A Paleoenvironmental Study of the Nyac Terrane, SW Alaska

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ABSTRACT

The Nyac Terrane, composed of Mid to Late Jurassic island-arc volcano-sedimentary facies, provides a record of Late Jurassic and Early Cretaceous volcanism and sedimentation in an island-arc setting off the northwestern margin of the North American Continent. Changes in the composition, volume, and textures of the Nyac Terrane volcanic, volcaniclastic, and sedimentary rocks reveal a progression from active volcanism towards permanent quiescence, punctuated by brief periods of volcanic activity. This volcanic activity can be characterized by subaerial and submarine eruptions of basaltic andesite and basaltic trachyandesite forming volcanic islands and submarine volcaniclastic aprons followed by non-volcanogenic shallow marine sedimentation. These volcanogenic rocks were gradually reworked into extensive volcaniclastic deposits both during and after the in situ volcanism had ceased, and finally capped by terrigenous shallow marine facies, marking a shift from active island arc volcanism to volcanic quiescence associated with the collision and accretion of the terrane onto the North American Backstop.

Keywords: Nyac, metavolcanic, metasedimentary, Island Arc Accretion, Late Jurassic, South West Alaska
LIST OF FIGURES

Figure 1: Simplified Terrane Map of South West Alaska.................................2
Figure 2: USGS 1:250,000-scale geologic map of the Nyac area........................3
Figure 3: Interpretive geologic map of the Nyac district..................................7
Figure 4: Core logs/stratigraphic columns.......................................................10
Figure 5: Composite stratigraphic column......................................................11
Figure 6: Field photographs of lithofacies......................................................13
Figure 7: Photomicrographs of rare units.......................................................16
Figure 8: Photomicrographs of representative lithofacies.................................19
Figure 9: Photomicrographs of alteration facies.............................................20
Figure 10: Photomicrographs of alteration facies............................................21
Figure 11: Schematic of island volcanism.....................................................29
Figure 12: Subaqueous/Subaerial Boundary....................................................31
LIST OF APPENDIXES

Appendix A: Sample, structure, and drill hole location data
Appendix B: Lithology Polygons
INTRODUCTION

Southwest Alaska is made up of several tectonostratigraphic terranes, which have been regionally mapped at a 1:250,000-scale (Figure 1). However, little detailed mapping has occurred in the area, and the mapping that has occurred is in small, isolated areas of economic interest. The Nyac Terrane, located in the Kilbuck Mountains, approximately 63 miles east of Bethel (Figure 2), is one of four arc and oceanic terranes that make up the Bristol Bay portion of the Yukon-Kuskokwim region (Decker et al., 1994). Due to a lack of exploration and poor exposure, the role of the Nyac Terrane during deposition, accretion, and postaccretionary strike slip faulting is not well defined. The goal of this study is to combine detailed mapping of the Nyac Terrane and petrographic analysis of the lithofacies in the terrane to better define the local stratigraphy, paleoenvironment, and add to the understanding of the regional tectonic history.

Previous Work

The Nyac Terrane is arguably the least understood of the many accretionary terranes of Early Cretaceous to Paleozoic age that make up SW Alaska. Previous research in the area began in 1945 when USGS geologist Robert E. Wallace first discovered a lode gold source in quartz veins (Foley, 2000). Further research occurred in 1974-75 by the Resource Associates of Alaska while conducting a large scale mapping and sampling project, in 1990 by Frost when he discovered anomalous Hg in quartz veins, and in 1996-97 when another mapping and sampling program was executed by Placer Dome Exploration. More recently, Wenz (2005) completed the most thorough investigation of
indicated as geographic markers.

Figure 1. Simplified terrane map of South West Alaska, Yukon Kuskokwim Region, Modified from Wallace et al. (1989). Field Area contained in red box. Orange highlights terranes associated with the Nyac Terrane. Kuskokwim River, Bethel, and Bristol Bay indicated as geographic markers.
Figure 2: Geologic Map of the Nyac area adapted from Box et al. (1993). Study area enclosed by outlined polygon.
the geology in the Nyac area, with a focus on gold mineralization.

Despite this prior research and the presence of an economic interest over the past 60 years, very little research has focused on the metavolcanic and metasedimentary rocks of the area, which make up the majority of the Nyac District. Prior to Wenz (2005), only a rudimentary understanding of the geologic history existed. Wenz (2005), the most comprehensive publication on Nyac to date, was aimed at producing a model for gold mineralization in the region and includes detailed descriptions for many of the lithologies in the Nyac area.

**Purpose of study**

The main purpose of this study is to determine the stratigraphy and depositional setting of the Nyac Terrane by defining easily recognizable and mappable units, followed by an investigation of the stratigraphy and spatial relationships of these units. In addition, petrographic analysis is used to distinguish between diagenic and hydrothermal and metamorphic alteration and explain some of the difficulties in interpreting these rocks. The field data, combined with detailed petrographic analysis is then used to compile a detailed map of the bedrock geology, and develop a loose model for the depositional and tectonic history of the area defining the Nyac Terrane as an intraoceanic volcanic arc complex.

**REGIONAL GEOLOGY**

Much of the state of Alaska is an amalgamation of pieces of continental crust transported from further south and accreted onto the North American Backstop. The
Western and Southern fringe of Alaska in particular, is mostly composed of terranes accreted in the Late Mesozoic to Cenozoic. The majority of the lower Kuskokwim-Bristol Bay region has undergone repeated NW-SE shortening and subsequent faulting as these exotic terranes were accreted. The rocks of this region range in age from Precambrian to Quaternary in age, the general stratigraphy of which, from oldest to youngest, is as follows: metamorphic rocks of Precambrian age, limestone of Devonian age, sedimentary and volcanic rocks ranging in age from Carboniferous to Early Cretaceous, andesitic volcanic rocks of middle and Late Jurassic age, the Kuskokwim group consisting of greywacke and shale of Cretaceous Age, continental basalts of Tertiary and Quaternary age, and surficial deposits of Quaternary age (Figure 1) (Hoare, 1961).

The Nyac Terrane makes up part of the mid to late Jurassic volcanic and sedimentary rocks. However, the structural relationship between the Nyac Terrane and the surrounding rocks is unclear. The Middle and Late Jurassic period in this region is characterized by the Togiak arc complex and Yukon-Koyukuk arc, which may have at one time been a single arc, being built upon oceanic crust or rifted fragments of continental crust from the North American Backstop (Wallace, 1989).

From the Mid to Late Jurassic to approximately 85 Ma, the Farallon plate lay offshore of North America and was being displaced westward to northwestward, converging with the northwestern North America (Wallace, 1989). This plate reconstruction provided the mechanism for the formation and accretion of these island arcs onto North America, followed by extensive postcollisional strike slip faulting (Decker et al., 1994). These mid to late Jurassic island arc volcanics and sediments have also been intruded and variably
metamorphosed by Early Cretaceous granitic plutons and Tertiary dikes post accretion, but prior or during the ongoing, postcollisional faulting (Wenz, 2005).

To the North, the Nyac Terrane is bounded by Proterozoic metamorphic rocks that make up the basement of the Ruby, Innoko, and Farewell Terranes and, to the south and east, by the younger Kuskokwim Group. The boundary between the Kuskokwim group and Nyac is formed by the Golden Gate - Sawpit Fault, which trends NE, and may be a continuation of the Iditarod-Nixon Fork Fault, which is offset by the Aniak Fault (Figure 2; Decker et al., 2004).

The Jurassic assemblage that makes up the Nyac Terrane has previously been divided into metavolcanics, primarily andesite and basalt, with some rhyodacite, interbedded with metasediments including graywacke, siltstone, argillaceous limestone, and conglomerate (Wenz, 2005). The metasediments, which overly the metavolcanics, are primarily more mature volcaniclastics, conglomerates, mudstone and siltstone. They typically show bedding, evidence of reworking, more varied clast composition, and more distinctly sedimentary textures and facies.

**GEOLOGY OF THE NYAC TERRANE**

Fieldwork was performed during June and July of 2006 and consisted of mapping and sampling of the North East corner of the Nyac Terrane. The study area is bounded by Bear Creek to the South East, the Nyac Pluton to the North, and the Tuluksak River to the West (Figure 2). Mapping and sampling data were recorded in the field on an ArcGIS program run on a Trimble PDA. Access to the field area was by Jet Ranger helicopter and ATV along previously established mining roads. Outcrop and exposure make up less than
Figure 3: Interpretive map of bedrock geology adapted from Wenz (2005).
1% of this region and is primarily along ridgelines. The overwhelming majority of the rocks in this region are prone to rubblization and have little to no extended exposure. Also, all units have undergone variable degrees of contact metamorphism caused by the intrusion of Late Cretaceous plutons. (Wenz, 2005)

Based on my mapping, the Nyac Terrane can be divided into 4 distinct units, from oldest to youngest, the Shamrock Volanics, the Pipe Formation, the Rocky Ridge Formation, and the Table Mountain Formation. Boundaries between units are gradational and the distinction between most units is used as a means of gaining an improved understanding of stratigraphy and structures rather than evidence for a sharp contact. These formations will be described in more detail below.

**Structure**

The geologic map of the Nyac Terrane (Figure 3) shows these 4 distinct units, and their contacts with each other as well as with the intrusive plutons. This map also shows two fault sets modified from Wenz 2005.

The first of the two fault sets trends northeast-southwest and is presumed to be affiliated with the high-angle, right lateral Golden Gate-Sawpit fault system and its related faults. The second set trends north-south, is high angle, left lateral, and presumably includes the Aniak-Thompson Creek Fault. The interpretation of the two lobes of the Bonanza Pluton as having been separated due to faulting suggest a minimum of approximately 3.5 km of horizontal offset. The lateral offset is unknown for the other north-south faults and northeast-southwest faults. Due to the tectonic history of this terrane and poor exposure it can be assumed that a great deal of smaller scale faulting is
The orientation of bedding varies considerably throughout the study area. The most representative measurements are included in Figure 3. The dip of the bedding is primarily shallow to moderate to the north-northeast. Also, it is important to note that the bedding orientation was measured less frequently proximal to plutons and in the stratigraphically lower, less sedimentary units, as shown in Figure 3, due to lack of definitive bedding. In the northwestern part of the study area there are a set of southwestward dipping measurements. These may be evidence for folding throughout the terrane; however, no conclusive or corroborating evidence was collected concerning their interpretation.

**Unit Architecture**

Approximate unit and facies thickness was recorded from 600 meters of logged core from three different sites (see Appendix A for locations). Figure 4 shows the high degree of variability for bed thickness, composition, and continuity at a scale of 1-meter intervals over three 200-meter sections. The dashed lines indicate similar facies between columns. Note the inconsistencies in facies type, thickness and stratigraphic order. For instance, the correlation between Drill Hole 5 and 7 shows three similar facies types, but each example’s thickness and neighboring facies varies. Also, take note of the general consistency of the facies represented overall. All three Drill Holes contain roughly the same seven interbedded volcaniclastic facies.

Figure 5 shows the combined data from the logged core and field data in the form of a simplified, composite stratigraphic column and field and petrographic analysis. The table in Figure 4 summarizes the majority of the data contained in the following unit
Figure 4. Correlating core from Drill Holes. Each core was logged at 1 meter intervals. This figure shows within unit variation and discontinuity of both unit composition and thickness. Lines between drill holes indicate possible correlation between beds and facies.

**Legend**
- Present only in Figure 5
- Indicates possible correlation
- Pebble conglomerate
- Cobble conglomerate
- Volkmanite, non-dendritic
- Volkmanite, dendritic
- Interbedded mudstone and siltstone
- Basaltic flows
- Andesite flows w/ hornblende
- Andesite flows w/ amphibole
- Basaltic flows w/ olivine
- Interbedded mudstone and siltstone
- Pebble conglomerate
- Cobble conglomerate
- Secondary volcaniclastics with oriented and sorted matrix
- Secondary volcaniclastics with varied clast composition
- Secondary volcaniclastics with oriented and sorted matrix
**Figure 5.** Simplified composite stratigraphic column showing distinctive characteristics of the main volcanic facies in the Nyac Terrane. Logged at approximately 20 m intervals.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Characteristics</th>
<th>Textures</th>
<th>Microfacies/Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuffaceous mudstone</td>
<td>1-7 cm linear beds, finely laminated</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plagioclase + quartz, rare sub-angular shards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shard rich</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volcaniclastic wacke</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobble conglomerate</td>
<td>6-70 mm clasts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pebble conglomerate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystal rich</td>
<td>Andesitic sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystal poor</td>
<td>Basaltic lava flows</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table Mountain Formation**

- Basaltic lava flows
- Massive flows
- Basaltic lavas and sills
- Massive flows and sills
- Basaltic lavas and sills
- Massive flows

**Table Mountain Formation**

- Basaltic lava flows
- Massive flows
- Basaltic lavas and sills
- Massive flows and sills
- Basaltic lavas and sills
- Massive flows

**Pipe Formation**

- Basaltic lava flows
- Massive flows
- Basaltic lavas and sills
- Massive flows and sills
- Basaltic lavas and sills
- Massive flows

**Rocky Ridge Formation**

- Basaltic lava flows
- Massive flows
- Basaltic lavas and sills
- Massive flows and sills
- Basaltic lavas and sills
- Massive flows
Contact Metamorphism

Contact metamorphism is observed in various degrees throughout the entire Nyac Terrane most commonly hornfels, but up to greenschist facies. Metamorphic recrystallization has made the majority of igneous and sedimentary textures unrecognizable on a fresh face and only somewhat visible on a weathered face. Because of poor exposure and contact metamorphism, most classification of unit composition and structure was done using petrography, which greatly limits the scale of observable structures and sedimentary and depositional relationships within and between units. Further details on metamorphism and alteration effects are within the Unit Petrography descriptions.

Shamrock Volcanics

The Shamrock Volcanics unit, the lowest unit of the Nyac Terrane, is exposed in rare outcrops in the South Southeast portion of the study area (Figure 3). The lower boundary of the unit is unexposed so the unit thickness is estimated as at least 400 meters.

The unit is dominated by basaltic, andesitic, and minor dacitic lava flows, primary pyroclastics and volcanioclastics. This includes flow-banded and autobrecciated lavas and immature volcanioclastics with very little grading, orientation, or other evidence for a sedimentary mode of deposition. Individual flows are typically indistinguishable. The beds may represent multiple flows and range in thickness from 1 to 20 meters with dramatic lateral variation at a scale of tens of meters.
Figure 6. Field photographs of the representative lithofacies of the Nyac Terrane. A. Andesite lava flows within the Shamrock Formation. B. Andesite breccia within Shamrock Formation. C. Andesite volcaniclastic within Pipe Formation. D. Cobble conglomerate within E. Interbedded purple tuffaceous mudstone and gray siltstone. Hammer length = 33 cm.
This unit is defined by having > 50% non-reworked, in situ volcanic flows (Figure 6A). The unit also contains massive primary volcaniclastics, which have undergone little to no transportation and are from the same source. Figure 6B shows an andesitic autobreccia interpreted as the fragmentation of lava as it cools during flow. The volcaniclastics have a fine to coarse-grained matrix and primarily andesite clasts ranging in size from <1mm to 20cm. The clasts and matrix are angular- sub angular and show little to no sign of orientation or sorting. In hand sample, the flows appear as gray to gray green, and black, aphanitic and fine-grained porphyries.

**Pipe Formation**

The Pipe Formation makes up the second lowest unit of the Nyac Terrane and stratigraphically overlies the Shamrock Volcanics. This unit is especially prone to rubblization and the outcrops of the unit are frequently indistinguishable from the surrounding talus. The unit thickness, estimated from bedding orientations and unit contacts, ranges from 300-700 m and individual beds range in thickness from 20 cm to 5 meters with a great deal of discontinuity and lateral variation at the meter scale.

The flows in this unit are predominantly andesitic in composition and the beds, made up of multiple flows, range in thickness from 1-9 meters. In hand sample the flows appear as gray, to gray green aphanitic porphyries, with rare amygdaloids.

The unit is defined by having >50% reworked, secondary andesitic and basaltic volcaniclastics, crystal rich andesitic sandstone, as well as minor amounts of intact volcanic flows. The volcaniclastics range from polymictites with 1-18 cm angular – sub rounded clasts to wackes with 1-4mm, oriented, sub angular-sub rounded grains, and are
composed of over 90% volcanically sourced material, either as clasts of andesite or clasts of andesitic volcanoclastic, which commonly resemble weathered and reworked pieces of the Shamrock Volcanics unit (Figure 6C). The remaining clasts are composed of volcanogenic sandstones with a minor amount of felsic material. The matrix ranges from aphanitic siltstone and mudstone to very coarse to granular volcanogenic sandstone.

This unit also contains minor amounts of a pelecypod fossil bearing wacke, which is one of the few beds to be positively correlated across ridgelines, and a welded tuff (Figure 7A). The fossils range in size from 5-17 cm when whole, are rarely found in <1 mm fragments, and are in distinctive beds with no consistent convex up or down orientation. Also, the fossil data was collected from shell casts, as all whole shells and most fragments are no longer present within the wacke.

Finally, the unit contained an enigmatic mylonite, presumed to be a faulted contact zone between a lava flow and an overlying debris flow deposit (Figure 7B). The appearance of the mylonite could also suggest partially deformed flow structures caused by the load of overlying material, accentuated by later hydrothermal and metamorphic alteration.

**Rocky Ridge Formation**

The Rocky Ridge Formation is bounded by the Pipe Formation below and the Table Mountain Formation above. The unit is best exposed along the northern portion of Rocky Ridge and the north-northwest ridge of Bonanza Peak (Figure 3). The approximate thickness of the unit ranges from 100-200 meters making it the thinnest unit of the Nyac Terrane.
Figure 7. Photomicrographs of lithofacies of the Nyac Terrane. A. Welded tuff with rare angular plagioclase crystals within Pipe Formation. (M4; plain polarized light). Fiamme visible as distorted, discontinuous, darker layers. B. Mylonitic texture in altered debris flow within the Pipe Formation. (M4; plain polarized light). Chlorite alteration throughout. Rare mafic volcanic clasts visible. C. Interbedded wacke and volcanic litharenite within the Table Mountain Formation. (M1.25; cross polarized light). Note mm scale vertical variation within beds.
Conglomerates make up the majority of the unit and are both clast supported (80%) and matrix supported (20%). The conglomerates are composed of up to 20% non-volcanic material, primarily quartz grains and rare mudstone and sandstone clasts with sedimentary textures. The clasts range in size from 3-70 mm and are typically rounded, oblong to subspherical and oriented, but rarely graded (Figure 6D). The Rocky Ridge Formation also contains fine grained siltstone and volcanogenic sandstone beds, which appear in poorly defined layers, minor amounts of pure volcanioclastics, which are distinctive due to their uniform andesitic clast composition, and argillaceous limestone and skarn, which appears in <1-20 m poorly defined beds.

**Table Mountain Formation**

The Table Mountain Formation forms the upper most unit of the Nyac Terrane. The thickness of the unit is estimated at >200 meters due to a lack of an upper contact. Almost all exposure of the unit is along ridgelines in the northern section of the study area, centered around Table Mountain.

The unit consists of interbedded tuffaceous mudstone, siltstone, and wacke as well as occasional sorted and oriented clast-supported beds interpreted as debris flows. The beds range from <1 mm to 7 cm thick with an average thickness of 3 cm. The mudstone typically appears purple in the field due to metamorphic biotite (Figure 5E), and rarely shows scour structures. The siltstone is gray and aphanitic and is occasionally found intermixed with more granular sandstone beds. The sandstone beds present in the Upper Fines Unit are gray to purple to black, and primarily of volcanogenic composition with 5-20% quartz grains. The sandstone beds are composed of fine to medium grain, volcanic
and quartz sand grains. The grains are oblong, subspherical and oriented, but rarely graded. Also, the sand beds are the only subfacies of the Upper Fines to have common visible mixing with other beds and lateral variation.

**PETROGRAPHY**

A total of 47 covered thin sections were prepared, 40 commercially at Bernham Petrographic and the remaining 7 using the facilities at Carleton College. The thin sections were analyzed under plain and cross-polarized light using an Olympus BX51 microscope. The variable metamorphism of the Nyac Terrane resulted in the majority of sedimentary and igneous textures and structures becoming indistinguishable in outcrop and hand sample. Thus, it is only in thin section that many of the four lithofacies’ distinctive attributes are observed. Also, alteration facies can be described in terms of the alteration mineral assemblages, distribution, intensity, and texture. This can help distinguish between units, as well as help in the description of syneruptive and posteruptive characteristics, and the distinction between subaerial and submarine depositional environments.

**Shamrock Formation**

In thin section, the Shamrock Formation contains immature volcanics and volcaniclastics. The phenocrysts range in size from <1-5mm, make up 5-25% of the rock, and are primarily composed of plagioclase (5-17%), pyroxene (0-5%) and hornblende (0-3%) crystals with a groundmass made up of intergranular to aphanitic plagioclase, clinopyroxene, and magnetite (Figure 8A). Up to 75% of the phenocrysts have been
Figure 8. Photomicrographs of representative lithofacies of the Nyac Terrane. A. Basaltic andesite lava flow (M4; cross polarized light). Pyroxene phenocrysts and plagioclase and pyroxene groundmass. B. Andesite autobreccia, andesitic angular clasts with altered/replaced volcanic glass groundmass. (M4; plain polarized light) C. Reworked andesite volcaniclastic. (M1.25; cross polarized light)D. Rounded plagioclase grains and oriented lathlike plagioclase groundmass. D. Rounded, oriented and varied pebble-conglomerate. (M4; cross polarized light) E. Interbedded wacke, siltstone, and volcanic litharenite. (M4; cross polarized light) F. Oriented wacke with bedded mudstone, volcanic and quartz clasts. (M1.25; plain polarized light).
Figure 9. Photomicrographs of alteration in representative lithofacies of the Nyac Terrane. A. Plagioclase-pyroxene-porphyritic basalt within Shamrock Formation (M10; cross polarized light). The phenocrysts and groundmass are extensively altered. Euhe- dral pyroxene crystal is replaced by chlorite-epidote, and both plagioclase phenocrysts and groundmass are heavily sericitized. B. Andesite secondary volcaniclastic within Pipe Formation (M4; plain polarized light). Sericite is disseminated throughout the heavily chloritized groundmass and has partially to completely replaced all plagioclase phenocrysts. C. Andesite secondary volcaniclastic within Pipe Formation (M10; plain polarized light). Actinolite growing outwards from fractures in plagioclase crystals into groundmass of partially sericitized plagioclase crystals and lithic fragments.
Figure 10. A. Altered Basalt with calcite veins within Shamrock Formation (M1.25; cross polarized light). Basalt is completely altered to sericite and surrounded by calcite grains. B. Carbonate within Pipe Formation (M4; cross polarized light). Tremolite and magnetite disseminated throughout calcite grains. C. Metamorphosed volcanic wacke within Table Mtn Formation (M4; cross polarized light). Plagioclase crystals are recrystallizing in aphanitic, round groups throughout clay rich, fine grained beds.
altered to sericite, epidote and chlorite (Figure 9A) with rare calcite veining.

The clast and matrix material in the volcaniclastics present in the Shamrock Formation are almost all angular to sub angular, and show no visible orientation, sorting, or sedimentary structures caused by water flow. The matrix is dominantly plagioclase supporting 10-20% plagioclase and 0-5% pyroxene phenocrysts and 0-5% magnetite grains ranging from <1-2 mm. Figure 8B shows a photomicrograph of a mafic volcaniclastic breccia, presumably an autobreccia, with angular, fresh, fine-grained andesite clasts within a plagioclase rich matrix. Also, within the lower Shamrock Formation, calcite is present filling fractures within basalt.

Pipe Formation

In thin section, the Pipe Formation appears dominantly clast supported (85). The clast matrix relationship is rarely bimodal, but instead is gradational, with an intermixing of fine-grained material, granules, pebbles, and cobbles. The clasts and interstitial material appear similar to the Shamrock Formation; however, the Pipe Formation can be distinguished by consistent evidence for reworking in both clasts and matrix. This distinction is evidenced by sub rounded to sub angular clasts and crystals in the matrix with minor orientation and grading. Compositionally, the clasts and matrix are mostly of andesitic composition, with minor amounts, less than 5%, angular, <1 mm quartz grains (Figure 6C).

The phenocrysts within flows range in size from <1-3mm, make up 5-20% of the rock, and are primarily composed of plagioclase (5-12%), pyroxene (0-5%) and hornblende (0-3%) crystals with a groundmass made up of aphanitic plagioclase and
clinopyroxene (Figure 8C). Up to 80% of the phenocrysts have been altered to sericite, epidote and chlorite (Figure 9B). The amygdules are filled with epidote and actinolite.

The welded tuff is composed of plagioclase grains (45%), <1 mm angular plagioclase phenocrysts (10%), 3-7 mm flame composed of volcanic ash (25%), and 20% chlorite-epidote, which replaces the matrix (Figure 7B). The pelecypod bearing wacke is compositionally similar to other wackes in the Pipe Formation. The matrix is primarily sub rounded-sub angular, fine-grained plagioclase, volcanic, and volcaniclastic fragments supporting the carbonate shells and shell fragments.

Within the Pipe Formation epidote and chlorite alteration can be seen evenly distributed throughout the matrix and clasts. Also, in some cases actinolite appears growing in between phenocrysts, within the fractures of the phenocrysts and outward into the matrix, all of which indicates lower greenschist facies metamorphism (Figure 9C).

Rocky Ridge Formation

In thin section, the Rocky Ridge Formation shows a great deal of compositional diversity in both clasts and matrix and further signs for multiple episodes and modes of deposition. The conglomerates are composed of 3 types of volcanic and volcanioclastics; basaltic andesite, aphyric andesite, and porphyritic andesite. There are also clasts of tuffaceous wackes and minor (<5%) felsic epiclastics and volcanioclastic rocks. The matrix is primarily aphanitic to very coarse volcanic litharenite and tuffaceous wacke made up of plagioclase (40%) and monocrystalline and polycrystalline quartz crystals (30%), and it regularly appears sorted (Figure 8D).

More than 60% of the matrix is altered to chlorite, epidote, and sericite and > 20%
of the plagioclase present in clasts has altered to sericite.

**Table Mountain Formation**

In thin section, the interbedded mudstone, siltstone, and wacke of the Table Mountain Formation is dominantly composed of quartz poor clay (50%), wacke (40%) and silt (10%). The mudstone and siltstone beds (Figure 8E) range in thickness from 1 mm to 10cm and have rare uneven, non-linear contacts, scours and intermixing. Both mudstone and siltstone contain sand sized grains composed of volcanic fragments (75%) and quartz or quartz rich lithic fragments (25%).

The wacke is composed of medium-grained volcanic rocks, monocrystalline and polycrystalline quartz grains and plagioclase laths, and minor (<10%) granitic fragments (Figure 7C). The occasional clast supported beds have varied composition of volcanics (50%), basalt, basaltic andesite, and andesite, as well as volcaniclastic (15%) and sedimentary (15%) clasts. The matrix is primarily intermixed clay, tuffaceous wacke, and volcanogenic sandstone, and is often oriented around and parallel to the clasts (Figure 8F).

Metamorphism of the Table Mountain Formation is evidenced by regional chlorite-epidote alteration in the matrix and volcanic clasts, metamorphic porphyroblasts of albite within clay rich wacke beds (Figure 10C), and calc-silica veins and pyroxene, hornblende and epidote present near plutons.

**DISCUSSION AND CONCLUSIONS**

The Nyac Terrane is a complex assemblage of volcanics, volcaniclastics, and shallow
marine sediments, within which exists a great deal of variation between individual rocks, facies, and formations. The following sections attempt to group these variations by respective scales: 1) Microscopic to regional alteration facies, 2) local changes in deposition in relation to submarine and subaqueous environments, and 3) regional changes in deposition and terrigenous input controlled by the tectonic history of the Nyac Terrane.

Interpretation of Alteration Facies in the Nyac Terrane

In this study, diagenetic, hydrothermal and metamorphic alterations are distinguished on the basis of mineralogy, texture and distribution. It is difficult to differentiate between these three types of alteration as the conditions of one type of alteration may overlap with those of other types of diagenetic alteration, all of which may have been variably overprinted by local contact metamorphism.

The following is one possible explanation of the alteration facies recorded in the Nyac Terrane, beginning with the interaction of sea water and extruding and cooled magma, followed by later hydrothermal alteration taking advantage of the high porosity of the volcaniclastic and sedimentary deposits, and finally contact metamorphism variably overprinting and altering the mineralogy.

Spilitization (diagenesis)

The rapid cooling of lava characteristic of submarine volcanism results in glassy rather than crystalline volcanic rocks. Typically this is seen in the glassy groundmass of sheet and pillow basalts, hyaloclasites, and peperites. If this glass is exposed to water the
resulting diagenesis called palagonitization is likely to occur. Palagonitization is the process of original volcanic glass, which comprises a large portion of the parent volcanics in submarine and submarine-subaerial volcanism, recrystallizing into palagonite (Dreif, 2004). Evidence of this recrystallization is primarily seen within the Pipe Formation as a clay rich groundmass within flows, but reworked clasts and volcaniclastics with evidence of devitrification are present throughout the terrane.

**Hydrothermal alteration (transition)**

The hydrothermal alteration, seen as chlorite-epidote facies, pervasive sericite alteration, and magnetite (Figure 5), is more regional in distribution, but also contains local variation interpreted as the distinction between diagenetic, intrusive generated hydrothermal alteration and seafloor alteration. Both forms of hydrothermal alteration are represented by the sericite, chlorite-epidote, and magnetite coating clasts and fractures and growing throughout the groundmass. Typically the clasts have undergone less alteration than the matrix, suggesting a correlation between porosity and increased alteration, which indicates post spilitization alteration.

**Metamorphic alteration (overprinting)**

Contact metamorphism is seen primarily in the Shamrock and Pipe Formations, evidenced by actinolite, tremolite, and cordierite mineralization (Wenz, 2005), seen overprinting preexisting diagenetic alteration. This is due to those two formations close proximity to the plutons. Figure 10C shows recrystallized spheres of albite within a mud rich layer in the Table Mountain Formation, and Figure 9C shows the growth of actinolite
outwards from spaces within and between crystals in the Pipe Formation. In some cases actinolite is visibly overprinting preexisting sericite as well as unaltered matrix.

The three alteration facies defined above are one interpretation of the sequential diagenesis of the Nyac Terrane shifting from syn-eruptive spilitization, to post-eruptive hydrothermal alteration, to thermal and hydrothermal alteration directly related to the early Cretaceous contact metamorphism. Below, these microscopic trends are combined with local changes in composition, stratigraphy, and structure, to describe possible depositional models.

**Local Depositional Models**

All prior research and current evidence suggests that the Nyac Terrane is of island arc origin, however, this somewhat genetic statement leaves many unanswered questions concerning whether the terrane was deposited in a subaerial or subaqueous environment, whether the timing of tectonic events and the beginning of continental input and accretion can be placed stratigraphically, and whether the Nyac terrane fits within the current tectonic history of SW Alaska. To answer these questions requires a thorough understanding of the compositional and morphological complexities of island arc volcanism, through which local variation within the Nyac Terrane can be understood as functions of the variables that drive them.

*Island arc volcanism*

Active volcanos produce massive quantities of pyroclastic material, resulting in
continuous burial and reworking on the volcano’s naturally steep and shifting sides. When combined with the rugged topography of a volcanic island, a complex distribution of interfingering deep and shallow marine to subaerial facies occurs (Decker et al., 2004). Figure 11 shows a schematic view of island volcanism, including subaerial, island shelf, shallow marine, and trench facies. This is a simplified way of distinguishing the formations as a function of proximity to volcanism. Note that all four formations are placed on this figure in horizontal stratigraphic relationships.

Characteristics of this type of depositional environment are seen in the Nyac Terrane in the form of extreme lateral variation and discontinuity of beds and facies, as well as complex local and regional stratigraphic relationships. This is seen the most in the Pipe Formation, which has the largest amount of lateral and vertical variation of the four units in the Nyac Terrane, with a total thickness estimated from 300-700 m and common meter scale variation in bed thickness within outcrops.

Increased compositional and structural variation within a unit can also be interpreted as an increase in the rate of sediment deposition in relation to effusion rates. The presence of ferromagnesian mineral grains and fresh igneous fragments in the Shamrock Formation suggests an increase in these rates in the lower Nyac Terrane. Their presence is evidence that the material has undergone little transport after their initial deposition, which is likely in an environment with high burial rates (Adams, 1984). Increased burial rates can be caused by increased volcanic activity or increased terrigenous input and results in less time for reworking and further sediment transport and sorting to occur (Hesse, 1990).

Another, possibly more realistic model for the formation of the Nyac Terrane depends
Figure 1. Schematic vertical and lateral facies variations in subaerial and subaqueous environments for an explosive island volcano, modified from Lajoie and Stix (1992).
on water depth as well as proximity to volcanism. This model assumes the environment changes over time, allowing for vertical and horizontal stratigraphical relationships between facies and formations.

**Subaerial to subaqueous deposition**

One possible interpretation of the variations between the formations comprising the Nyac Terrane is a gradual transition from a subaerial to subaqueous depositional environment. The stratigraphic column in Figure 12 shows how the Nyac Terrane is dominated by andesitic flows and primary and secondary volcaniclastics in the lower two formations and capped by epiclastic conglomerates, semi-volcanic wackes, siltstones and mudstones in the upper two formations. The initial progression of facies, from lava and primary volcaniclastics proximal to volcanism to secondary volcaniclastics distal to volcanism, matches with the schematic for active island volcanism shown in Figure 11. This implies syn-deposition of the two formations, however a change from subaerial to subaqueous deposition may also be a driving variable.

The Shamrock Formation, characterized by lava flows and poorly sorted volcanic breccias, can be interpreted as a subaerial volcanic environment. The lava flows are primarily crystalline and contain only minor evidence for water-magma interaction and hydrated debris flows, and there is no evidence for pillow lavas, peperites, or hyaloclastites, all of which would be expected in a volcanically active, subaqueous environment. Also, the breccias within the Shamrock Formation contain angular, crystalline clasts, and are interpreted as autobreccias, which are a subaerial phenomenon.

A shift from subaerial to subaqueous depositional environments occurs Shamrock at
Figure 12: Schematic stratigraphic column illustrating hypothesized boundary between subaqueous and subaerial depositional environments suggested by associated facies, submarine fossils, and stratigraphic trends in angularity and grain size.

<table>
<thead>
<tr>
<th>Depositional Environment</th>
<th>Average Grain Size</th>
<th>Angularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subaqueous</td>
<td>Angular</td>
<td></td>
</tr>
<tr>
<td>Subaqueous</td>
<td>Round</td>
<td></td>
</tr>
<tr>
<td>Shallow marine basin</td>
<td>Round</td>
<td></td>
</tr>
<tr>
<td>Normal graded</td>
<td>Angular</td>
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<tr>
<td>Debris flows</td>
<td>Subaqueous</td>
<td></td>
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<tr>
<td>Subaqueous reworking</td>
<td>Subaerial</td>
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<tr>
<td>Autobreccia</td>
<td>Subaerial</td>
<td></td>
</tr>
<tr>
<td>Lava flows and sills</td>
<td>Subaerial</td>
<td></td>
</tr>
<tr>
<td>Debris flows and lahar</td>
<td>Subaerial</td>
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<td>Subaerial volcanic slope</td>
<td>Subaerial</td>
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<tr>
<td>Subaerial volcanic slope</td>
<td>Subaqueous</td>
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<tr>
<td>Lava flows and sills</td>
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<tr>
<td>Epiclastic beach deposits</td>
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<td>Epiclastic beach</td>
<td>Subaqueous</td>
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<tr>
<td>Table Mountain Formation</td>
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<tr>
<td>Rocky Ridge Formation</td>
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<td>Pipe Formation</td>
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<td>Rex Creek</td>
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</tbody>
</table>
the contact between the Shamrock and Pipe Formation. The volcaniclastics that compose
the majority of this formation exhibit sorting and orientation that is consistently
pronounced in debris flows suggesting hydrated and most likely subaqueous flows. The
lack of fines in preserved debris flows is interpreted as completely hydrated flows where
separation of grain size could easily occur during single or multiple events of sediment
transport. Also, the presence of pelecypod shells deposited as a distinct layer within a
submarine flow or turbidite suggests a submarine environment adequate for the growth of
pelecypods and adequate for the shells to have been transported and segregated due to
their size and shape and deposited in distinguishable horizontal beds.

The most distinctive characteristic of the Rocky Ridge Formation is the rounded
and oriented clasts that make up the conglomerates. This process could take place in a
beach or fluvial environment. Surprisingly little energy and time is required to round a
clast on a geologic time scale. The incredibly rounded clasts could be the result of short
term reworking of old debris flows in any moderate to high-energy environment
(Bourgeois, 1984). It is also important to take into account the burial rate on the slopes
of an active volcano. Substantial and uniform rounding may not be able to occur in an
active volcanic environment because the time required for rounding exceeds the burial
time (Davies, 1978).

The Table Mountain formation contains intercalated mudstone facies with planar
laminated and graded wacke. Both the stratigraphic relationship and composition of these
two facies indicates a subaqueous, around fair weather wave base environment. Minor
amounts of ripples were seen within interbedded mudstone and siltstone beds; however,
the Table Mountain Mudstone unit contains much more evidence for low energy
deposition in the form of fine clay, silt, and sand grains forming laminar bedding and an almost complete absence of visible bedforms or other indicators of flow (Leyrit, 2000). One interpretation of this difference is that the Table Mountain Formation marks a shift from magmatic island arc and apron deposition to basin and continental deposition, which is consistent with the tectonic history of the terrane and formation of established continental basins during accretion.

Within these four units the facies display several upward stratigraphic trends including increased terrigenous non-volcanic content in the form of clay and quartz, better defined sedimentary structures, deeper marine facies, and less active volcanism or volcanic input. This creates a proximal-distal relationship between facies, as well as an overlying stratigraphic relationship if changes in volcanic output or sea level are taken into account (Figure 11).

Subaqueous volcanism

Another possible explanation for the deposition of the Nyac Terrane is that of continued subaqueous deposition. The typical interaction between magma and water results in accretionary lapilli, spheres of agglomerated fine ash, hyaloclastites, and welded ashes containing yellow colored glass from alteration (Leyrit, 2000) and no unaltered evidence of these facies were evident in the Nyac Terrane, however, this does not mean that they were not originally present. Given the age and degree of alteration documented throughout the Nyac Terrane, the low amount of volcanic glass is not conclusive evidence. The devitrification of volcanic glass creates a somewhat similar volcanic groundmass to that of subaerial volcanism, and with the degree of hydrothermal
alteration and metamorphism that these rocks have undergone it is plausible that conclusive evidence for distinguishing between the two depositional environments on the basis of mineralogy have been erased.

**Regional Changes in Sediment Input and Depositional Environment**

Changes in facies composition and provenance suggest a shift from an oceanic arc to island shelf and continental basin environment. Input into the Nyac Terrane began as pure volcanic and volcaniclastics (~95%), shifting abruptly at the boundary between the Pipe Formation and Rocky Ridge Formation to more mixed granitic (~18%), sedimentary (~12%), and reworked volcanic input (~70%). More specifically, this shift appears as increased clay and quartz content, as well as the stratigraphical trend of fining upwards. This alternative terrigenous material is most likely sourced from the North American Backstop, upon which the Nyac Terrane accreted. Due to postcollisional strike slip faulting and a lack of fault exposure, it is unclear exactly what the Nyac Terrane accreted onto, but current assumptions are that it was either the Nixon Fork-Dillinger-Mistic-Minchumina terranes, Ruby, Kilbuck, or some combination (Figure 1).

**Conclusions**

There are 4 overall assumptions and conclusions that can be made concerning the Nyac Terrane. First of all, the Nyac Terrane can be divided into 4 formations, The Shamrock, Pipe, Rocky Ridge, and Table Mountain Formation, each with distinct facies and stratigraphy. Second, the correlation between trends represented by angularity and average grain size suggest a stratigraphic point mid Pipe Formation for a shift from
subaerial to subaqueous environments. Although there is a great deal of complexity and ambiguity indicating one depositional environment over another, the characteristic sorting of hydrated sediment transport, marine fossils, shallow marine facies, and overlapping local and regional alteration facies suggest that the Nyac Terrane was dominated by subaqueous deposition. Third, these formations represent a progression from predominantly volcanic towards more varied terriginous input signifying a shift from active arc volcanism to permanent volcanic quiescence.
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Appendix A. Lithology polygons as recorded in field. Each polygon represents outcrop scale mapping.
Appendix B. Sample points, Strike and dip measurements, Map points including, lithology points, alteration points, minerology points, and drill hole locations.