CHAPTER 4

# Geologic Structures of Unga Island, their Relations to Mineralization, and some Speculations on their Origins

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Geological and Geophysical Setting of the Gold-Silver Vein Systems of Unga Island, southwestern Alaska

## CONTENTS

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## INTRODUCTION

The mineralized veins of southeastern Unga Island are clearly structurally controlled. The age and structural history of the mineralized trends, however, remain uncertain, because mapping cannot unambiguously demonstrate net offset across the trends. Consideration of regional tectonics, though, provides some insight into their origins. In this chapter, large- and small-scale structures on Unga Island are described and the evidence for their relative age is discussed. The mid-Tertiary structural history of the region is then summarized. Lastly, inferences are drawn about how the crustal strains that produced the regional structures may have governed development of the mineralized trends on Unga Island.

## LARGE-SCALE FOLDS AND FAULTS

The least ambiguous, large structural feature on Unga Island is a broad, northeast-trending syncline at the southeastern corner of the island (see geologic map, Riehle and others, Chapter 2). This feature is defined by opposing dips in well-bedded clastic rocks of unit Tps and there is little doubt of its existence. Sedimentary rocks of the Stepovak Formation on the north coast of Popof Island have opposing shallow dips, but whether these dips continue south to define a synclinal axis in the Popov volcanic rocks is uncertain. The queried anticline in the northeastern corner of Acheredin Bay is defined chiefly by dips of geomorphic benches in lava flows (unit Tpu) and by dips in tuff unit Tpth on only one limb.

Beds in the Miocene Unga Formation typically dip 10 degrees or less on average and define a gentle, northwest-dipping homocline. The homocline may reflect either mild folding or uplift of the center of Unga Island. The erosional outlier of volcaniclastic sandstone and siltstone between Orange Mountain and Apollo Mountain, assigned to the Unga Formation, has randomly oriented, intermediate dips (e.g., N10E 46E, N65E 24SE, and N45W 35SW). Such a range of attitudes in close proximity to one another probably reflects small fault blocks that formed either as a brittle alternative to folding, or in accommodation to vertical uplift.

Mapped faults on Unga Island have a dominant orientation of NE $\pm$ 30º 60-80º S and two lesser modes of NW and NS, near-vertical (fig. 1A). Slickenlines are about equally divided between two diffuse modes: those having steep SE plunges and those that are nearly horizontal, broadly NE (fig. 1D). The steeply plunging slickenlines occur mainly on steep, NE-trending faults and mark dip-slip offsets (open circles on figs. 1B and 1D), whereas subhorizontal slickenlines occur mainly on steep, N-trending faults and indicate strike-slip motion. Only the direction of displacement, and not the sense (i.e., left- or right-lateral), can be inferred from the slickenlines.

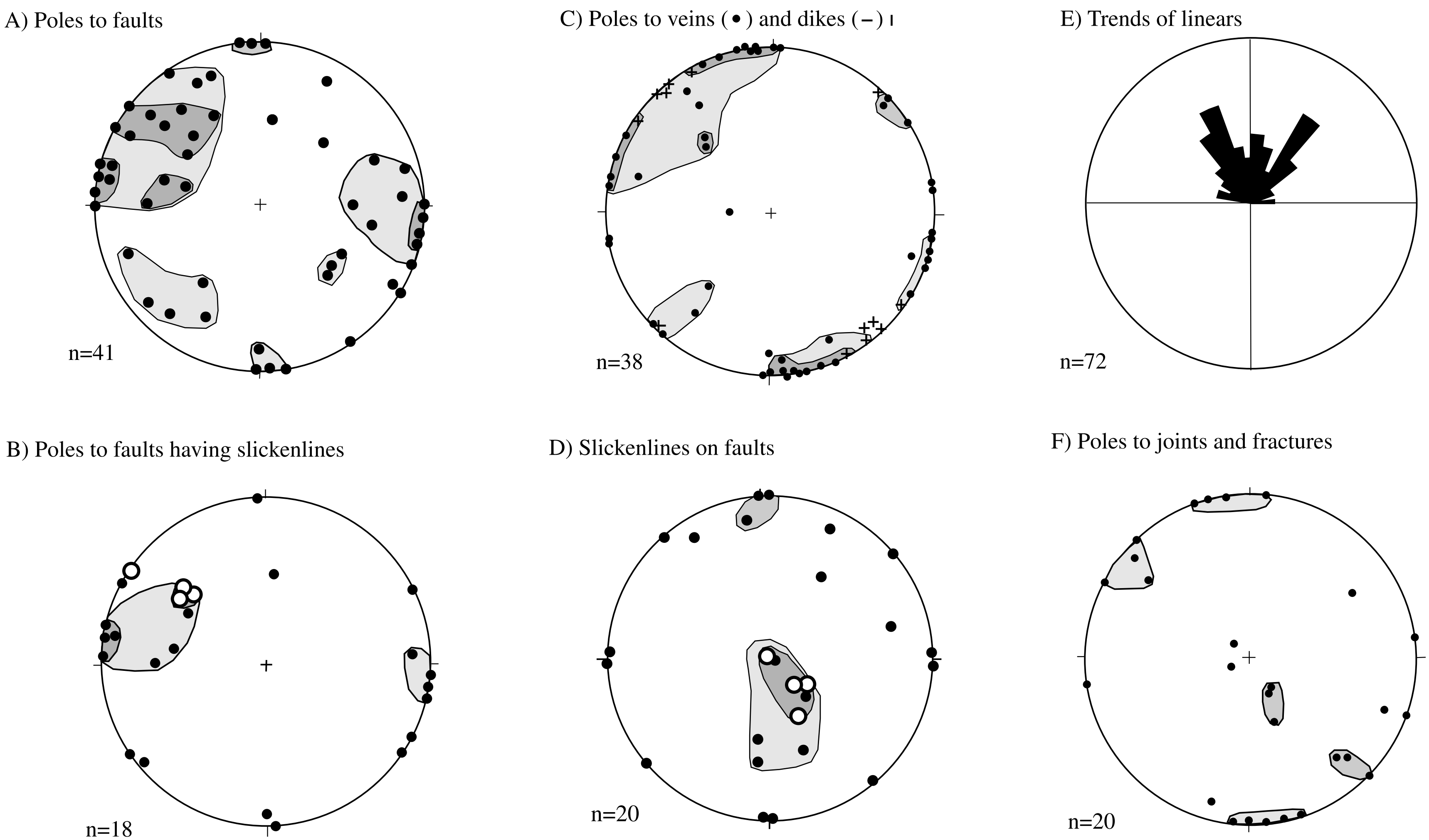


Figure 1. Lower hemisphere, equal area projections of various structural features on Unga Island. Shaded contours are visually estimated to emphasize clustering and have no statistical significance. Open symbols in figure D identify the particular fault planes on figure B.

## MINERALIZED TRENDS

The main mineralized trends on Unga Island are the Apollo and the Shumagin. The Apollo and Sitka mines are located on the Apollo trend. Each trend is characterized by physiographic lineaments, elongate zones of silicification and quartz veins, and local faulting (see frontispiece and Riehle, Chapter 1, fig. 1). Such features that define the Apollo trend extend continuously from south of Apollo mountain, north-northeast through the Apollo mine, then east through the Sitka mine and to the east coast of Unga Island. Exposures in exploration tunnels (Sanford, 1947) support the extension of the Apollo vein system in the subsurface to the Sitka mine, although locally truncated by NW-trending cross-faults. Consequently, the entire extent of the zone across southeastern Unga Island is referred to as the Apollo trend.

The Shumagin trend has been drilled at its northeastern end, where it is clearly a fault that offsets two unambiguously recognizable lithosomes: tuff and andesitic lava (fig. 2A). Two fault-breccia units are older than six vein systems; the oldest vein system is the economic target (White and Queen, 1989). Cross-cutting relations among the fault-breccia units and the vein systems indicate multiple and (or) protracted movments. The *sense* of offset is uncertain, however, for two reasons: first, the age of the tuff relative to the adjacent lava flows is unknown; and second, the distribution of tuff deposits elsewhere on Unga Island is locally highly irregular as a result of ponding in paleotopographic depressions (figs. 2B and C). Both vertical and horizontal slickenlines occur on the Shumagin fault at the ground surface. The attitude of the fault is N60E 80-85SE; minor northwest-trending cross-faults offset the main fault with both left- and right-lateral map separation.

The Apollo trend has been generally described in the mining engineering literature but has not been systematically mapped underground. For example, there are no slickenline measurements on the Apollo or its cross faults, nor has the sense of offset been clearly demonstrated. Becker (1898) used the term "reticulated vein system" for the Apollo trend, and noted that the sugary appearance of the gold-bearing quartz veins implied repeated fault movements. The system trends N43E; the main ore chute is 40 ft (12 m) wide and pitches northward. The orebody in the Sitka mine, 1 mile (1.6 km) to the northeast, trends east-west as does the mapped physiographic lineament (Riehle, Chapter 1, fig. 1). As in the Shumagin trend, wallrock clasts have sharp boundaries that indicate little dissolution, and calcite is a minor and late phase.

Sanford (1947), interpreting an unpublished company report from the 1930's, suggests that there are three subparallel veins about 50 ft (15 m) apart and that two of these may merge several hundred feet below the ground surface. The veins dip steeply northwest (Becker [1898] described them as vertical), which suggests that the N-pitching ore chute is a swell within the fault plane. At least two NS-striking cross-faults offset the Apollo and Sitka trends, one of which may dip steeply to the west and have a normal sense of movement.

The extension of the Apollo trend splits east of the Apollo mine and intersects seacliffs as two strands one-half mile (0.8 km) apart (fig. 3; see also Riehle, Chapter 1, fig. 1). Possibly a third strand--the least well-developed of the three--extends northeast from the intersection of the other two strands. It is appealing to interpret the central block between the two strands (unit Tpu) as structurally down, based on the assumption that the volcaniclastic rocks of the block to the south (unit Tps) are overlain by submarine lava flows of unit Tpu in the central block. But the central block is a chaotic mixture of andesitic lava masses, quartz porphyry, tuff, and breccia, in which relative ages and original horizontal are unclear. The central block could equally well be structurally up, exposing peperite that was originally beneath volcaniclastic rocks of unit Tps.

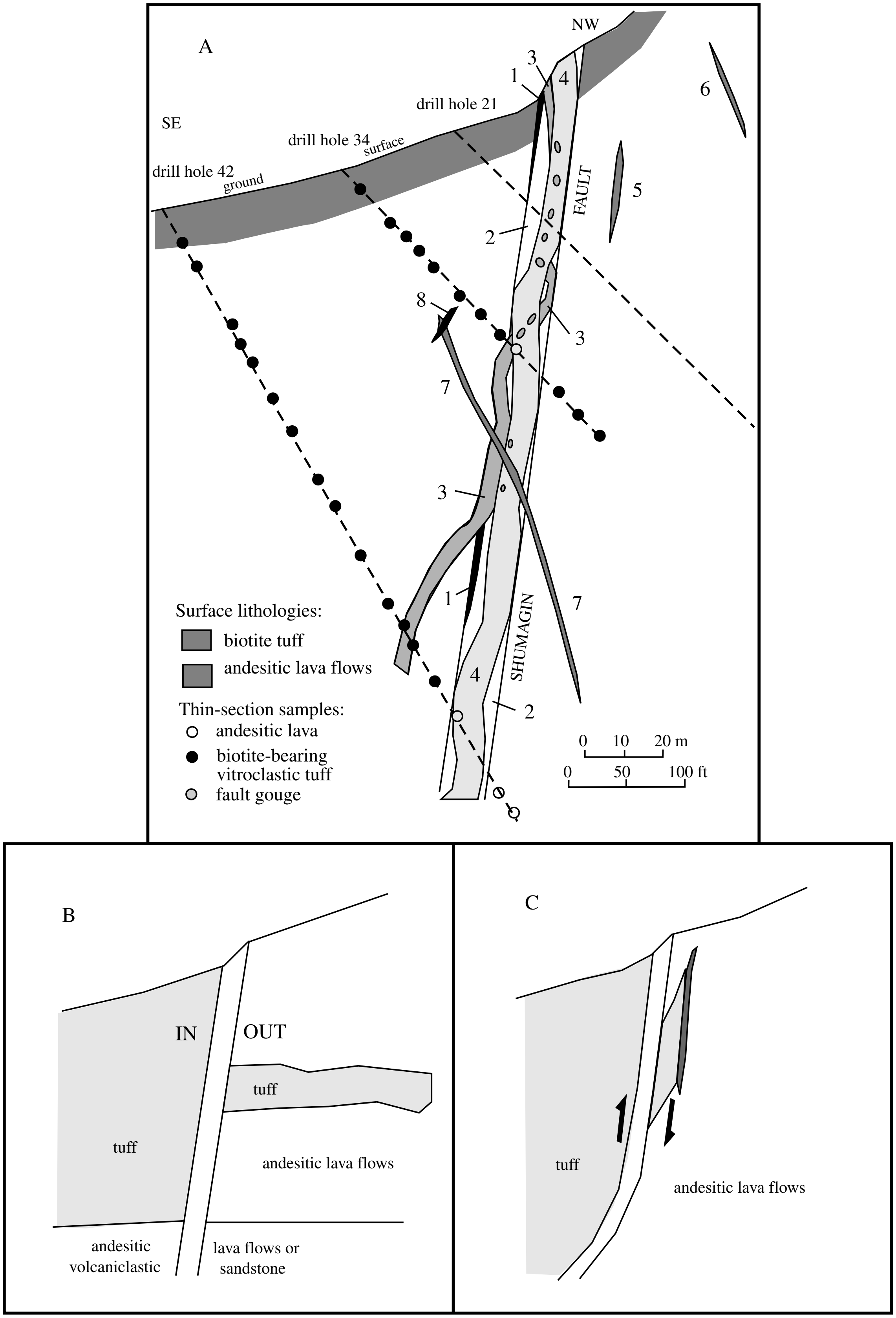


Figure 2. The Shumagin fault at the northeastern end of the Shumagin mineralized trend, Unga Island. (A) NW-SE cross-section based on surface examinations and drilling at the Shumagin deposit. Two units of fault breccia (units 1, 2) were followed by as many as 6 younger vein systems (units 3-8), the oldest of which is the main economic target. From White and Queen (1989). (B) One possible interpretation to explain the occurrence of tuff on both sides of the fault is that movement was dominantly strike-slip and juxtaposed different parts of the tuff unit whose original distribution was controlled by irregular paleotopography. (C) Another alternative is that the the tuff on the NW side of the fault is a structural sliver (a "horse") formed during dominantly reverse movement.

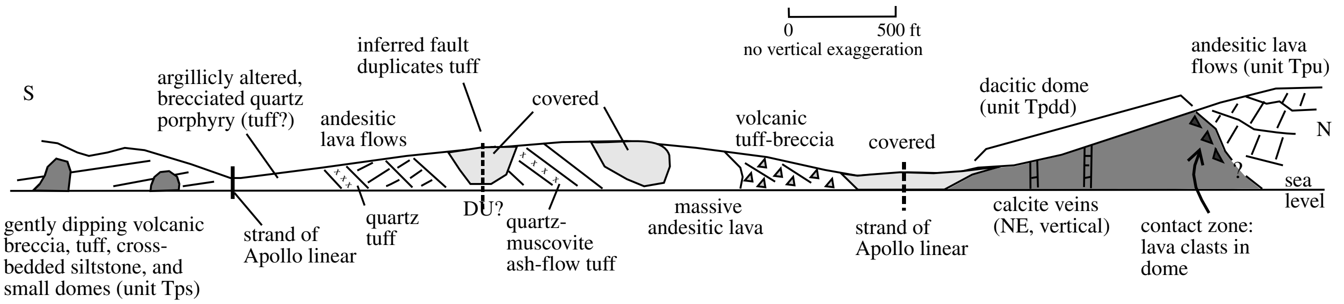


Figure 3. Cross-section showing distribution of rock units in the sea cliff where the Apollo trend intersects the eastern shore of Unga Island.

## DIKES, VEINS, AND LINEAMENTS

Dikes and veins of mainly quartz and calcite are dominantly subvertical. The main strike of both dikes and veins is broadly northeasterly; a minor strike is northwesterly (fig. 1C). The number of observations is too small to determine whether the orientation of veins and dikes differs significantly from that of the faults. At a few sites, multiple sets of quartz veins having slightly different strikes are observed to cross-cut one another. For example, up to five quartz vein systems and one late calcite vein occur at the Shumagin fault (White and Queen, 1989). Some quartz veins occupy the fault itself and are brecciated, while other veins cross-cut the fault and are clearly post-faulting.

Topographic lineaments were identified from stereoscopic examination of aerial photographs and from the hillshaded digital elevation model (frontispiece). Lineaments have two distinct trends: N40E and N30W (fig. 1E). Joints and fractures are mainly either EW and subvertical, or are NE and steeply to shallowly dipping to the NW (fig. 1F). Although the number of observations is small, it appears that the joints and fractures are conjugate to the NE-trending faults.

## THE AGE OF STRUCTURES ON UNGA ISLAND

There is no direct evidence for structures that developed contemporaneously with volcanism, such as a caldera-margin fault that cuts older volcanic rocks and is covered by younger deposits. Moreover, there are no cases known from geologic mapping of quartz veins or mineralized trends having been buried or truncated by volcanic rocks.

The most critical piece of evidence bearing directly on the age of Unga Island vein systems is the radiometric age of vein adularia from the Apollo system. The sample was collected from the portal tailings pile at the Apollo mine by W.H. White and has an age of 34.0 million years (Riehle and others, Chapter 2, Table 1: sample 89AWw130), which overlaps the narrow range of ages of three dome samples (82ACc021, 34.2 m.y.; 82ACc023, 34.0 m.y.; 85AWs293, 32.2 m.y.). An alteration age from unit Tpu on Acheredin Bay (82AWs015, 31.8 m.y.) also falls in the range of 32-34 Ma, which indicates a period of overlapping intrusive activity, faulting, and veining late in the lifetime of the Oligocene volcanic center.

Indirect evidence that some structures developed contemporaneously with magmatism is found in the resistivity data: An alignment of bedrock conductors extends east-northeast from the Shumagin lineament toward Bloomer Peak and ends at the contact with the Bloomer Peak dome (unit Tpdd, geologic map, pl. 1; see Cady and Smith, Chapter 5, fig. 8). The alignment of the conductors is probably structurally controlled, so truncation of the alignment implies that the controlling structure developed prior to emplacement of the dome.

Open folds on southeastern Unga Island are of unknown age: If the homoclinal dip of the Unga Formation is the result of folding, they probably formed as late as a Miocene folding event on the Alaska Peninsula (Vallier and others, 1994, p. 383). Alternatively, the folds may have originated by draping over basement fault blocks like the central ridge of the Shumagin basin (fig. 4), rather than by compressional shortening. There may be support for this possibility in the distribution of volcanic vents: One NE-trending belt is defined by the domes on the southeastern headlands of Unga Island. A second belt lies 1 to 2 miles (2-3 km) to the NW of the first and includes domes on the northeastern shore of Acheredin Bay, Apollo Mountain, and the southern headland of Baralof Bay. Such belts may be apparent rather than real, reflecting the vagaries of erosion and exposure. But if real, a NE-oriented alignment of vents implies control by deep crustal structures.

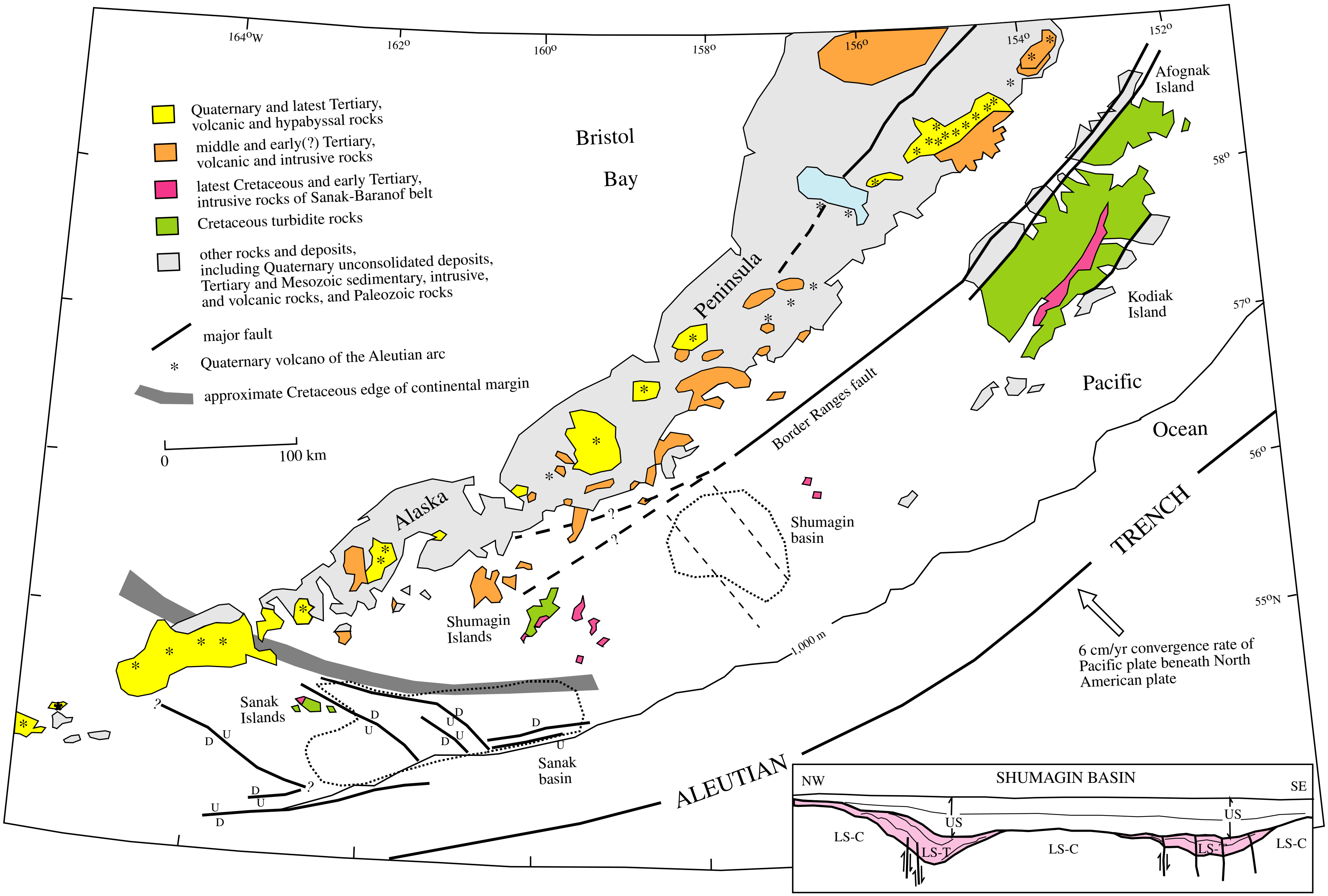


Figure 4. Simplified regional geologic map (sources in fig. 1 of Riehle and others, Chapter 2) including offshore structures and basins from Bruns and others (1987). A structural cross-section of the Shumagin basin (inset) based on seismic profiles (dashed lines) provides a possible analogue for NE-trending, mid-Tertiary structures on Unga Island. "LS-C" is probable Cretaceous basement of the Shumagin basin, "LS-T" are post-Cretaceous, pre-late-Tertiary(?) rocks that were deposited as the basin subsided along extensional faults, and "LS" are largely undeformed, Miocene and younger rocks (Bruns and others, 1987).

Although total offset is geologically small, the Shumagin and Apollo trends each show evidence of multiple displacements. Initial faulting without veining was followed by faulting accompanied by veining, which in turn was followed by more vein sets. These relations mean that vein fluids were available soon after secondary permeability had developed along faults. The NE-trending features were later truncated by N- to NW-trending cross-faults. There are some NW-trending quartz veins, but NW-trending silicified zones and veins are not nearly so voluminous as are NE-trending ones. Therefore, the NW trends must be distinctly younger than the NE set. Indeed, some NNW-trending faults cut the Miocene Unga Formation, indicating a younger age than the mineralized northeasterly trends in southeastern Unga Island. Slickenlines (see fig. 1) indicate that both vertical and strike-slip movements occurred on the northeast-trending faults, whereas movement on younger northwest-trending faults was chiefly strike-slip. Three domes southwest of Zachary Bay are aligned next to a NNW-trending fault (see geologic map, Riehle and others, Chapter 2), suggesting that these faults served to control the siting of Miocene volcanism.

Seven samples of quartz veins from the Apollo and Shumagin trends have $\delta^{18}O$ values of -0.1 to +3.0 (W. White, written commun., 1991). These are low values compared to magmatic water and, as at the Comstock lode (Criss and others, 1990), indicate deposition from heated meteoric (surface) waters that most likely circulated in geothermal cells driven by subsurface intrusions.

## REGIONAL TECTONICS DURING THE OLIGOCENE AND EARLY MIOCENE

The most recent major change in plate motions in the northern Pacific region occurred 43 Ma, when spreading ceased at the Kula-Pacific ridge. Convergence of the Pacific plate on the southern Alaska margin shifted from northerly to its present northwesterly direction and the rate slowed to one-half or less of its previous rate (Engebretsen and others, 1985). Oroclinal bending of mainland Alaska had ended by this time, based on broadly consistent results of paleomagnetic studies on volcanic rocks younger than 43 Ma throughout southwestern Alaska (Hillhouse and Coe, 1994). Since then, dextral-oblique convergence at the latitude of Unga Island has been at an angle of about 75 degrees relative to the Aleutian trench (fig. 5).

An angular(?) unconformity extends along the continental shelf from southwest of the Shumagin Islands (Bruns and others, 1987) to northeast of Kodiak Island (von Huene and others, 1987) and documents regional uplift during Oligocene to early Miocene time. Two seismic profiles across the Shumagin basin show steep, northeast-trending growth faults that Bruns and others (1987) infer to have been active during the early Tertiary (see inset, fig. 4). Such growth faults indicate northwesterly crustal extension, presumably a consequence of regional uplift. Uplift may have been caused by changes in factors such as the rate of sediment supply to the trench (e.g. Clendenen and others, 1992) or in underplating of Alaska at the Aleutian trench for the first few million years after the shift in subduction direction.

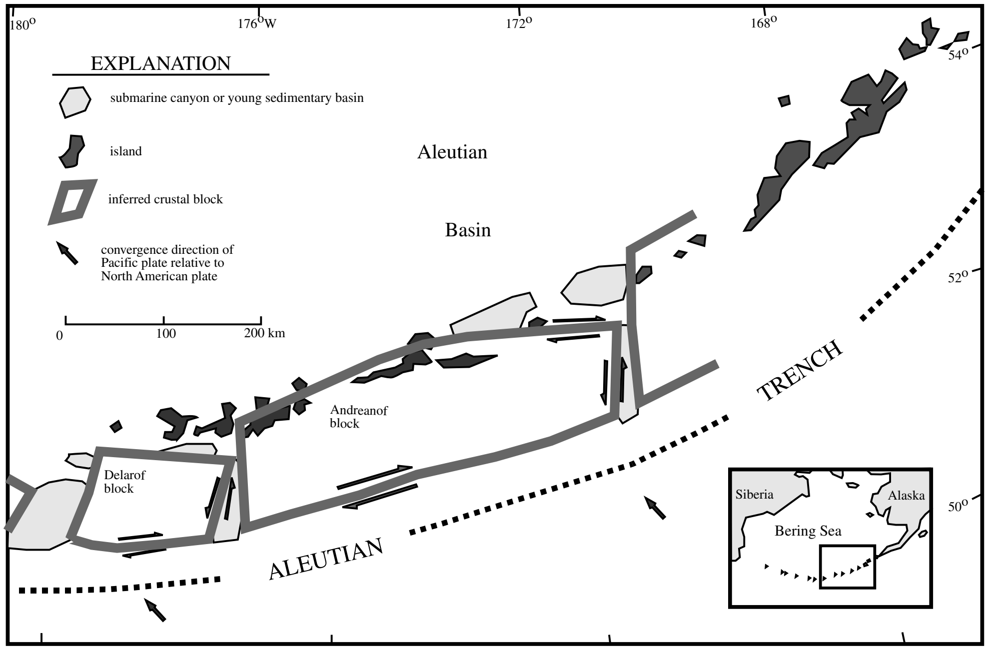


Figure 5. Counterclockwise rotation of forearc crustal blocks is proposed by Geist and others (1988) to explain the occurrence of geologically young, extensional features in the insular part of the Aleutian arc. Rotation is in response to oblique plate convergence.

But regional tectonics during middle Tertiary time are more complex than just uniform crustal extension. On the Alaska Peninsula adjacent to Unga Island, Oligocene and older rocks are tightly folded and faulted in a linear zone that Wilson and others (1985) suggest may be the onland extension of the Border Ranges fault. The zone of shortening is truncated by 10 Ma plutons and so is Miocene age. Rocks involved with folding include the Stepovak Formation, which occurs on the Alaska Peninsula only within 100 km of Unga Island (Detterman and others, 1996). The deep-water turbidite deposits of the lower siltstone member are disconformable on lower Tertiary continental deposits and older rocks; the siltstone member may be evidence of local extension contemporaneous with that in the offshore Shumagin basin. In any case, by the beginning of Miocene time, the Alaska Peninsula north of Unga Island experienced uplift and at least local shortening *while the margin of the continental shelf remained under extension* (Bruns and others, 1987, p. 182).

Additional complexities are shown by structures in the Sanak basin, southwest of the Shumagin Islands (fig. 4). The Sanak basin is a post-early-Miocene feature that has no direct bearing on Oligocene structures on Unga Island, except to illustrate the structural complexity at this junction of the Cretaceous plate margin with the modern Aleutian margin. The Sanak basin is bounded by steep, northeast-trending growth faults--like those in the Shumagin basin--that have produced a basement high that encloses the basin on its seaward side (Bruns and others, 1987). These margin-parallel extensional faults are cut by steep, northwest-trending faults that have formed a graben in the central Sanak basin. The margin-oblique faults are unique to the Alaska Peninsula part of the continental shelf: They may reflect older, reactivated Beringian-margin faults, or they may be right-lateral, strike-slip faults (Bruns and others, 1987). Alternatively, extensional summit basins in the insular part of the Aleutian arc are thought by Geist and others (1988) to be the result of clockwise rotation of crustal blocks due to oblique convergence (fig. 5). Obliquity on the Aleutian trench becomes pronounced at about the latitude of the Sanak basin, so incipient block rotation in addition to right-lateral faulting may have played a role in developing the margin-oblique faults. In any case, the northwest-trending, dominantly strike-slip cross faults that truncate the Apollo and Shumagin trends may belong to this post-early-Miocene set of structures.

## IS THERE A CALDERA ON UNGA ISLAND?

The issue of whether there is a caldera on Unga Island has long been a matter of interest and debate among geologists who have worked on the island. The impetus has been in part to identify an analogue for the gold-silver deposits in caldera-hosted deposits such as Creede or Goldfield.

Williams (1941) defined calderas--at least *large* calderas--as sub-circular volcanic depressions that formed by tectonic collapse as a result of a large-volume eruption. We have found no observable field evidence for a collapse caldera, which would include:

* part or all of a former, subcircular topographic depression having
* steep sides, bounding faults, and (or) landslide breccia inside the depression, and
* voluminous homogeneous deposits ("outflow deposits") that would document a large, geologically instantaneous eruption.

Deposits of intermediate to silicic, caldera-forming eruptions are typically ash-flow tuffs, for the reason that large eruptions involving viscous magmas tend to be explosive. Effusive eruptions such as on the Island of Hawaii can form calderas because basaltic magmas have sufficiently low viscosity that a large enough volume can erupt as lava in a short enough time to cause collapse. Calderas may have formed during effusive andesitic eruptions in the Wrangell Mountains of eastern Alaska, where large volumes of nearly aphyric, homogeneous lavas imply rapid eruption of hot, low-visocosity magma (D. Richter, written commun., 1997).

There are neither voluminous, homogeneous aphyric lava flows nor voluminous ash-flow tuffs on Unga Island. The lack of potential outflow deposits, however, is the least compelling argument against caldera formation, for their apparent absence could be the result of glacial erosion of poorly consolidated pyroclastic deposits, and (or) burial by later deposits.

Bloomer Peak, Apollo Mountain, and unnamed domes to the southwest of Apollo Mountain roughly define a north-concave arc. There are, however, no facing features to the north or west that could be opposing walls, nor have we seen evidence for buried arcuate structures in the distribution of altered areas, density of quartz veins, or the occurrence of secondary (tectonic) breccias. Volcanic clasts to 6-8 m across occur in submarine landslide deposits along 1 km of the south shoreline of Delarof Harbor, where they are part of a sequence that includes submarine lava flows, flow breccias, and bedded tuffs (unit Tps). But we could not extend these deposits in an arcuate pattern, nor could we find a topographic submarine scarp that might have been the source of the deposits. Instead, we interpret the landslide deposits to have formed adjacent to local slopes at the toes of volcanic cones and lava flows.

Buried caldera walls could be reflected in aeromagnetic data, but the available geophysical data do not extend northwest of Orange Mountain (Cady and Smith, Chapter 5). Within the coverage of data, there are no closed, arcuate anomalies that suggest a caldera wall (but see Cady and Smith, "Interpretation of Magnetic Anomalies").

Alternatively, vein mineralization on Unga Island can be explained by the combination of two geologic factors: (1) protracted or recurring magmatism, simultaneously with (2) extensional structures that provided permeable paths for geothermal circulation above and adjacent to shallow magma bodies. Both factors occur as well in caldera systems, but in any case, the type of vein mineralization found on Unga Island does not require a caldera structure.

## SUMMARY OF STRUCTURAL DATA AND CONCLUSIONS

* Unga Island is sited near the overlap of the Cretaceous margin of the North American plate (the Beringian margin) and the modern Aleutian subduction zone. The region has undergone a transition from extensional tectonics in the middle Tertiary to compressional tectonics during the late Tertiary. The site also marks a transition from margin-parallel extensional faults to the NE, to margin-oblique extensional or strike-slip faults to the SW.
* The most important structural features on southeastern Unga Island are the Shumagin and Apollo trends--NE-trending zones of intense alteration, silicification, and mineralization. The zones are in part faults that have experienced repeated but minor movements. Brecciation provided pathways for heated meteoric waters that were circulated in geothermal cells by subsurface intrusions during a 2-million-year period near the end of the Oligocene (Popof volcanics) stage of volcanism.
* The mineralized trends are cross-cut by later, N- to NW-trending faults that have less significant silicification associated with them. Some of these younger faults in the northwestern part of Unga Island may have served to localize Miocene volcanic vents, and possibly alteration and mineralization as well.
* Net offset of geologic units across the Shumagin and Apollo trends is uncertain, and slickenlines at the ground surface are both steeply plunging and subhorizontal. Thus, both structures are only incipiently developed and in fact have experienced both dip-slip and strike-slip movements, perhaps repeatedly.
* A possible analogue of the Unga Island trends are steep, NE-trending growth faults in the offshore Shumagin basin that were active during early to middle Tertiary time. The Shumagin basin faults are inferred to be extensional features. Probably the Unga Island trends were initially extensional features that were reactivated by lateral

motions when the NW-trending cross-faults formed, to accommodate to increasingly oblique convergence to the southwest on the post-43-Ma Aleutian subduction zone.

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