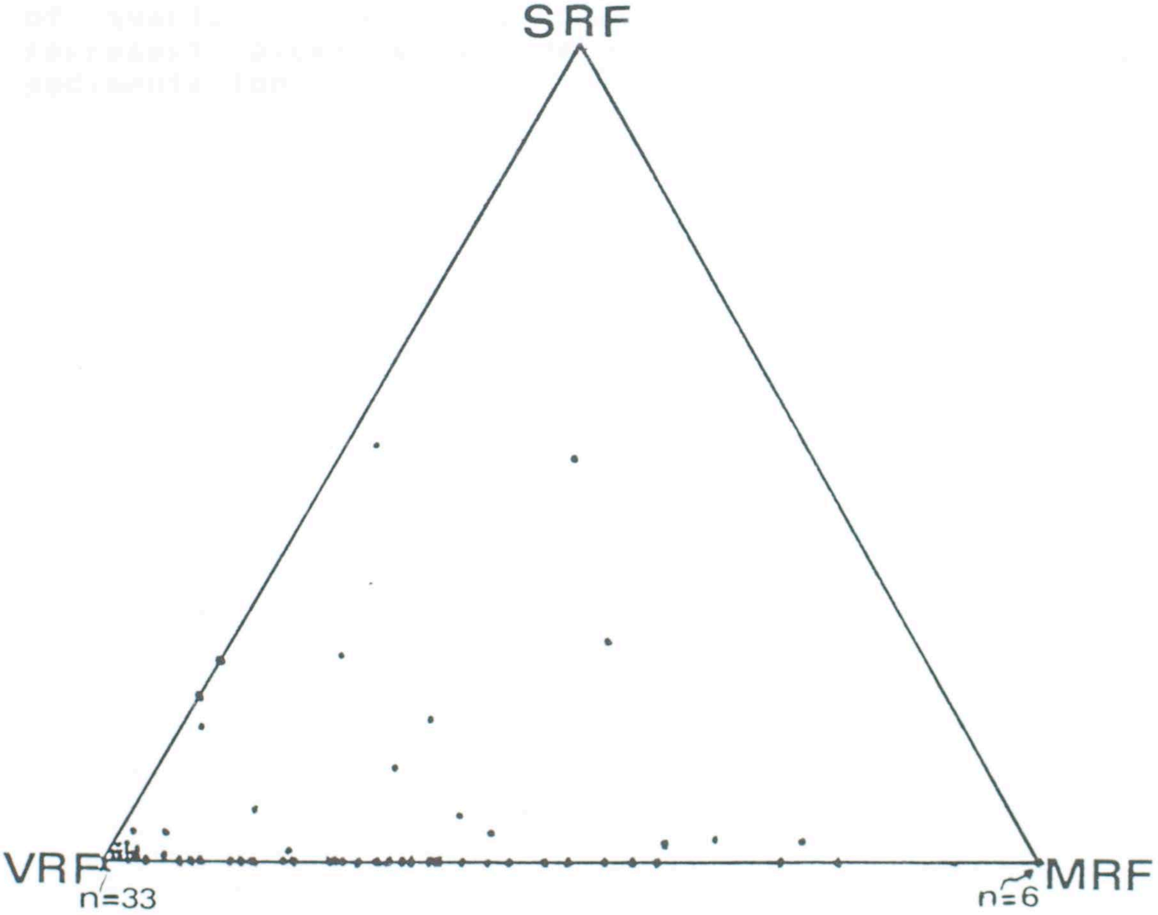
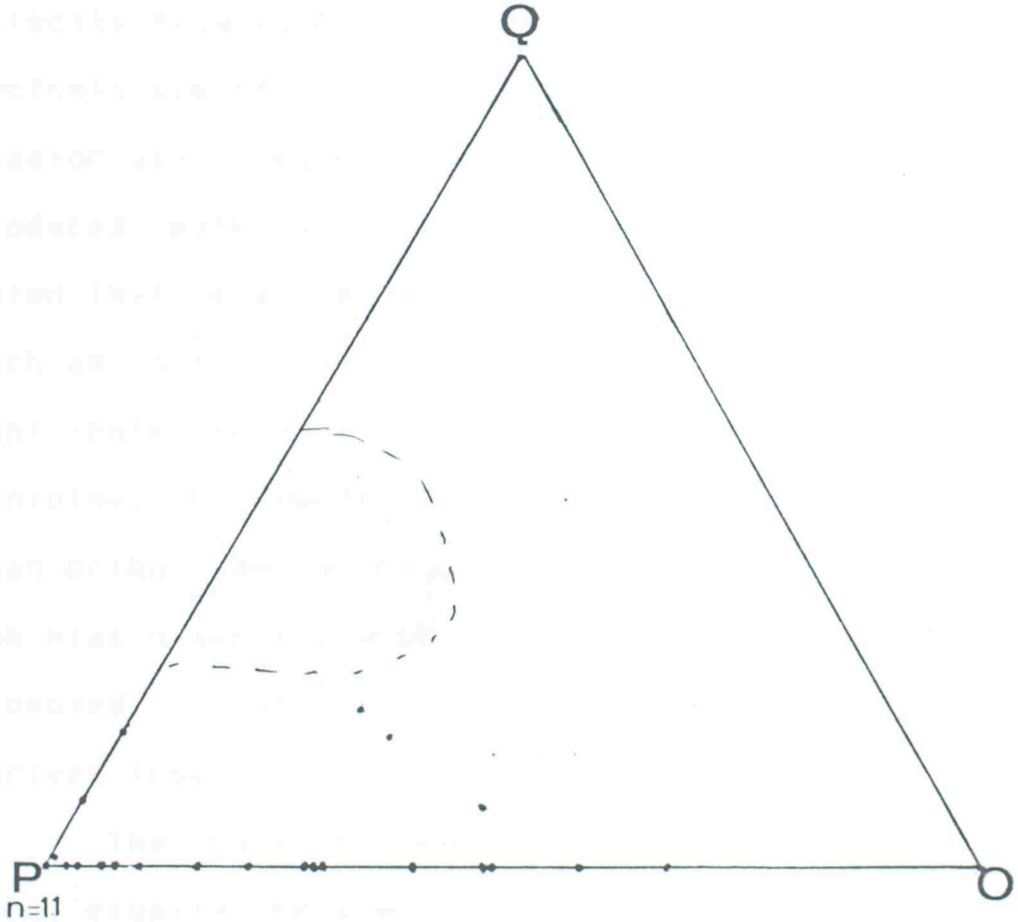

SRF
VRF
n=33
MRF
n=6

Figure 42. Triangular diagram illustrating the relationship of quartz, plagioclase, and orthoclase. Dotted lines represent Dickinson's findings of characteristic fore-arc sedimentation.


Q
P
n=11
O

rock fragments indicates derivation from a volcanic source, because most of the rocks are volcanic litharenites. Many of the volcanic rock fragments have feldspar phenocrysts and thus it can be assumed the feldspars may have been derived at least partly from the volcanic rocks.

Further evidence is observed in Figure 42 with the dominance of plagioclase over orthoclase. Rocks which contain large amounts of plagioclase indicate derivation directly from volcanic sources. Folk (1980) discussed the tectonic significance of plagioclase arkoses. He suggested plagioclase arkoses are formed when volcanic activity produces material that is rapidly deposited. Folk also noted that granites and gneisses commonly yield feldspars such as orthoclase and microcline, whereas volcanic rocks contribute feldspars that are mostly plagioclase and sanidine. Folk postulated that if there is more plagioclase than orthoclase, a volcanic source is likely, especially if the plagioclases are zoned. This would be consistent with a proposed tectonic model of the Windsor sediments to be derived from the rapid erosion of volcanic highlands.

The rock fragments and feldspars are distributed about equally between the two bottom axes with about the same amount of samples with all rock fragments as samples with all feldspars. Owing to the relative instability of the feldspar, it would be expected to be decomposed rapidly in a hot, humid environment such as Jamaica (Folk, 1980).

This should result in disproportionate amount of lithic rock fragments. Because the amount of feldspar remains in abundances almost equal to the lithic rock fragments, rapid decomposition must have been retarded, perhaps by uplift or deposition related to tectonics.

Serpentine, an important constituent of the Windsor, is typically found in island arc environments (Hyndman, 1972); therefore, its association in Jamaica is supportive of the island arc hypothesis. Serpentine is thought to form from olivine by the addition of water and silica (Hyndman, 1972). The reaction is:

$$\underset{\text{(olivine)}}{3Mg_2SiO_4} + SiO_2 + H_2O \rightleftharpoons \underset{\text{serpentine}}{2Mg_3Si_2O_5(OH)_4} \qquad \text{(I.)}$$

Owing to the common occurrence of serpentine as large sheet-like peridotite serpentine bodies along major thrust faults and because of their association with island arcs, Hyndman has suggested that these bodies are upper mantle oceanic crust thrust onto the land (obduction). He suggests serpentinite may be used as an indicator of oceanic crust. The serpentinite becomes exposed when the oceanic crust is not subducted but instead is thrust onto land. Hyndman (1972) notes that subduction, prior to its cessation, may produce serpentinization by the addition of water. The process of serpentinization can produce a decrease in density of the crust from 3.2 to as low as 2.6. This lighter density would tend to cause the crust to rise to the surface, facilitating obduction.

The occurrence of serpentine fragments in the Windsor rocks might be anticipated because of the proximity of the subduction zone. The serpentine fragments mentioned in the above discussion may have been emplaced along major thrust fault zones as the subduction ended.

The cherts of the Windsor occur as rock fragments, possibly from bedded deposits. Ehlers and Blatt (1982) note the typical association of bedded cherts with graded sandstones, melanges, and ophiolites. They postulate these cherts must have formed in a deep ocean basin in a tectonically active region. This model of deposition fits well in the tectonic model of subduction. If the chert was deposited on ocean floor which later became thrust onto land as subduction ended, chert fragments could well be expected.

The relatively low percentages of quartz grains are expected due to the distance from the nearest potential source. Quartz is commonly derived from the weathering of continental crust. This very low value may indicate Jamaica's far distance to any continent during the Cretaceous.

Therefore, petrologic data yields a model of island arc subduction. The VRFs and plagioclase feldspars indicate derivation from volcanic sources. The relative freshness of the feldspars suggests rapid uplift and deposition, perhaps tectonically controlled, in this humid paleoenvironment.

THERMAL ANALYSIS

HEAT FLOW

The heat flow of a region is an important parameter in tectonic interpretation, both in terms of basin type and in degree of hydrocarbon maturation. Relatively higher heat flow values occur over spreading centers, volcanic ridges, and other extensional areas of tectonic activity than those areas at which there is no hot mantle material rising. A back arc basin can be such an extensional setting (Ugeda and Kanamori, 1979), and is generally expected to be thermally hotter than its related fore arc basin, (Aadland and Phoa, 1981; Riva, 1982).

Heat flow can be related to the geothermal gradient as indicated by the classic Fourier heat flow equation in one dimension:

$$Q=-k \quad dT/dZ \qquad (II.)$$

where K is a constant of thermal conductivity.(calcm^{-1}sec^{-1}°C).

T is temperature (°C), and Z is depth (meters) (Turcotte and Schubert, 1982). PetroJamaica has provided access to well log data from the area including a calculated geothermal gradient of 2.41 °C/100m. Using the Fourier heat flow equation, this translates into Q=0.96HFU, assuming an estimate of K as $4 \cdot 10^{-3}$ cal $cm^{-1} sec^{-1}$°C for these sedimentary layers. This estimated conductivity was determined from noting that an average shale $K=3.55 \cdot 10^{-3}$ $calcm^{-1} sec^{-1}$°C (Berry No. 1 from 1000ft to 5240ft) and average sandstone $K=4.7 \cdot 10^{-3}$ $calcm^{-1} sec^{-1}$°C (Karoo sandstone) as compiled by Clark (1966), and assuming an equal distribution of sandstones and shales in the section. This K value is probably a good estimate in that it is close to the $4 \cdot 10^{-3}$ $calcm^{-1} sec^{-1}$°C determined for sediment layers overlying oceanic crust in a well bore by King and Simmons (1972) and also yields a heat flow (0.96 HFU) very close to that of a nearby offshore heat flow value (1.18 HFU) determined at 80.32°W, 18.33°N and reported in Jessop *et al.* (1975).

In comparison with heat flow values reported by Epp *et al.* (1970), of other parts of the Caribbean, the St. Ann's Basin is relatively cool today. For example, a heat flow of 1.6 HFU was obtained in a shallow part of the Cayman Trough, the Cayman Ridge had characteristic heat flows of 1.2 to 1.5 HFU, and the Yucatan Basin had average values from 1.3 HFU to 1.8 HFU. The Cayman Ridge is a youger tectonic basin and may well be expected to have a higher heat flow. The Yucatan Basin, however, was formed during the Jurassic as a result of spreading (Uchupi, 1975) and yet this basin still retains a higher heat flow.

VITRINITE REFLECTANCE

The vitrinite reflectance of sedimentary organic matter is a commonly used indicator of hydrocarbon maturation by the industry and represents a kinetic measure of the maximum temperature that organic matter has experienced. Consequently, it may be used to record the maximum temperature that sediments have experienced. The procedure to be used is the Shell Oil Company method of Hood et al. (1976) which incorporates both Ro (vitrinite reflectance) and age. Heroux et al. (1979) discuss possible sources of error involved in using Ro which include sediment reworking, oxidation, and large changes in host lithology. For these St. Ann deepwater muddy fan deposits, these effects are probably of minor variation and influence.

Rodriques (1982) in a vitrinite reflectance study of the Windsor shales in outcrop, found the Windsor to have an average value of 0.65%. He interpreted this value as indicating the Windsor sediments to have had a relatively cool thermal history.

Proximal to the outcrop section are vitrinite reflectance data from the Windsor #1. The Ro as a function of depth is shown in Figure 43. Note that the 0.65% Ro of Rodrigues' study also approximates the mean of the Windsor #1 well (0.63±0.07). Let us use the 0.65% Ro and make the following Tmax (maximum temperature calculation according to the methods of Hood _et al._ (1975). The maximum age uncertainty for Windsor deposition in adjacent outcrop is late Coniacian to late Santonian (Esker, 1969) or 88.5 to 87.5my old. For the Ro of 0.65% or Level of Organic Maturation (LOM) of 9 (see Fig. 44), we obtain using Figure 45 a Tmax for 88my of 73° C. These vitrinite reflectance findings then also suggest a cool thermal history for the Windsor.

Of importance to Jamaica's hydrocarbon explortion, for the age of 88my, the Ro of 0.65% or LOM or 9 also places these sediments within the oil generation window of Hood _et al._ (1975). At least in terms of organic maturation, this thermal history then is favorable to hydrocarbon maturation, a rather unusual event for typical fore-arc basins worldwide (Pigott, 1984).

Figure 43. Depth versus vitrinite reflectance values observed by PetroJamaica in the Windsor #1.

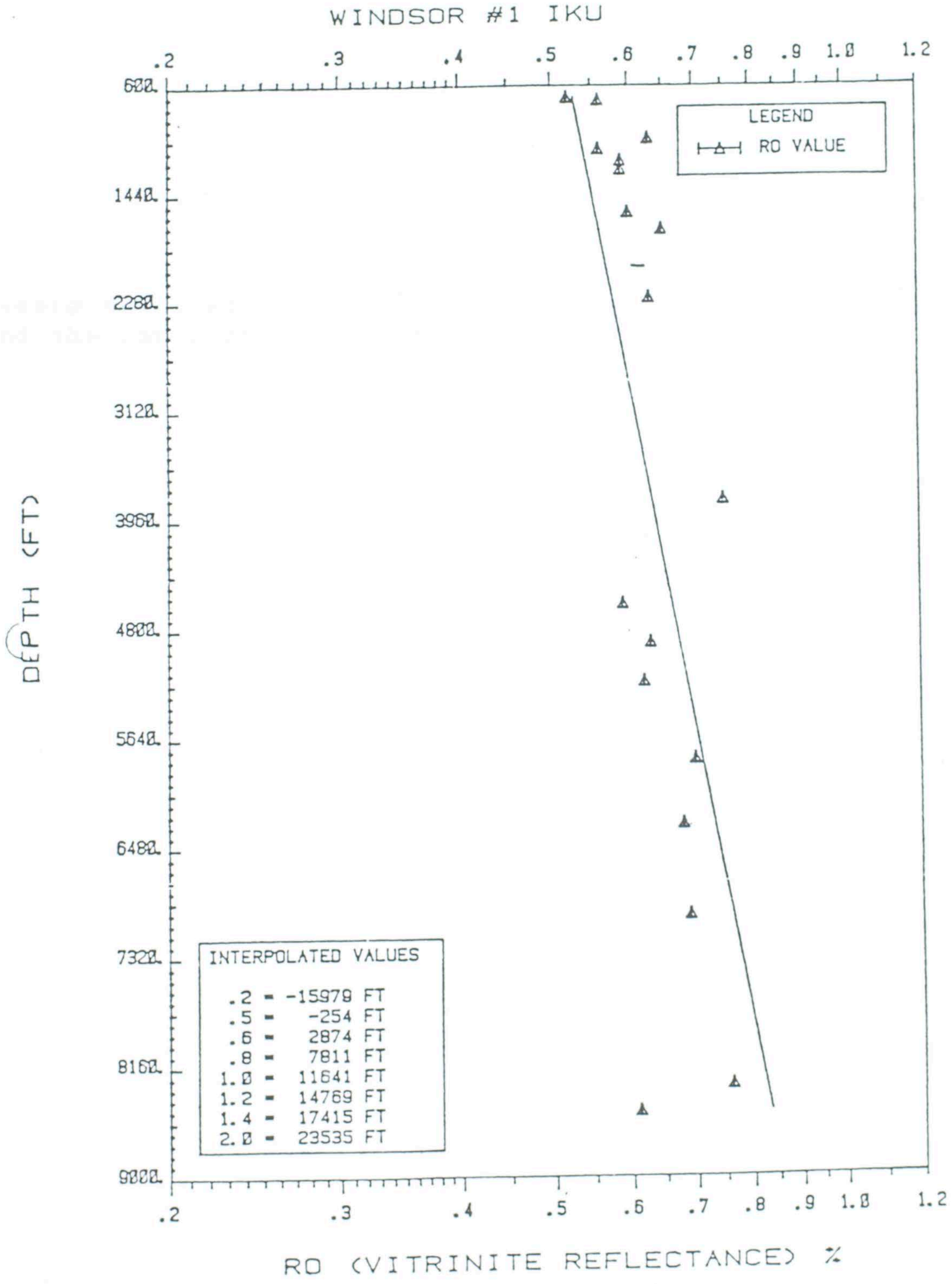

WINDSOR #1 IKU
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.2
600.
1440.
2280.
3120.
3960.
4800.
5640.
6480.
7320.
8160.
9000.
DEPTH (FT)
LEGEND
RO VALUE
INTERPOLATED VALUES
.2 = -15979 FT
.5 = -254 FT
.6 = 2874 FT
.8 = 7811 FT
1.0 = 11641 FT
1.2 = 14769 FT
1.4 = 17415 FT
2.0 = 23535 FT
RO (VITRINITE REFLECTANCE) %

Figure 44. Vitrinite feflectance values from PetroJamaica and the corresponding level of organic maturation (LOM).

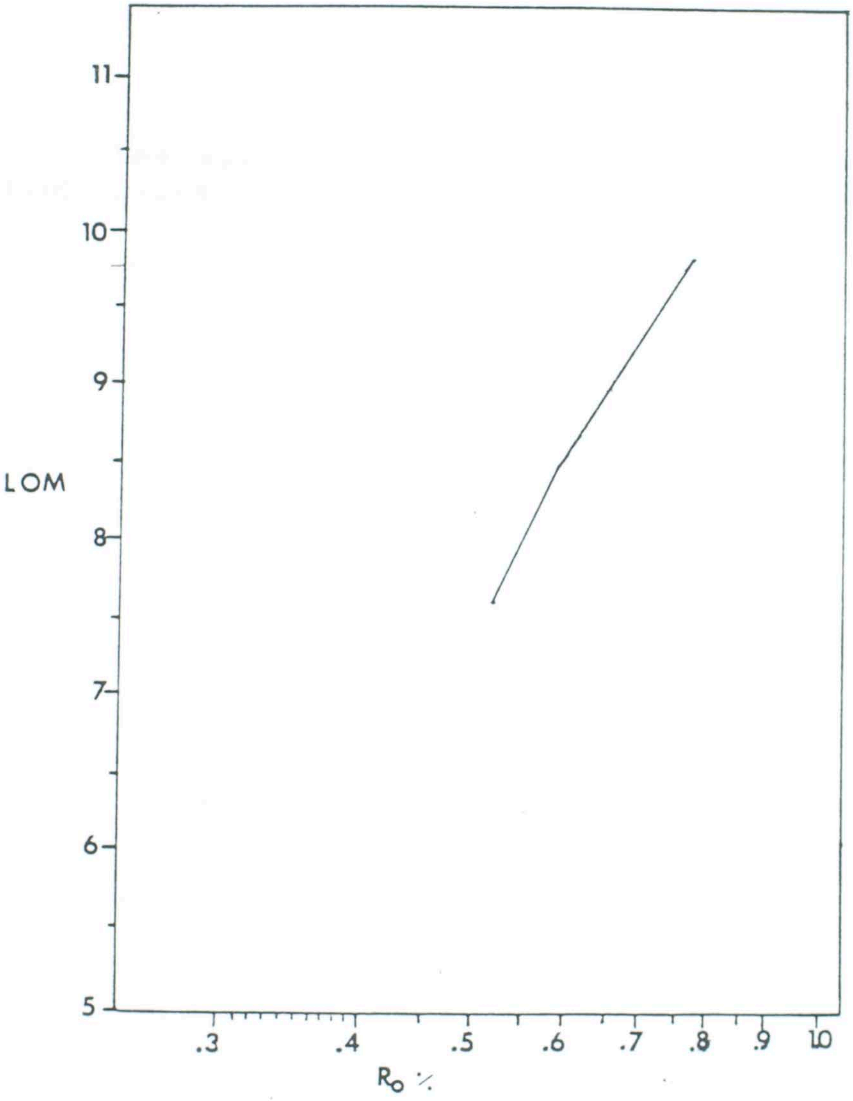
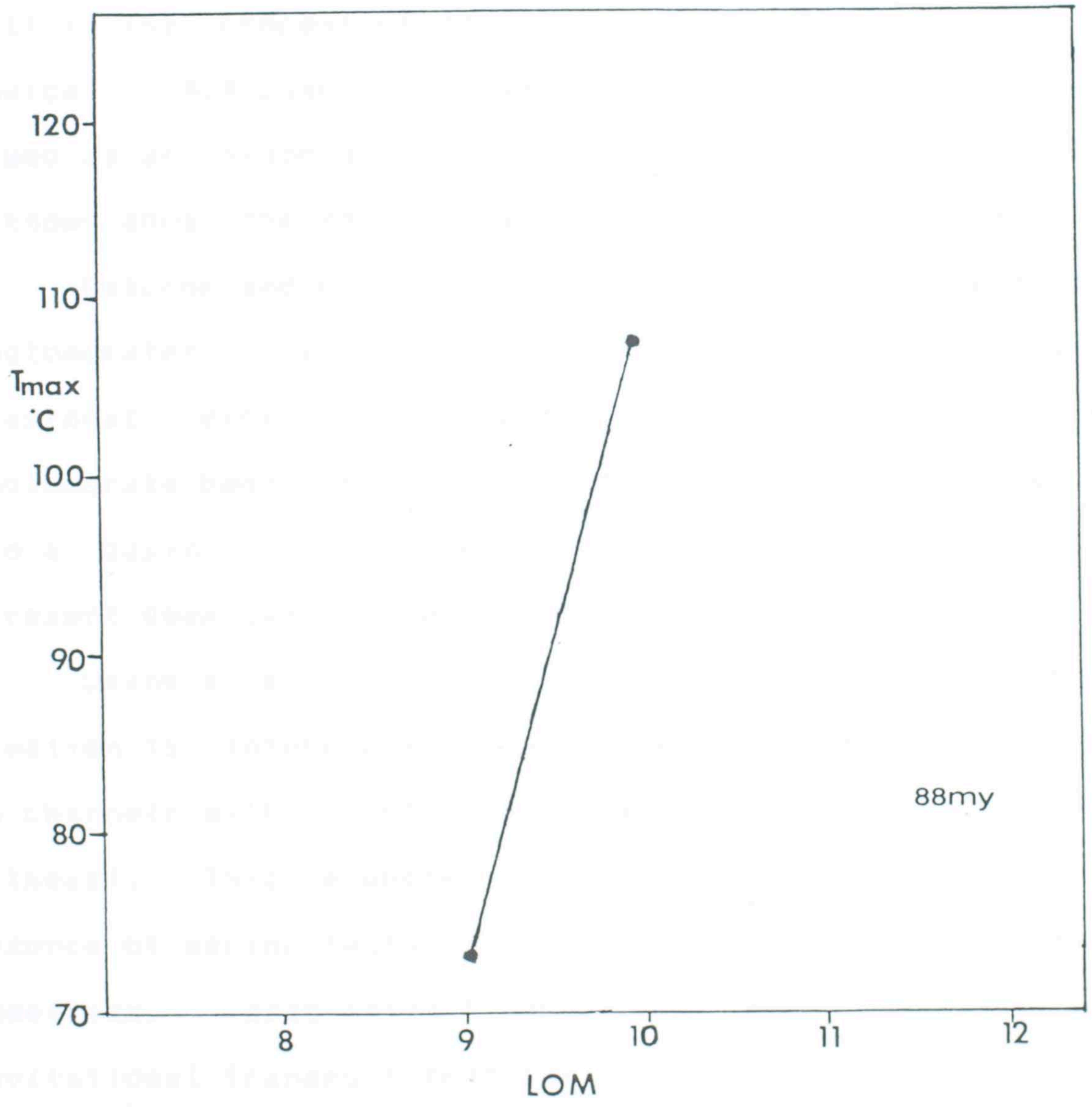

11
10
9
LOM
8
7
6
5
.3
.4
.5
.6
.7
.8
.9
1.0
Ro %

Figure 45. The maximum temperature corresponding to the observed LOM values for the Windsor sediments.


120
110
Tmax
°C
100
90
80
70
8
9
10
11
12
LOM
88my

TECTONIC SYNTHESIS AND CONCLUSIONS

The Windsor Formation represents the Cretaceous deposition of terrigenous sediments into a tectonic basin still in the process of formation on the northern coast of Jamaica. Although it is generally accepted Jamaica was formed as an island arc from subduction at this time, little is known about the specific mechanisms of this subduction.

Outcrop and core study reveal a series of alternating conglomerates, sandstones, siltstones, and shales with occasional micritic limestones. The cobble-sized conglomerate beds represent pulses of very coarse material into a basin. The shales, often tens of meters thick, represent deep basinal conditions.

Using a depositional systems approach, the Windsor Formation is interpreted from outcrop data as a submarine fan channels with a Cretaceous paleocurrent direction to the Northeast. This proposed model was interpreted from the presence of marine fauna, lack of fresh water fauna, channel geometries, assoicated submarine fan facies, and gravitational transport features.

Compositionally, the Windsor Formation is comprised exclusively of arkoses, lithic arkoses, feldspathic litharenites, and litharenites. The rocks are especially rich in plagioclase and volcanic rock fragments. The significant abundances of the palgioclases (often zoned) and VRFs indicate derivation from predominantely volcanic sources. Paradoxically, the feldspars are relatively fresh considering their potential weathering in a tropical surface paleoenvironment. These unaltered feldspars, coupled with the subequal amounts of feldspars and VRFs, indicate rapid uplift and deposition from volcanic sources. Serpentine, chert, and marine fossils are other important constituents. The Windsor sediments, however, are relatively quartz-free.

Cement types found in the Windsor includes low Mg calcite, albite, clays, and phyllosilicates. From the cement stratigraphy, the depth of burial of the sediments is inferred to be approximately 3000 to 4000ft (900 to 1200m). However, these depths can only be used as approximate ranges.

An analysis of the present geothermal gradient and vitrinite reflectance values from the Windsor #1 well contribute important information concerning the thermal history of the basin. The present-day calculated heat flow is Q=0.96HFU. Compared with the present-day heat flows of the Cayman Ridge (1.2 to 1.5 HFU) and the Yucatan Basin's 1.3 to 1.8 HFU (Epp et al., 1970), the St. Ann's Basin is low.

The heat flow data implies the St. Ann's Basin to have been a fore-arc basin. If the St. Ann's Basin was indeed a fore-arc basin, subduction would have been to the south or southwest. Since the heat flow data alone may not be conclusive, other data must also be examined. Evidence indicating convergence and southward subduction beneath a fore-arc basin includes:

1. Sedimentologic Constituents: Fresh volcanic rock fragments and plagioclases, the predominant constituents, are indicative of volcanic highlands. Serpentine, chert, and deep water limestones are indicative of ophiolite sequences. These sandstone compositions are typically found in island arc environments (Galloway, 1974).

2. Paleocurrent Directions: In a convergent margin system, the deep sea fans shedding volcanics and terrestrial materials generally radiate away from the emergent volcanic arc into the trench. Therefore, the paleocurrent direction of transport is expected to be toward the trench. The St. Ann's Basin has a predominant paleocurrent direction to the northeast, locating the volcanic source to the southwest.

3. Paired Metamorphic Belt: The existence of a paired metamorphic belt with contrasting high and low temperature metamorphic facies indicates a subduction zone dipping to

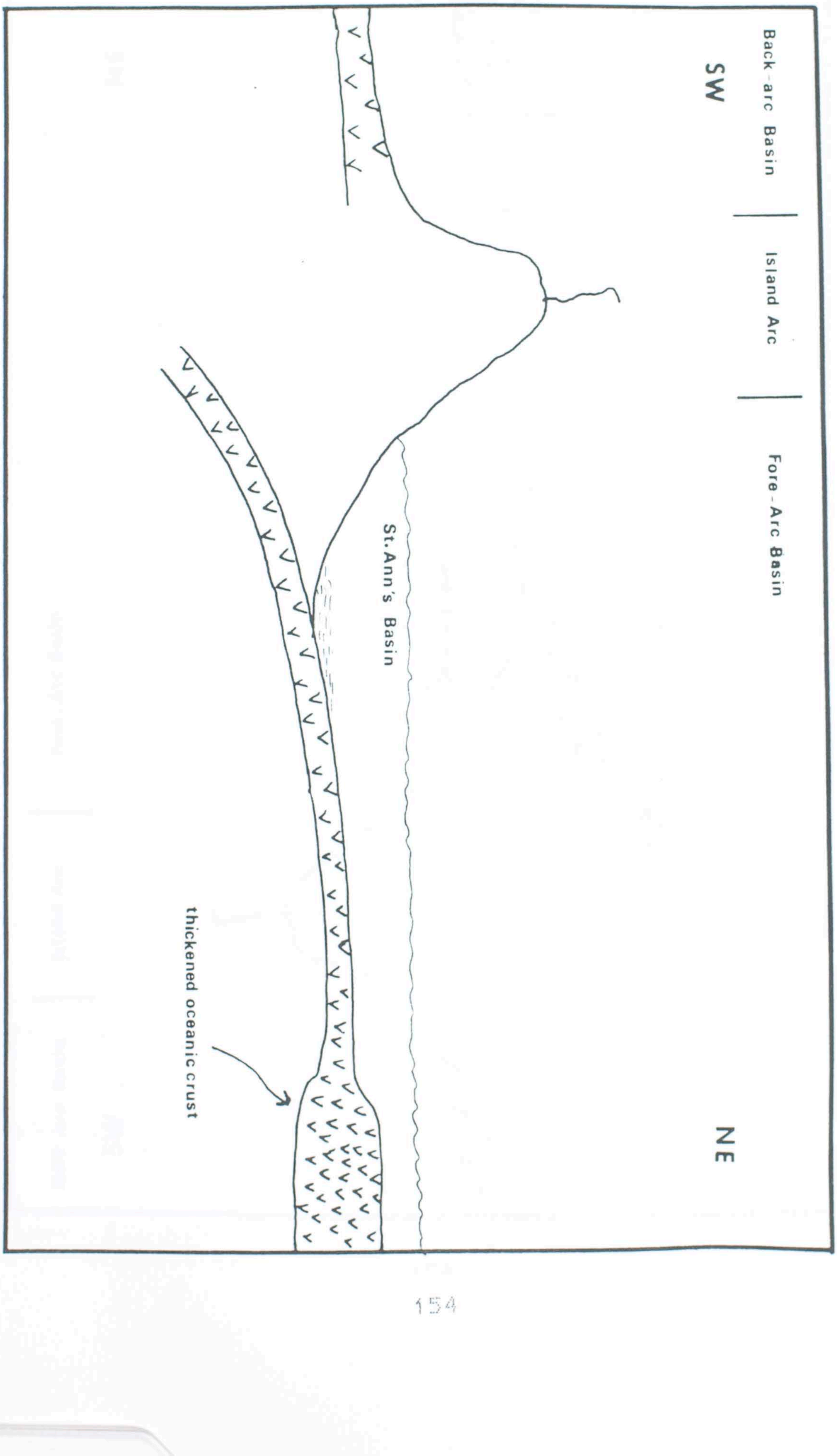
the southwest (Draper *et al.* 1976).

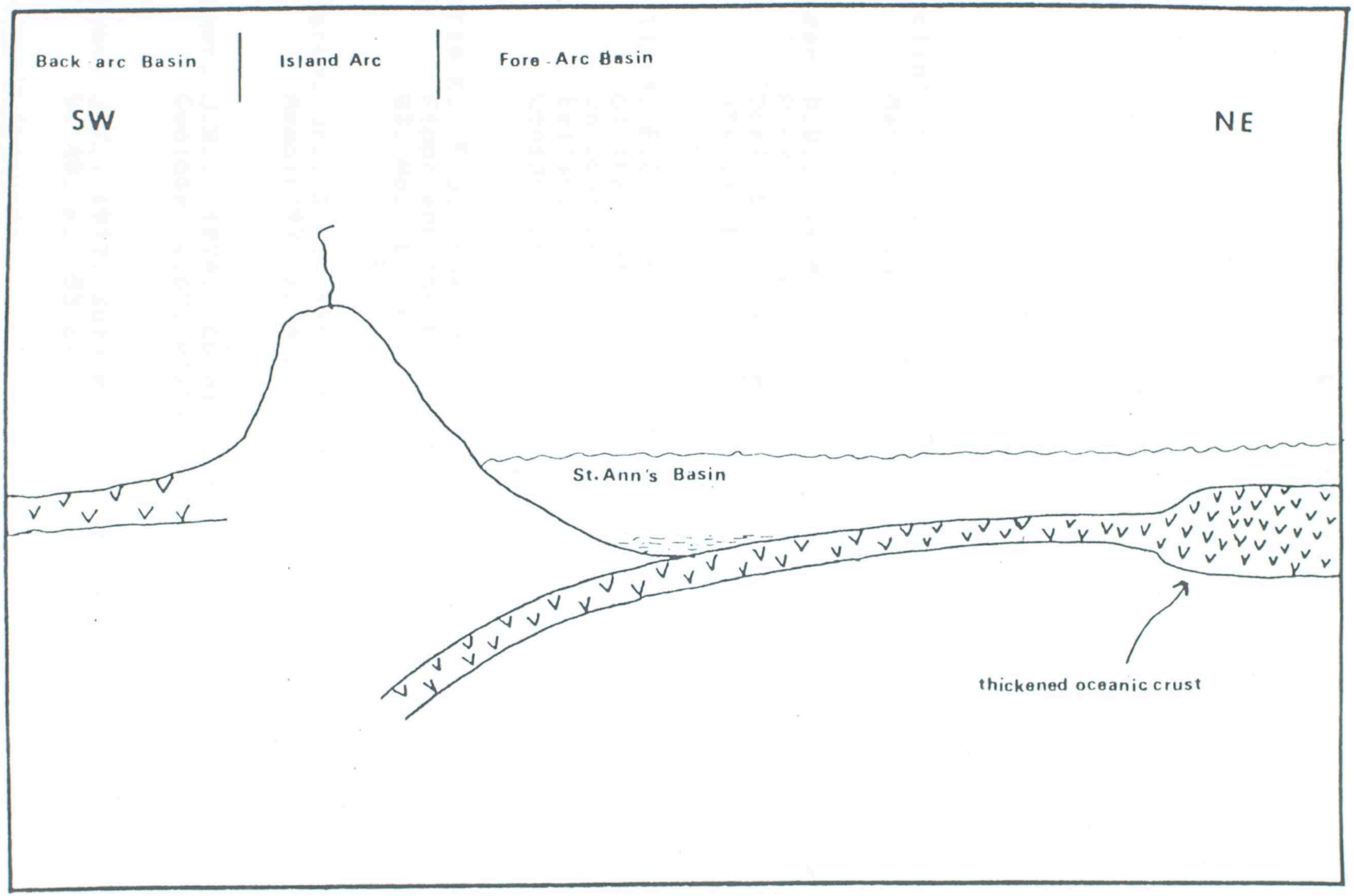
4. Paleomagnetic Data: Movement measured from paleomagnetic data (MacDonald and Opdyke, 1972) indicates Jamaica migrated to the north relative to the North American plate during the Cretaceous, consistent with the consumption of ocean floor (subduction) between.

From the above evidence, the St. Ann's Basin can best be modeled as a fore-arc basin (Fig. 46). A paleosubduction zone dipping to the southwest beneath Jamaica's present location formed the volcanics. As the volcanoes emerged and were uplifted, debris was shed rapidly off the highlands, down a steep paleoslope similar to the present-day Aleutians, and deposited quickly. This debris was the source for the VRFs and plagioclases. As uplift waned and the sedimentation rate subsided, the resulting deep basinal conditions led to the deposition of thick shale sequences.

In this study a correlation between sediment compositional types and tectonics was drawn. The Windsor Formation is representative of island arc sedimentation in the Caribbean. The sediment compositional types present here may serve as a guide for the recognition of similar island arc sedimentary environments in other areas worldwide.

Figure 46. Proposed tectonic model for Late Cretaceous subduction beneath northern Jamaica. Jamaica is the island arc in the southwest abd tge Windsor sediments were deposited in the St. Ann's fore-arc basin.


SW
NE
Back-arc Basin
Island Arc
Fore-Arc Basin
St.Ann's Basin
thickened oceanic crust


Back-arc Basin
Island Arc
Fore-Arc Basin
SW
NE
St. Ann's Basin
thickened oceanic crust

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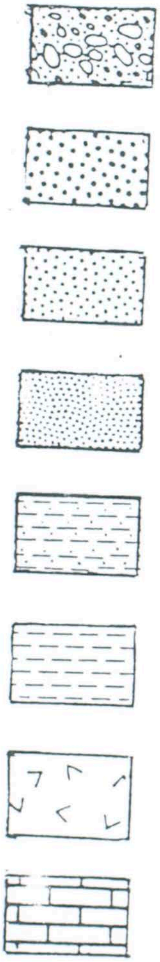
Appendix I
Outcrop Stratigraphy

The outcrops of the Windsor define two limbs of an anticline. Therefore, the two stratigraphic sections represent the two limbs of the anticline, and thus two different places in the basin. The southernmost limb, represented by samples W-11 to W-24 is a more complete section. The northern limb, represented by W-10 to W-1 is cut by a reverse fault and is not complete. Divisions represent 5m intervals. Station numbers (W-12, etc.) refer to locations shown on Figure 3.

LEGEND



Conglomerate

Coarse Sandstone

Medium Sandstone

Fine Sandstone

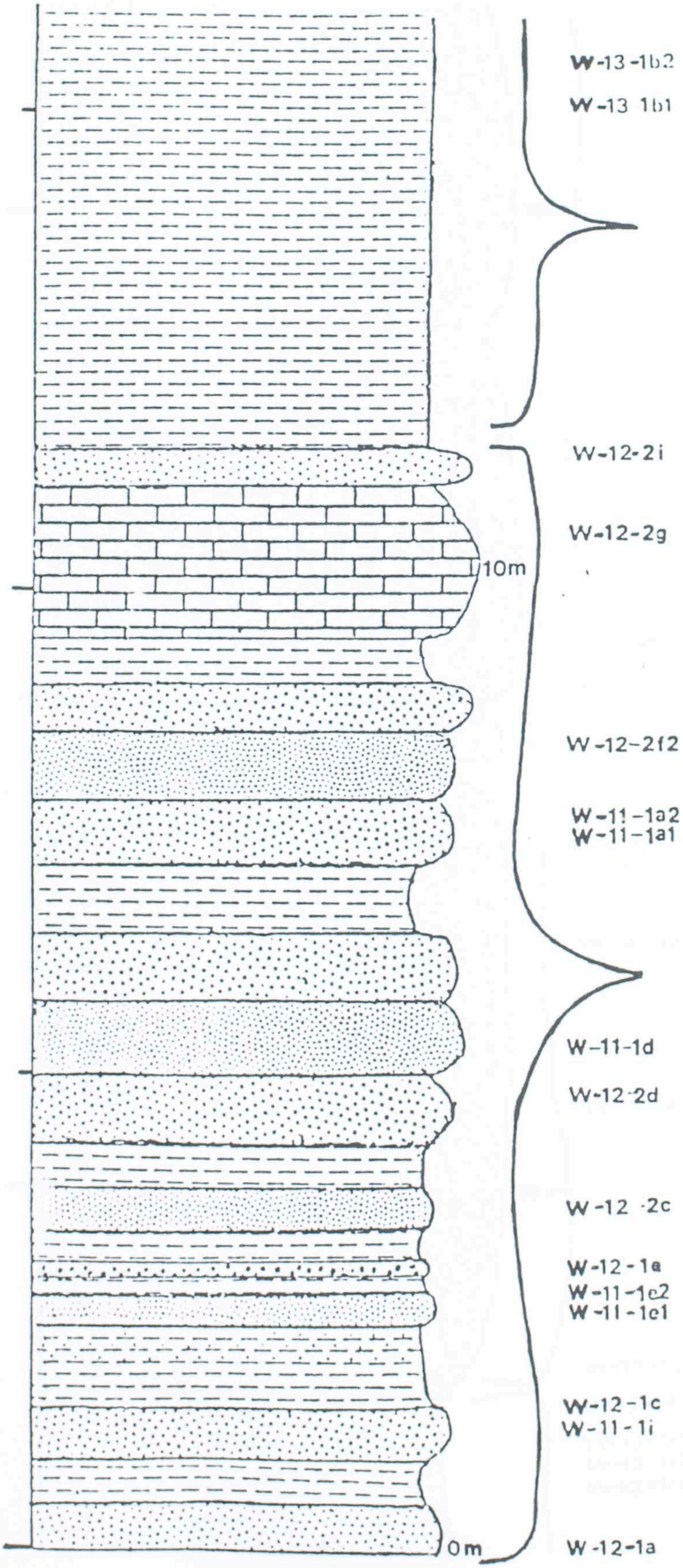
Siltstone

Shale

Ash Flow

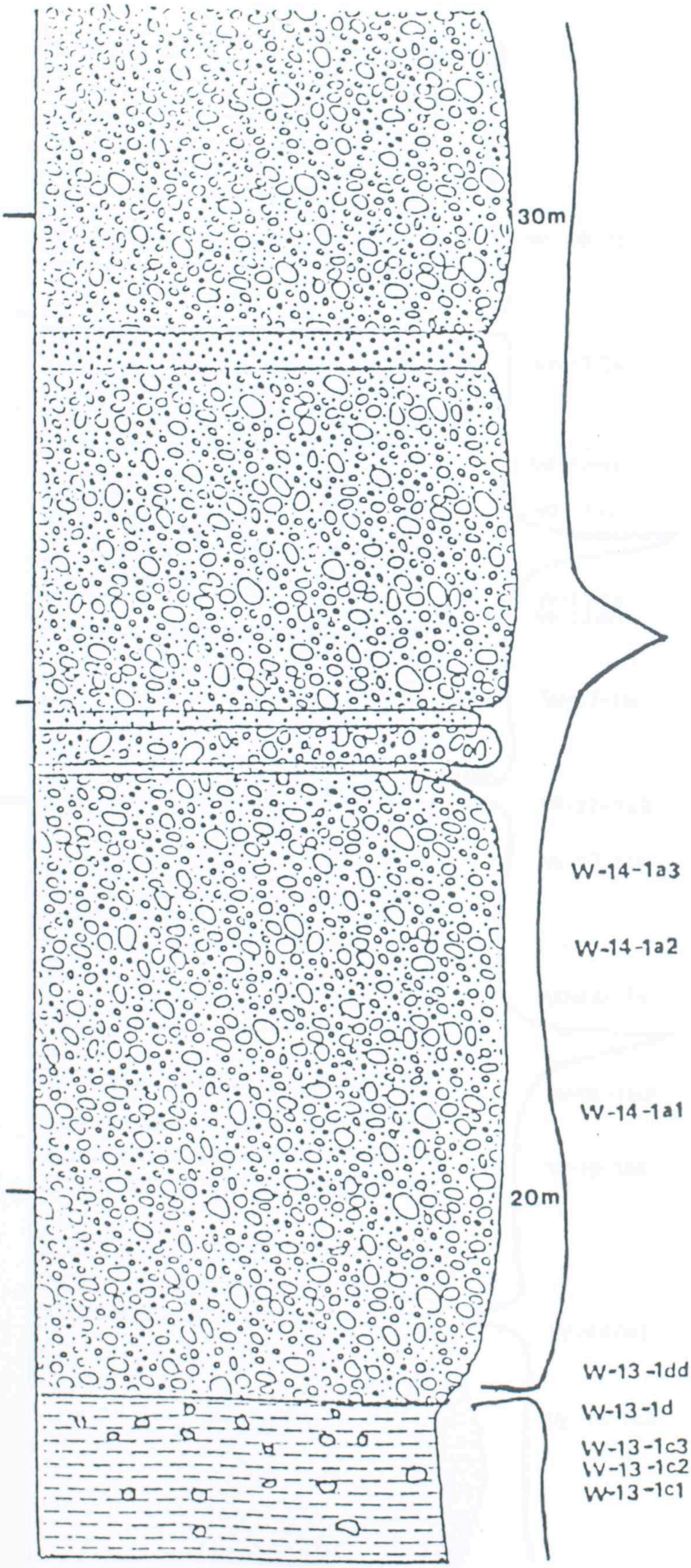
Limestone

Southern Limb

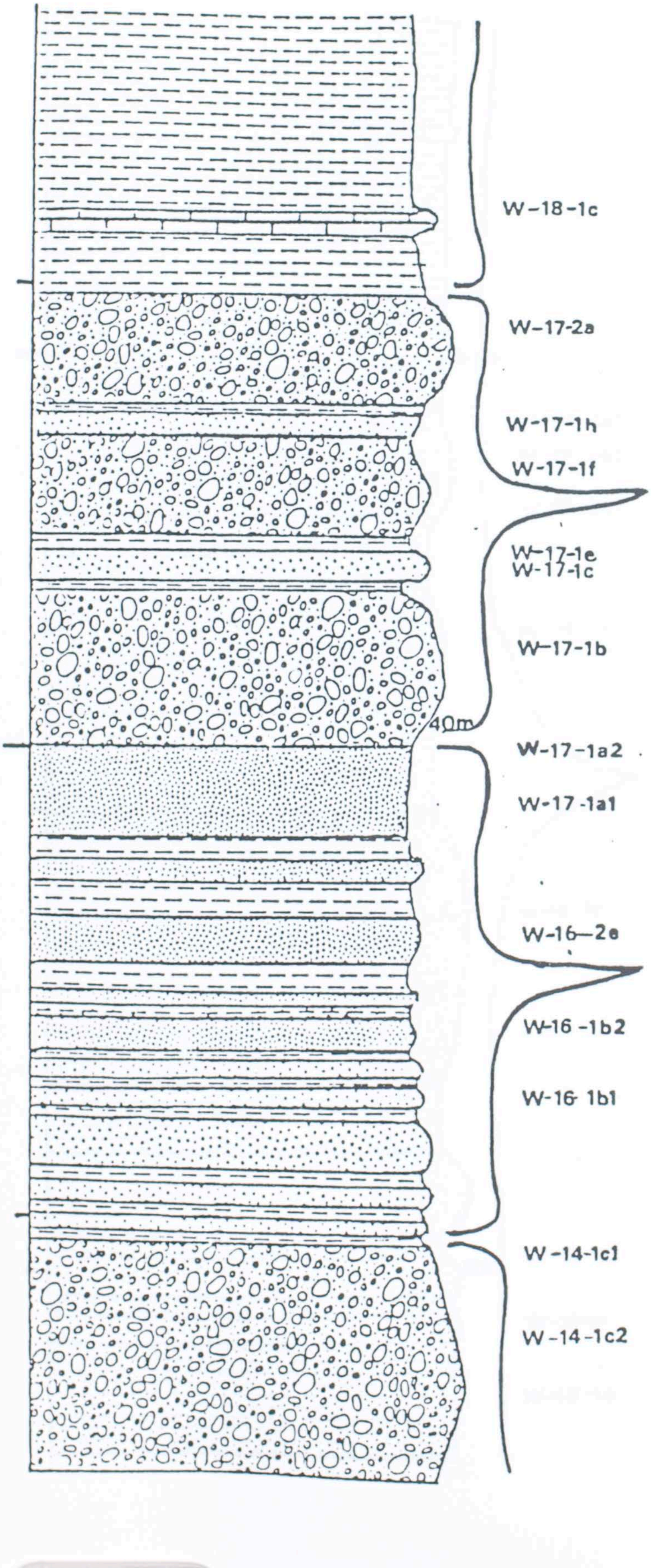


The next depositional unit is a thick shale sequence with thinnly-bedded, fissile, blue-gray, non-resistant shale. Calcite infills fractures within the shale. Well-rounded cobble-sized clasts begin to appear in the upper part of the shale. The shale exhibits intense soft-sediment deformation in the uppermost portion.

Deposition begins with a series of alternating sandstones and shales. Both the shales and the sandstones are fractured and infilled by calcite. The sandstones are brownish-tan. Several of the sandstone beds exhibit channel geometries. The contacts between the beds are sharp. The upper part of the sequence has a thick limestone as a resistant bed.

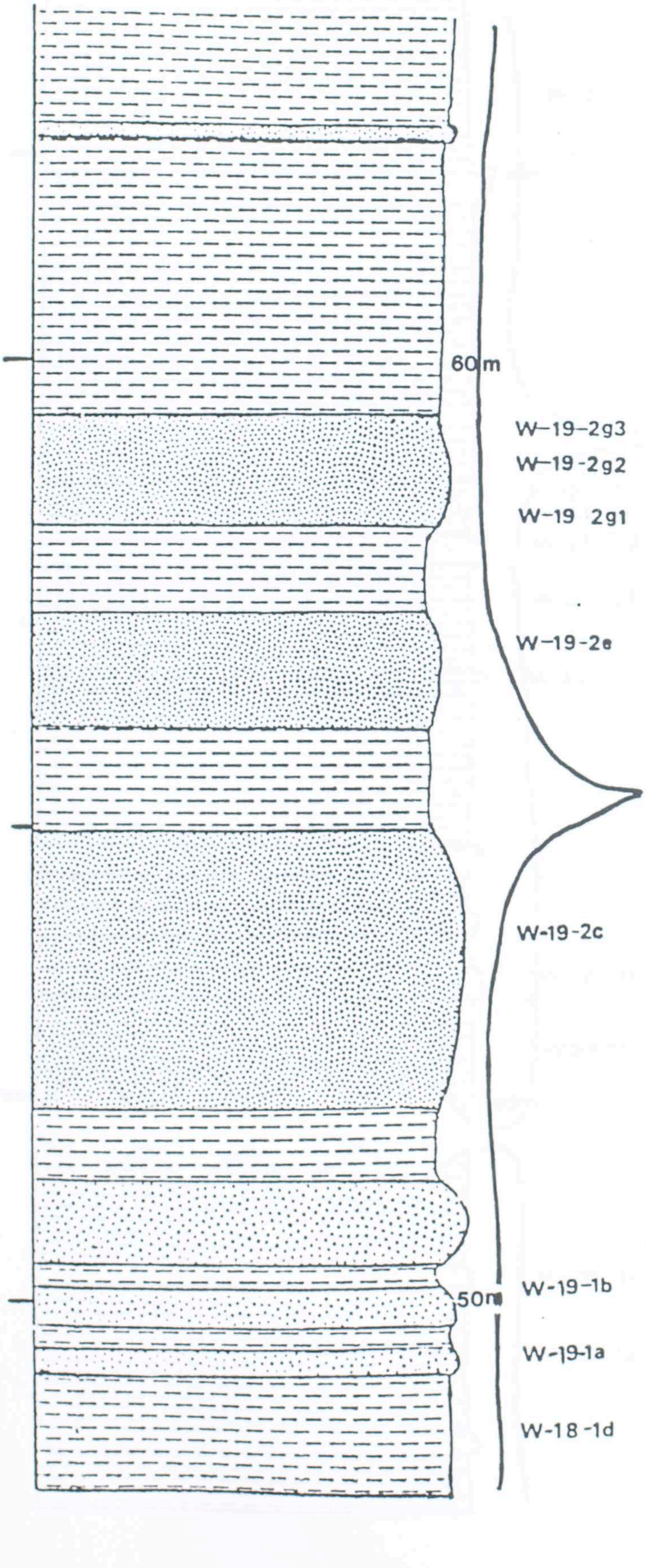


Three beds of conglomerate deposition makes an abrupt contact on the shale. The conglomerate has rounded cobble-sized clasts, non-resistant clay matrix, and is poorly sorted. Interbedded with conglomerate beds are thin beds of sandstone and pebble conglomerate. The sandstones are laminated, brownish-tan, and moderately sorted. The pebble conglomerate is poorly sorted with a weathered clay matrix. These coarse sandstone and pebble conglomerate beds have gradational contacts with the underlying cobble-sized beds but, are abruptly truncated by the overlying conglomerate.

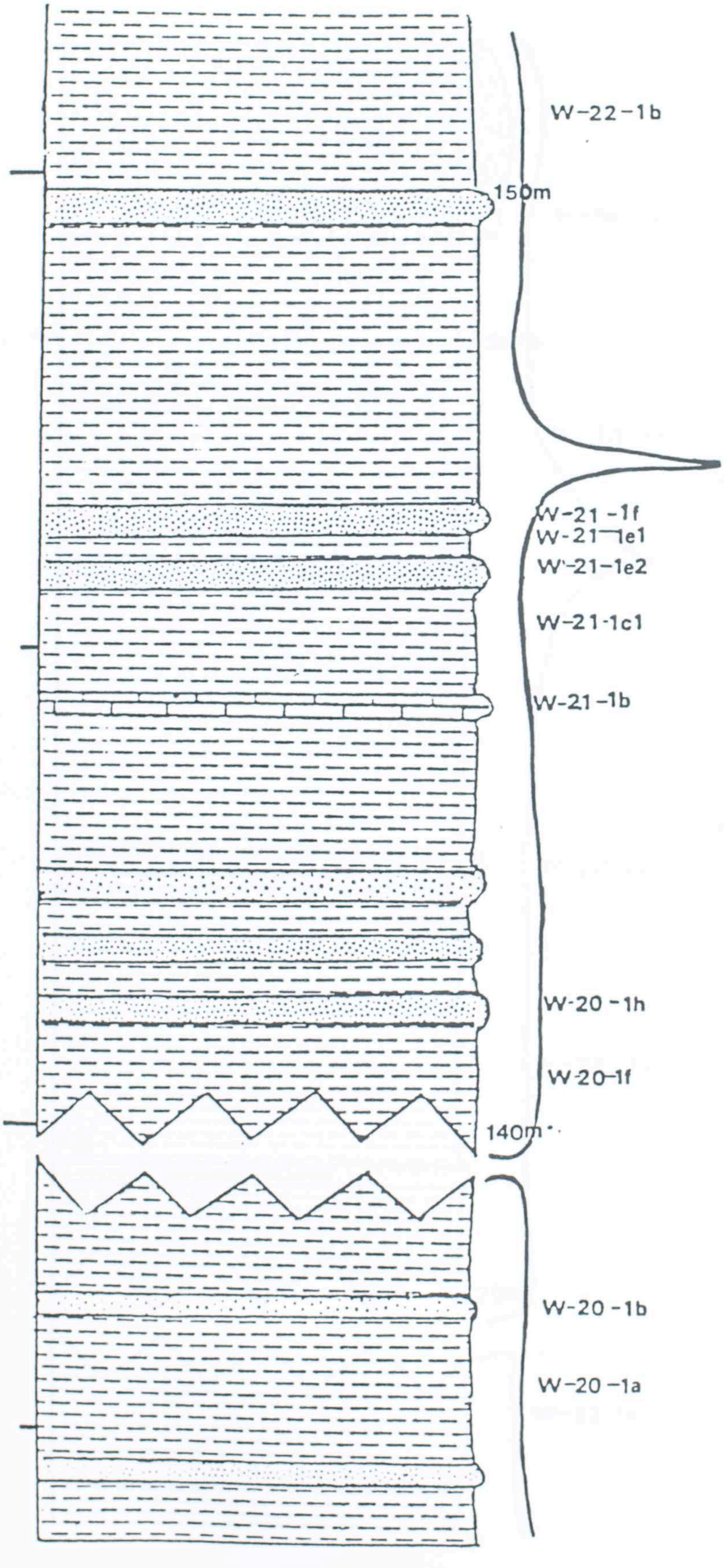


A reoccurrence of conglomerate beds. forms a very coarse depositional sequence. These conglomerates are poorly sorted and have cobble-sized rounded volcanic clasts. Interbedded with the conglomerates are alternating beds of sandstone and shale These sandstone beds are well sorted, brownish and have parallel laminations. The shales are thinnly-bedded and fissile.

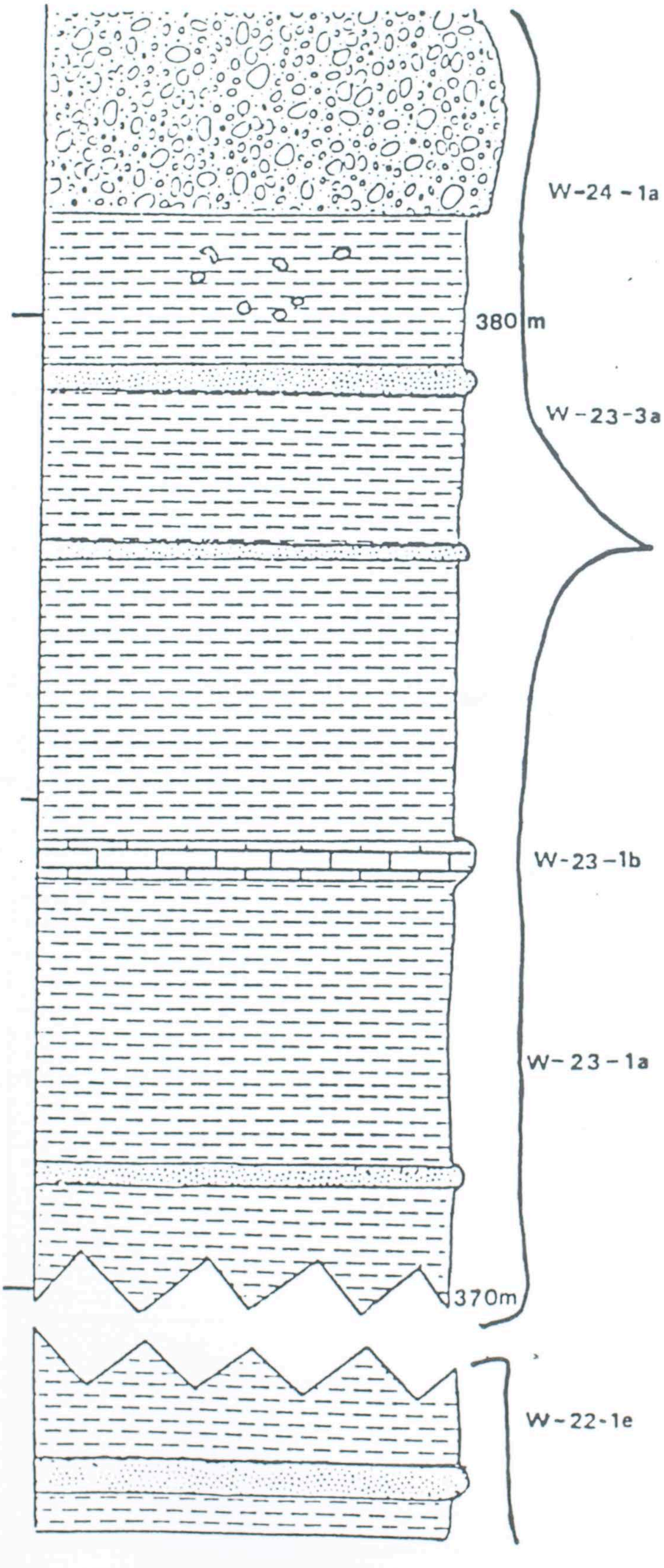
Series of alternating thinnly bedded sandstones and shales. The shales are blue-gray and fractured with calcite infilling the fractures. The sandstones range from fine- to medium-grained. The sandstones are weathered to a brownish-gray color. The contacts between the sandstones and overlying shales are sharp.



Thick, non-resistant shale deposition with calcite infilled fractures running throughout predominates deposition. The shale is fissle and weathers blue-gray. A thin, brown, micritic limestone forms a resistant bed within the shale. Further up in the shale, medium-grained, brownish-tan sandstone beds with channel geometries form resistant layers. Even higher in the section, the sandstone beds become finer-grained and thicker and without channel geometries.

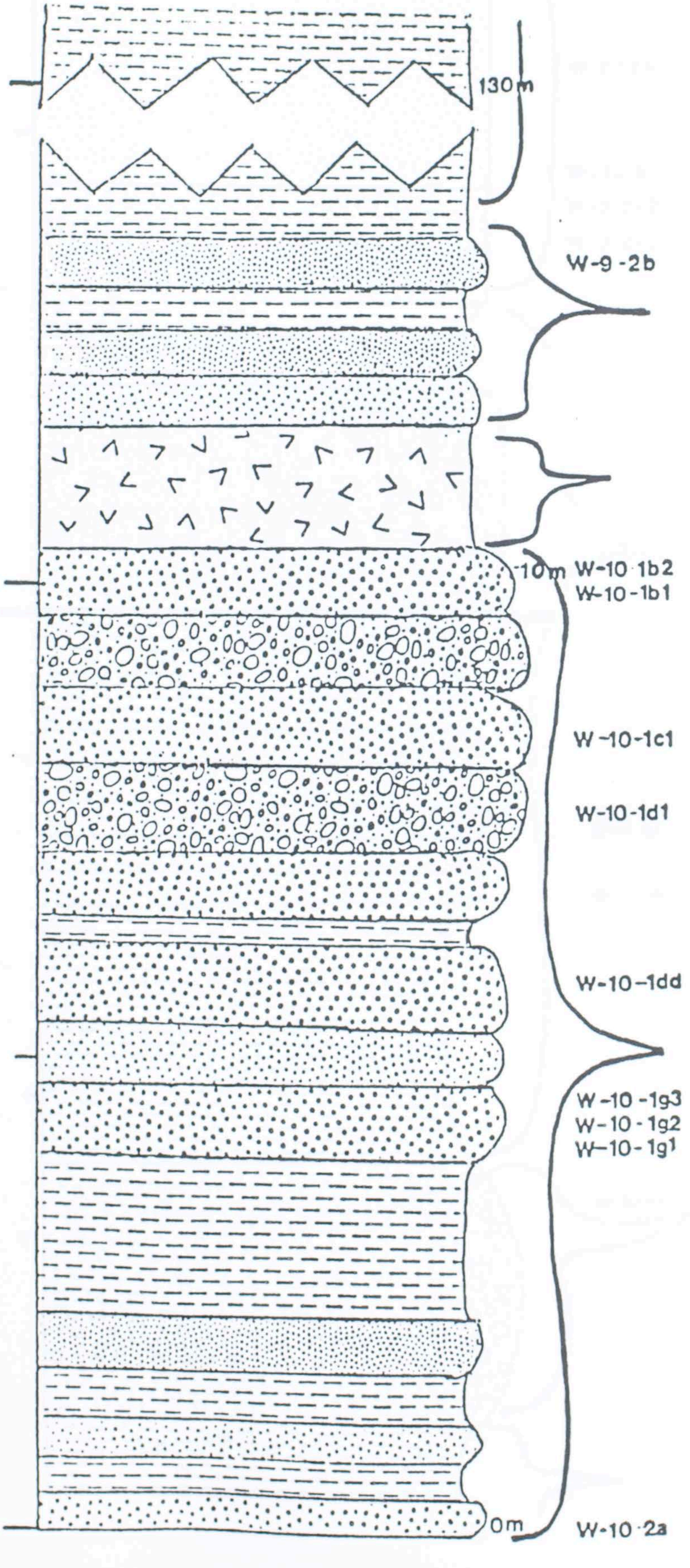


Deposition fines as alternating shale, siltstone, and fine-grained sandstone comprise the remainder of the section. The shales are blue-gray, non-resistant, and often have calcite infilled fractures. The fine-grained sandstones are resistant, well sorted, and weathered to a brownish-tan color. Occasional micritic limestones occur as resistant beds within the shale. Several of the medium sandstone beds have festoon cross-stratification.



At the top of the shale rounded clasts begin to appear marking the beginning of deposition of the Cascade Conglomerate. The Cascade is poorly sorted with cobble-sized clasts. Soft sediment deformation of the directly underlying shale occurs. The first Cascade bed marks the end of Windsor deposition.

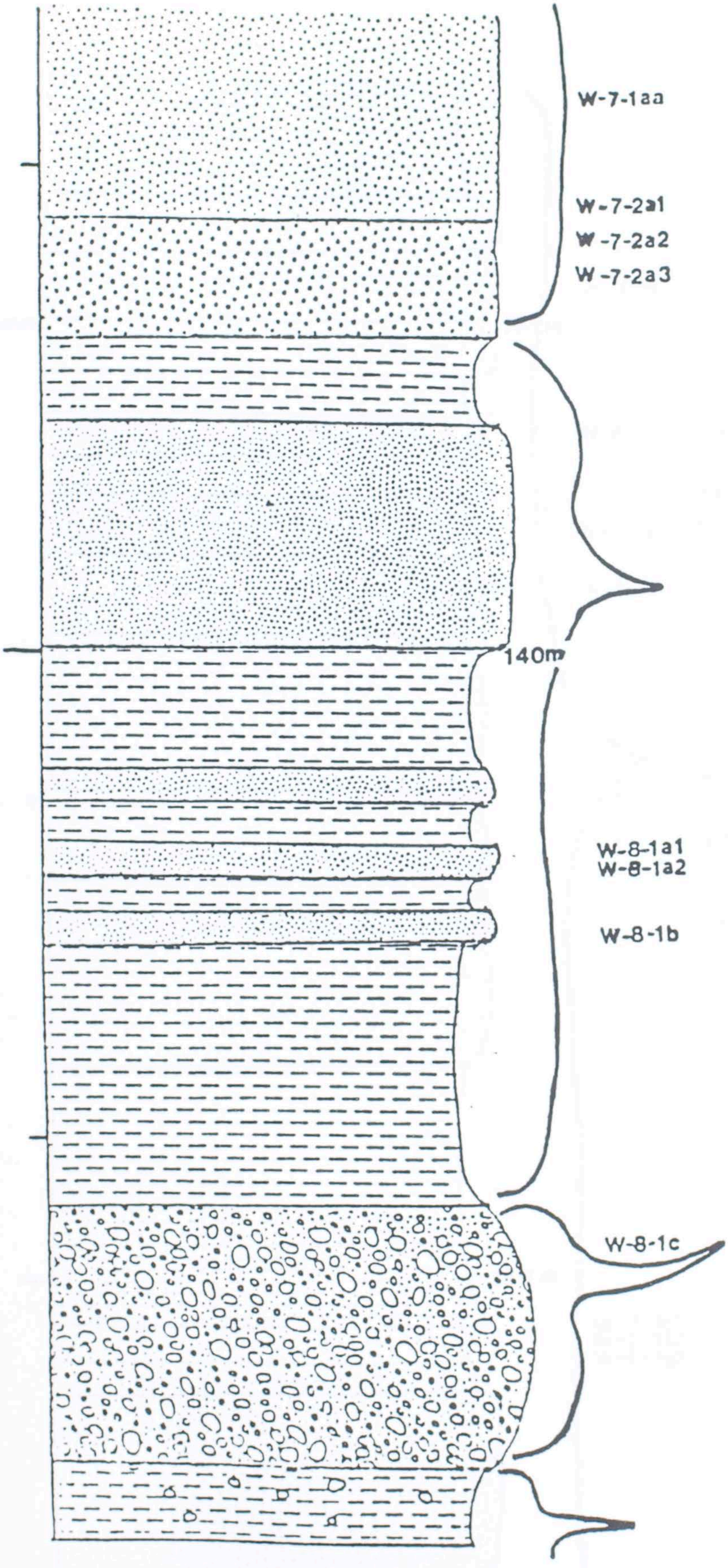
Northern Limb



Overlying the ash flow are alternating beds of sandstone and shale with gradational contacts. Deformational forces have produced minor folding. The sandstones have planar laminatons, are weathered tan, and have exfoliation weathering features.

A clay bed that was formerly an ash flow unconformably cuts across the underlying units. Volcanic bombs are seen within the bed. The ash is totally altered to clay.

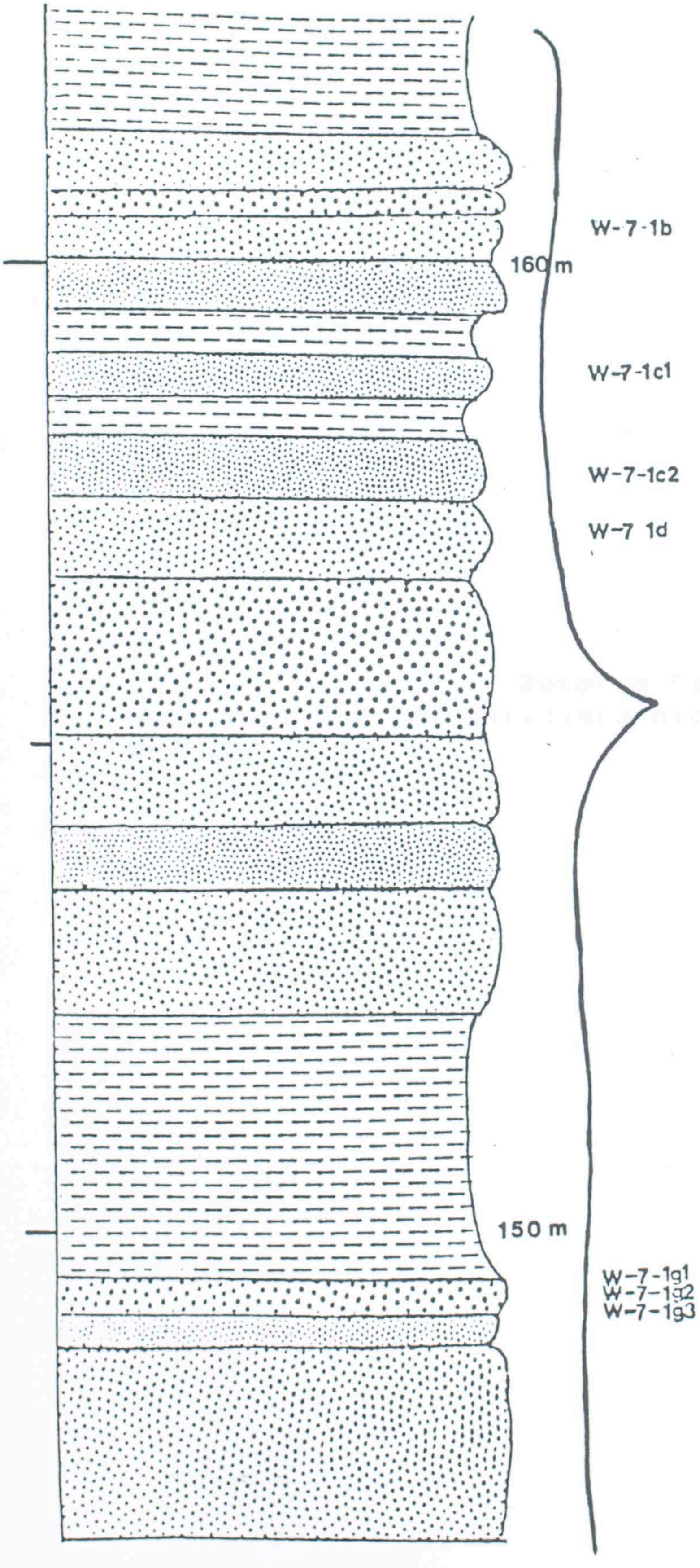
Series of alternating sandstones and shales coarser at the top. The sandstones are moderately sorted and weathered to a brown-tan color. The shales are blue-gray. The contacts between the beds are sharp. The lowermost sandstone bed has planar laminations, but the others appear to be massive. The uppermost beds are extremely coarse-grained sandstone and pebble conglomerate. The clasts in these beds are well rounded, but poorly sorted. The conglomerates have a weathered clay matrix.



A non-resistant, blue-gray shale with thin fine-grained sandstone beds distributed throughout forms the next sequence of deposition. These fine-grained brownish-tan sandstone beds are moderately sorted with no discernible sedimentary structures.

The next depositional unit is a cobble-sized conglomerated bed with rounded clasts and an extremely weathered clay matrix. The bed fines upward to a pebble conglomerate. At the bottom of the conglomerate are mud-clasts.

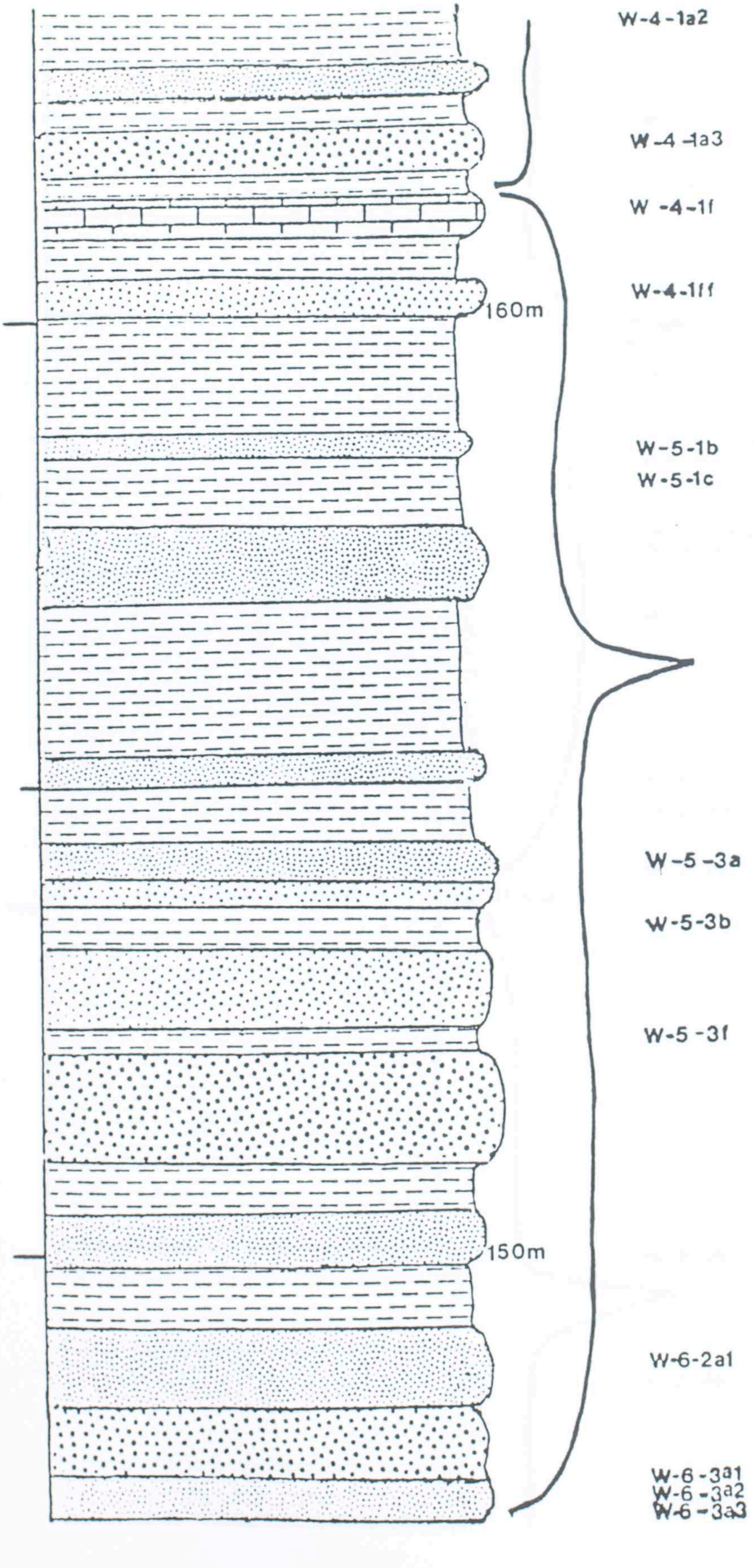
This grades quickly to a thick, black, fissile shale, reduced in scale to represent 120m of shale deposition. In the uppermost part of the shale, cobble-sized rounded clasts begin in appear.



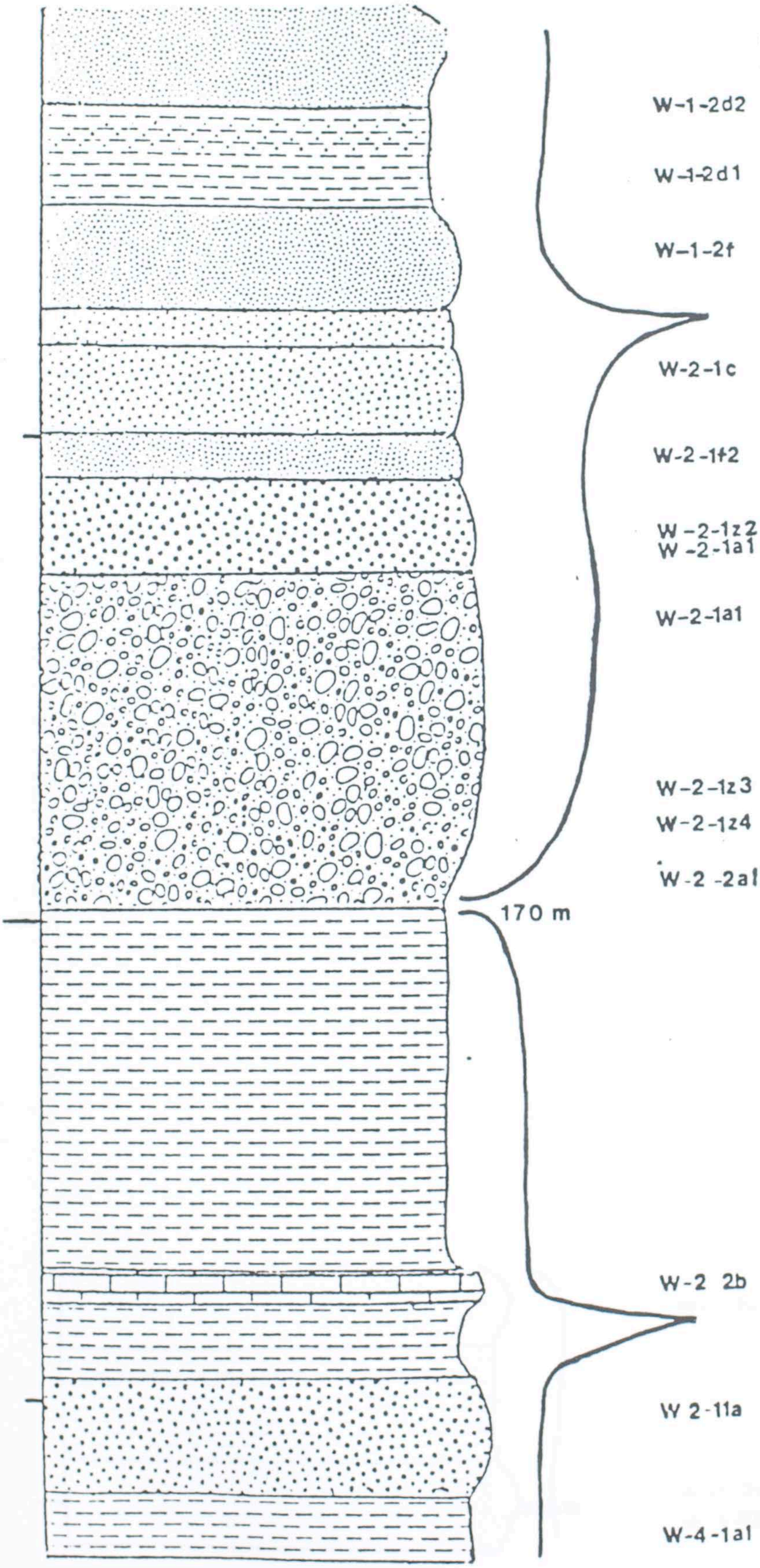
The following depositional sequence is a series of alternating sandstones and shales. The sandstones are brownish-tan and thick. The shales are blue-gray and thinnly bedded. The uppermost portion of the section consists of sandstones with planar laminations. W-7-1d displays a distinct channel geometry. The lower part of the section has gentle folding. This folding intensifies at the top of the section where reverse fault displacement occurs.

Reverse Fault

Note that W-4-1ff stratigraphically corresponds to W-7-1b.

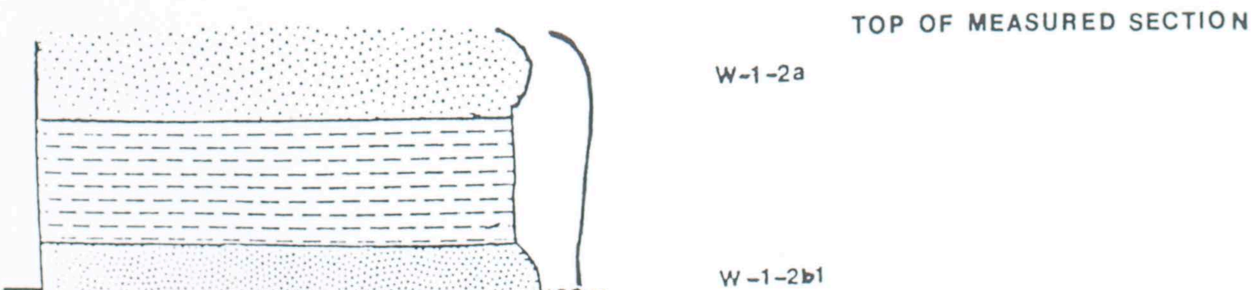


After the fault, a series of alternating sandstones and shales is encountered. Since this is a reverse fault, these beds represent a repeat of the previous section. This correlation is interpreted to represent a repeat of the section beginning at W-7-1g1. These sandstones are weathered brownish-tan and have planar laminations and festoon cross-stratification. A few beds display channel geometries. The shales are non-resistant and weathered blue-gray. At the top of the sequence is a micritic limestone (mudstone) bed. This forms a resistant bed within the non-resistant shale.



A cobble-sized conglomerate with rounded clasts in a weathered clay matrix cuts down into the shale, beginning the next sequence of deposition. Deposition fines upward slightly as sandstones, shales, and siltstones form the remainder of the sequence. The sandstones are brownish-tan, resistant, and weathered with exfoliation features. A few of the sandstone beds have festoon cross-stratification. The shales are non-resistant and gray in color. Contacts between units are gradational.

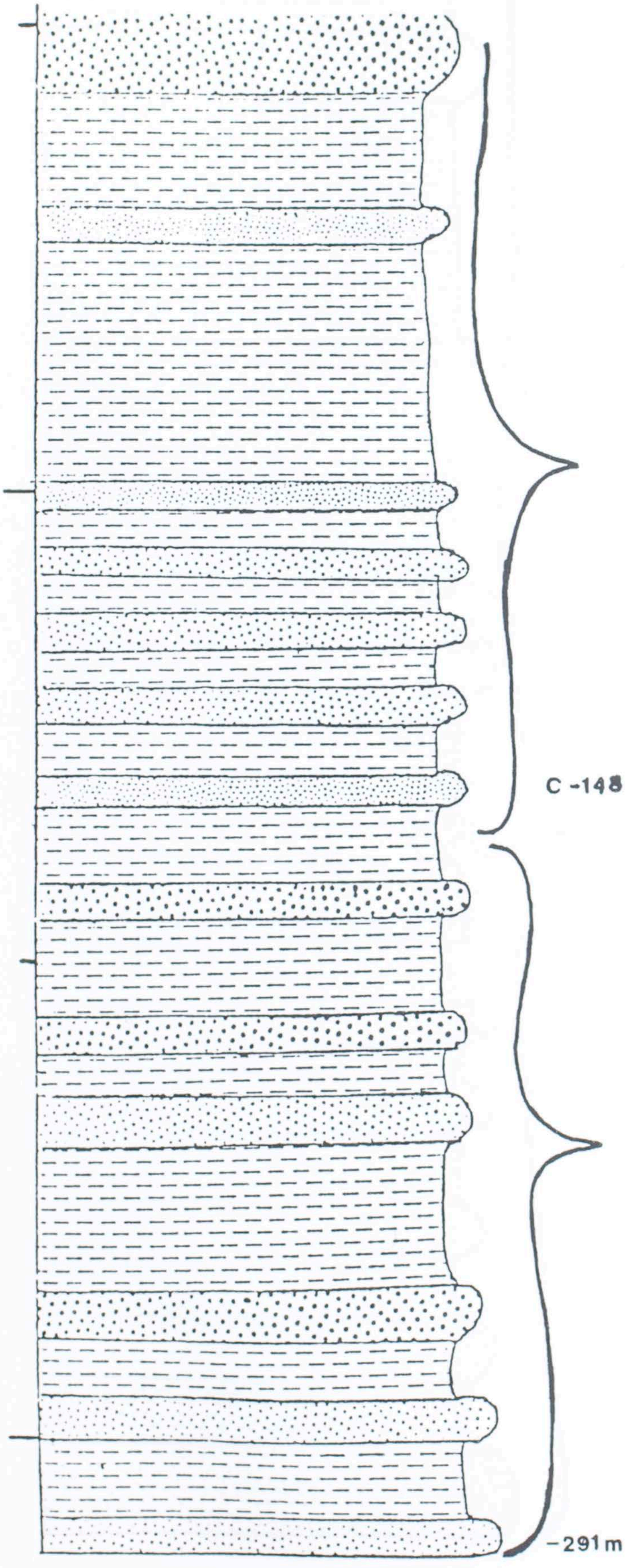
Deposition continues similar to the underlying units with alternating sandstones and shales. The sandstones are weathered brownish-tan and are resistant beds within the non-resistant blue-gray shale. Contacts between the sandstones and shales are gradational. A micritic limestone (mudstone) occurs near the top of this sequence.


TOP OF MEASURED SECTION
W-1-2a
180 m
W-1-2b1
W-1-2b2

Appendix II

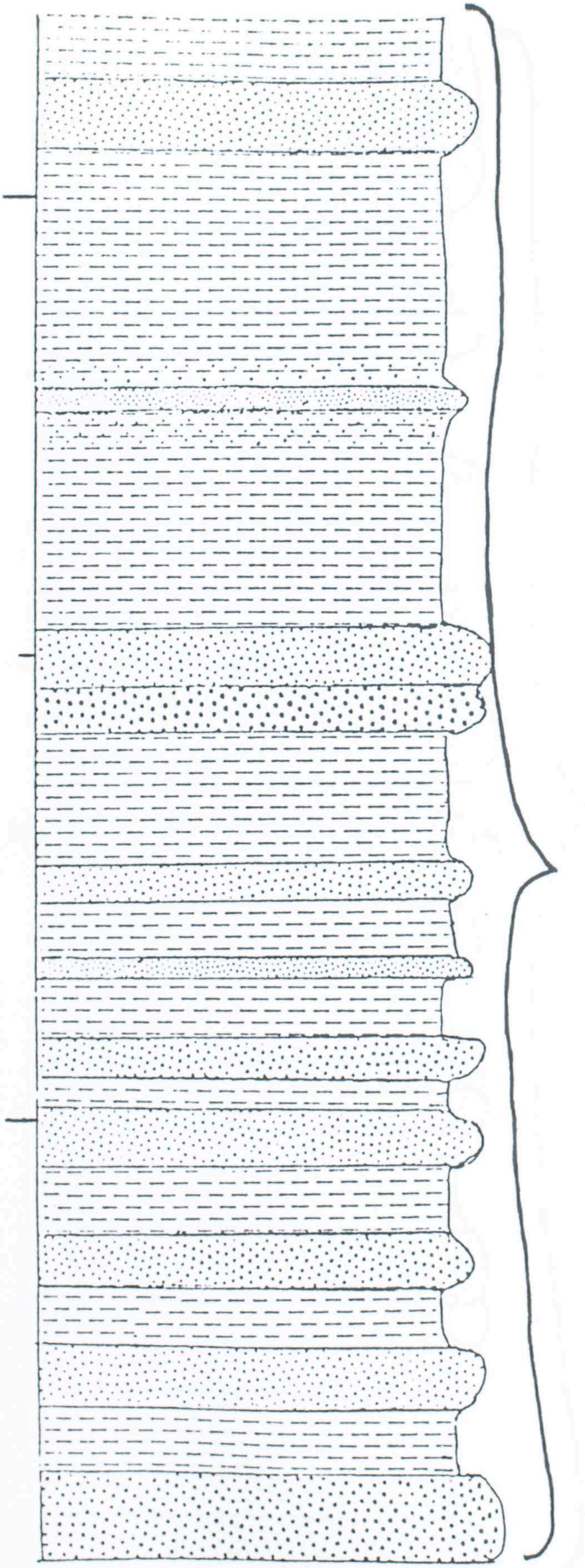
Core Stratigraphy

Location shown on Figure 3.

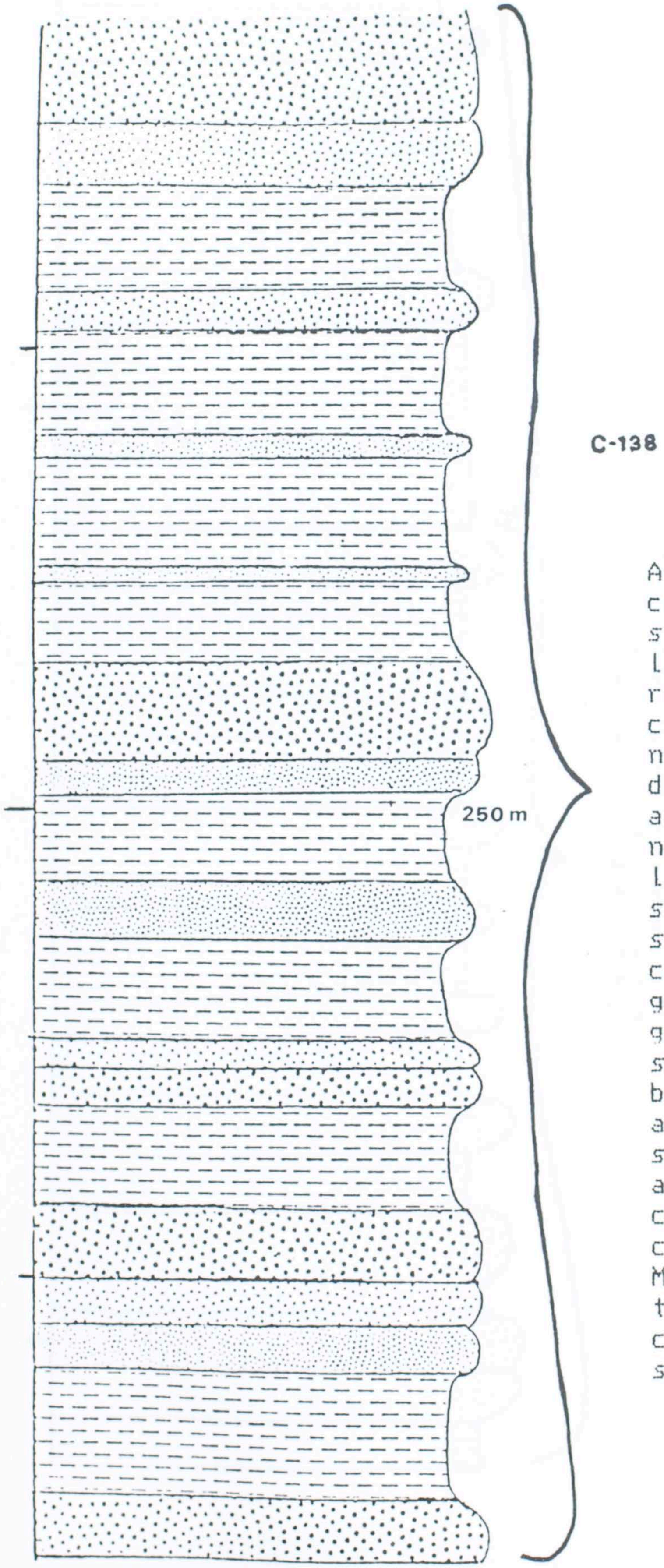


Well sorted medium- and fine-grained sandstone beds alternating with thinnly bedded shales mark an overall fining of deposition. The contact between the sandstones and shales are more gradational than the previous deposition. Calcite veins are present in fractures in the shale.

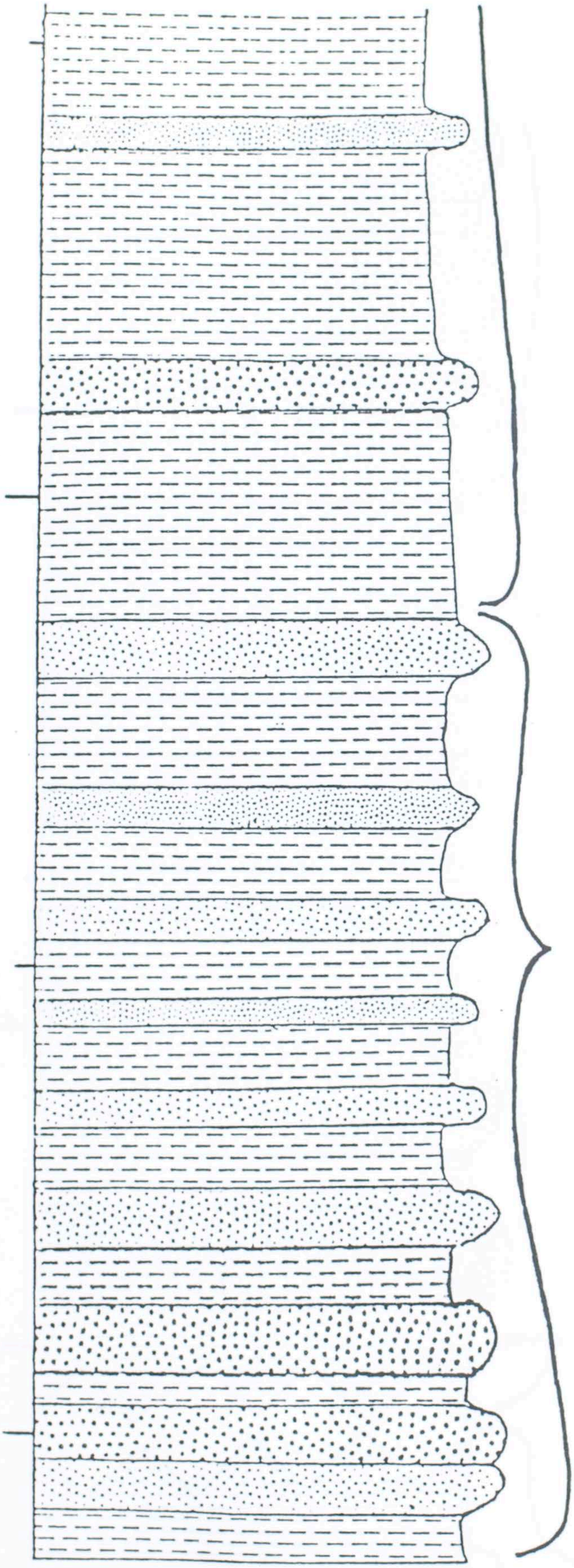
Deposition begins with alternating beds of shale and medium and very coarse-grained sandstones. The shales are thinnly bedded with parallel laminations. The shales are gray-black and the sandstones are gray. The very-coarse grained sandstone is poorly sorted and borders on being a pebble conglomerate. The medium-grained sandstones are fairly well sorted. The contacts between the sandstones and shales are abrupt, with the coarse-grained sandstones cutting down into the shale.



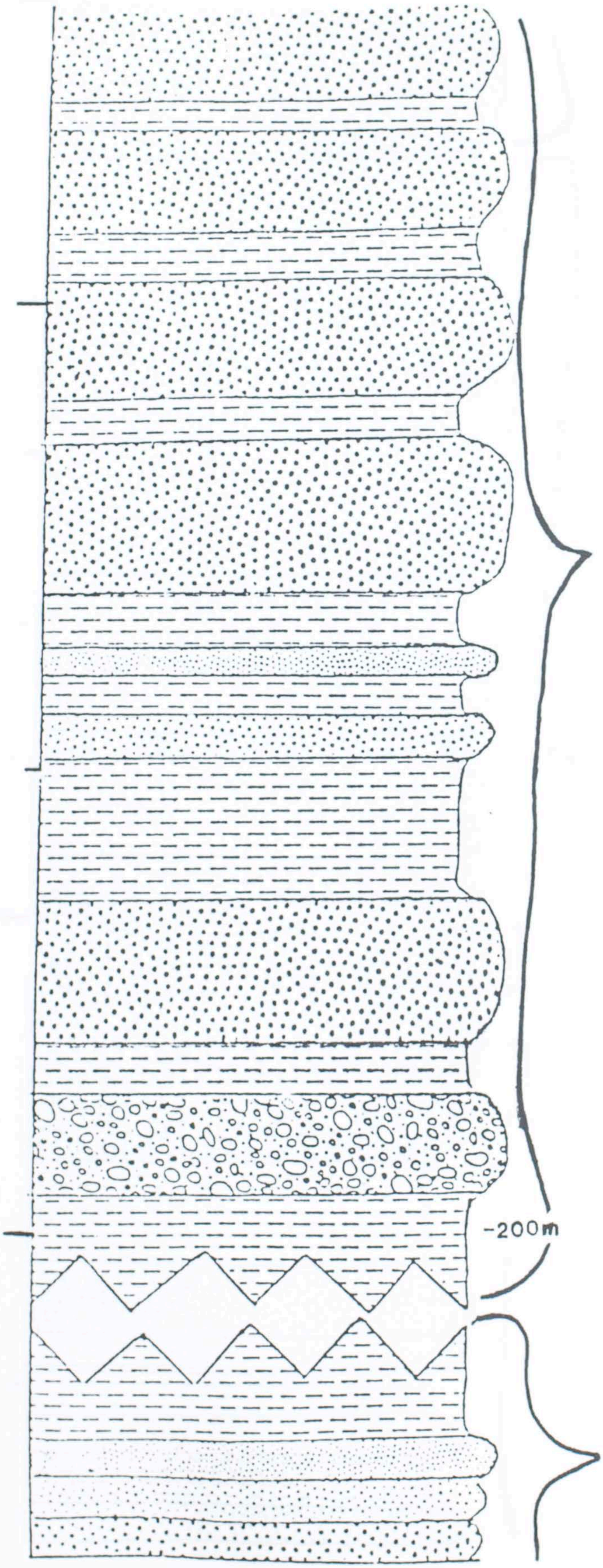
Deposition fines slightly as medium- and fine-grained sandstones and shales predominate. The contacts between these beds are gradational. One coarse-grained sandstone bed fines to medium-grained sandstone and then to alternating shale, fine-grained sandstones and siltstones. The contact between the siltstones and fine-grained sandstones is gradational. The shales are all thinnly bedded with planar laminations.



A poorly sorted, coarse-grained sandstone unit with angular mudclasts and rounded volcanic clasts marks the next sequence of deposition. It begins a sequence of alternating thinnly bedded, laminated shales and sandstones. The sandstones range from coarse- to fine-grained and are generally moderately sorted. Contacts between the shales and overlying sandstones are usually abrupt, with the coarser beds downcutting into shale. Mudclasts are seen in the two lowermost coarse-grained sandstone beds.

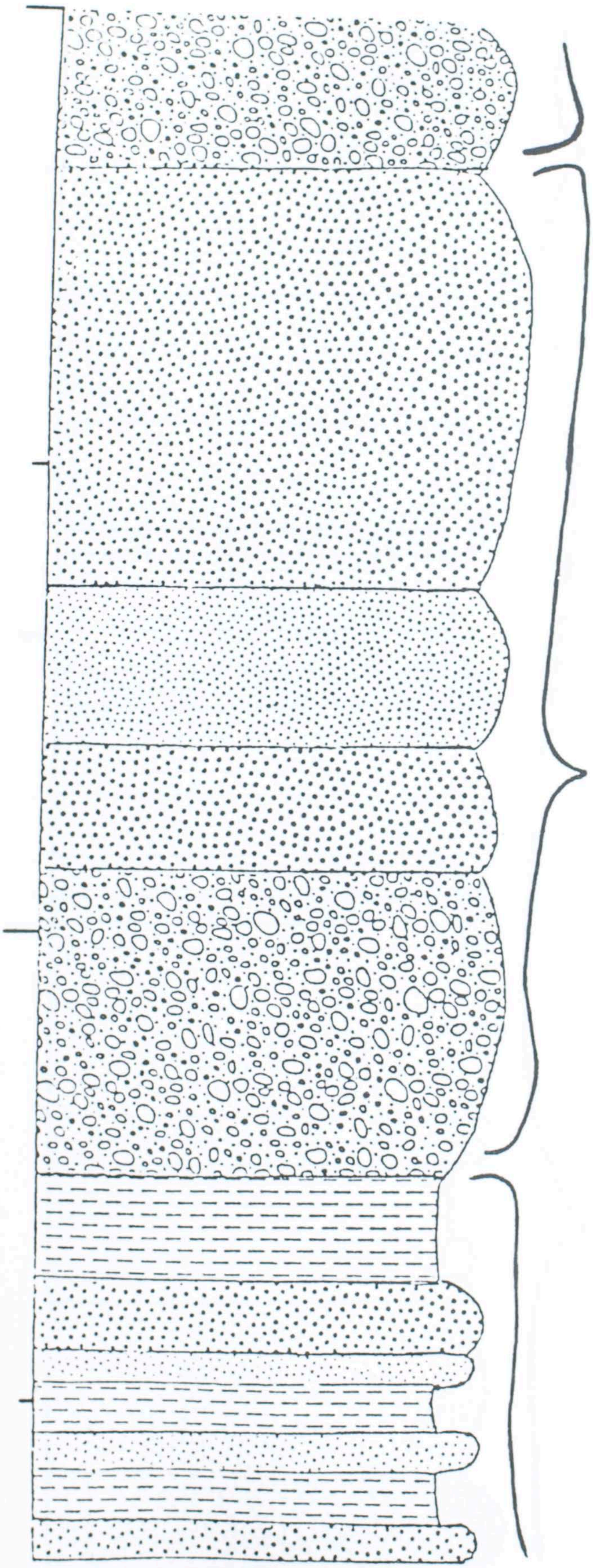


Alternating sandstones and shales predominate in the following section. These sandstones are moderately sorted and tend to have abrupt contact with the overlying shale. The shales are thinnly bedded and are becoming thicker between the sandstone beds.

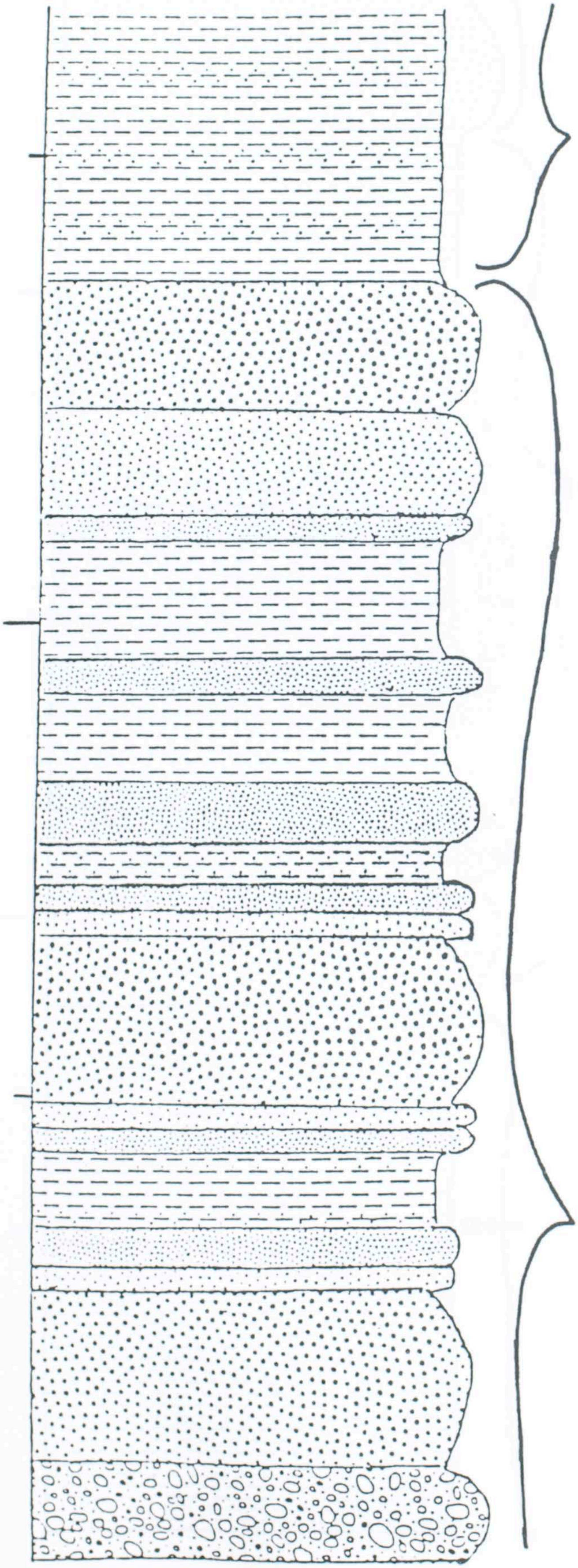


Ensuing deposition coarsens as a pebble conglomerate containing both angular mudclasts and rounded volcanic clasts. Alternating coarse- and medium-grained, moderately sorted sandstone and shale beds follow.

The next sequence of deposition consists of coarse-grained sandstone fining to medium-grained sandstone, to fine-grained sandstone, and then to shale.
A break in the section is made as the next 12m of deposition consists of alternating sandstones, siltstones, and shales identical to deposition in the last 10m.

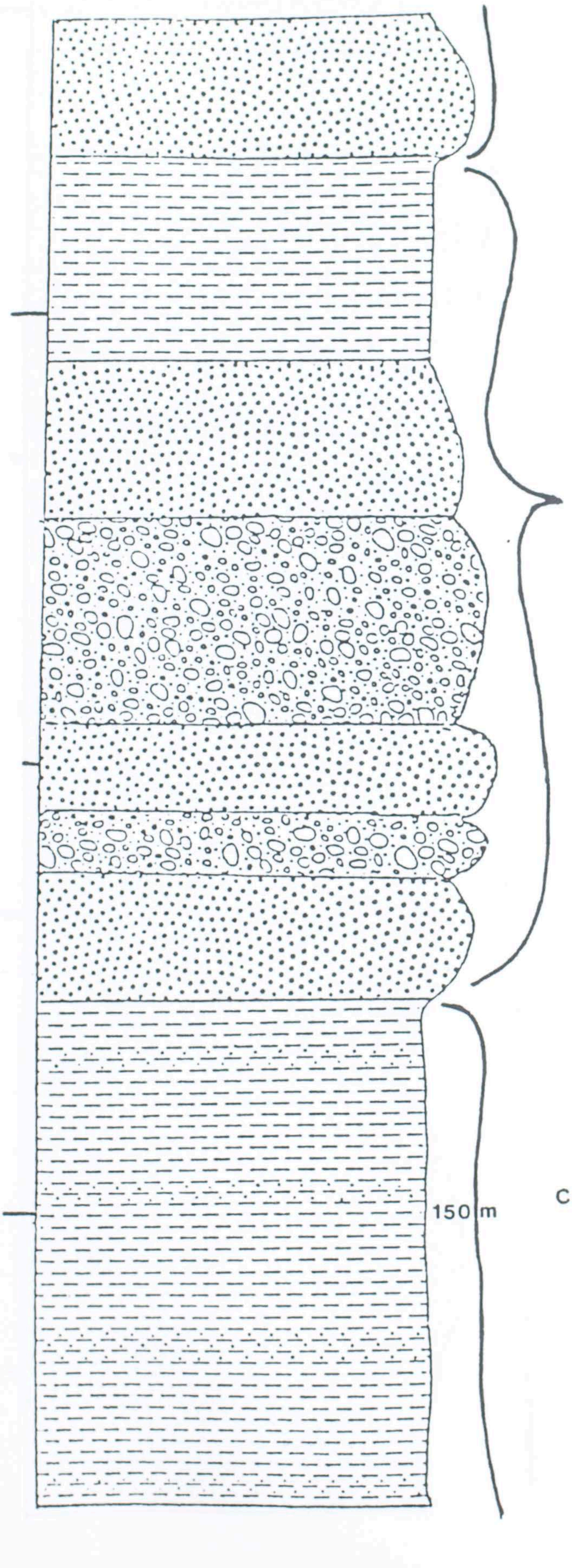


At -183m, very coarse-grained deposition ensues as a poorly sorted pebble conglomerate grades into a coarse-grained, poorly sorted sandstone to a medium-grained, moderately sorted sandstone. Next, the section coarsens upward again. These beds are several meters thick.

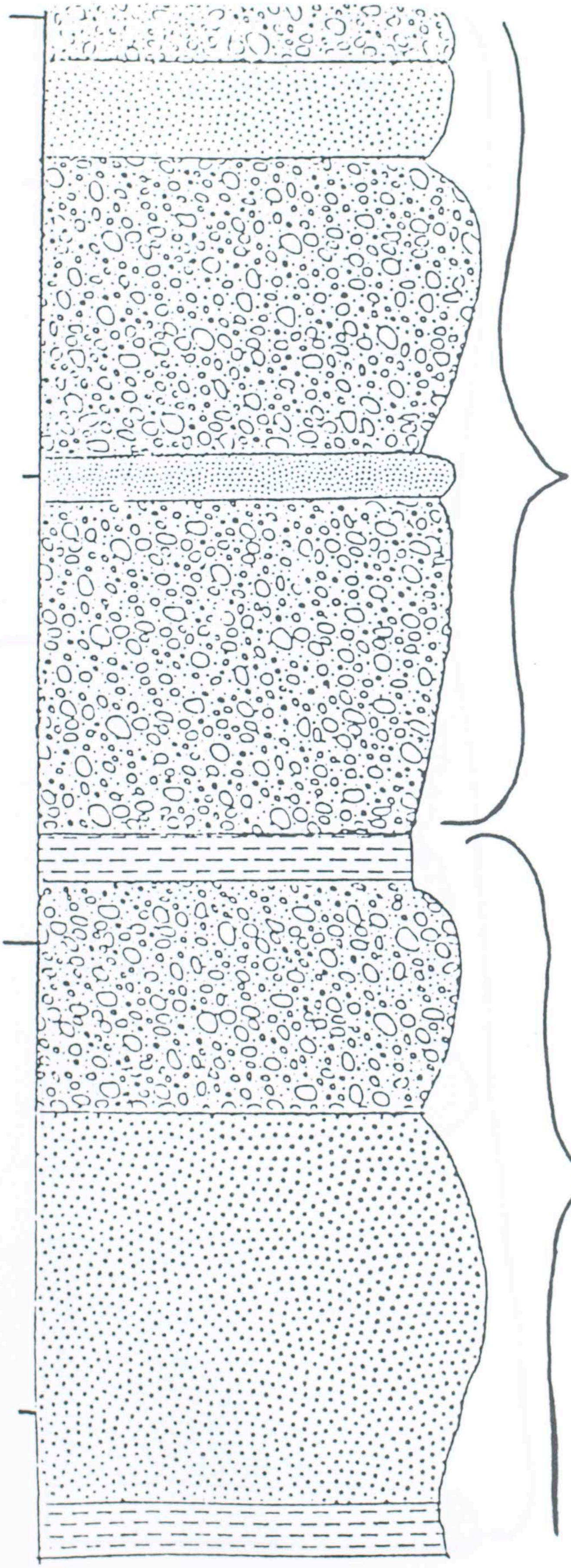


At -**156** m deposition fines to alternating sitlstone and shale beds. The recovery of the core in this sequence is very poor as the shale is very friable. The shales in this sequence are thinnly bedded.

Deposition coarsens gradually and the next stage of deposition cosists of a pebble conglomerate gradationally fining to shale, then coarsening, and finally fining upward again. The coarse-grained sandstones are poorly sorted, but the finer sandstones are moderately well sorted.

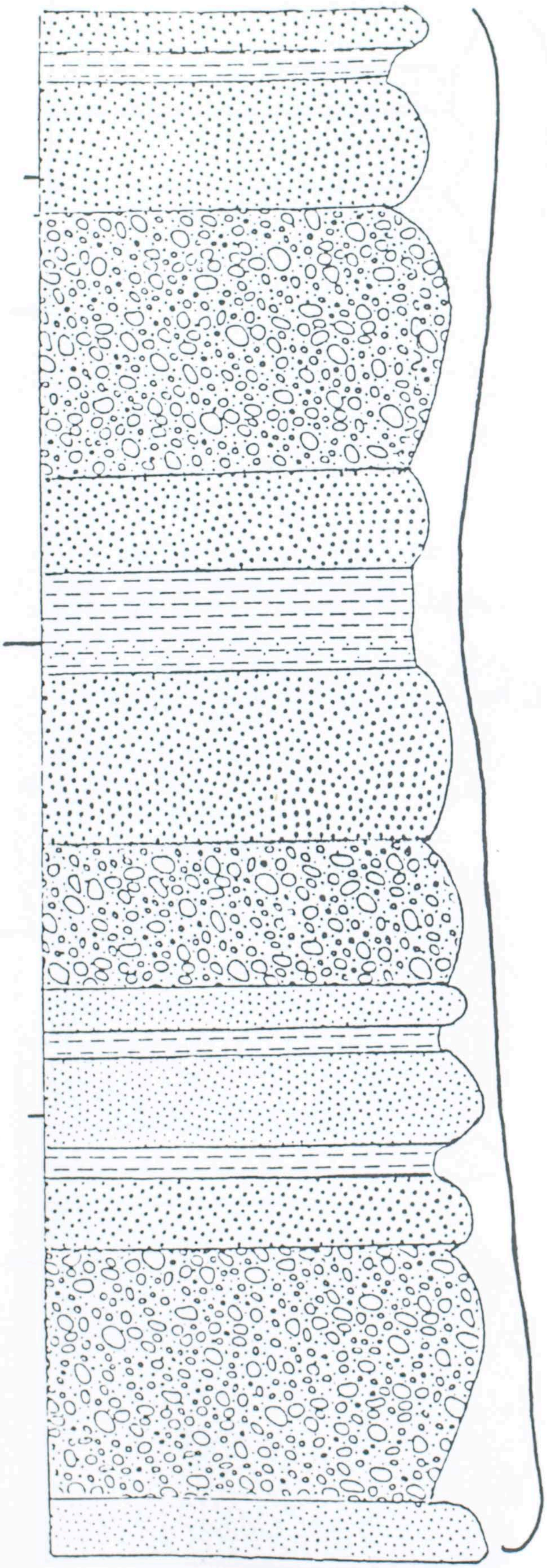


An abrupt contact between overlying coarse-grained sandstone and shale marks the resumption of coarse-grained deposition. This coarse-grained sandstone grades into a pebble conglomerate and then alternates coarse-grained sandstone and pebble conglomerate. Overlying deposition consists of alternating coarse-grained sandstones, pebble conglomerate, and thick shale units. The shale in this sequence was unconsolidated and core recovery was poor. The coarse-grained sandstones are poorly sorted, but as the sandstones become finer the sorting is better.

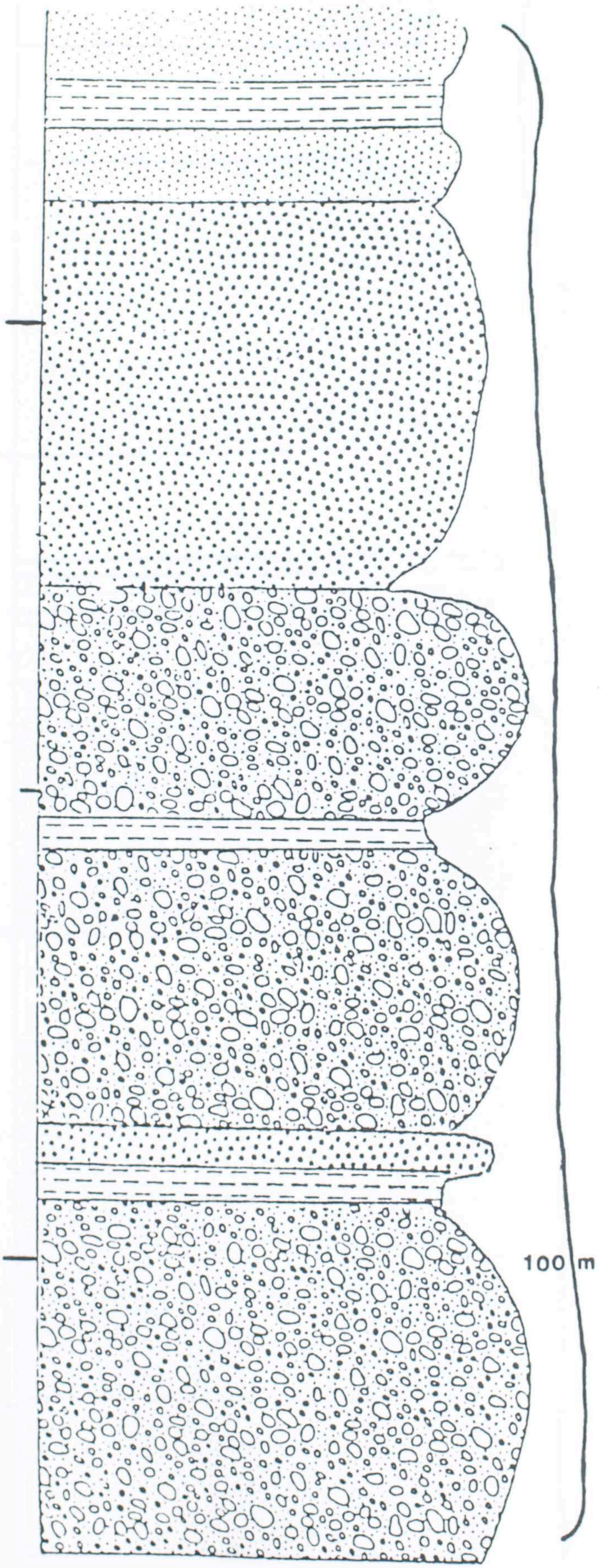


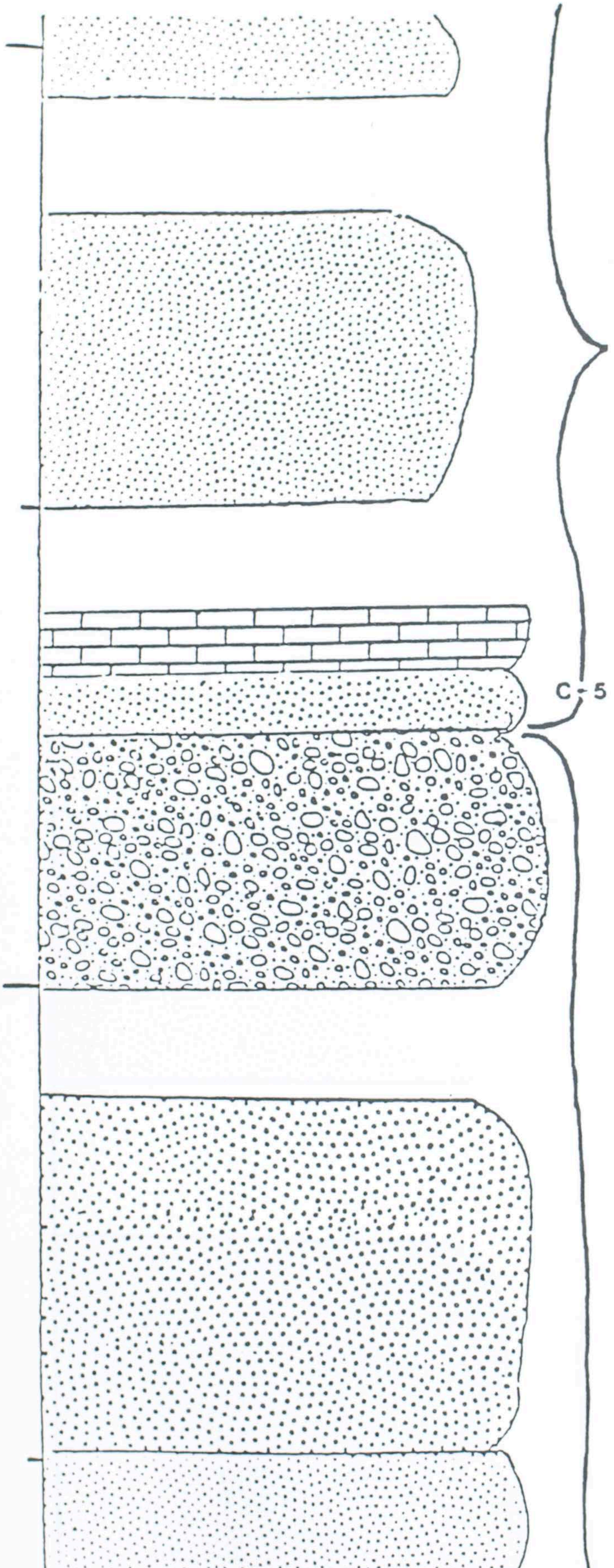
Deposition of coarse, cobble-sized, poorly sorted conglomerate with rounded volcanic clasts and a clay matrix predominates. Between these thick conglomerate beds are sandstone and shales. The uppermost conglomerate contains mudclasts, possibly derived from the underlying shale. The contacts between the conglomerates and the underlying beds are generally sharp but may be gradational at the upper contact. Calcite veins run throughout the sequence infilling cracks in the shale and sandstone beds.

Overlying the shale, a very thick, coarse-grained sandstone grades into a cobble-sized conglomerate. The conglomerate consists of both volcanic clasts and mudclasts. The mudclasts are angular, whereas the volcanic clasts are rounded. Overlying is a thinnly bedded shale with little recovery.

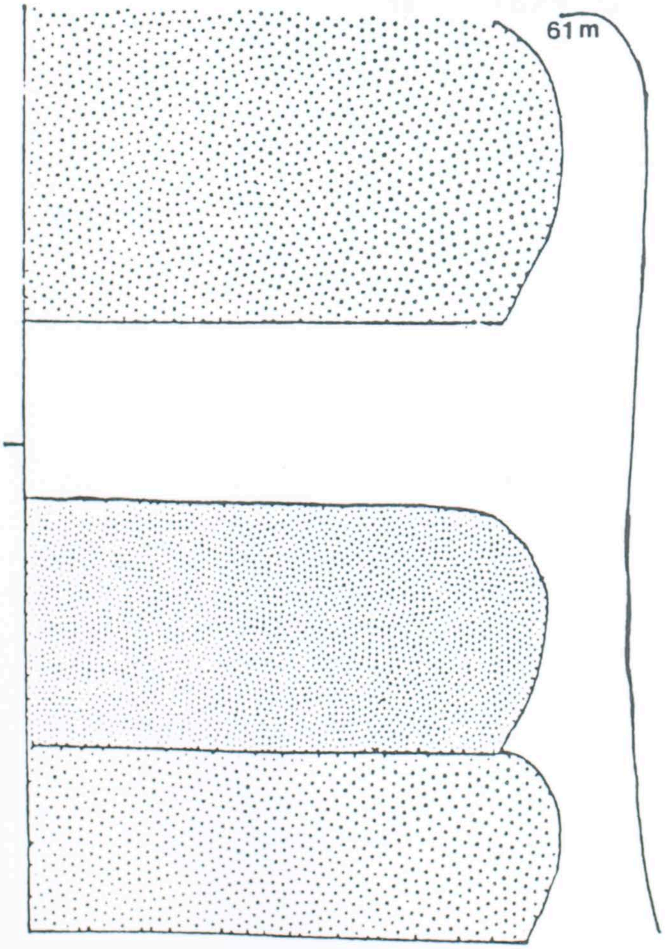


C-36


100 m



The final sequence of deposition consists of medium- and fine-grained, well sorted, and subrounded sanstones. In several places on the core no analysis was possible for several feet due to no recovery. These areas are represented on the column by the blank portions. These intervals probably represent shale beds which were too unconsolidated to recover. The sandstone beds were well consolidated. A micritic limestone, tan in color and containing fossils, occurs at about -76m.



TOP OF CORE
(Note: Upper portion not
recovered)

Appendix III
Thin Section Descriptions

Sample Number	Mineralogy and Petrologic Description	Name	Average Grain Size	Sorting and Rounding
W-1-2a	51% feldspar, 17% VFR, 17% clay, 9% MRF, 3% opaques, 3% porosity, trace *SRF* (chert); clay matrix, VRFs are plagioclase with a clay groundmass, feldspars are altered to calcite, MRFs are serpentines An12 and An18 (or An24 and An28).	lithic arenite	0.31mm medium sandstone	σ=.38 well sorted range from R=3.1 (feldspar) to R=4.2 (MRF)
W-1-2b1	59% feldspar, 4% VRF, 2% *SRF*(chert), 24% clay, 9% MRF, 2% opaques; feldspars are altered to calcite (85%), clay is both matrix and grain alteration	arkose	0.31mm medium sandstone	σ=1.38 poorly sorted range from R=2.8 (feldspar) to R=3.6 (MRF)
W-1-2b2	5% quartz, 33% feldspar (20% plagioclase, 13% orthoclase), 38% VRF, 9% MRF, 1% *SRF* (chert), 7% clay, 3% opaques, 2% calcite, 2% gibbsite; feldspar is both cement and grains, clay forms grain coat, VRFs are altered to clay and gibbsite, MRFs are serpentine	feldspathic litharenite	0.08mm very fine sandstone	σ=0.98 moderately sorted range from R=2.3 (quartz) to R=3.1 (feldspar)
W-1-2d2	36% feldspars, 2% VRFs, 11% MRFs, 50% clay, 1% opaques; feldspars 60% altered	lithic arkose	0.77mm coarse sandstone	σ=0.50 well sorted range from R=1.8 (VRF)

	to calcite, clay both alteration on VRFs and matrix, VRFs are plagioclase phenocrysts in clay groundmass, MRFs are serpentines			to R=2.2 (feldspar)
W-1-2f	2% quartz, 14% feldspars, 22% VRFs, 25% clay, 5% porosity, 32% MRF; feldspars have minor gibbsite alteration, VRFs have both plagioclase and mafic phenocrysts, clay occurs as both alteration and matrix	feldspathic litharenite	0.14mm fine sandstone	σ=0.48 well sorted range from R=3.0 (feldspar) to R=4.1 (MRF)
W-1-2d1	64% feldspar, 30% clay, 6% MRFs (serpentine); feldspars are 75% altered to calcite, trace opaques, clay is both matrix and alteration product	arkose	0.03mm medium siltstone	σ=1.00 poorly sorted range from R=2.2 (MRF) to R=2.4 (feldspar)
W-2-1a1	one large VRF (10% plagioclase, 72% groundmass, 3% opaques, 15% hornblende); groundmass is altered clay, hornblende has chlorite alteration	clast		
W-2-1a2	33% feldspar, 36% VRF, 30% clay, 1% gibbsite, trace chert; chlorite and biotite alterations occur on mafic phenocrysts in VRFs, feldspar has sericite alteration but only 1% calcite alteration, clay occurs as both matrix and VRF alteration	feldspathic litharenite	0.65mm coarse sandstone	σ=2.00 poorly sorted range from R=2.3 (feld- to R=4.0 (VRF)

W-2-1c	1% quartz, 31% feldspar, 8% VRF, 20% MRF, 1% SRF, 9% clay, 3% porosity, 27% opaques; the feldspars are 2% altered to calcite, trace of fossils, MRFs are 19% altered pyroxenes and amphiboles and 1% serpentine, the opaques occur in layers within the rock	lithic arkose	0.37mm medium sandstone	$\sigma=0.45$ well sorted range from R=3.1 (VRF) to R=2.1 (MRF)
W-2-1f2	48% feldspar, 10% VRF, 16% MRF, 1% SRF 4% clay, 8% porosity, 13% calcite, 1% opaques; 27% of the feldspars are completely altered to calcite with minor sericite alteration, clay occurs as grain coating, the cement is calcite, both micritic and sparry	lithic arkose	0.10mm very fine sandstone	$\sigma=0.35$ very well sorted range from R=3.8 (MRF) to R=3.0 (feldspar)
W-2-1z2	12% feldspar, 70% VRF, 13% clay, 5% porosity; 9% of the feldspars are altered to calcite and minor sericite, VRFs have both calcite alteration on feldspars and clay alteration of matrix, VRFs are plag microlites with clay matrix, clay occurs as matrix	volcanic-arenite	0.75mm coarse sandstone	$\sigma=1.50$ poorly sorted range from R=1.5 (feldspar) to R=3.1 (VRF)
W-2-1z3	2% plagioclase, 85% VRF, 2% MRF, 1% clay, 9% micrite cement, 1% opaques; sericite alteration on all feldspars, MRFs are serpentine, VRFs are	volcanic-arenite	4.96mm pebble	$\sigma=8.50$ extremely poorly sorted range from R=2.1 (feldspar) to

	unaltered feldspar in clay groundmass, great zonation in plagioclases			R=4.3 (serpentine)
W-2-1z4	one VRF (20% plagioclase phenocrysts, 20% mafics altered to chlorite phenocrysts, 60% clay groundmass)	clast		
W-2-2a1	one VRF (35% plagioclase phenocrysts with 70% alteration to calcite, 65% clay); small amount of clay matrix	clast		
W-2-2b	bryozoan, crinoid fragments, echinodermata spines, 25% quartz, 8% feldspar in a micritic cement, the quartz and feldspar are fairly unaltered but the fossils are completely micritized	intraclast-bearing biomicrudite (fossiliferous packstone)		
W-2-11a	11% feldspar, 70% VRF, 9% clay, 6% porosity, 4% calcite, trace chert; see 9% calcite alteration on the feldspars, clay occurs as rim, see trace of gibbsite alteration	volcanic-arenite	0.96mm coarse sandstone	σ=1.25 poorly sorted range from R=2.1 (feldspar) to R=3.1 (VRF)
W-4-1a1	2% quartz, 31% feldspar, 11% VRF, 42% micrite, 10% clay, 1% porosity, 1% opaques, 2% MRF; 21% feldspars altered to calcite, VRFs have both plagioclase and altered mafics mineral phenocrysts,	lithic arkose	0.14mm fine sandstone	σ=0.50 well sorted range from R=0.9 (quartz) to R=3.1 (MRF)

	micrite occurs as both cement and alteration			
W-4-1a2	4% quartz, 2% feldspar, 5% VRF, 5% clay, 37% micrite, 29% MRF, 12% sparry calcite, 6% gibbsite; much sericite alteration on the feldspars, VRFs are altered to gibbsite, sparry calcite occurs as alteration (probably feldspars), micrite occurs as alteration and cement, clay coats a few grains	phyllarenite	0.17mm fine sandstone	σ=0.95 moderately sorted range from R=1.5 (quartz) to R=3.0 (MRF)
W-4-1a3	1% quartz, 28% feldspar, 11% VRF, 10% SRF, 2% clay, 19% MRF (serpentine), 29% micrite, only 3% of the feldspars are unaltered, micrite occurs both as grain alteration and cement, clay occurs as alteration	lithic arkose	0.93mm coarse sandstone	σ=0.88 moderately sorted range from R=1.2 (quartz) to R=3.1 (MRF)
W-4-1ff	4% quartz, 24% feldspar (3% orthoclase, 21% plagioclase), 1% SRF (chert), 13% clay matrix, 3% MRF; VRF phenocrysts are all plagioclase and mafic minerals altered to biotite, clay forms both rim and matrix, feldspars are relatively unaltered	feldspathic litharenite	0.40mm medium sandstone	σ=1.13 poorly sorted range from R=1.8 (quartz) to R=3.0 (VRF)
W-4-1f	recrystallized fossils are too obliterated to determine exact	fossiliferous wackstone		

	compositions, only identifiable fossils are forams, micrite cement	(biomicrite)		
W-5-1b	78% feldspar, 17% calcite cement, 2% opaques, 3% fossils; feldspars are completely recrystallized to calcite, fossils are echinodermata spines and forams, the cement is micritic calcite	arkose	0.23mm fine sandstone	σ=1.13 poorly sorted range from R=2.9 (feldspar) to R=5.5 (fossils)
W-5-1c	2% quartz, 54% feldspar, 38% micrite, 1% MRF, 5% fossils; the feldspars are altered to both sparry calcite (14%) and micrite, micrite includes both cement and alteration, MRF is serpentine, fossils are forams	arkose	0.38mm medium sandstone	σ=0.91 moderately sorted range from R=2.8 (feldspar) to R=5.5 (fossils)
W-5-3a	24% feldspar (21% altered to calcite), 33% VRF (2% altered to calcite), 35% micrite, 5% clay, 3% opaques; VRFs have both calcite (2%) and chlorite (16%) alteration on phenocrysts and gibbsite alteration, trace of serpentine, micrite is both alteration and cement	feldspathic litharenite	0.24mm fine sandstone	σ=0.30 very well sorted range from R=2.6 (feldspar) to R=3.1 (VRF)
W-5-3b	3% quartz, 19% feldspar, 29% VRF, 23% MRF (serpentine), 6% clay, 4% porosity, 8% gibbsite, 8% opaques, clay forms a matrix, MRFs are serpentine, feldspars are ex-	feldspathic litharenite	0.12mm very fine sandstone	σ=0.85 moderately sorted range from R=2.0 (quartz) to R=3.3 (MRF)

	tremely (95%) altered to calcite			
W-5-3f	3% quartz, 20% feldspar, 19% VRF, 9% MRF, 27% clay, 19% porosity, 1% opaques, 2% sanidine; the clay represents both VRF alteration and clay matrix, Carlsbad twinning angles on the plagioclase represent An2 or An36, feldspars have minor sericite alteration	feldspathic litharenite	0.12mm very fine sandstone	σ=0.63 moderately well sorted range from R=2.1 (feldspar) to R=2.7 (VRF)
W-6-2a1	1% quartz, 22% feldspar, 43% VRF, 8% clay, 26% MRF, trace SRF (chert); 1% of feldspar totally altered to calcite with rest having minor alteration, 30% of VRFs altered to clay, the MRFs are biotite and chlorite altered mafic minerals, clay forms the matrix	volcanic-arenite	0.29mm medium sandstone	σ=1.00 poorly sorted range from R=2.8 (feldspar) to R=3.2 (quartz/VRF)
W-6-3a2	2% quartz, 42% feldspar, 13% VRF, 4% opaques, 30% MRF, 9% clay; feldspars are fairly altered, VRFs have plagioclase and mafic minerals as phenocrysts, quartz has undulose extinction, clay forms matrix, MRFs are both sepentine and altered mafic minerals	phyllarenite	0.12mm very fine sandstone	σ=0.61 moderately well sorted range from R=2.8 (feldspar) to R=3.1 (MRF)
W-6-3a1	51% feldspar, 8%% feldspar altered to	lithic arkose	0.14mm fine	σ=0.58 moderately

	calcite, 12% VRF, 7% porosity, 14% MRF; feldspars are altered to sericite and calcite, VRFs have mostly plagioclase phenocrysts, MRFs are both serpentine and altered mafic minerals, porosity probably resulted from clay dissolution during thin section construction		sandstone	well sorted R=2.6 (feldspar) to R=2.2 (VRF)
W-6-3a3	4% quartz, 50% feldspar, 27% VRF, 2% clay, 3% MRF, 14% opaques; not much cement to this rock, just a clay matrix, MRFs are biotite and chlorite alteration of pyroxene or amphibole, VRFs have both plagioclase and mafic phenocrysts	lithic arkose	0.11mm very fine sandstone	σ=0.53 moderately well sorted range from R=1.5 (qtz) to R=2.5 (VRF)
W-7-1b	18% plagioclase, 60% VRF, 28% clay, (10% of clay is one mudclast), 5% MRF, 1% opaques; feldspars all show sericite alteration, the clay represents both VRF alteration and matrix, VRFs have mostly plagioclase phenocrysts, MRFs are serpentine	volcanic-	0.27mm medium sandstone	σ=0.35 well sorted range from R=2.0 (feldspar) to R=2.6 (VRF)
W-7-1c1	18% quartz, 33% feldspar (5% altered to calcite), 10% VRF, 4% clay, 13% opaques, 9% porosity, 13% MRF; feldspar alters to calcite in different	lithic arkose	0.16mm fine sandstone	σ=0.85 moderately sorted range from R=2.3 (qtz) to R=2.9 (VRF)

	zones, VRFs have mostly plagioclase phenocrysts, quartz has undulose extinction			
W-7-1c2	79% feldspar, 11% VRF, 7% porosity, 3% calcite; VRFs are very plagioclase-rich, trace of serpentine, see minor calcite alteration on the feldspars, porosity represents dissolution of clay matrix	arkose	0.18mm fine sandstone	$\sigma=0.40$ well sorted range from R=2.9 (feldspar) to R=3.3 (VRF)
W-7-2a1	17% feldspar, 66% VRF, 2% clay, 7% cement, 2% MRF, 3% gibbsite, 1% opaques, 2% calcite; the VRFs have trachytic texture of plagioclase microlites, the feldspars display zonation, cement is sparry calcite, gibbsite is alteration on VRFs and clay	volcanic-arenite	1.07mm very coarse sandstone	$\sigma=0.50$ well sorted range from R=2.0 (feldspar) to R=3.4 (VRF)
W-7-2a2	1% quartz, 10% feldspar, 3% feldspar altered to calcite, 76% VRF, 3% clay, 4% cement, 3% calcite pore-fill; most of the VRFs consist of plagioclase in clay groundmass, trace MRF (serpentine), less than 1% of VRFs are altered to calcite, inoceramus fossil	volcanic-arenite	0.47mm medium sandstone	$\sigma=0.53$ moderately sorted range from R=2.1 (feldspar) to R=3.1 (VRF)
W-7-2a3	23% feldspar, 67% VRF, 2% clay, 1%	feldspathic	0.59mm coarse	$\sigma=0.75$ moderately

	gibbsite, 6% calcite, 1% MRF; calcite is alteration on VRFs and cement, clay occurs as rims, VRFs are all plagioclase and altered clay groundmass, gibbsite is feldspar alteration	litharenite	sandstone	sorted range from R=2.7 (feldspar) to R=4.2 (VRF)
W-7-1d	4% plagioclase, 6% othoclase, 1% feldspar altered to calcite, 47% altered VRF, 2% MRF, 1% SRF, 1% clay, 19% cement, 1% porosity; trace of calichite, most alterations on VRFs to clay, but at least one alteration to calcite, cement is sparry calcite (An12 or An28 from angles taken	feldspathic litharenite	0.35mm medium sandstone	σ=0.45 well sorted range from R=2.4 (plagioclase) to R=3.6 (MRF)
W-7-1g1	83% VRF, 8% MRF, 1% SRF, 1% clay, 1% calcite, 5% feldspar cement, 1% micritized grains; VRFs are mostly plagioclase altered to clay groundmass, calcite occurs as pore-fill, about 30% of MRFs have mafic minerals. MRFs are serpentine	volcanic-arenite	0.73mm coarse sandstone	σ=1.50 extremely poorly sorted range from R=1.9 (MRF) to R=3.2 (VRF)
W-7-1g2	3% feldspar, 85% VRF, 9% calcite cement, 1% MRF; mostly VRFs with plagioclase phenocrysts in an altered-to-clay groundmass, calcite cement is sparry, MRF is altered amphibole	volcanic-arenite	1.33mm very coarse sandstone	σ=0.30 very well sorted range from R=2.1 (feldspar) to R=3.7 (VRF)

W-7-1g3	1% quartz, 94% VRF, 4% cement, 1% MRF; cement is sparry calcite, the VRFs have mostly plagioclase phenocrysts, but some have mafic minerals, MRF is serpentine	volcanic-arenite	2.21mm granule	σ=1.63 poorly sorted range from R=2.5 (quartz) to R=4.0 (VRF/MRF)
W-7-1h	3% quartz, 25% feldspar, 6% feldspar altered to calcite, 14% porosity, 16% opaques, 5% MRF, 31% VRF; the MRFs are altered to chlorite pyroxenes, the porosity is due to dissolution of clay matrix during thin section construction	feldspathic litharenite	0.09mm very fine sandstone	σ=1.25 poorly sorted range from R=1.9 (quartz) to R=3.6 (MRF/VRF)
W-7-1aa	8% plagioclase, 1% orthoclase, 74% VRF, 3% SRF (chert), 6% porosity, 6% feldspar cement, 2% MRF (serpentine); VRFs are plagioclase with altered-to-clay groundmass, porosity due to clay dissolution during thin section construction	volcanic litharenite	0.34mm medium sandstone	σ=0.88 moderately sorted range from R=1.8 (feldspar) to R=3.0 (MRF)
W-8-1a1	18% feldspar. 3% feldspar altered to calcite, 44% VRF, 8% clay, 19% feldspar cement, 7% MRF, 1% opaques, trace SRF (chert); VRFs are plagioclase-rich with clay groundmass, MRFs are serpentines and altered amphiboles	feldspathic litharenite	0.10mm very fine sandstone	σ=0.70 moderately sorted range from R=2.9 (feldspar) to R=3.7 (VRF)

	pyroxenes			
W-8-1a2	1% quartz, 18% plagoclase, 6% feldspar altered to calcite, 57% VRF, 11% clay, 5% MRF, 1% opaques, 1% calcite. VRFs are all plagioclase with clay groundmass, feldspars have minor sericite alteration clay forms matrix, MRFs are 1% serpentine and 4% amphiboles	feldspathic lith-arenite	0.13mm fine sandstone	σ=0.90 moderately sorted range from R=2.1 (quartz) to R=3.2 (MRF)
W-8-1b	4% feldspar, 9% feldspar altered to calcite, 77% clay, 2% MRF, 6% opaques, 2% fossils; fossils are all forams that are now recrystallized to calcite, clay may be alteration of VRFs (too obliterated to determine, MRFs are serpentine	arkose	0.10mm very fine sandstone	σ=0.30 very well sorted range from R=2.9 (feldspar) to R=3.9 (fossils)
W-8-1c	89% VRF, 5% SRF, 3% clay, 1% opaques; VRFs are plagioclase phenocrysts in a clay groundmass with pyroxenes and amphibolets, SRF is chert, minor gibbsite alteration on VRFs	volcanic-arenite	2.04mm granule	σ=0.50 moderately sorted range from R=2.4 (VRF) to R=2.9 (SRF)
W-9-2b	1% quartz, 70% feldspar, 4% feldspar altered to calcite, 20% microspar. 3% opaques, 2% MRF; microspar is cement, micritized grains occur	arkose	0.11mm very fine sandstone	σ=0.65 moderately sorted range from R=2.1 (quartz) to R=3.3 (MRF)

	(possibly fossils) minor gibbsite alteration on feldspars			
W-10-1b1	2% quartz, 5% feldspar, 1% feldspar altered to calcite, 54% VRF, 10% clay grains, 9% porosity, 10% cement (sparry calcite), 2% opaques, 2% MRF, 7% fossils	volcanic-arenite	0.67mm coarse sandstone	σ=0.58 moderately sorted range from R=1.0 (fossils) to R=2.5 (VRF/feldspar)
W-10-1b2	3% feldspar, 1% feldspar altered to calcite, 80% VRF, 1% VRF altered to calcite, 5% SRF, 5% porosity, 4% fossils, 1% calcite pore-fill; most feldspars unaltered, SRFs are 3% mudclasts and 2% chert, trace clinopyroxene (MRF)	volcanic-arenite	0.16mm fine sandstone	σ=0.88 moderately sorted range from R=1.9 (feldspar) to R=3.0 (fossil)
W-10-1c1	2% feldspar, 70% VRF, 1% ofVRF altered to calcite, 2% clay, 21% calcite, 1% opaques, 1% gibbsite, 2% MRF (serpentine); calcite is both cement and alteration, VRFs are both plagioclase- and mafic mineral-rich	volcanic-arenite	0.71mm coarse sandstone	σ=1.38 poorly sorted range from R=1.5 (feldspar) to R=3.5 (MRF)
W-10-1d1	10% feldspar, 89% VRF, 1% opaques; feldspars completely altered to calcite, VRFs completely altered to gibbsite	volcanic-arenite	0.54mm coarse sandstone (feldspar)	σ=1.29 poorly sorted R=2.6 (feldspar)
W-10-1d2	6% feldspar, 7% feldspar altered to calcite, 42% VRF,	volcanic-arenite	0.91mm coarse sand-	σ=1.25 poorly sorted

	1% SRF (chert), 32% clay, 6% porosity, 6% gibbsite; VRFs are all clay, gibbsite is alteration on VRFs, clay is both matrix and VRF alteration		stone	range from R=2.0 (quartz) to R=3.4 (VRF)
W-10-1d3	one VRF: 18% bauxite alteration of feldspar phenocrysts, 72% clay groundmass	clast		
W-10-1g1	1% quartz, 8% feldspar, 73% VRF, 13% SRF (chert), 5% clay; VRFs are plagioclase and mafic mineral phenocrysts in a clay groundmass, clay forms matrix	volcanic-arenite	0.54mm coarse sandstone	σ=1.80 poorly sorted range from R=2.3 (quartz) to R=4.5 (SRF)
W-10-1g2	2% quartz, 8% feldspar, 66% VRF, 1% SRF (chert), 10% clay, 3% porosity, 10% opaques; contains both feldspar cement and clay matrix, VRFs are plagioclase phenocrysts in a clay groundmass	volcanic-arenite	0.70mm coarse sandstone	σ=1.53 poorly sorted range from R=1.5 (quartz) to R=2.4 (VRF)
W-10-1g3	2% quartz, 16% plagioclase, 69% VRF, 1% SRF (chert), 11% clay, 1% MRF (serpentine); VRFs are plagioclase phenocrysts with clay groundmass, clay forms both matrix and alteration of grains	volcanic-arenite	0.69mm coarse sandstone	σ=0.63 moderately well sorted range from R=2.6 (quartz/VRF) to R=2.8 (MRF)
W-10-2a	86% VRF, 9% clay, 2% porosity, 3% calcite; about 10% of VRFs are altered	volcanic-arenite	1.12mm very coarse sand-	σ=1.10 poorly sorted range from

	to gibbsite, clay forms matrix, calcite grains are altered feldspars		stone	R=2.2 (quartz) to R=3.5 (VRF)
W-11-1a1	46% plagioclase, 30% MRF, 10% calcite, 9% clay matrix, 5% opaques; MRFs are all serpentine, opaques are aligned parallel as if along bedding planes, plagioclases are very altered to sericite	lithic arkose	0.31mm medium sandstone	σ=0.41 well sorted range from R=2.6 (feldspar) to R=3.6 (MRF)
W-11-1a2	1% quartz, 16% plagioclase, 20% orthoclase, 27% VRF, 28% clay, 2% opaques, 6% calcite; the clay represents both cement and alteration upon grains, calcite is feldspar alteration, VRFs are mainly plagioclase with altered clay groundmass	lithic arkose	0.42mm medium sandstone	σ=0.35 very well sorted range from R=2.2 (plagioclase) to R=4.0 (VRF)
W-11-1d	6% quartz, 20% feldspar, 8% feldspar altered to calcite, 30% VRF, 12% clay, 12% porosity, 7% sparry calcite cement, 2% opaques, 8% fossils, 2% gibbsite, 13% MRF (altered mafic grains), fossils are too micritized to identify, VRFs are plagioclase phenocrysts in a clay groundmass	feldspathic litharenite	0.22mm fine sandstone	σ=0.425 well sorted range from R=1.2 (fossils) to R=3.6 (MRF)
W-11-1e1	23% feldspar, 4% feldspar altered to calcite, 17% VRF, 2% SRF (chert), 4%	lithic arkose	0.16mm fine sandstone	σ=0.60 moderately well sorted range from

	clay grains, 4% MRF (serpentine), 7% fossils, 1% opaques, 25% calcite (alteration and cement)			R=1.0 (feldspar) to R=3.6 (MRF)
W-11-1e2	35% feldspar, 27% VRF, 31% clay, 7% opaques; opaques occur as stringers concentrated in layers, minor gibbsite alteration on clay occurs as both alteration of grains and coating, VRFs are clay matrix with feldspars	lithic arkose	0.08mm very fine sandstone	σ=0.50 moderately well sorted range from R=2.7 (feldspar) to R=3.6 (VRF)
W-11-1i	2% quartz, 27% feldspar, 20% feldspar altered to calcite, 16% VRF, 1% SRF, 17% clay, 3% porosity, 11% MRF, 3% opaques; very altered grains in a clay matrix, MRFs are serpentine, opaques occur linearly through the rock, SRF is a mud clast	lithic arkose	0.93mm coarse sandstone	σ=1.10 poorly sorted range from R=2.0 (feldspar) to R=3.1 (MRF)
W-12-1a	1% quartz, 5% feldspar, 44% VRF, 1% VRF altered to calcite, 4% clay, 33% micrite, 11% MRF, 1% sparry calcite crack infill; feldspars are undergoing much (90%) calcite and sericite alteration, MRFs are serpentine, micrite represents both cement and grain alteration	volcanic-arenite	0.06mm coarse siltstone	σ=0.50 moderately well sorted range from R=2.0 (feldspar) to R=3.0 (MRF)
W-12-1c	41% feldspar, 4% feldspar altered to	lithic arkose	0.34mm medium	σ=1.03 poorly

	calcite, 24% VRF, 10% clay, 4% porosity, 17% opaques, trace chert, trace serpentine; the VRFs have both plagioclase and mafic minerals altered to chlorite and biotite as phenocrysts in a clay groundmass, clay forms matrix		sandstone	sorted range from R=2.0 (feldspar) to R=3.5 (VRF)
W-12-1e	6% quartz, 4% feldspar, 48% VRF, 3% clay, 21% sparry calcite, 3% gibbsite, 15% fossils, trace calichite; VRFs are plagioclase-rich, well-preserved fossils, sparry calcite is both cement and alteration of feldspars	volcanic-arenite	0.72mm coarse sandstone	σ=1.50 poorly sorted range from R=2.2 (quartz) to R=3.7 (VRF)
W-12-2c2	29% plagioclase, 21% orthoclase, 19% VRF, 24% clay 16% matrix and 8% grains), 1% porosity, 6% MRF; MRFs are both altered amphiboles and pyroxenes (3%) and serpentines (3%), VRFs have plagioclase phenocrysts in an altered-to-clay groundmass, clay forms matrix	lithic arkose	0.16mm fine sandstone	σ=1.00 poorly sorted range from R=2.0 (feldspar) to R=3.1 (MRF)
W-12-2d	trace quartz, 5% plagioclase, 1% orthoclase, 87% VRF, 4% clay, 3% porosity, trace MRF (serpentine); clay froms the	volcanic-arenite	0.34mm medium sandstone	σ=1.13 poorly sorted range from R=2.5 (feldspar) to R=3.5 (MRF)

	matrix, VRFs are very rich in phenocrysts with mafic minerals altered to biotite or chlorite, plagioclases have a composition of An9 (or An31)			
W-12-2g	carbonate rock: 52% micrite, 7% fossils, 1% opaques, 36% feldspar, 3% VRF, 1% sparry calcite alteration, trace MRF (serpentine); fossils are forams, opaques are inside fossils, VRFs have both plagioclase phenocrysts and altered to biotite and chlorite and mafic minerals	feldspar-rich biomicrite (feldspar-rich mudstone)		
W-12-2f2	24% feldspar, 13% feldspar altered to calcite, 36% VRF, 16% MRF, 7% clay, 1% porosity, 1% opaques, 2% calcite; VRFs have both plagioclase and mafic mineral phenocrysts. MRFs are altered mafic minerals, clay forms matrix, minor gibbsite alteration	feldspathic lith-arenite	0.20mm fine sandstone	σ=0.50 moderately well sorted range from R=1.9 (feldspar) to R=3.8 (MRF)
W-12-2i	2% quartz, 6% feldspar, 63% VRF, 29% clay; VRFs are plagioclase and mafic mineral phenocrysts in an altered-to-clay groundmass, trachytic texture in plagioclase phenocrysts, all	volcanic-arenite	0.42mm medium sandstone	σ=0.80 moderately sorted range from R=2.2 (feldspar) to R=3.2 (VRF)

	mafics are altered to biotite, the clay represents both matrix and alteration on VRFs			
W-13-1b1	16% feldspar, 60% VRF, 10% clay, 6% porosity, 5% opaques; VRFs and feldspar have much feldspar alteration, clay represents matrix, VRFs also have altered-to-clay groundmass	volcanic-arenite	0.20mm fine sandstone	σ=1.60 poorly sorted range from R=2.1 (feldspar) to R=3.4 (VRF)
W-13-1b2	10% plagioclase, 69% orthoiclase, 6% calcite, 7% clay, 8% VRF, sparry calcite occurs as cement, clay occurs as rims, trace of gibbsite, minor feldspar alteration, see calcite vein infill	arkose	0.05mm coarse siltstone	σ=0.73 moderately sorted range from R=2.3 (plagioclase) to R=3.3 (VRF)
W-13-1c1	VRF: 30% plagioclase, 1%MRF, 6% clay, 3% calcite, 2% opaques, 58% groundmass; feldspars have minor calcite (3%) and sericite alteration	clast		
W-13-1c2	VRF: 30% plagioclase, 11% MRF, 58% groundmass, 1% opaques; VRF has both mafic mineral and plagioclase phenocrysts, zonation pronounced in the feldspar, composition of An8 (or An30)	clast		
W-13-1c3	VRF: 30% plagioclase, 62% groundmass, 7% MRF, 1% opaques; have both plagioclase and	clast		

	mafic minerals phenocrysts in an alterd-to-clay groundmass			
W-13-1d	30% feldspar, 22% feldspar altered to calcite, 42% micrite, 4% sparry vein calcite, 1% opaques, 1% clay; micrite occurs as cement and grain alteration, trace micritized fossil	arkose	0.14mm fine sandstone	σ=0.38 well sorted R=2.8 (feldspar)
W-13-1dd	VRF: 35% plagioclase, 3% calcite alteration, 62% groundmass; groundmass is all clay, find albite twins which yield compositions of An10 (or An29)	clast		
W-14-1a2	VRF: 5% feldspar, 12% feldspar altered to calcite, 60% groundmass, 2% calcite vein infill, 20% gibbsite, 1% calichite	clast		
W-14-1a3	VRF: 25% feldspar, 5% feldspar altered to calcite, 63% groundmass, 7% mafic mineral phenocrysts; groundmass is all altered-to-clay groundmass	clast		
W-14-1c1	2% plagioclase, 5% orthoclase, 72% VRF, 2% MRF, 19% clay; clay forms matrix, VRF 99% altered to gibbsite, feldspars are relatively unaltered, clay forms matrix and	volcanic-arenite	1.32mm very coarse sandstone	σ=2.75 very poorly sorted range from R=2.2 (plagioclase) to R=4.8 (MRF)

	grain alteration			
W-14-1c2	74% VRF, 21% calcite (both micrite and sparry), 1% clay, 3% MRF, 1% fossils; sparry calcite forms cement (11%), micrite is alteration of VRF and pore-fill, fossil is echinoid, MRFs are altered amphiboles	volcanic-arenite	2.30mm granule	σ=4.25 extremely poorly sorted range from R=2.5 (MRF) to R=4.5 (fossil)
W-16-1b1	trace quartz, 10% feldspar, 13% feldspar altered to calcite, 66% VRF (1% altered to calcite), 4% clay rim, 5% porosity, 2% opaques; VRFs are mostly plagioclase phenocrysts with a few mafic mineral phenocrysts, plagioclase has An9 (or An32) composition	feldspathic litharenite	0.31mm medium sandstone	σ=0.13 very well sorted range from R=2.1 (feldspar) to R=3.2 (VRF)
W-16-1b2	3% quartz, 28% feldspar, 8% feldspar altered to calcite, 8% MRF (serpentine), 1% SRF (chert), 10% clay matrix, 10% altered to clay grains, 29% VRF, 3% opaques; VRF phenocrysts are plagioclase with a few mafic mineral phenocrysts, clay grains are altered VRFs	feldspathic litharenite	0.09mm very fine sandstone	σ=0.75 moderately sorted range from R=2.2 (quartz) to R=3.0 (MRF/VRF)
W-16-2e	2% quartz, 30% plagioclase, 23%	lithic arkose	0.13mm fine	σ=0.88 moderately

	orthoclase, 15% VRF, 9% clay, 13% calcite cement, 2% opaques, 6% MRF; the VRFs are plagioclase with altered-to-clay groundmass, plagioclase angles yield An16 (or An24) composition		sandstone	sorted range from R=2.1 (plagioclase) to R=3.5 (MRF)
W-17-1a1	11% feldspar, 64% VRF, 8% clay, 16% feldspar cement, 1% opaques; VRFs are almost all plagioclase phenocrysts in an altered-to-clay groundmass with minor gibbsite alteration, clay infills cracks, cement is albite	volcanic-arenite	0.14mm fine sandstone	σ=0.30 very well sorted range from R=3.3 (VRF) to R=2.7 (feldspar)
W-17-1a2	92% sparry feldspar (both cement and altered feldspars), 1% porosity, 7% opaques; once feldspars with calcite cement but now every feldspar is altered to calcite	arkose	0.15mm fine sandstone	σ=0.25 very well sorted R=2.9 (feldspar)
W-17-1b1	VRF: 6% plagioclase, 7% orthoclase, 85% groundmass, 2% opaques; minor alteration on feldspars to calcite	clast		
W-17-1b2	trace quartz, 21% feldspar, 5% feldspar altered to calcite, 66% VRF, trace serpentine, trace chert, 3% clay, 3% porosity, 2% micrite; VRFs have both plagio-	feldspathic litharenite	0.30mm medium sandstone	σ=0.43 well sorted range from R=2.2 (VRF/feldspar) to R=3.0 (MRF)

	clase and mafic mineral phenocrysts, twinning angles reveal An10 (or An20), trace gibbsite, clay forms matrix, porosity reflects clay dissolution during thin section construction			
W-17-1c	trace quartz, 12% plagioclase, 4% plagioclase altered to calcite, 75% VRF, 1% VRF altered to clay, 7% calcite cement, 1% calcite pore fill; sparry calcite cement, VRFs have both plagioclase and mafic mineral phenocrysts	volcanic-arenite	0.41mm medium sandstone	σ=0.75 moderately sorted range from R=0.5 (quartz) to R=4.1 (MRF)
W-17-1e	5% feldspar, 63% VRF, 1% MRF (serpentine), 1% SRF, 6% cement, 13% porefill, 5% gibbsite, 3% calichite; cement is sparry calcite, most VRFs are altered to bauxite, plagioclase angles reveal compositions of An18 (or An27), An20, An18 (or An23)	volcanic-arenite	1.10mm very coarse sandstone	σ=1.75 poorly sorted range from R=2.5 (feldspar) to R=3.8 (VRF)
W-17-1f	VRF: 47% feldspar, 45% groundmass, 8% feldspar phenocrysts altered to calcite	clast		
W-17-1h	49% feldspar (47% plagioclase, 2% orthoclase), 26% VRF, 19% clay, 2% chert, 4% porosity; VRFs are mainly plagioclase	lithic arkose	0.38mm medium sandstone	σ=0.58 moderately well sorted range from R=2.1 (plagioclase) to R=3.1

	phenocrysts with an altered-to-clay groundmass, minor calcite alteration on the feldspars, plagioclase angles indicate An11 (or An29) composition, clay represents matrix and grain alteration			(VRF)
W-17-2a	84% VRF, 15% calcite cement, 1% MRF (serpentine); VRFs are altered-to-calcite feldspar phenocrysts in a clay groundmass, sparry calcite makes up cement	volcanic-arenite	too coarse to determine	
W-18-1c	carbonate rock: 5% feldspar with only minor alteration, 24% altered VRFs; micrite with fossils not identifiable (if present)	plagioclase, VRF-bearing micrite (plagioclase-VRF mudstone)		
W-18-1d	8% quartz, 18% feldspar, 6% feldspar altered to calcite, 8% VRF, 3% MRF (serpentine), 52% clay, 5% opaques; the clay is both matrix and VRF alteration, feldspars are highly altered to calcite	lithic arkose	0.02mm medium siltstone	σ=1.50 poorly sorted range from R=1.9 (quartz) to R=2.5(MRF)
W-19-1a	trace quartz, 7% plagioclase, 2% orthoclase, 74% VRF, 5% MRF, 12% clay; VRFs are plagioclase phenocryst-rich with an altered-to-clay groundmass, feld-	volcanic-arenite	0.44mm medium sandstone	σ=0.88 moderately sorted range from R=1.5 (plagioclase) to R=3.6 (VRF)

	spars are fairly unaltered, MRFs are serpentine, clay forms matrix			
W-19-1b	1% feldspar, 93% VRF, 1% VRF altered to calcite, 2% clay, 1% calcite pore fill, 2% gibbsite; see a trace of a fossil, gibbsite is alteration on VRF	volcanic-arenite	0.40mm medium sandstone	σ=1.15 poorly sorted range from R=2.2 (feldspar) to R=3.7 (VRF)
W-19-2c	20% plagioclase, 19% orthoclase, 20% feldspar altered to calcite, 7% opaques, 2% calcite, 32% clay (both grains and matrix); opaques occur in layers, almost all of the calcite is at least partially altered to calcite	arkose	0.21mm fine sandstone	σ =1.00 poorly sorted range from R=3.2 (plagioclase) to R=3.8 (opaques)
W-19-2e	1% quartz, 30% feldspar, 6% feldspar altered to calcite, 45% VRF, 2% SRF (chert), 4% MRF, 11% clay, 1% calcite pore fill; clay forms matrix and altered grains, VRFs have plagioclase phenocrysts in an altered-to-clay groundmass, may be the beginnings of phyllosilicate cement	feldspathic litharenite	0.15mm fine sandstone	σ=0.60 moderately well sorted range from R=1.0 (quartz) to R=3.7 (MRF)
W-19-2g1	trace quartz, 24% plagioclase, 5% feldspar altered to calcite, 36% VRF, 19% clay, 14% MRF, 2% opaques; thick clay coat surrounds	feldspathic litharenite	0.12mm very fine sandstone	σ=0.38 well sorted range from R=2.5 (plagioclase) to R=3.0 (VRF/MRF)

	all grains, MRFs are serpentine, VRF phenocrysts are mafic mineral-rich, may be beginnings of phyllosilicate cement			
W-19-2g2	2% quartz, 47% feldspar, 2% feldspar altered to calcite, 16% VRF, 9% MRF, 16% clay, 5% micrite, 3% calichite; clay forms matrix. VRFs have plagioclase phenocrysts with an altered-to-clay groundmass, MRFs are serpentine and pyroxene, may have beginnings of phylllosilicate cement	lithic arkose	0.13mm fine sandstone	σ=0.63 moderately well sorted range from R=1.6 (quartz) to R=3.2 (VRF)
W-19-2g3	25% feldspar, 9% feldspar altered to calcite, 43% VRF, 11% clay matrix, 4% altered grains (to clay), 3% opaques, 5% MRF; opaques aligned parallel to bedding, much alteration of plagioclase in VRFs	feldspathic litharenite	0.11mm very fine sandstone	σ=1.10 poorly sorted range from R=2.8 (feldspar) to R=3.6 (VRF)
W-20-1a	5% quartz, 10% feldspar, 12% feldspar altered to calcite, 1% VRF, 37% altered to clay grains, 6% MRF, 4% fossils, 25% opaques; fossils are forams, clay grains are probably relict VRFs	arkose	0.05mm coarse siltstone	σ=1.50 poorly sorted range from R=1.1 (quartz) to R=3.6 (MRF)
W-20-1b	5% quartz, 13% feldspar, 23% feldspars	feldspathic	0.54mm coarse	σ=0.75 moderately

	altered to calcite, 34% VRF, 1% SRF (mudclast), 11% clay, 7% MRF, 1% gibbsite, 5% micritized grains; many feldspars (mainly plagioclase) and VRFs in a clay matrix, MRFs are serpentine, plagioclase angles reveal composition of An2 (or An32)	litharenite	sandstone	sorted range from R=2.1 (quartz) to R=4.0 (MRF)
W-20-1f	19% plagioclase, 8% orthoclase, 1% VRF, 1% MRF, 2% SRF, 11% clay grains, 40% micrite, 5% porosity, 13% clay matrix, trace forams; plagioclase angles (albite) reveal An13, An2 (or An34), An6 (or An34), the micrite is micritized grains, the clay grains are probably altered VRFs	arkose	0.19mm fine sandstone	σ=0.55 moderately well sorted range from R=2.8 (plagioclase) to R=4.5 (MRF)
W-20-1h	15% orthoclase, 14% plagioclase, 26% VRF, 37% clay, 4% calcite vein infill, 13% sparry calcite cement, 5% MRF; clay represents altered grains (probably once VRF)	feldspathic litharenite	0.16mm fine sandstone	σ=1.00 poorly sorted range from R=2.0 (feldspar) to R=3.2 (VRF)
W-21-1a	carbonate rock: 28% feldspar, 69% micrite, 3% opaques; micrite is cement	feldspar micrite (mudstone)		
W-21-1e1	4% quartz, 37% plagioclase, 6% orthoclase, 31% VRF, 21% micrite, 21% micrite (both grains and	lithic arkose	0.15mm fine sandstone	σ=0.38 well sorted range from R=1.9 (feldspar) to

	cement) 1% opaques; VRFs are altered-to-clay groundmass with both plagioclase and mafic mineral phenocrysts			R=2.7 (quartz)
W-21-1e2	27% feldspar, 25% feldspar altered to calcite, 23% VRF, 6% MRF, 16% calcite cement, 3% porosity; feldspars are 90% altered to calcite, VRFs have mostly plagioclase phenocrysts in an altered-to-clay matrix, clay rims around the grains MRFs are serpentine	lithic arkose	0.18mm fine sandstone	σ=0.30 very well sorted range from R=2.1 (feldspar) to R=4.0 (MRF)
W-21-1f1	13% plagioclase, 13% orthoclase, 19% feldspar altered to calcite, 23% VRF, 3% VRF altered to calcite, 5% MRF, 6% clay, 13% sparry 5% micrite, trace chert; the micrite represents fossils completely altered to micrite, clay forms rim around grains, VRFs have plagioclase phenocrysts in a clay groundmass. plagioclase compositions are An14 (or An26)	lithic arkose	0.17mm fine sandstone	σ=0.37 well sorted range from R=2.4 (feldspar) to R=3.9 (MRF)
W-21-1aa	23% feldspar, 30% feldspar altered to calcite, 10% VRF, 1% SRF (chert), 2% clay rim, 11% sparry calcite cement, 1% porosity, 14% micrite, 8% MRF, feldspars are very	lithic arkose	0.31mm medium sandstone	σ=1.05 poorly sorted range from R=1.9 (feldspar) to R=3.6 (VRF)

	altered to calcite, micrite represents altered grains			
W-22-1b	22% feldspar, 51% feldspar altered to calcite, 15% sparry calcite cement, 5% opaques, 3% clay, 4% MRF, minor fossils; opaques occur as infilling of fossils, difficult to distinguish between feldspar altered to calcite cement, MRFs are serpentine	arkose	0.15mm fine sandstone	σ=1.13 poorly sorted range from R=2.9 (MRF) to R=3.4 (feldspar)
W-22-1e	trace quartz, 39% plagioclase, 28% clay, 9% calcite, 10% opaques, 7% MRF (serpentine), 7% fossils; clay occurs as matrix and as grain alteration, plagioclase is fairly unaltered, fossils are globogerinid and echinodermata, calcite occurs as pore fill and vein infill	arkose	0.16mm fine sandstone	σ=1.75 poorly sorted range from R=3.5 (plagioclase) to R=4.1 (opaques)
W-23-1a	5% feldspar, 4% feldspar altered to calcite, 12% VRF, 75% clay, 1% MRF, 1% opaques, 2% fossils; feldspars very altered to calcite, fossils are forams, plagioclase compositions are An12 (or An26)	feldspathic litharenite	0.21mm fine sandstone	σ=2.00 poorly sorted range from R=2.0 (feldspar) to R=5.0 (fossil)
W-23-1b	carbonate rock: 29% feldspar, 4% fossils, 3% opaques, 10% MRF,	feldspar, MRF-		

	54% calcite; opaques form pore fill for fossils, a few fossils have been recrystallized, fossils are forams and echinoids, MRFs are serpentine	bearing biomicrite (fossiliferous mudstone)		
W-23-3a	6% quartz, 48% feldspar (completely altered to calcite), 35% clay, 4% porosity, 1% calcite, 6% opaques, trace fossils; clay occurs in lineations, trace serpentine clay represents both matrix and alteration of VRF grains	arkose	0.07mm very fine sandstone	σ=2.00 poorly sorted range from R=2.3 (feldspar) to R=2.9 (quartz)
W-24-1a	19% feldspar, 17% VRF, 3% MRF (serpentine), 2% clay, 32% calcite, 1% opaques, 23% SRF (fossils); fossils are echinoid plates, inoceramus, and forams, some micritized and some recrystallized, VRFs are relatively unaltered, sparry calcite includes both cement and recrystallized fossils	feldspathic litharenite	1.30mm very coarse sandstone	σ=1.10 poorly sorted range from R=2.5 (feldspar) to R=4.1 (fossils)
core 138	20% MRF, 61% feldspar, 1% quartz, 6% opaques, 12% clay; MRFs are both serpentine and mafic minerals altered to chlorite, see trace of echinoid fragment, one well preserved clinopyroxene, opaques occur linearly, feldspars are too	arkose	0.14mm fine sandstone	σ=0.38 well sorted range from R=1.0 (quartz) to R=3.3 (feldspar)

	altered to calcite to distinguish type			
core 148	1% quartz, 62% VRF, 11% feldspar, 11% MRF, 2% chert, 13% albite cement; VRFs are all plagioclase and clay with albite cement, MRFs are serpentine and altered igneous, see 50% of VRFs altered to clay composition, trace opaques, feldspars look to be all plagioclase	volcanic-arenite	0.20mm fine sandstone	σ=0.81 moderately sorted range from R=2.1 (quartz) to R=3.6 (chert)
core 65	2% quartz, 61% VRF, 12% MRF, 15% calcite cement and vein infill, 9% plagioclase, 1% orthoclase, MRFs are both serpentine and altered mafic minerals, VRFs have mostly plagioclase but a few mafic minerals as phenocrysts,	volcanic-arenite	0.18mm fine sandstone	σ=0.57 moderately sorted range from R=2.0 (quartz) to R=3.3 (VRF)
core 5	35% feldspar, 14% MRF (serpentine), 19% calcite vein infill, 32% clay; clay is both matrix and alteration of grains, see very large calcite vein	lithic arkose	0.30mm medium sandstone	σ =0.61 moderately sorted range from R=3.6 (feld- to R=4.0 (MRF)
core 52	74% VRF, 9% quartz, 6% feldspar altered to calcite, 10% clay, 1% MRF; VRFs have both plagioclase and mafic minerals as phenocrysts, feldspars completely altered	volcanic-arenite		σ=1.05 poorly sorted range from R=2.6 (feldspar) to R=4.2 (MRF)

	to calcite. MRFs are serpentine			
core 36	6% quartz, 20% plagioclase, 4% orthoclase, 59% VRF, 10% calcite, 1% MRF (serpentine); calcite occurs as both cement and pore-fill, feldspars are relatively unaltered, VRFs have both plagioclase and mafic mineral phenocrysts	feldspathic litharenite	0.41mm medium sandstone	σ=0.62 moderately well sorted range from R=2.5 (quartz) to R=3.1 (VRF)