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PETROGRAPHIC REPORT ON THREE SAMPLES:
#7, #6, and Welded NM

By

Jennifer S.Getsinger, Ph.D., P. Geo.

For

INMET Mining Corporation

January 22, 1996

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SUMMARY REPORT ON PETROGRAPHY OF THREE SAMPLES:
#7, #6, and Welded NM

This report is written at the request of Ian R. Morrison , District Geologist, and Peter Daubeny, INMET Mining Corporation, Vancouver, B.C. The purpose is to answer specific petrologic questions and to describe three hand specimens and thin sections, each from a different location and geologic setting.

Three rock samples (labelled #7, #6, and Welded NM) were provided with one thin section for each. Detailed hand specimen and thin section descriptions are in Appendix I, including interpretations of alteration history and conditions of formation. Summary comments on the three petrographic samples are presented below, each on a separate page for inclusion in the appropriate file or report.

Sample #7 is from the Chaco Bear project. It is a propylitically altered intermediate volcanic porphyry, consisting of plagioclase phenocrysts and groundmass altered to alkali feldspar, epidote, and calcite, with mafics altered to chlorite and oxides. It contains no significant mineralization. There is no evidence to support interpretation as a hydrothermal breccia, as it is not a breccia in any sense of the word, although the alteration is likely to be hydrothermal (perhaps located near a pluton) rather than regional metamorphic, even though the mineral assemblage is consistent with greenschist facies metamorphism.

Sample #6 is from NWT property (?).

It is a quartz-muscovite-spinel schist with pyrite. The spinel is likely to be gahnite, $ZnAl_2O_4$, perhaps in solid solution with spinel ($MgAl_2O_4$), as it is a pale bluish-green color. This rock is a typical metamorphic schist with helicitic porphyroblasts and crystalliztion foliation, except that the minerals are unusual due to the sulphide content. Iron and zinc mineralization was premetamorphic, resulting in recrystallized pyrite and gahnite porphyroblasts, along with more typical metamorphic minerals such as cordierite and staurolite. Gahnite is altered locally to sphalerite, supporting the idea of Zn content. Conditions of formation are consistent with regional metamorphism and deformation in the hornblende-hornfels facies.

Sample "Welded NM" is from the New Moon Property, 80 km SSE of Smithers, B.C., from the lower Jurassic Hazelton Group volcanics. The main question was, is it a *welded* tuff? It is most certainly an andesitic lithic lapilli tuff containing a lot of volcanic glass, but it may not count as completely "welded". However, presence of lensoidal *fiamme* and some vitroclastic texture suggests at least incipient welding. It looks very much like Figure 9-2C in Williams, Turner, and Gilbert (1982), *Petrography.* Origin is more likely an ash-flow tuff from a subaerial, land-based volcano, rather than an aquagene tuff from an undersea eruption.

STATEMENT OF QUALIFICATIONS

I, Jennifer S. Getsinger, do hereby certify:

1. That I am a consulting geologist with offices at 2150 Macdonald Street, Vancouver, B.C. V6K 3Y4.

2. That I have studied geology and anthropology at Harvard University (A.B. 1974), and have graduate degrees in geology from the University of Washington, Seattle (M.S. 1978), and from the University of British Columbia, (Ph.D. 1985).

3. That I have practiced within the geological profession since 1974.

4. That I am a Fellow of the Geological Association of Canada and a member of the Geological Society of America.

5. That I am a Professional Geoscientist and member in good standing of the Association of Professional Engineers and Geoscientists of British Columbia, as of 1992.

6. That the opinions, conclusions, and recommendations contained herein are based on petrographic analysis and research done by me.

7. That I hold no direct, indirect, or contingent interest in the subject property, or in any shares or securities of the owner or operator of the property, or in any associated companies.

8. That this report may be utilized for inclusion in a Prospectus or Statement of Material Facts.

Signed J. S. Getsinger

Jennifer S. Getsinger, Ph.D., F.G.A.C., P.Geo.

January 22, 1996
Vancouver, B.C.

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January 22, 1996
Vancouver, B.C.

APPENDIX I

HAND SPECIMEN AND THIN SECTION DESCRIPTIONS

(SAMPLES #7, # 6, and Welded NM)

PETROGRAPHIC REPORT by J.S. Getsinger, PhD [signature]

For: INMET Mining Corporation
Project: Chaco Bear
Sample: #7

Date: January 1996
Collector: P. Daubney (?)
Date Collected: 1995

LOCATION: Chaco Bear Project, British Columbia

ROCK TYPE: Epidote-altered intermediate to mafic volcanic or volcaniclastic

LITHOGEOCHEMISTRY: None provided

HAND SPECIMEN: Grab sample, a long, narrow specimen in the shape of a right triangular prism (approx. 4 x 4 x 15 cm). Rock is greyish-green, and breaks with straight fracture and angular edges. One long face (4 x 15 cm) is polished and lacquered to show the texture. Rock is mottled, with larger, rounded blebs (0.4 to 2 cm or so in diameter) composed mainly of epidote and darker minerals that look like chlorite and/or amphibole (+/- iron oxide), probably altered mafic minerals. The darkest areas are very weakly magnetic, suggesting minor magnetite. Grain size both in blebs and in "matrix" is generally about 1 mm, ranging from 0.1 mm to 5 mm. Bluish-green minerals might be clinozoisitic epidote and/or celadonitic phyllosilicates, alterations from plagioclase feldspar. Pale grey to whitish areas are probably feldspar altered to carbonate (calcite, reacts vigorously to HCl) +/- quartz alteration. Pinkish-red minerals may be oxidation products of Fe- or Mn-bearing minerals, and there are whitish and brownish grains that suggest leucoxene and/or other Ti-minerals such as sphene or rutile. Rock contains 40-50% epidote throughout. Texture of rounded blebs in matrix suggests altered volcanic breccia of intermediate composition, in which clasts were more mafic than matrix, and the whole rock has been subjected to propylitic alteration. Tiny, minor metallic minerals might be disseminated iron sulphides and oxides, residual from alteration of mafic minerals. There is no evidence for hydrothermal mineralization in this rock, although it has been extensively propylitically altered, or metamorphosed to greenschist facies.

THIN SECTION:

Percent (Approx.)	MINERALS (and observed diagnostic properties and textures)
30-50	Plagioclase - Altered, euhedral blocky and rectangular phenocrysts and microphenocrysts, zoned and with albite twinning. In many, the core zones are altered to epidote, and the rim zones are now albite to oligoclase in composition. Altered to epidote and calcite. Could be a major component of fine-grained groundmass.
5-30 (?)	Alkali feldspar (K-feldspar) - Some of the fine-grained groundmass feldspar, and some around the altered phenocrysts is mottled like K-feldspar, and also exhibits negative relief, but so does untwinned albite. This is a later alteration, contemporaneous with epidote.

30-40	Epidote (Pistacite) - Colorful second order biref. and med.-high relief, with yellowish color are diagnostic. Occurs as fine-grained aggregates and blebs replacing cores of plagioclase feldspar and mafics throughout rock.
1-3	Chlorite - Anomalous blue biref. phyllosilicate with green pleochroism, pseudomorphic after rectangular amphibole phenocrysts, with associated oxides and leucoxene.
10-15	Calcite - High biref. carbonate replacing plagioclase feldspar, spotty throughout.
1-3	Opaques and Ti-oxides (?) - Finely disseminated black grains all over, as well as leucoxene and sphene-like grains. Much of this "dirty"-looking material is concentrated in areas interpreted as altered amphibole or mafics, along with chlorite and epidote.

ROCK TEXTURES/STRUCTURES: Bimodal porphyritic texture with more altered larger phenocrysts and less altered microphenocrysts. Phenocrysts are mainly plagioclase altered to epidote and calcite, and lesser amphibole shapes altered to chlorite plus other products such as epidote and iron oxides. Mottling effect is due to varying amount of epidote alteration, but texture of rock is actually very consistent throughout, especially if the veil of alteration is lifted. Groundmass is composed of fine-grained crystalline feldspar (plagioclase +/- alkali feldspar +/- quartz), in an even texture that suggests there has been some metasomatism / infiltration of K-feldspar and recrystallization of plagioclase.

PROTOLITH: Intermediate volcanic, probably andesite lava

ALTERATION/MINERALIZATION: Propylitic alteration includes alteration of plagioclase feldspar to albitic plagioclase, alkali feldspar, epidote and calcite; and alteration of amphibole to chlorite and oxides. Fine-grained groundmass may have been altered with alkali feldspar +/- quartz, with perhaps secondary silicification accompanying propylitic alteration.

CONDITIONS OF FORMATION/HISTORY: Rock began as an andesitic lava flow, cooling slowly enough to form plagioclase phenocrysts, and then erupted, with microphenocrysts forming. Propylitic hydrothermal alteration and possible alkali feldspar metasomatism / silicification are secondary. Conditions of formation would be similar to greenschist facies metamorphism in temperature. Lack of directional fabrics in this rock supports an interpretation of hydrothermal alteration rather than formation in an active fold belt or metamorphic terrane.

PETROGRAPHIC REPORT by J.S. Getsinger, PhD [signature]

For: INMET Mining Corporation
Project: NWT property (?)
Sample: #6

Date: January 1996
Collector: Ian Morrison (?)
Date Collected: 1995

LOCATION: NWT property (?), Canada

ROCK TYPE: Muscovite-quartz-spinel schist with pyrite

LITHOGEOCHEMISTRY: None provided

HAND SPECIMEN: Grab sample from ground surface. Largest cut piece is approx. 2.5 x 3 x 7 cm, with one weathered surface showing dark orange-brown weathering rind 1 mm thick. Rock is a metamorphic schist, well-foliated, with muscovite mica defining foliation, and hard, pale-grey minerals in between, apparently quartz, possibly feldspar, or even cordierite. Grey-green porphyroblasts (1-3 mm; 5-10%) are equant, rounded to angular, and H > 5.5 [spinel]. Dark red-brown porphyroblasts (to 2 mm) and smaller grains (0.5 to 1 mm) may be garnet, staurolite, or sphene (1-3%); they are mainly associated with pyrite. There is perhaps some chlorite, and chloritoid is also a possibility. There is about 5-7% irregularly disseminated pyrite in rectangular and anhedral grains about 0.5 to 2 mm. Pyrite appears to be prekinematic, occurring along metamorphic trends, although somewhat recrystallized. Non-magnetic;no reaction to HCl.

THIN SECTION:

Percent (Approx.)	MINERALS (and observed diagnostic properties and textures)
50-60	Quartz - Metamorphically recrystallized, relatively free of inclusions, with many 120 degree grain boundaries, although some show sutured boundaries and undulose extinction, indicating deformation has outlasted crystallization to some extent.
15-20	Muscovite - Colorless mica with med. biref., elongate, defining metamorphic crystallization foliation. Wraps around porphyroblasts, and in one place forms polygonal arcs around asymmetrical S-folds in foliation.
5-10	Opaques - Mainly pyrite, as seen in hand specimen. Rectangular to anhedral grains are somewhat aligned on folation trends. Has been somewhat recrystallized, and has partial inclusions of spinel.
3-5	Cordierite (+/- Feldspar) - Occurs as large grains with quartz; has low relief, low biref., looks like feldspar, but is characteristically poikiloblastic with lots of inclusions, some pinitic alteration, and faint yellow pleochroic haloes in places.

7-10 Spinel / Gahnite ($MgAl_2O_4$ - $ZnAl_2O_4$) - Very high positive relief, isotropic, light bluish-green mineral with shapes ranging from triangular to square to anhedral. Forms helicitic porphyroblasts, which, like garnet, have S-shaped trails of inclusions (snowball texture). There are fewer inclusions in the cores, and more toward the rims, consisting mainly of quartz, and some rutile or sphalerite, as well as opaques. The rotation shown by the inclusions indicates at least two phases of metamorphic history, with earlier porphyroblast growth on one foliation, and later rotation from shear stress. Locally it is altered to red-brown sphalerite.

1-3 Staurolite - Sparse but large porphyroblasts with characteristic yellow pleochroism, low biref.

1-3 Sphalerite (+/- Rutile) - Very high positive relief mineral resembling rutile, with dark reddish to orange-brown color; isotropic; associated with gahnite spinel, filling in fractures, and probably an alteration of the spinel, although it could also have occured premetamorphically.

<1 Rutile - Very high positive relief mineral in elongate prisms along foliation, with strong brown to red-brown absorption, but not isotropic, and less red than the sphalerite. Occurs also as inclusions in staurolite and spinel porphyroblasts.

ROCK TEXTURES/STRUCTURES: Rock is clearly regionally metamorphic with distinct crystallization foliation defined by alignment of muscovite, recrystallization of quartz, and pyrite. Mineralization is premetamorphic, as shown by alignment of pyrite and its euhedral recrystallization. Crystallization of gahnite spinel porphyroblasts was synkinematic as shown by snowball pattern of inclusions, with two periods of metamorphic growth. Sphalerite fills cracks in spinel, so is a later alteration. Cordierite is poikiloblastic, and also metamorphic. Muscovite also forms polygonal arcs around asymmetrical S-folds, supporting a shearing model for formation of the latest foliation.

PROTOLITH: Mg-bearing argillaceous sediment with sulphide component, something like a sediment-hosted massive sulphide, shale with aluminum, magnesium, iron and zinc.

ALTERATION/MINERALIZATION: Alteration is in this rock a result of metamorphic recrystallization. There may have been premetamorphic alteration, or the sulphides may have been primary. Mineralization is now iron sulphide (pyrite) and zinc (+/- magnesium) aluminum oxide (gahnite spinel), with later alteration to zinc sulphide (sphalerite).

CONDITIONS OF FORMATION/HISTORY: Sediment-hosted sulphide rock, something like a Mg-bearing argillaceous shale with Fe and Zn sulphides, was regionally metamorphosed during deformation (including shear folding) that formed foliation. Porphyroblast growth lasted through at least two metamorphic growth phases, and some minor deformation may have outlasted metamorphic crystallization. Temperatures and pressures are consistent with the hornblende-hornfels facies, or approximately 475°C at about 0.2 GPa (2 kb) pressure (or somewhat higher), as indicated by the coexistence of staurolite and cordierite.

NOTE: The following minerals were **not** observed in this rock, although predicted as possibilties from hand specimen description: chlorite, chloritoid, garnet.

PETROGRAPHIC REPORT by J.S. Getsinger, PhD [signature]

For: INMET Mining Corporation
Project: New Moon Property
Sample: "Welded NM"

Date: January 1996
Collector: Ian Morrison (?)
Date Collected: 1995

LOCATION: New Moon Property, 80 km SSE of Smithers, B.C., from lower Jurassic Hazelton Group volcanics

ROCK TYPE: Intermediate lithic lapilli tuff, incipiently welded

LITHOGEOCHEMISTRY: None provided

HAND SPECIMEN: Grab sample is of a dry, reddish-brown, angular volcaniclastic rock; largest cut piece is approx. 3 x 5 x 6 cm. Fragmental clasts are 1 mm to 5 cm, and consist of angular to subangular, aphanitic maroon-brown volcanic (?) rock, and rounded to lensoidal scoriaceous lava (one grain 1 cm in diameter contains vesicles 0.5 to 1 mm). Lensoidal, vesicular clasts may be pumiceous fiamme. Rock has a dry, baked character. Non-magnetic. Irregular vesicles are either empty or amygdaloidal with calcite (reacts to HCl). Rock could be volcaniclastic breccia (intermediate lithic lapilli tuff) or welded tuff.

THIN SECTION (Polished):

<u>Percent (Approx.) MINERALS (and observed diagnostic properties and textures)</u>

Total brown to black opaque volcanic glass is about 40-50%. Other minerals include laths of plagioclase feldspar altered to sericite and calcite, and chlorite filling vesicles, and greyish, round spherulitic devitrification features.

40-50% Lithic Fragments: Aphanitic, brown to opaque volcanic glass fragments with some feldspar laths; also bits of feldspar-porphyritic rock. Some fragments are amygdaloidal, with chlorite filling vesicles. Locally lensoidal clasts are interpreted as *fiamme*.

40-50% Matrix / Groundmass: Also contains about 40-50% brown to opaque volcanic glass, and abundant plagioclase laths altered to calcite and sericite. Some odd, curvy, triangular shapes of crystal grains or fragments are believed to be glass shards.

ROCK TEXTURES/STRUCTURES: Lithic fragments are either aphanitic or porphyritic with plagioclase laths, indicating volcanic origin. Some lensoidal fiamme are vesicular, probably squished pumice. Vitroclastic texture is indicated by glass shards and odd shaped fragments throughout. Volcanic glass dominates texture. Round vesicles are filled with chlorite. Some round features may be devitrification spherulites.

PROTOLITH: This rock is a relatively fresh andesitic volcaniclastic tuff

ALTERATION/MINERALIZATION: Glass has become very dark brown, almost opaque, in hardening. Some may be devitrifying in little round spherulites. Plagioclase feldspar is altered to sericite and perhaps other clay-type minerals, and calcite. Some vesicles are filled with chlorite.

CONDITIONS OF FORMATION/HISTORY: This rock is a subaerial tuff, probably from an ash-flow eruption, of an intermediate (andesitic) volcano. The rock could be consided incipiently welded, due to large amount of glass and some *fiamme* features. However, it is not particularly fused, or squished overall, so not from the most welded part of the ash-flow tuff.

PETROGRAPHY

An Introduction to the Study of Rocks in Thin Sections

Second Edition

Howel Williams
Late of the University of California, Berkeley

Francis J. Turner
University of California, Berkeley

Charles M. Gilbert
University of California, Berkeley

W. H. Freeman and Company
New York San Francisco

9

Pyroclastic Rocks

PYROCLASTIC MATERIAL: GENERAL NATURE AND TERMINOLOGY

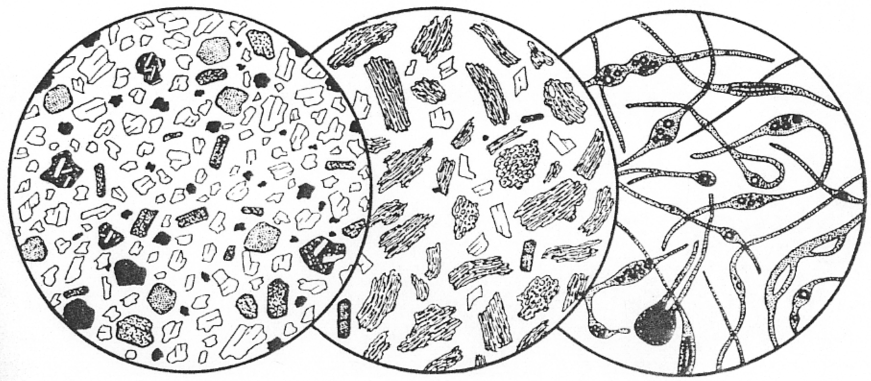
Pyroclastic rocks are volcanic rocks that have clastic texture; in other words, they are fragmental deposits formed as a direct result of volcanic action. The vast majority of them are products of explosive volcanic eruptions. But fragmentation of the material may also be caused by continuing growth of partially solidified volcanic domes, and it generally occurs where lavas are quenched by water.*

Pyroclastic material is classified primarily according to particle size. Pebble-size fragments between 2 mm and 64 mm in diameter are called *lapilli*. Smaller particles are called *ash*; larger ones are called *bombs* if during their formation they were partly or wholly molten, *blocks* if they were angular chunks of solid rock. Volcanic rocks consisting of ash and lapilli are called *tuff* if they consist largely of ash and *lapilli tuff* if lapilli predominate. Rocks composed chiefly of bombs are *agglomerate*, and those consisting chiefly of blocks are *volcanic breccia*. Those in which blocks are mixed with abundant ash are called *tuff-breccia*.

*The term *pyroclastic* is used here in the broad sense recommended by the IUGS Subcommission on the Systematics of Igneous Rocks (*Geology*, vol. 9 (1981): pp. 41–43; *Neues Jahrbuch fur Min gie* 1981, pp. 190–196). Many geologists, however, prefer to restrict the term to the n ial and deposits produced by explosive eruptions, in particular to fall, flow, and surge deposits.

Ash and lapilli deposited in and adjacent to low-lying areas where sedimentary detritus is accumulating are likely to become intimately mixed with mud, sand, and gravel. The resulting deposits are *tuffaceous sediments*, or *tuffites*. Such mixtures of pyroclastic and epiclastic material are to be distinguished, however, from wholly epiclastic deposits of volcanic debris derived by weathering and erosion of older volcanic formations. Discussion of these rocks is reserved for Chapters 10 and 13.

Ashes and tuffs may be classified further by their content of glass, crystal (mineral), and rock particles (Figure 9-1A, B). Those made up largely of particles of glass (glass shards) are termed *vitric ash* and *vitric tuff* and are said to have *vitroclastic texture*. The term *crystal ash*, or *crystal tuff*, signifies a deposit in which crystals are the predominant constituent, and the term *lithic ash*, or *lithic tuff*, refers to one in which rock fragments predominate. In this distinction between vitric, crystal, and lithic material: *lithic* refers to polycrystalline rock particles, mostly aphanitic; *crystal*



A B C

Figure 9-1. Volcanic Ashes

A. Andesitic crystal ash erupted from the volcano Santa María, Guatemala, in 1902. Diam. 2 mm. Broken crystals of plagioclase, dark-green hornblende, paler-green pyroxenes, rounded biotite flakes, magnetite, and a few lithic chips of andesite.

B. Dacitic vitric ash showing pumiceous texture. Diam. 2 mm. Product of the culminating explosions of Mount Mazama, which led to the formation of Crater Lake, Oregon. Shredded and cellular bits of pumiceous glass accompanied by fewer broken chips of plagioclase and small prisms of hypersthene.

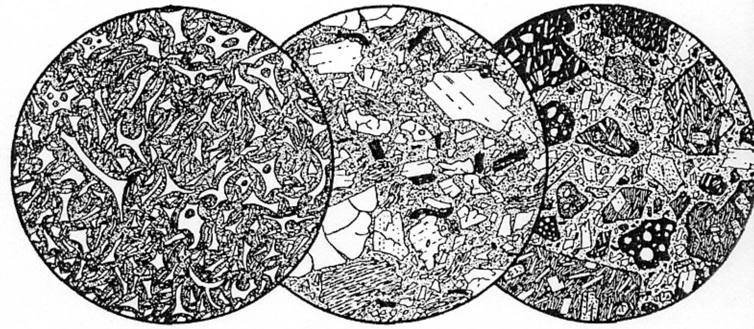
C. Basaltic ash (Pele's Hair), Kilauea, Hawaii. Diam. 2 mm. Threads of brown basaltic glass containing bubbles of gas. Material discharged by lav untains in the form of spray.

denotes single crystals and fragments of crystals; and *vitric* denotes particles that are essentially noncrystalline and glassy throughout. Lithic particles occur in all sizes from ash to the largest blocks, whereas single crystals and crystal fragments seldom are larger than coarse ash or small lapilli; vitric particles may be any size, but most of them are small.

Tephra is a general term that refers collectively to any or all pyroclastic material, regardless of size, that is ejected into the air during volcanic eruptions. Material produced by disruption of new magma is called *juvenile* or *essential* tephra. Fragments of older volcanic rock broken from the conduit and walls of the eruptive edifice are designated as *accessory*, and any derived from the subvolcanic basement are called *accidental*.

Most juvenile tephra is produced when gas-rich magmas vesiculate and become fragmented by the bursting of expanding gas bubbles. Extreme vesiculation of the very viscous silica-rich magmas produces the glassy foam called *pumice* and leads readily to violent disruption and to large volumes of vitric ash and pumiceous lapilli and bombs. Pumice is generally so porous that lapilli and bombs composed of it often will float on water and may drift for long periods before becoming sufficiently water-saturated to sink. Typically the vesicles are spheroidal or ellipsoidal, though they may be drawn out into slender tubes producing a silky, fibrous texture (Figure 9-3A). Comminution results in vitric ash composed of bits of the glassy septa between the pumiceous vesicles, chiefly curved glassy splinters and pointed chips with concave borders (Figure 9-2A).

Scoria is the general name applied to dark, highly-vesicular rock of basaltic composition; it is usually at least partially glassy but may appear aphanitic. Most basaltic lapilli and bombs are composed of scoria and are referred to as *cinders*. Extreme vesiculation of fluid basaltic magma may produce foamlike glass in which the vesicle walls are paper-thin, often threadlike septa of brown or black glass. This is called *thread-lace scoria*, or *reticulite pumice*, and is found commonly among the products of the spectacular lava fountains that play during the opening phases of Hawaiian eruptions; it also forms as crusts on fluid, gas-rich pahoehoe lava flows. If the lava is particularly fluid, as it tends to be in lava lakes of Kilauean type, bursting bubbles may hurl out the liquid as a fine spray that cools quickly to form small glassy pellets (*Pele's Tears*) or delicate glassy threads (*Pele's Hair*) like those illustrated in Figure 9-1C. These and other pyroclastic particles whose external forms are determined by the surface tension of the ejected lava, rather than by fracture surfaces, are called *achneliths*.[1]



A B C

"welded NM" ← 9-2C similar, but no pyroxene

Figure 9-2. Tuffs

A. Rhyolitic vitric tuff, Shasta Valley, California. Diam. 2 mm. Shows typical vitroclastic texture. Arcuate shards of glass lie in a matrix of almost impalpable glass dust.

B. Rhyolitic crystal tuff, Etsch valley, Italy. Diam. 2 mm. Broken crystals of quartz and sodic plagioclase, together with small flakes of biotite, in a matrix of glass dust and pumice fragments.

C. Andesitic lithic tuff, near Managua, Nicaragua. Diam. 2 mm. Fragments of various kinds of andesite predominate; between these lies a matrix made up of plagioclase and pyroxene crystals and pale-brown glass dust.

Particles of scoria and pumice may be porphyritic (Figure 9-4C), the phenocrysts representing early-formed crystals that were suspended in the magma prior to eruption. Similar crystals usually occur along with vitric particles as constituents of finely comminuted ash; as might be expected, many of these have been broken and some have glass adhering to their margins. Also, some juvenile basaltic ejecta are aphanitic and may be classed as lithic fragments.

Accessory and accidental ejecta typically are either lithic or crystal fragments. Accessory ones are invariably angular chips blasted from the flow or dike rocks that constitute early-formed portions of the eruptive center; however, accidental fragments derived from the prevolcanic basement may represent any type of rock—igneous, sedimentary, or metamorphic. Both accessory and accidental ejecta sometimes exhibit the effects of contact metamorphism. Among the products of the 1924 steam-blast eruption of Kilauea, for instance, are fragments of plagioclase-hypersthene hornfels produced by reheating of basalt that formed the conduit walls; and on the flanks of Monte Somma, Vesuvius, are blocks of metamorphosed limestones and dolomites that were presumably torn from the roof of the magma chamber. Occasionally lithic fragments have been partially fused before ejection. For example, many lapilli and blocks of plutonic rock blown from the Parícutin volcano in Mexico contain vesicular glass formed by partial melting of feldspars.

Pyroclastic material may be deposited in a number of different ways, but two general types of deposits are most widespread: fall deposits and flow deposits.* *Fall*, or *airfall, deposits* consist of tephra that have been blown into the atmosphere and deposited by gravitational settling of individual particles. Deposits produced in this way usually show the effects of gravity sorting both in the size and in the composition of component particles, and they tend to be well stratified. The strata generally blanket an entire terrane covering hills and valleys alike, although they may be quickly removed from steep slopes by slumping and erosion.

In contrast, *flow deposits* typically are unsorted and unstratified. They are emplaced by relatively dense yet mobile mixtures of solid fragments and fluids that flow along the ground under the influence of gravity. Flows consisting largely of blocks, lapilli, and ash mixed with water are volcanic mudflows, or *lahars;* they may be either hot or cool. Other block and ash flows are avalanches that result from fracturing and collapse of newly formed domes or spines, or they may be produced by lateral blasts from the sides of developing domes. Flows of this kind may be very hot, as were those produced during the eruptions of Mount Pelée in 1902 and 1929–1932. Other pyroclastic flows are exceedingly hot masses of juvenile pumice lapilli and ash dispersed and fluidized by escaping magmatic gases. Flows of this type develop from rapid vesiculation of fresh magma and are hotter and more mobile than other types; the deposits they produce are called *ignimbrite*. They may be initiated when a relatively dense mixture of comminuted magma and gas in the lower part of an eruption column above a vent collapses altogether and flows rapidly downslope along the ground, impelled by gravity and by momentum from the initial collapse.[2] Small flows of this kind are generally directed by existing volcanic slopes and their deposits are more or less confined to valley areas. Very large flows, some of which probably are erupted from fissures, may surmount moderate relief and bury irregular terranes

*Surge deposits and various types of volcanic breccia are distinguished and identified primarily by their large-scale features and by their distribution and relationships as seen in the field; they are not considered separately in this book.

under extensive subhorizontal sheets of ignimbrite. Ignimbrites produced by some very large eruptions in the past have aggregate volumes of tens or hundreds of cubic kilometers. Most of these large effusions apparently occurred along ring fracture zones above relatively large, high-level bodies of silicic magma, and generally they were followed by collapse of the roof of the magma chamber and formation of a caldera.

VOLCANIC BRECCIA AND TUFF-BRECCIA

Coarse-grained pyroclastic rocks are invariably lithic; in other words, the blocks and lapilli that typically predominate are fragments of volcanic rock. Often it is newly solidified lava that has been fragmented to form the blocks, but accessory fragments of older lavas are also common. In most volcanic breccias and tuff-breccias, the rock fragments consist largely of a single general rock type, and the deposits may be designated according to the predominant lithic component (e.g., dacite breccia, andesite tuff-breccia, etc.). Although hand specimens and thin sections are necessary to identify individual components in breccias and tuff-breccias, the texture and bulk composition of such coarse-grained deposits is rarely well represented in a single sample and never in a single thin section. For this reason, breccias and tuff-breccias must be studied and described in the field prior to selection of small samples for laboratory analysis. Furthermore, the origin of a volcanic breccia or tuff-breccia is usually inferred from its field distribution and relationships; most of them have been produced by volcanic mudflows or by avalanches of blocks and ash.

AIRFALL DEPOSITS

Ash blown high above eruptive vents may be dispersed afar by the wind, and it is cold before it falls back to earth. Airfall deposits, particularly those derived from highly silicic magmas, invariably show effects of eolian differentiation. The largest and densest particles are not carried as high or as far as smaller and lighter particles, and they tend to accumulate closer to the parent volcano. The coarsest tephra falls relatively near the eruptive vent, whereas fine ash may be carried far away from it. But although tephra generally becomes finer away from the vent, at moderate range, lapilli composed of low-density pumice or scoria are often intermixed with much finer ash composed of nonvesicular glass and crystals. Other things being equal, crystal and lithic fragments tend to fall more quickly and closer to the source than vitric fragments, which are usually less dense. Thus in the deposit of a single ash fall, the denser crystal and lithic tephra tend to be relatively concentrated in the lower portion of the layer and the vitric tephra in the upper portion. Corresponding lateral transitions may also be observed as a layer of ash or tuff is followed away from the parent volcano. A single sample of airfall tuff, therefore, may not exactly reflect the composition of the parent magma.

Successive airfall strata also reflect variations in successive eruptive phases. At many volcanoes, accessory lithic fragments are more abundant during initial eruptions than during later ones, and the composition of juvenile ejecta may differ as successive eruptions tap different portions of the magma reservoir. Also, corresponding to changes in the force of eruption and in wind conditions, the different strata in any one locality may differ markedly in grain size.

The most widespread airfall tuffs have highly silicic compositions and consist largely of vitric ash and pumice lapilli. Unaltered acid glass tends to be clear and colorless and has a refractive index that is usually substantially less than 1.51. A few crystals of quartz, sanidine, sodic plagioclase, or biotite are commonly scattered among the glass shards, and they may occur also as phenocrysts in pumice lapilli. In some tuffs, crystals are relatively abundant, either because of an abundance of early-formed crystals in the erupting magma or because of sorting of the erupted particles (Figure 9-2B).

Airfall deposits of basic composition are numerous but generally less widespread than more silicic ones. In the coarse-grained deposits, lapilli composed of scoria are usually the principal constituents, as for example on typical basaltic cinder cones. Finer-grained basaltic tuffs consist largely of fragments of clear brown glass (*sideromelane*) or of black glassy particles that are opaque except along thin edges (*tachylite*); most of the latter, although they may appear glassy, are cryptocrystalline as revealed by X rays. Basaltic glass has a refractive index distinctly higher than 1.54, and the glass particles in basaltic ash tend to be more granular (less splinterlike) than typical shards of acid glass. Among the crystals occurring in basaltic tuffs, calcic plagioclase usually predominates, but olivine, pyroxene, and hornblende are characteristic and may be abundant.

When ash falls through moisture-laden eruptive clouds, some fragments may gather successive layers of very fine wet ash forming spheroidal ashy "mudballs" that are called *accretionary lapilli*. These form most commonly as a result of phreatomagmatic eruptions, many of which involve eruption through ponds or water-saturated ground. Most accretionary lapilli range from 2 mm to 10 mm in diameter, although larger ones are not uncommon, and they tend to accumulate relatively near the eruptive center. Consolidated deposits of accretionary lapilli are referred to as *pisolitic tuff*.

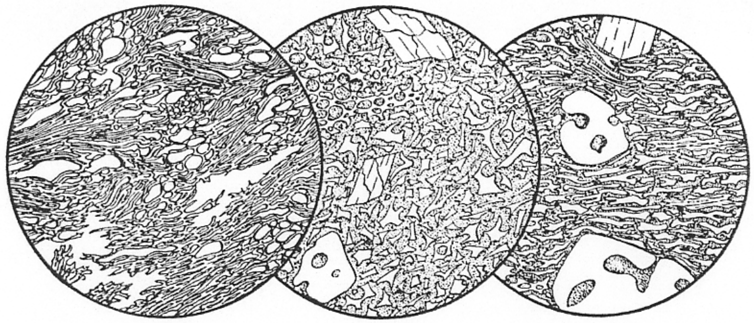
IGNIMBRITE

The term *ignimbrite* refers in general to the deposits laid down by very hot pyroclastic flows made up of comminuted viscous magma and gases.* Flows of this type move very rapidly, and the deposits are emplaced quickly at temperatures in the general range of 600° to 900°C. Some ignimbrites are the product of a single flow. The largest ones, however, consist of multiple flow units and are emplaced by several flows in such rapid succession that the deposit does not cool appreciably between them and the entire accumulation constitutes a single cooling unit. The rate at which an ignimbrite sheet cools is, of course, largely a function of its initial temperature and its extent—especially its thickness (cf. p. 43). The dimensions of the sheet depend on the volume of magma erupted and on the underlying topography. A few ignimbrites are no more than 1 m thick, but the largest ones—typically of acid composition—are very extensive and may reach thicknesses of several hundred meters, particularly where they fill valleys. Indeed, rhyolitic and dacitic ignimbrites of mobile belts are probably the most extensive surface manifestation of acid magma.[3]

Ignimbrites are unsorted mixtures of vitric ash and pumice lapilli. Most have rhyolitic or dacitic composition; some are andesitic. The lapilli may be small and sparsely scattered through a matrix of ash, but usually they are abundant and some reach the size of bombs. Crystals and crystal fragments are sparse in some ignimbrites and abundant in others, and most of them represent minerals that crystallized early and were suspended in the magma at the time of eruption (Figure 9-3B,C). A few crystal and lithic fragments of accessory and accidental origin are also to be expected in most ignimbrites.

The general composition of an ignimbrite is reflected both by the refractive index of the glassy fragments and by the assemblage of crystals

*The deposits produced by such flows are commonly referred to as *ash-flow tuffs*.



A B C

Figure 9-3. Rhyolitic Pumice and Ignimbrite

A. Rhyolitic pumice, Lipari Island, Italy. Diam. 3 mm. Entirely composed of extremely vesicular glass.

B. Incipiently welded ignimbrite, near Bishop, California. Diam. 3 mm. Specimen from the unwelded top of an ignimbrite. Crystals of quartz and sanidine, in a matrix of undeformed glass shards and dust, with well-preserved vitroclastic texture.

C. Welded tuff, from same locality. Diam. 3 mm. Specimen from the welded interior portion of the same ignimbrite. Constituents as in B, but here the glass shards are deformed and flattened.

included in the deposit. In highly silicic ignimbrites, the glass typically has a refractive index less than 1.50, and associated feldspars are usually sanidine and oligoclase; in the more alkaline types, the feldspar may be anorthoclase. In andesitic ignimbrites, the glass has a refractive index approximating 1.54, and andesine or labradorite is the feldspar to be expected. Quartz and biotite are commonly present in rhyolitic and dacitic ignimbrites. Hornblende, augite, and hypersthene may be present but are common only in the less silicic ones. Minor accessory minerals, such as magnetite, ilmenite, fayalite, zircon, apatite, and perhaps a few others, are commonly present but are invariably sparse.

Phenocrysts in pumice lapilli are indicative of the minerals that crystallized in the magma before eruption. Typically these phenocrysts are euhedral or subhedral, but similar crystals scattered through the ash matrix are likely to be broken. Crystals of feldspar and quartz are commonly rounded and embayed (Figure 9-3B,C). Biotite may be reddened by oxidation, and if temperatures were very high, hornblende crystals

may have been altered to oxyhornblende. Accessory and accidental crystal and lithic inclusions alien to the magma that was erupted usually can be recognized by forms and compositions not consistent with those of the magmatic mineral assemblage present as phenocrysts in the lapilli.

Where large volumes of magma have been erupted by a rapid succession of flows, the later flow deposits are commonly less siliceous than the early ones. The final flows from Mount Mazama (Crater Lake, Oregon), for example, were andesitic and in marked contrast to earlier dacitic flows (Figure 9-4C). Presumably such changes reflect compositional differences in different portions of an erupting magma body, more basic portions perhaps being deeper and tapped by later eruptions. In any case, distinctly bounded compositional zones must exist in some magmas, for the changes in sequential ignimbrite compositions may be abrupt, as was the case at Mount Mazama. Also, a few ignimbrites contain pumice lapilli of two distinct compositions, as shown both by differences in the refractive indices of the glasses and in the phenocrysts, and some single lapilli may be hydrid and show streaks of contrasting composition.

As they cool, a few ignimbrites may remain masses of incoherent fragments, but usually the hot glassy particles are bonded at their points of contact and the deposit as a whole becomes coherent.* Ignimbrites bonded in this fashion without compaction or distortion of the glass particles are said to be incipiently welded. They have typical vitroclastic texture (Figure 9-3B) and, although coherent, they are soft porous rocks that can be sawed easily into blocks. Often, however, the vitric fragments have been deformed and flattened by compaction and then they become more firmly welded together, forming hard rocks of relatively low porosity that are called *welded tuff*. While still hot and under appreciable overburden, the glass shards are squeezed and flattened and may be bent between and around more rigid crystal fragments (Figure 9-3C). At the same time pumice lapilli and bombs are flattened into discoid lenses; when viewed edgewise, these commonly appear as thin lenticular streaks of dense glass, called *fiamme*.† As seen in thin section, most fiamme are traversed lengthwise by dark streaks or septa, which are traces of original pumice vesicles that have collapsed and coalesced during compaction and

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*The bonding of hot glass particles is the result of a process called *sintering* in glass technology; it is dependent on temperature, composition, and viscosity of the particles.

†These glassy lenticular streaks are called *fiamme* [fee-ah'-me], Italian for "flames," because many of them are shaped somewhat like tongues of flame. The term is generally extended, however, to include all flattened lapilli in welded tuffs.

welding. The degree of welding in some ignimbrites has been so extreme as to reduce an original pumiceous lapilli tuff to nonporous, dense glass resembling obsidian, in which the flattened vitric fragments produce a streaky lamination deceptively like the fluidal banding seen in many lava flows. Additionally, as they cool, they may develop columnar jointing and crystalline spherulitic structures, so that their resemblance to lavas is increased. Little wonder that welded tuffs have often been wrongly identified as lava flows; the fact is that extensive flows of silicic composition usually are firmly welded ignimbrites. Features that aid in their recognition are the presence of relict vitroclastic textures and transitions of firmly welded tuff into less-compacted tuff of obvious pyroclastic origin. Such transitions occur near the tops, bottoms, and sides of most ignimbrites.

The welding of glassy fragments in ignimbrites is a function principally of temperature, composition, thickness, and rate of cooling. In many thick ignimbrites, firmly welded tuff occurs only in the lower-central portions of the deposit. However, if the vitric fragments have relatively low viscosity, perhaps because of unusually high temperature or concentration of H_2O and other fugitive components, even thin ignimbrites may become firmly welded throughout. In some of these rocks, small spherical vesicles occasionally appear in the densely welded fiamme, indicating continued emission of gas and the formation of bubbles even after compaction and welding, and structures produced by postwelding mass flowage have also been reported.[4]

As they cool, ignimbrites commonly lose their initial glassy texture and become wholly or partially aphanitic. The devitrification involves crystallization of the hot glass to a microcrystalline, generally fibrous, aggregate having the same bulk composition as the original glass, and also vapor-phase crystallization induced by hot gases escaping through the deposit. The effects of vapor-phase crystallization are most evident in the less-compacted, porous portions of ignimbrites.

Vitric fragments usually devitrify individually, so that original vitroclastic texture, although somewhat hazy, tends to be preserved in devitrified rocks. Typically in firmly welded ignimbrites, the glass is altered to fine-grained crystal aggregates that have distinctly fibrous texture. In thin section, the fibrous texture is clearly apparent and in some cases shows positive in others negative elongation, but the individual crystals are so slender that they usually cannot be discriminated by optical means. X-ray diffraction analyses generally identify the constituents as cristobalite and feldspar. Beginning at the fragment margins with fibrous crystals oriented at high angle to the margin, the crystallization progresses inward until the glass is completely devitrified. In the larger flattened shards and in fiamme, devitrification commonly produces *axiolitic texture* in which the crystal fibers are oriented normal to opposing walls and meet to form a septum along the central axis of the fragment. In some cases, radial fibrous plumes and spherulitic growths develop from separate centers along fiamme margins, and occasionally these may extend across the fragment margins. In a few welded ignimbrites, large spherulites have been formed; some of those, called *lithophysae*, contain central cavities that may be encrusted with crystals formed from a vapor phase or filled with chalcedony. Commonly, where devitrification has begun, it has progressed essentially to completion, but devitrified and unaltered glass may occur side by side within single fiamme, or the smaller fragments may be devitrified completely and the larger fiamme remain glassy.

Where crystallization occurs in porous, uncompacted portions of an ignimbrite, the pumice lapilli lose their original glassy vesicular texture and are converted to porous aggregates made up of minute crystal rosettes, and cavity walls are encrusted with small crystals precipitated from a vapor phase. Here tridymite and feldspar, usually with cristobalite, are the most abundant minerals, although the individual crystals are generally too small for visual identification. Other minerals of similar origin commonly include aegirine, hornblende, and scapolite. As a consequence of vapor-phase crystallization, incipiently welded ignimbrites may become somewhat more coherent, but they remain generally porous and soft.

AQUAGENE TUFF (HYALOCLASTITE)

Volcaniclastic deposits resulting from the fragmentation of magmas when quenched by water are termed *aquagene tuff* or *hyaloclastite*.[5] Generally they are related to submarine eruptions, but they also may form where lavas flow into the sea or into fresh water and where extrusion of magma occurs beneath glacial ice (common in Holocene volcanic deposits of Iceland). Most of them have basaltic composition and consist largely of sharply angular fragments of glass bounded by smooth fracture surfaces. Typical fragments are clear brown basaltic glass (sideromelane) in which vesicles either are lacking or are relatively sparse, in contrast to the highly vesicular glassy and cryptocrystalline fragments (tachylite) that characterize basaltic ash and lapilli produced in subaerial eruptions. But