CHAPTER 2

Geology of Unga Island and the northwestern part of Popof Island

By James R. Riehle, Frederic H. Wilson, Nora Shew, and Willis H. White

U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT 99-136

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

CONTENTS

Geology of Unga Island and the northwestern part of Popof Island

James R. Riehle, Frederic H. Wilson, Nora Shew, and Willis H. White

PREVIOUS GEOLOGIC STUDIES

The first geologic map of Unga Island was published by Atwood (1911; scale 1:250,000), who correctly inferred the middle Tertiary age of the volcanic rocks and made the important distinction between the lava flows and the intrusive domes. Although Burk's (1964) reconnaissance map of the Alaska Peninsula (scale 1:250,000) has been modified in some respects, it does correct Atwood's map by replacing the Kenai Formation on northwestern Unga Island with the Unga Conglomerate and by recognizing the older Stepovak Formation elsewhere on Unga and Popof Islands.

U.S. Geological Survey (USGS) field studies that were focused on the mineral-resource potential of the Alaska Peninsula began in the late 1970's. These studies led to a geologic map of the Port Moller quadrangle--including Unga Island--at 1:250,000 scale (Wilson and others, 1995), as well as summaries of mineral occurrences and geochronological studies (Wilson and others, 1988, 1994) and a formal revision of the stratigraphic units of the Alaska Peninsula (Detterman and others, 1996). As follow-up to the regional studies, a detailed study of the vein systems on Unga Island was undertaken as a collaborative effort between USGS and private industry (White and Queen, 1989). The fieldwork leading to the present report and geologic map was started in 1978 (Riehle and others, 1982) and was completed as part of the vein study. The objective was a better understanding of the geologic setting of the vein systems: the geologic history of the host rocks, the structural controls on the veins, and the types of processes that likely caused the mineralization.

SUMMARY OF THE REGIONAL GEOLOGIC AND TECTONIC HISTORY

The Shumagin Islands are sited on the continental shelf 350 km southwest of Kodiak Island. The group lies from 40 to 120 km toward the Aleutian trench from the active Aleutian volcanic arc and so is part of the Aleutian forearc (fig. 1). The northwestern islands of the group, including Unga and Popof Islands, are informally referred to as the inner Shumagins and the remainder as the outer Shumagins. A recent summary of the geology of the Alaska Peninsula and the adjacent continental shelf by Vallier and others (1994) is the main source for the geologic overview here. Regional geologic maps are those by Beikman (1980, scale 1:2,500,000; re-published as Plate 1 in Plafker and Berg, 1994) and an Alaska Peninsula compilation (Wilson and others, in press) at 1:500,000, which includes recent USGS mapping.

Besides subduction, two major and controversial tectonic processes that have helped to shape the southern Alaska continental margin are terrane migration and rotation of the mainland. Both are a consequence of plate tectonics: Terranes of previously separated crustal blocks have migrated due to sea-floor spreading, and some believe that southwestern Alaska has rotated counterclockwise in response to collision of the northwest-migrating collection of terranes with Siberia. The two types of evidence for these processes--geologic and paleomagnetic--have been summarized by Plafker and Berg (geologic; 1994) and Hillhouse and Coe (paleomagnetic;

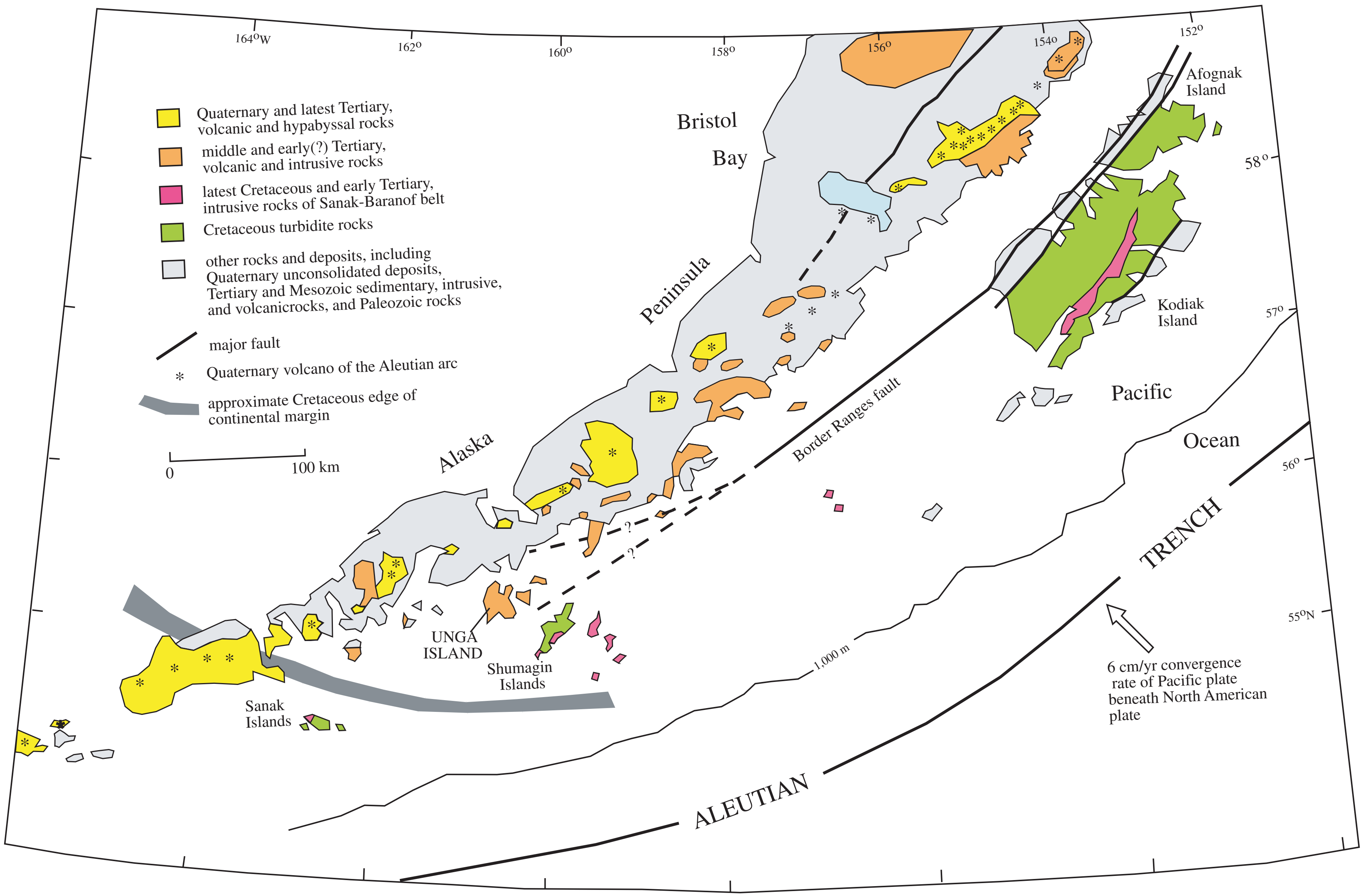


Figure 1. Simplified geologic map of the Alaska Peninsula and islands in the region of the Shumagin Islands, Alaska. Geology from Beikman (1980), Vallier and others (1994), and Wilson and others (in press). Location of the Border Ranges fault where shown as solid is from Fisher (1981); dashed portions are from Vallier and others (1994) and Wilson and others (1985a). Cretaceous margin of North American continent is from Scholl and others (1992).

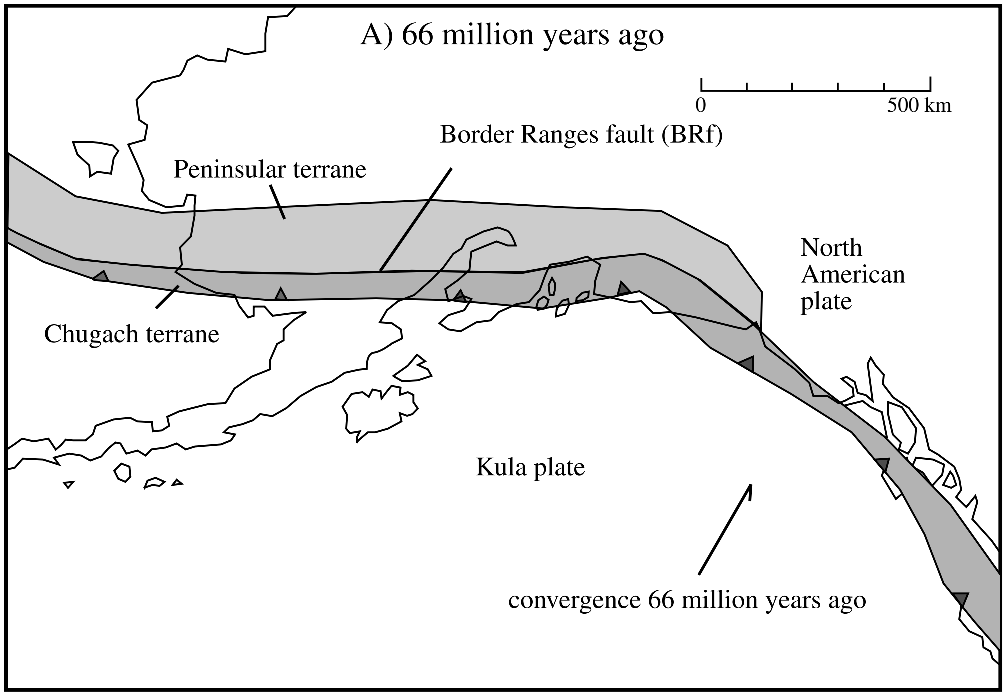
1994). Because the oldest rocks exposed on Unga Island postdate the latest terrane movement and rotation of the basement, only the main conclusions of these authors are summarized here without discussion of details or uncertainties.

The Alaska Peninsula is underlain mainly by arc-related, volcanic and plutonic rocks and shallow marine and continental sedimentary rocks that range from Paleozoic to Holocene in age. These rocks are the Peninsular terrane of Jones and Silberling (1979; proposed to be renamed the Alaska Peninsula terrane by Wilson and others, 1985b), which is inferred to have ceased northwestward migration relative to North America--that is, accreted to Alaska--by between 65 and 55 million years ago (Ma) (Hillhouse and Coe, 1994). Seaward of the Peninsular terrane, upper Cretaceous turbidites are exposed on the outer Sanak and Shumagin Islands (Shumagin Formation) and Kodiak Island (Kodiak Formation) (fig. 2). The turbidites, together with submarine basalt flows and dikes, are part of the Chugach terrane. The Chugach terrane is separated from the Peninsular terrane by the Border Ranges fault (BRf), which may mark the megathrust where the trench and slope turbidites of the Chugach terrane were subducted beneath the Peninsular terrane (Plafker and Berg, 1994) (see fig. 2A).

The BRf is exposed on northwestern Kodiak Island, from which it has been traced southwestward to within about 200 km of the Shumagin Islands on the basis of marine magnetic data (Fisher, 1981). The BRf is inferred by Vallier and others (1994; their fig. 7) to lie between the inner and outer Shumagin Islands, although Wilson and others (1985a) suggest that a zone of late Tertiary folding may be the onshore extension of the BRf on the Alaska Peninsula north of Unga Island. The significance of the exact location of the BRf to mineralization on Unga Island is whether the island is underlain by arc-derived clastic sedimentary rocks of the Peninsular terrane, or by flysch and tonalitic plutons of the Chugach terrane. We have no new evidence bearing on this issue.

Regional paleomagnetic evidence implies that, after accretion of the Peninsular and Chugach terranes, southern Alaska rotated counterclockwise by 30 to 50 degrees (fig. 2B). Two paleomagnetically measured samples of the Shumagin Formation indicate rotation of 30 to 40 degrees, although the uncertainty at 95 percent confidence is $\pm$15 degrees (Stone and Packer, 1979; see summary by Hillhouse and Coe, 1994). Paleomagnetically measured volcanic rocks from the Alaska Peninsula indicate that the rotation was completed by no later than 43 Ma. The Shumagin Formation and other turbidites around the Gulf of Alaska margin were intruded by tonalitic (i.e., low-K) to granitic plutons of the Sanak-Baranof belt, which are interpreted to be anatectic melts of the turbidites (Hudson and others, 1979; Barker and others, 1992) caused by subduction of the Kula-Farallon ridge (Bradley and others, 1993). Plutons on Sanak Island and in the outer Shumagin Islands (fig. 1) have radiometric ages ranging from about 58 to 63 Ma (Bradley and others, 1993). If the Sanak-Baranof belt in fact marks a progression of the subducting Kula-Farallon Ridge, then the Sanak-Shumagin plutons were intruded *before* significant rotation occurred because tonalitic plutons to the northeast of the Shumagin Islands, in Prince William Sound, are *younger* than the Sanak-Shumagin plutons.

At 43 Ma, subduction beneath the southwestern Alaskan margin shifted outboard to the present Aleutian trench and the subduction direction changed to its present, more northwesterly direction (Engebretsen and others, 1985; see fig. 2B) in response to demise of spreading at the Kula-Pacific ridge. Volcanism on the Alaska Peninsula and inner Shumagin Islands began shortly thereafter (Meshik Volcanics and Popof volcanic rocks; see unit descriptions, chapter 2).



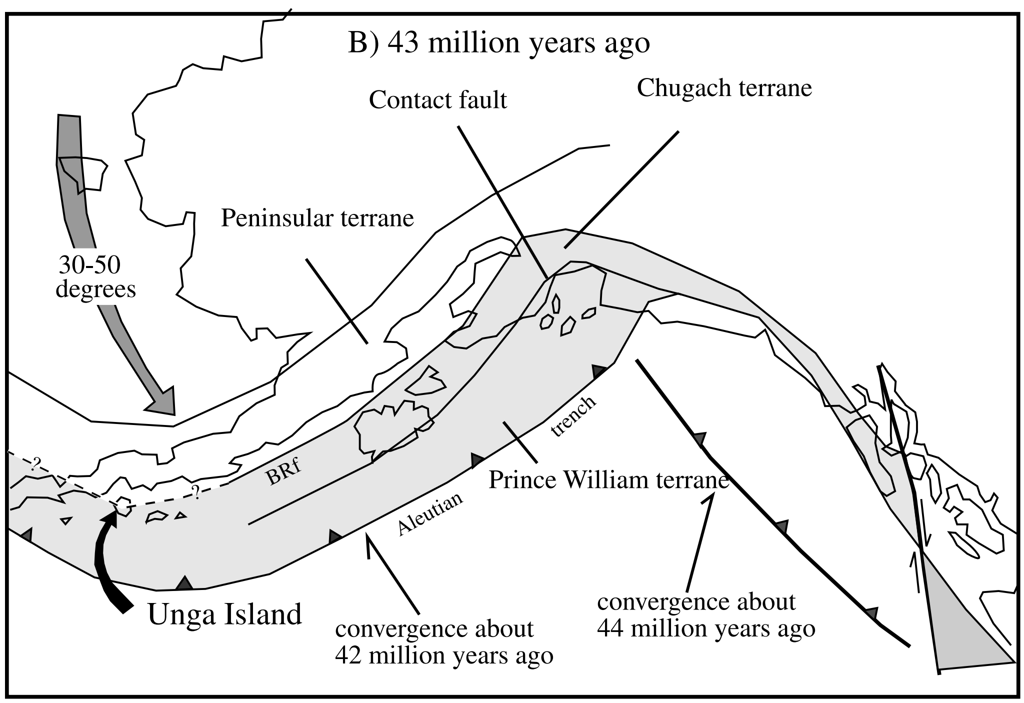


Figure 2. Cartoons showing the generalized distribution of the Peninsular, Chugach, and Prince William terranes relative to the modern coastline of Alaska (from Plafker and Berg, 1994, figs. 5F and 5G). (A) Before the onset of oroclinal bending at about 66 Ma: the Peninsular terrane has previously joined mainland Alaska and turbidites of the Chugach terrane have formed as an accretionary complex above a subduction zone outboard of the Peninsular terrane. (B) After 30 to 50 degrees of counterclockwise rotation of mainland Alaska from about 60 Ma to about 43 Ma: turbidites of the Prince William terrane have been accreted outboard of the Chugach terrane. Convergence of the Kula plate is relatively northward until about 43 Ma, when the convergence direction shifts to the northwest and the modern Aleutian subduction zone and accretionary complex begin.

The Meshik Volcanics and age-equivalent rocks to the north in the Katmai and Iliamna quadrangles formed a discontinuous volcanic arc about 110 km inboard from the Aleutian subduction zone during late Eocene and Oligocene time (fig. 1).

GEOLOGIC HISTORY OF UNGA ISLAND AND NORTHWESTERN POPOF ISLAND

The oldest rocks exposed on Unga Island and northwestern Popof Island are intertidal to shallow marine, sandstone and siltstone of the Stepovak Formation (unit Ts) of late Eocene and early Oligocene age. The Stepovak Formation was deposited on the continental shelf inboard from the Aleutian trench, which had shifted southward from a position at the Beringian margin (Scholl and others, 1992) a few million years earlier.

Popof volcanism

Volcanism began with eruption of submarine lava flows in latest Eocene or earliest Oligocene time. The oldest dated lava flow from Unga Island is 37 Ma (unit Tpu; Table 1) and there are four other ages of unit Tpu between 34 and 37 Ma. The Stepovak Formation (unit Ts) grades laterally and vertically into coarse volcaniclastic rocks of the Popof volcanic rocks, or is disconformably overlain by lava flows of the Popof volcanic rocks (Detterman and others, 1996). Evidence for contemporaneous sedimentation and volcanism includes clastic dikes rooted in fossiliferous sandstone that cut through submarine lava flows on the northwest shore of Popof Island, and soft-sediment deformation of marine sediments where they are adjacent to submarine lava masses on the south shore of Unga Island.

Volcaniclastic deposits having angular clasts to several meters diameter and intimately mixed and deformed masses of lava and sediments--peperites--are mapped together as unit Tps. The volcaniclastics and peperites are distinguished from the Stepovak Formation, although unit Tps is interpreted to be a near-vent equivalent of the Stepovak Formation. Clast pores of some breccias are filled by calcite, which was probably deposited from seawater heated by lava flows. Unit Tps also includes small-volume, submarine ash-flow deposits.

Possible vents are marked by opposing dips of stratocone deposits on the headland 2 km south of Apollo Mountain and in the northwestern corner of Acheredin Bay. Other vents of the initial lava flows are now obscured by burial or erosion. The dominant composition of these early lavas on Unga Island is andesitic, and it is unlikely that such viscous lavas would have spread more than a kilometer or two from vents, especially if erupted into seawater. Andesitic domes (unit Tpd), which are mapped separately from unit Tpu, may have been coeval with some of the initial lava flows and in any case mark vent sites.

Although lava flows of unit Tpu are mainly andesitic, lava flows and a small dome on northwestern Popof Island of low-silica basaltic andesite composition (51-52% SiO_2) are included in unit Tpu. Additional low-silica lavas may be mixed with andesitic lavas at the base of unit Tpu on Unga Island. Other lava masses included in unit Tpu have dacitic and even low-silica rhyolitic compositions and are probably small, poorly exposed domes.

Ash-flow deposits that are sufficiently voluminous to be mapped separately compose a biotite-bearing tuff unit (Tptb) and a hornblende-bearing tuff unit (Tpth). Both are dacitic in bulk composition and although they could be the result of a single heterogeneous eruption, their spatial separation on Unga Island suggests that they are instead the products of different eruptions. Because of pervasive silicification and alteration, the hornblende tuff has not been dated. The biotite tuff contains marine radiolaria (B. Murchey, written commun., 1991; see fig. 3A) at 100 ft above present sea level in drill core from the Shumagin prospect. At two other occurrences the biotite tuff rests on, or is interbedded with, marine sedimentary rocks. A sample of biotite tuff from Popof Strait yielded a potassium-argon age of 33.7 $\pm$ 1.3 m.y. (Table 1) and another from the west shore of Zachary Bay is 31.3 $\pm$ 0.3 m.y. (Marincovich and Wiggins, 1990). The analytical uncertainty of the Zachary Bay sample is one sigma (J. Obradovich, written commun., 1991) and the ages of the two samples are identical at 95% uncertainty (2 sigma), so the two occurrences of tuff could be the deposit of a single eruption. But even if these occurrences of biotite tuff are the products of multiple, closely succeeding eruptions, the tuff should serve as a stratigraphic marker on Unga Island and adjacent Popof Island.

The distribution of both tuff units was controlled in part by paleotopography: Unit Tpth south of Apollo Mountain was deposited on the irregular slope of a stratocone to the southeast. The base of unit Tpth on the valley floor 1 km north of the Apollo mine is altered, blue-green (clay?) tuff and interbedded volcanic breccia. Southwest of Apollo Mountain, unit Tpth is interbedded at its base with tuffaceous siltstone that contains plant fragments. Therefore, both tuff units were deposited at least partly in water, the biotite tuff in seawater. Sources of the tuffs were probably dacitic domes like the dome of Bloomer Peak and other, smaller domes southwest of Apollo Mountain.

Units Tpu, Tps, and the ash-flow deposits south and west of Baralof Bay have been intruded by domes (units Tpdu, Tpdb, Tpda, Tpdd, and Tpdr). Radiometric ages of three domes (32 to 34 Ma; Table 1) overlap with the youngest ages of lava flows, indicating that hypabyssal intrusions were contemporaneous with the closing stages of effusive activity. The domes range from basaltic andesite to rhyolitic in composition, a range of compositions that includes higher silica contents than those of the lava flows. Domes such as the basaltic andesite dome of Apollo Mountain are nearly aphyric and were emplaced at very high temperatures, probably in excess of 1,000 deg C.

Foliation in ash-flow tuff (unit Tpth) dips steeply on the north and south sides of the Apollo Peak dome (unit Tpdb). The foliation could be a mylonitic fabric acquired during faulting, such as development of the Apollo linear, or it could be a folded compaction foliation. Because it has been observed only closely adjacent to the dome on both sides, we prefer the interpretation that it is the result of dome-margin deformation during intrusion.

Other, volumetrically minor ash-flow deposits occur throughout southeastern Unga Island in close proximity to domes. These are probably carapace deposits around the domes, and they are included in the dome map units. Some of the carapace tuffs may correlate with some of the submarine tuff deposits in unit Tps. One such deposit is sufficiently high in silica to be classified as rhyolitic, but the rock has clearly been altered (Na_2O is <1.0% and the sample contains 5% normative corundum). Thus, the unaltered composition of the deposit may have been dacitic. If there are true rhyolitic tuffs, they could have originated at one of several rhyolitic domes (unit Tpdr).

Vents between Zachary Bay and Baralof Bay erupted high-silica andesitic lava flows. These lavas (unit Tpz) were more viscous than most andesitic Popof lava flows, both for having a high silica content (up to 63% SiO_2; see Riehle, Chapter 3) and a higher average phenocryst content (about 35% compared with about 20%). Consequently, lavas of unit Tpz accumulated near their vents to create the high peaks which dominate the physiography of the island. Because the lavas of unit Tpz are pervasively altered, they have not been radiometrically dated.

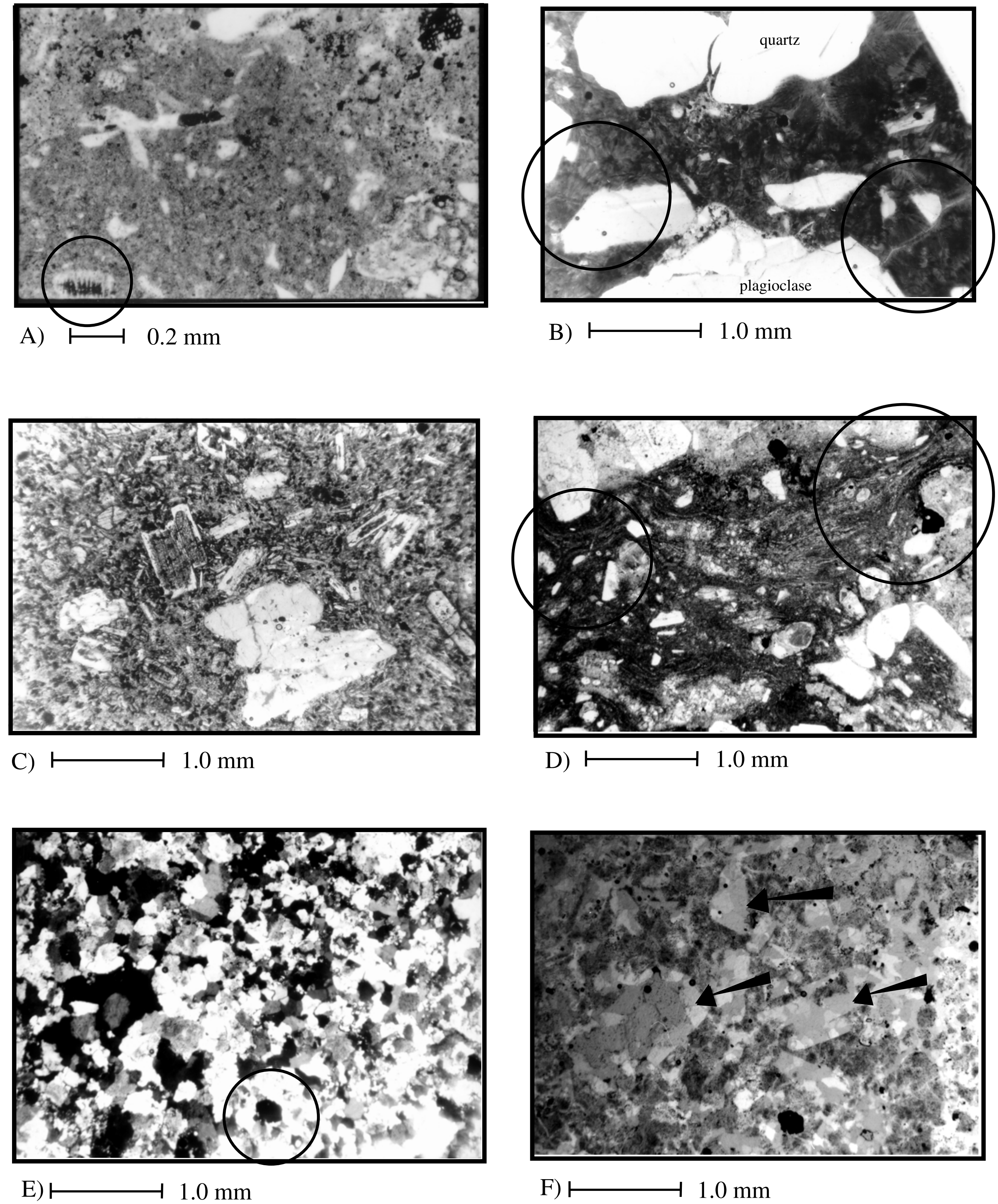


Figure 3. Photomicrographs showing textures of representative samples of Popof volcanic rocks. A) Tuffaceous siltstone faulted against lava flows, drillcore at Shumagin prospect (see Riehle, Chapter 4, fig. 2). The radiolarian (encircled) indicates deposition in water, probably seawater (B. Murchey, written commun., 1991). The deposit was called a tuff (e.g., White and Queen, 1989) but is clearly a marine sedimentary rock rather than a pyroclastic tuff, although one consisting mainly of freshly eroded volcanic material including glassy shards. B) Dacitic vitrophyre dome. Large quartz and plagioclase phenocrysts set in a formerly glassy groundmass that now has microcrystalline devitrification textures like radiating spherules (encircled, left) and axiolitic fibers (encircled, right). C) Typical porphyritic lava flow. Pyroxene (right margin) and zoned plagioclase phenocrysts, some having resorbed cores, occur with progressively smaller grains (seriate texture) that are locally aligned due to flow just before solidification. A little glass fills interstices of the finest grains. D) Andesitic ash-flow tuff. Classical compaction texture due to deformation of pumice clasts between rigid crystals (encircled, right), including Y-shaped shards (encircled, left) that are former broken bubble walls. E, F) Example of replacement silica. Section at left (crossed polars) shows only fine-grained anhedral quartz grains. The section at right is the same view but uncrossed polars (note the same opaque grain in each view; encircled at left). Relict phenocrysts are visible as ghostly outlines (arrows, right view). The relict texture most resembles porphyritic lava like that in C, above.

There is no evidence for an unconformity between lavas of unit Tpz and the underlying(?) lavas of unit Tpu; moreover, the degree of erosional modification is more similar to that of unit Tpu than that of the younger Miocene volcanic rocks (discussed below). Thus, the lavas of unit Tpz are probably approximately coeval with the Popof volcanic rocks. However, a bulk-rock quartz-sericite age from unit Tpz is 14.6 Ma (Table 1, sample 88AWs028) so we conservatively allow that unit Tpz could be as young as Miocene. But the alteration age is most likely an effect of the Miocene volcanism that occurs 3 km west of the sample site.

Lava flows of unit Tpz were intruded by hornblende-bearing sills and dikes. The occurrence of hornblende in these hypabyssal intrusives is not due simply to a higher silica content, because high-silica andesites of unit Tpu either have no hornblende or (rarely) have reacted pseudomorphs. Hornblende in the dikes and sills may have been stabilized by a higher water pressure in the hypabyssal environment. In any case, pervasive hydrothermal alteration of unit Tpz is indicated by widespread calcite, chlorite, and epidote (propylitic alteration) and by color anomalies (oxidized pyrite) on bedrock surfaces. The alteration is presumably a result of the combination of protracted effusive volcanism, a longer period of cooling in the thick pile of lava flows, and hypabyssal intrusive activity.

Miocene volcanic rocks and deposits

A distinctly younger period of volcanism followed Popof volcanism, producing lava flows, domes, carapace breccias and tuffs in the northwestern part of Unga Island. Tuffs interbedded with early Miocene sedimentary rocks on the southern shore of Zachary Bay may be equivalents of carapace breccias around domes from 2 to 3 km away. Tuff samples include low-silica rhyolite and andesite based on silica contents, but most of these younger tuffs have been chemically altered (see Riehle, Chapter 3) and their initial compositions are uncertain. Six radiometric ages range from 11 to 21 Ma (Table 1). Some color anomalies and alteration in Popof volcanic rocks (units Tpu and Tpz) southeast of the Miocene domes may be Miocene effects on the Oligocene rocks.

No Miocene volcanic rocks occur in southeastern Unga Island. A small outcrop of sedimentary rock midway between Apollo Mountain and Orange Mountain may be what Ellis and Apel (1991, p. 16) refer to as "andesite sediments...beneath the fresh andesite flow...". If the sedimentary rock is stratigraphically beneath the flow, then this rock belongs to unit Tps. But this sedimentary rock has leaf casts and conglomerate in which volcanic pebbles are highly rounded. Such features are previously unknown in the Stepovak Formation but are characteristic of the Miocene Unga Formation, so we interpret the outcrop to be an erosional outlier of Unga Formation.

ALTERATION

Alteration, silica replacement, and quartz veining have affected lava flows, tuffs, and volcaniclastic rocks of the Miocene volcanic rocks but even more so those of the Popof volcanic rocks. Alteration ranges from propylitic (widespread) to argillic or sericitic (more localized). Some of the alteration is concentrated along lineaments such as the Apollo trend or local faults. Ellis and Randolph (1991) suggest a progression in which introduced pyrite increases in abundance from weak to intense argillic. They also report the occurrence of secondary gypsum and barite, which we did not see.

A K-Ar age on vein adularia from the Apollo lineament is 34.0 m.y. (Table 1, sample 89AWw130), which indicates that at least some of the alteration and silicification was contemporaneous with the main period of Popof volcanism. The chemical aspects of alteration are discussed more fully by Riehle (Chapter 3) and the nature and origins of the lineaments by Riehle (Chapter 4).

An important aspect of the alteration is discussed here in detail because it bears on the geologic map--the origin of the "Orange Mountain Resistivity Low" (OMRL) identified by Ellis and Apel (1991). The OMRL occupies the area between Orange and Apollo Mountains and the Shumagin claims (see geologic map, pl. 1, and Cady and Smith, Chapter 5, figs. 5-7). Ellis and Apel conclude that elevated bedrock conductivity in this broad area is due to extensive alteration of Popof volcanic rocks, and that alteration preferentially affected tuffs because of their high initial porosity and permeability. The implication is that the OMRL is underlain chiefly by tuffs. However, we include the area of the OMRL in unit Tpu, which is mainly lava flows but having local tuffs, and this merits brief explanation.

Ellis and Apel (1991) and Ellis and Randolph (1991) acknowledge that alteration and silicification (map unit "S" near Orange Mountain, pl. 1) are so extensive that in most cases the original lithology cannot be discerned; in the one case where it could, the parent rock was a porphyritic lava flow. We examined about 15 thin sections, both USGS and industry, from within and adjacent to the OMRL expressly to try to identify the origin of the silicified rocks. In 5 cases, no hint of original texture remains. In one case, a rock that now consists entirely of fine-grained quartz retains a ghostly porphyritic texture; the rock was probably an andesitic lava flow (figs. 3E, F). Of the remaining sections, two are epiclastic tuffs and the remainder are porphyroaphanitic lavas. One of the lavas has veinlets of tuffaceous siltstone and is probably a peperite. The OMRL is an area of mainly low relief in which bedrock is obscured by soil and vegetation; nonetheless, the available data do not indicate that tuffs are the dominant lithologic type. Consequently we believe the area is best characterized as mainly lava flows including local tuffs, but further work, supported by abundant thin-section analysis, may reverse this classification.

One reason for the difficulty in identifying original rock types is that, in hand specimen, some rocks adjacent to the bodies of replacement silica appear to have lithic chips suggestive of tuff but that upon microscopic examination turn out to be clasts of a tectonic breccia. Moreover, drill-hole logs (on file at the Aleut Corp., Anchorage) along the Shumagin trend clearly show a dominance in the shallow subsurface of volcanic(?) clastic rocks. The Shumagin trend lies on or near the axis of an anticline (fig. 4 and pl. 1), thus, any clastic rocks are likely to be Stepovak equivalents (unit Tps) rather than pyroclastic tuffs.

In summary, we agree with Ellis and Apel (1991) that clastic rocks are generally more susceptible to alteration by hydrothermal fluids than lava flows: Tuffaceous horizons between lava flows would have been permissive of lateral fluid flow and silicification. Moreover, clastic rocks appear to dominate in the shallow subsurface along the Shumagin trend. But identification of primary lithologies in now-altered rocks in the OMRL has proven to be tricky, and without further detailed thin-section study, we believe that the exact proportion of lava flows and volcaniclastic rocks at the ground surface in the OMRL remains uncertain.

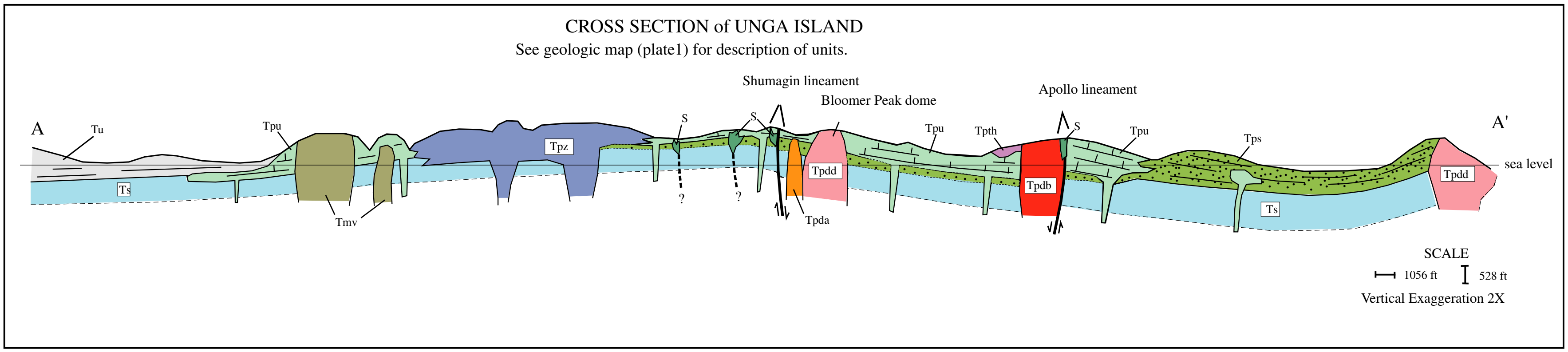


Figure 4. Structural cross-section of Unga Island; line of section shown on Plate 1.

REFERENCES CITED

Atwood, W.W., 1911, Geology and mineral resources of parts of the Alaska Peninsula: U.S. Geological Survey Bulletin 467, 137 p., 14 pl.

Barker, Fred, Farmer, G.L., Ayuso, R.A., Plafker, George, and Lull, J.S., 1992, The 50 Ma granodiorite of the eastern Gulf of Alaska: melting in an accretionary prism in the forearc: Jour. of Geophysical Research, v. 97, p. 6757-6778.

Beikman, H.M., 1980, Geologic map of Alaska: U.S. Geological Survey Special Map, scale 1:2,500,000, 2 pl.

Bradley, D.C., Haeussler, P.J., and Kusky, T.M., 1993, Timing of early Tertiary ridge subduction in southern Alaska, *in* Dusel-Bacon, Cynthia, and Till, A.B., eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1992: U.S. Geological Survey Bulletin 2068, p. 163-177.

Burk, C.A., 1965, Geology of the Alaska Peninsula--Island arc and continental margin: Geological Society of America Memoir 99, 250 p.

Dall, W.H., 1882, Notes on Alaska Tertiary deposits: American Journal of Science, 3d ser., v. 24, p. 67-68.

Detterman, R.L., Case, J.E., Miller, J.W., Wilson, F.H., and Yount, M.E., 1996, Stratigraphic framework of the Alaska Peninsula: U.S. Geological Survey Bulletin 1969-A, 74 p.

Ellis, W.T., and Randolph, D.B., 1991, Unga project, 1991 final report; Battle Mountain Exploration Co., Alaska District, 3 volumes, for The Aleut Corp., Anchorage, AK.

Ellis, W.T., and Apel, R.A., 1991, Unga/Alaska Peninsula Project, 1990 final report; Battle Mountain Exploration Co., Alaska District, 3 volumes, for The Aleut Corp., Anchorage, AK.

Engebretsen, D.C., Cox, Allan, and Gordon, R.G., 1985, Relative motions between oceanic and continental plates in the Pacific basins: Geological Society of America, Special Paper 206, 59 p.

Fisher, M.A., 1981, Location of the Border Ranges fault southwest of Kodiak Island, Alaska: Geological Society of America Bulletin, v. 92, p. 19-30.

Hillhouse, J.W., and Coe, R.S., 1994, Paleomagnetic data from Alaska, in Plafker, George, and Berg, H.C., eds., The Geology of Alaska: Geological Society of America, The Geology of North America, v. G-1, p. 797-812.

Hudson, Travis, Plafker, George, and Peterman, Zell, 1979, Paleogene anatexis along the Gulf of Alaska margin: Geology, v. 7, p. 573-577.

Jones, D.L., and Silberling, N.J., 1979, Mesozoic stratigraphy; The key to tectonic analysis of southern and central Alaska: U.S. Geological Survey Open-file Report 79-1200, 37 p.

Knappen, R.S., 1929, Geology and mineral resources of the Aniakchak district, Alaska: U.S. Geological Survey Bulletin, v. 797-F, p. 161-227.

Plafker, George, and Berg, H.C., 1994, Overview of the geology and tectonic evolution of Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska: Geological Society of America, The Geology of North America, v. G-1, p. 989-1022.

Scholl, D.W., Stevenson, A.J., Mueller, Steve, Geist, Eric, Engebretsen, D.C., and Vallier, T.L., 1992, Exploring the notion that southeast-Asian-type escape tectonics and trench clogging are involved in regional-scale deformation of Alaska and the formation of the Aleutian-Bering Sea region, *in* Flower, Martin, McCabe, Robert, and Hilde, Thomas, convenors, Southeast Asia structure, tectonics, and magmatism: Geodynamics Research Institute Symposium, Texas A&M University, p. 57-63.

Stone, D.B., and Packer, D.R., 1979, Paleomagnetic data from the Alaskan Peninsula: Geological Society of America Bulletin, v. 90, p. 545-560.

Vallier, T.L., Scholl, D.W., Fisher, M.A., Bruns, T.R., Wilson, F.H., von Huene, Roland, and Stevenson, A.J., 1994, Geologic framework of the Aleutian arc, Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska: Geological Society of America, The Geology of North America, v. G-1, p. 367-388.

Wilson, F.H., 1985, The Meshik arc--an Eocene to earliest Miocene magmatic arc on the Alaska Peninsula: Alaska Division of Geological and Geophysical Surveys Professional Report no. 88, 14 p.

Wilson, F.H., Case, J.E., and Detterman, R.L., 1985a, Preliminary description of a Miocene zone of structural complexity, Port Moller and Stepovak Bay quadrangles, *in* Bartsch-Winkler, Susan, and Reed, K.M., eds., The United States Geological Survey in Alaska: Accomplishments during 1983: U.S. Geological Survey Circular 945, p. 55-56.

Wilson, F.H., Detterman, R.L., and Case, J.E., 1985b, The Alaska Peninsula terrane--a definition: U.S. Geological Survey open-file report 85-450, 19 p.

Wilson, F.H., Detterman, R.L., and DuBois, G.D., in press, Geologic framework of the Alaska Peninsula, southwest Alaska, and the Alaska Peninsula terrane: U.S. Geological Survey Bulletin 1969-B, scale 1:500,000, 36 ms pages.

Wilson, F.H., Detterman, R.L., Miller, J.W., and Case, J.E., 1995, Geologic map of the Port Moller, Stepovak Bay, and Simeonof Island quadrangles, Alaska Peninsula, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-2272, scale 1:250,000.

Wilson, F.H., and Shew, Nora, 1992, Map and tables showing geochronology and whole-rock geochemistry of selected samples, Ugashik and part of Karluk quadrangles, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1539-E, scale 1:250,000.

Wilson, F.H., Shew, Nora, DuBois, G.D., and Bie, S.W., 1994, Sample locality map and analytical data for potassium-argon ages in the Port Moller, Stepovak Bay, and Simoneof Island quadrangles, Alaska Peninsula: U.S. Geological Survey Miscellaneous Field Studies Map MF-2155-E, scale 1:250,000.

Wilson, F.H., White, W.W., and DuBois, G.D., 1988, Brief descriptions of mines, prospects, and mineral occurrences in the Port Moller and Stepovak Bay quadrangles, Alaska Peninsula: U.S. Geological Survey Open-file Report 88-666, 128 p., 1 pl., scale 1:250,000.

White, W.W., and Queen, L.D., 1989, Preliminary geologic and rock-chip geochemical data from drill core and trenches at the Shumagin gold deposit, Unga Island, Alaska: U.S. Geological Survey Open-file Report 89-361, 36 p.

DESCRIPTIONS OF MAP UNITS [for Plate 1]

Qs Unconsolidated deposits (Holocene)--Chiefly sand and gravel on beaches and in alluvium, poorly sorted colluvium, and organic-rich swamp deposits. Local cobble- to boulder-sized talus deposits are not separately mapped. Locally, may include deposits of Qm.

Qls Landslide deposits (Holocene and Pleistocene)--Mainly large masses of rock that compose rotational block slides. Locally includes colluvium, glacial deposits, or talus not mapped separately.

Qm Glacial deposits (Pleistocene)--Poorly sorted deposits of silt, sand, cobbles, and boulders; identified as glacial in origin based on presence of striated or faceted boulders and the occurrence of striated bedrock at the site of the deposit and elsewhere on Unga Island. Irregular shape of mapped deposits suggests the deposits are ground moraine. A mapped occurrence of bedded sand and gravel up to tens of meters above sea level on the southern coast of Unga Island may be glacio-fluvial deposits. Unmapped glacial deposits may occur locally overlying any of the different types of bedrock.

Tmb Basalt flows (Miocene)--Vesicular, porphyritic lava flows of basaltic composition that cap mesas. Locally scoriaceous. Typically oxidized to reddish brown, else medium to dark gray. Two to 10 percent phenocrysts of altered olivine set in a fine-grained groundmass of plagioclase and opaque material.

Tmv Volcanic rocks, undifferentiated (Miocene)--Domes and associated tuff and carapace breccia, and lava flows. Mainly dacitic and andesitic in composition. Incipiently altered and mineralized, nearly aphyric quartz-bearing felsite 3 km SSW of the head of Zachary Bay may have initially had a rhyolitic composition. Level of dome emplacement inferred to range from shallow intrusive (within 200 m of ground surface) to extrusive, based on interfingering of carapace breccia with adjacent marine sedimentary rocks. Domes have 25-40% plagioclase, orthopyroxene, and hornblende (dacite) or clinopyroxene (andesite) phenocrysts in a groundmass that ranges from fine-grained holocrystalline to intersertal. Domes range from fresh, to incipiently replaced by calcite, chlorite, and mica or prehnite(?), to completely replaced by quartz and zeolite. Lava flows are porphyritic, having 20-30% plagioclase and two pyroxenes in a microcrystalline to intersertal groundmass.

Tu Unga Formation (Miocene and Oligocene)--Conglomerate and interbedded sandstone, siltstone, tuff, and diamicton (lahar deposits?), dominantly volcanic clasts. Planar bedded to locally cross-bedded. Bivalves, gastropods, and worm(?) tubes indicate shallow marine in basal part; petrified tree trunks indicate nonmarine deposits in upper part, on northernmost Unga Island. Unit was first described by Dall (1882) who used the term "Unga Conglomerate" for exposures on northern Unga Island. Atwood (1911) renamed the unit "Unga Formation"; Burk (1965) assigned the Unga Conglomerate Member to the Bear Lake Formation. Detterman and others (1996, p. 51) returned the unit to formational status because "...volcanic detritus constitutes only a small part of the Bear Lake Formation..." Detterman and others (1996) consider the Unga Formation to range from late Oligocene to middle Miocene in age, based on plant fossils and pollen.

Popof volcanic rocks. Age-equivalent volcanic rocks to those on Unga and Popof Islands occur on the nearby Alaska Peninsula, where they were named the Meshik Formation by Knappen (1929) and are now formally named the Meshik Volcanics (Detterman and others, 1996). Numerous K-Ar ages from the Meshik Volcanics fall mainly in the range of 28 to 38 Ma (see Wilson, 1985; Wilson and Shew, 1992; Wilson and others, 1994), which is in agreement with a late Eocene to early Oligocene age determination of plant fossils from an interbedded tuff (Detterman and others, 1996, p. 48). Tertiary volcanic rocks on the inner Shumagin Islands that are lithologically and temporally equivalent to the Meshik Volcanics were informally named the Popof volcanic rocks by Wilson and others (1995) and we retain use of the term here. Divided into:

Tpz Lavas of Zachary Bay (Tertiary)--Crystal-rich, porphyritic lava flows mainly of high-silica andesitic composition. From 25% to 40% phenocrysts of plagioclase, two pyroxenes, and trace amounts of hornblende and Fe-Ti oxide. Locally intruded by hornblende-bearing dikes and sills (not mapped separately). Incipient but pervasive replacement by chorite, calcite, and epidote (indicative of propylitic alteration) or by quartz and zeolites; locally, more intense alteration probably reflects proximity to sources of hydrothermal fluids such as the unmapped hypabyssal intrusives. Color anomalies (gossans) occur throughout the unit.

Tpdu Domes, undifferentiated (Oligocene)--Lava masses that are identified as domes based on steeply cross-cutting relations with adjacent rocks; outcrop pattern; large vertical extent; or presence of intrusive breccia at margins. Map units include aprons of noncompacted pumiceous tuff inferred to have formed in minor explosive eruptions during dome emplacement. Such carapace tuffs indicate that the domes are at least in part extrusive. Sparsely to moderately porphyritic vitrophyre, commonly devitrified.

Tpdb Basaltic andesite domes (Oligocene)--Phenocrysts of plagioclase, clinopyroxene, and olivine range from 5% to 15%. The basaltic andesite dome at Apollo Mountain has local veinlets and amygdules of zeolite and chert(?).

Tpda Andesitic domes (Oligocene)--Phenocrysts of plagioclase, hornblende, orthopyroxene, and quartz range from 10% to 25%. The quartz grains may be inclusions (xenocrysts).

Tpdd Dacitic domes (Oligocene)--Phenocrysts of plagioclase, hornblende, orthpyroxene, and quartz range from 10% to 20%.

Tpdr Rhyolitic domes (Oligocene)--Phenocrysts of quartz, plagioclase, hornblende, and biotite range from 10% to 20%. Typically altered and cut by veins of quartz, calcite, and zeolite.

Tpth Hornblende tuff (Oligocene)--Dacitic ash-flow tuff. Fine pumice lapilli and trace amounts of lithic inclusions in a vitric ash matrix. Densely compacted and strongly foliated in the vicinity of Apollo Mountain, noncompacted to partly compacted elsewhere. Such lateral variation in the degree of compaction may indicate either a source at Apollo Mountain, or that the dense compaction is due to heating and secondary deformation by dome intrusion. Phenocrysts range from 5% to 30% and consist of plagioclase, quartz, orthopyroxene, and hornblende. A single chemical analysis indicates a low-silica dacitic composition but variable phenocryst contents suggest the bulk composition may vary slightly as well. Locally altered or silicified, especially south and west of Apollo Mountain.

Tptb Biotite tuff (Oligocene)--Noncompacted, dacitic ash-flow tuff. Quartz, plagioclase, orthopyroxene, and biotite phenocrysts range from 5% to 20%. A single chemical analysis indicates a dacitic composition. The occurrence on Popof Strait, on northeastern Unga Island, is a bedded, pumice-clast conglomerate having abundant glass shards in a fine-grained matrix that was deposited on an erosional surface of 6-8 m relief cut in marine sandstone of the Stepovak Formation. The occurrence on the west shore of Zachary Bay is reported to be 31.3 Ma by Marincovich and Wiggins (1990), who considered the deposit and an overlying marine siltstone to be the lowermost part of the overlying Unga Formation.

Tps Volcaniclastic rocks (late Eocene to Oligocene)--Volcanic breccia and marine sandstone and siltstone, interbedded with ash-flow tuffs or submarine lava flows. Some of the clastic rocks were deformed prior to lithification by intrusion of adjacent lava masses. The volcaniclastic rocks range widely in grainsize and include breccias having blocks of porphyroaphanitic andesitic lava up to 6-8 m across. The coarse facies were deposited in proximity to submarine lava flows or domes. Unit is, in part, a peperite--mixtures of sedimentary and magmatic masses formed while each was plastic. A chemically analyzed, andesitic ash-flow tuff is included in this unit. The distinction between units Tps and Ts is the occurrence of volcanic materials--ash-flow tuff, coarse volcanic breccia, and peperite--in unit Tps.

Tpu Popof volcanic rocks, undifferentiated (late Eocene to Oligocene)--Mainly lava flows and flow breccias of andesitic composition and locally interbedded volcaniclastic rocks, but includes some lava flows of basaltic andesite composition. The unit on northwestern Popof Island is dominantly lava flows of basaltic andesite composition. Lava flows have from 15% to 30% phenocrysts of plagioclase and two pyroxenes in a hyalopilitic to trachytic groundmass. Poorly exposed lavas of dacitic or low-silica rhyolitic composition are probably small domes of unit Tpdd or Tpdr, which are not mapped separately. Incipient but widespread replacement of mafic minerals by chlorite, epidote, and calcite indicates pervasive propylitic alteration. Mafic phenocrysts are locally replaced by a deeply pleochroic brown mineral having parallel extinction that may be biotite, which suggests potassic alteration. Includes local areas not mapped separately of more intense alteration, oxidation of pyrite (gossans), or replacement by silica (silicification).

Ts Stepovak Formation (late Eocene and early Oligocene)--Fine-grained marine conglomerate, sandstone, and siltstone. Beds exposed on northern Unga and Popof Islands are rich in pelecypod and gastropod shells and worm(?) tubes, indicating an inner neritic environment and late Eocene age (R.C. Allison, written commun., 1980). The overall age range of the formation throughout its occurrence on the southern Alaska Peninsula and inner Shumagin Islands is late Eocene and early Oligocene (Detterman and others, 1996). The unit grades laterally and upwards into the volcaniclastic rocks of unit Tps and the Popov volcanic rocks. Originally named by Burk (1965) for exposures on the adjacent mainland, the unit is informally subdivided into a lower siltstone and upper sandstone by Detterman and others (1996). The lower member includes laminated siltstone of a deep-water turbidites, whereas the upper unit is mainly volcaniclastics, which are inferred to have had contemporaneous sources in the Meshik Volcanics. Rhythmically bedded mudstone and siltstone exposed in a seacliff on the eastern headland of Delarof Harbor may be the top of the lower member, or may be a local basin fill. Exposures elsewhere on northern Unga and Popof Islands, however, are clearly the upper sandstone member.

Table 1. Potassium-argon age determinations of volcanic rocks on Unga Island and northwestern Popof Island. See Wilson and others (1994) for methods and analytical data.

Sample No.	**Locality**	**Sample description**	**Map unit**	**Mean age and error (m.y.)**
85Aws302	55°19'15", 160°45'10"	Fine- to medium-grained leucobasalt flow; minor alteration of olivine and clinopyroxene to chlorite	Tmb	20.3 ± 1.6
85Ajm781	55°19'17", 160°51'38"	Porphyritic andesite plug; clinopyroxene altered to chlorite	Tmv	10.92 ± 0.19
56953	55°17'58", 160°45'50"	Leucobasalt flow; chlorite replacing groundmass glass(?)	Tmb	16.92 ± 0.23
85AWs300	55°17'19", 160°43'32"	Hornblende andesite dome; hornblende altered to chlorite and opaque material	Tmv	14.3 ± 0.1
82AJm507	55°12'40", 160°50'54"	Leucobasalt flow; minor alteration of mafic mineral(s) by chlorite	Tmb	21.18 ± 0.49
56228	55°18'23", 160°43'47"	Hornblende andesite dome; fresh	Tmv	17.76 ± 0.85
82AWs015	55°10'08", 160°46'32"	Altered volcanic rock; quartz and sericite pseudomorphs, plus pyrite	Tpu	31.8 ± 0.6 (wholerock date)
56968	55°11'20", 160°36'26"	Porphyritic andesite flow(?); minor chlorite, epidote, sericite(?)	Tpu?	30.9 ± 1.1
89AWw130	55°11'23", 160°34'25"	Adularia in sample of vein material from Apollo mine dump		34.0 ± 0.5
82ACc021	55°12'21", 160°33'57"	Porphyritic dacite dome; minor sericite alteration of plagioclase	Tpdd	34.2 ± 0.9
82ACc023	55°12'21", 160°33'21"	Rhyolitic porphyry, dome (or tuff?); quartz megacryts in devitrified(?) groundmass	Tpdr	34.0 ± 1.1
85AWs296a	55°11'54", 160°29'25"	Rhyolitic dike or dome; sparse quartz phenocrysts, trace of calcite in devitrified (?) groundmass	Tps	31.3 ± 0.3
85AWs321	55°16'30", 160°33'55"	Porphyritic andesite flow; chlorite replaces some pyroxene	Tpu	34.3 ± 0.9
88AWs028	55°16'50", 160°37'50"	Altered dike or sill; complete replacement by quartz, sericite, pyrite	Tpz	14.63 ± 0.27 (wholerock date)
82ASh009	55°19'00", 160°34'32"	Dacitic biotite tuff; vitroclastic groundmass	Tptb	33.7 ± 1.3
82ASh014	55°19'21", 160°34'10"	Andesitic flow(?); plagioclase, orthopyroxene, and clinopyroxene	Tpu	37.1 ± 1.2
85AYb743	55°22'53", 160°31'22"	Andesitic flow in breccia; minor chlorite alteration	Tpu	35.9 ± 1.4
85AWs290	55°21'27", 160°28'26"	Andesitic sill or dike(?); plagioclase, hornblende, and clinopyroxene	Tpu	34.5 ± 1.3
88AWw425	55°18'22", 160°29'48"	Andesitic plug; some secondary sericite and chlorite	Tpu	34.4 ± 0.5
85AWs293	55°19'38", 160°29'50"	Leucobasalt dome	Tpdb	32.2 ± 1.5