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# Seminar on Ancient and Modem Volcanoes

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Aller au sommaire du numéro

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# Seminar on Ancient and Modern Volcanoes

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## Introduction

The eruption of Mt. St. Helens on May 18, 1980 is becoming a classic in the annals of volcanology. The principal reasons that scientists have learned so much from this eruption are as follows:

(1) The United States Geological Survey mapped Mt. St. Helens in the mid-1970s and concluded that a major eruption was likely before the end of the century. As a result, the Survey was well prepared to monitor the eruption. In fact, a seismic network was put in place in 1978.
(2) The eruption began on the morning of a fine day and was photographed from many points of view, including from light aircraft.
(3) The eruption, and subsequent activity, involved a wide variety of volcanic processes.
(4) The eruption plume and its effects could be readily observed because it initially spread across a continent rather than an ocean, and because a geostationary satellite, radar and high altitude aircraft were available to observe it.

The studies of Mt. St. Helens have come at a time of advances in the study of volcanic rocks. The Toronto Geological Discussion Group thought it appropriate, therefore, to present a review of the present state of knowledge of volcanic processes and products to an audience composed largely of people who work with Precambrian volcanic rocks. Accordingly, on April 16, 1982, the Toronto Geological Discussion Group and the Geology Department of the University of Toronto jointly sponsored a seminar with the theme "How can observations on modern volcanoes help us understand ancient volcanic rocks?" This was the second such venture by the Discussion Group: our first was in February, 1981 when we outlined the significance of recent observations on "black smokers" to geologists working with and looking for massive sulphide deposits.

Sandy Colvine and Roly Ridler chaired the presentations and the lively discussion period which followed. The seminar covered five major topics: the flow of basaltic lava; the flow of intermediate to felsic lava; the formation of intermediate to felsic pyroclastic rocks; relationships between volcanism and structural geology; and the activity in 1980 of Mt. St. Helens.

## The Flow of Basaltic Lava

Dimroth outlined the theoretical background and gave many examples of basaltic flows. Downes confined his discussion to a single eruption, that of Etna in 1971, which he illustrated with his own colour movie.

Figure 1 illustrates how the morphology of lava flows is determined by the effusion rate and by the viscosity and shear strength of the lava. (As a proxy for ancient extrusion rates, volcanologists commonly use the volume of a flow, or the ratio of the volume to the length of the feeder vent.)As it cools from the liquidus to a temperature 35° lower, the viscosity of basalt increases by about three orders of magnitude and the shear strength increases considerably. As a result of these properties, there is a spectrum of types of basalt flow (Cousineau and Dimroth 1982; Dimroth in prep.). At one end of the spectrum is the *sheet flood* in which all parts of the flow spread outwards simultaneously. At the other end of the spectrum is the *channelled flow.*

A sheet flood is stable as long as lava is able to reach the flow front with little change in viscosity. This can occur only if the rate of extrusion is high: otherwise, the viscosity will rise sharply as the lava cools on its way to the front. In the latter case, the supply of lava becomes confined to individual flow lobes. These lobes advance while the rest of the front remains static.

The surface appearance of lava flows undergoes a sharp change at a critical level of viscosity. This critical level decreases as the flow rate increases. On land, the passage of lava through the critical viscosity is expressed as a transition from pahoehoe to a'a. The submarine equivalent of this transition is from massive lava to massive lava with a flow-top pillow breccia or, in extreme cases, to flow-top a'a (Ricketts *et al.,* 1982).

In constructing models for the formation of volcanic rocks, it is worthwhile to look at ancient examples. Ancient rocks offer a view of the third dimension. Furthermore, delicate primary textures are often seen to best advantage in glacially polished exposures of slightly metamorphosed rocks.

Dimroth discussed the following examples of basaltic flows. His comments were based upon his own field work in all except the first example.

Sheet floods include the Roza Member of the Columbia River Basalt Group (Swanson and Wright, 1981), which contains about 1,500 cubic kilometres of rock. The Roza Member was extruded on land, probably in less than a week. Lava was ponded as the leading edge froze.

In the Proterozoic Labrador Trough a single subaqueous basaltic sheet-flood, 350 m-450 m thick, contains several hundred cubic kilometres of lava (Fig. 1, I). This lava eventually travelled so far from its source that it could not maintain its flow as a sheet. As a result, the unit grades away from its vent from coarse-grained, massive basalt into fine-grained, pillow basalt. (The "pillows" in these rocks, as in most "pillow basalts", are actually tubes, and represent channelled flows.) Furthermore, the rate of extrusion declined during the eruption, as it does during most effusive eruptions. Once again, the result was that flow became confined to channels. As a consequence, the unit changes upwards from massive basalt into pillow basalt. In both the lateral and vertical changes from massive basalt to pillow basalt, the zone of transition is planar, with no re-entrants.

In a smaller (less than 100 cubic kilometres), subaqueous compound flow of the Archaean Kinojevis Group, north of Noranda, the transition between massive and pillowed facies is more complex. Lobate domains of massive lava are surrounded by pillow lava (Fig. 1, II).

Small (0.2 to 0.5 cubic kilometres per kilometre of feeder) subaqueous flows in the Archaean Amulet "Andesite", near Noranda, illustrate many features of channelled flows (Cousineau and Dimroth, 1982). Close to the vent the flows grade vertically from massive basalt to pillow basalt. Further from the vent channels up to 50 m wide, filled with massive basalt, feed tubes which branch away from their source. After some of the tubes and channels were drained, they collapsed to form localized breccias. The branches in the tubes indicate flow directions, as do asymmetrical pillows and foreset bedding in some of the pillow breccias and in massive/pillowed sequences. This more complicated organization is shown in Figure 1, III. However, some low-volume eruptions start with very high effusion rates, producing small but massive sheet-flood flows. If such a flow were to become channelled, the result would be a pile of pillow basalts set on a sheet of massive basalt.

The types of flows described so far would all, on repeated eruption, give rise to extensive volcanic terrains of comparatively subdued relief. Steep, cone-shaped volcanoes are all composed of much smaller flows which were extruded at much lower rates. All such flows are channelled. The

1971 flow from Mt. Etna is an example of this type of flow. According to Downes, the extrusion temperature was about 150°C below the liquidus temperature. Initially, about 50% of the flow consisted of crystals. As it ran down the mountain, the flow cooled and passed through the critical viscosity level, changing from pahoehoe to a'a.

The principal lessons provided by these examples are as follows:

(1) The modern record is biased towards subaerial events and small scale events. Had Downes been as close to the Roza Member eruption as he was to the 1971 Etna eruption, he would not have survived to show us his beautiful movie. Dimroth believes that only those eruptions which eject more than 10 km$^3$ of material will leave a recognizable record, in the form of a deep-sea tephra layer. Even the May 1980 Mt. St. Helens eruption, which was large by historical standards (2 km$^3$), was only a small eruption by geological standards. A thousand years from now, according to Dimroth, no recognizable trace of the eruption will remain outside the immediate vicinity of the volcano.

(2) As flow rates decrease, the internal organization of basaltic flows becomes more complicated.

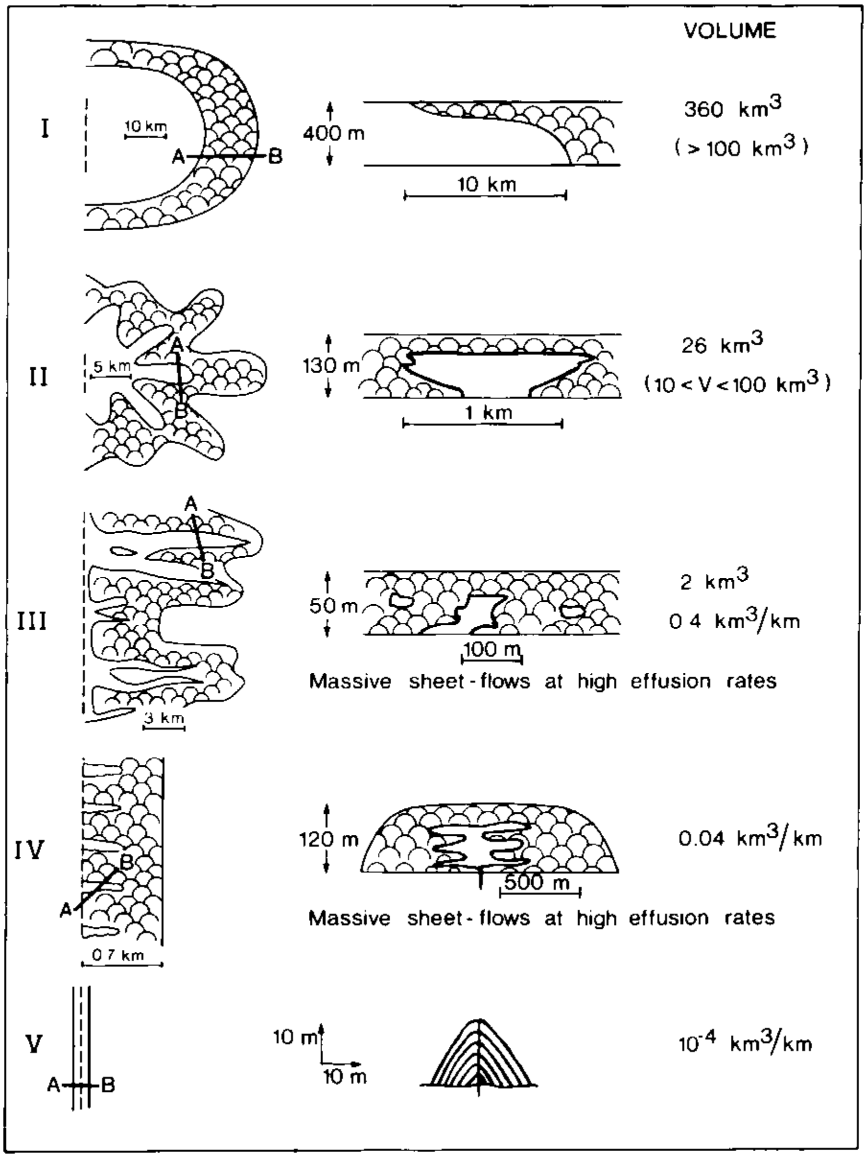

**Figure 1** *The effects of differing rates of effusion upon the morphology of submarine basalt flows (from Dimroth, in prep.). Left: schematic map of facies distribution; right: schematic cross-sections along lines A-B; extreme right: typical volumes of flows. I to V: Forms of organization that are characteristic of flows of decreasing volumes. Note that sheet flood flows of small volume exist; they form when a small eruption begins with a phase of high rate of effusion. Pillow basalt (channelled) shown by pillow symbols, massive lava (sheet-flood phase and filling of large channels) is left without pattern.*

(3) An understanding of the internal structure of basaltic flows can save a great deal of work. Dimroth displayed a very detailed map of part of the Kinojevis Group: the product of fourteen summers of field work. With his present knowledge of the behaviour of basaltic flows, Dimroth claimed that he could have obtained the essence of the information contained in this map after only a few weeks' work, provided a reasonably accurate map at a scale of about 1:50,000 had previously been available.

### The Flow of Intermediate to Felsic Lava

Goldie showed how viscous lava flows take various forms under different conditions; Rose spoke about the Santiaguito dome in Guatemala and Scott described Showa Shinzan, Japan. Gibson and Comba talked about their work on Archaean flows near Noranda, particularly the Millenbach "QFP".

The viscosities of some intermediate lava flows are comparable with those of basaltic flows. The most important of the conditions which produce low viscosities are a high temperature of extrusion and a high proportion of volatile constituents (the latter condition is favoured by extrusion under deep water). Intermediate lava flows of low viscosity produce landforms analogous to those formed by basaltic lavas: steep cones, low shields and even lava plateaux similar to that formed by the Roza Member. As an example of the latter, Cas (1978) has described subaqueous lava flows of intermediate composition (60% to 65% $SiO_2$), each of which is hundreds of metres thick and extends for thousands of square kilometres.

At the other end of the spectrum, felsic lavas commonly have viscosities so high that it is only with the utmost difficulty that they ever reach the surface. Figure 2A shows Middle Butte, an elevated and tilted block of basaltic lava in the Snake River plains. Spear (1977) suggested that Middle Butte may be like a trap-door which has been partially opened by a plug of silica lava.

Many of the rhyolitic and trachytic lavas which do reach the surface are extruded as a result of the encouragement they receive when basaltic magma is injected into a silicic magma. Because the liquidus temperatures of basalts are higher than those of rhyolites or trachytes, basaltic magma would heat silicic magma, decreasing its viscosity and density, and thereby increasing its mobility. Flows of very viscous lava, therefore, most commonly decorate volcanic landscapes of a bimodal compositional character.

The most viscous flows are extruded out of the ground like toothpaste squeezed vertically from a tube. Two examples of this type of flow are shown in Figures 2B and 2C; Showa Shinzan is a third example (Fig. 3). Showa Shinzan rose magnificently from under an iron bridge on a valley floor in 1944. Within 14 months it had risen to 440 m. Stream boulders and the iron bridge are still perched on top.

Lava which is somewhat less viscous than that which forms domes tends to flow laterally under the hydrostatic head of the magma upwelling at the surface. The resulting landform consists of a dome, capping the site of the vent, surrounded by a flat-topped apron, or *coulée*. Coulée fronts are very steep-sided, may be several hundred metres high, and are fringed with talus deposits. On flat or inward-facing slopes (such as at the bottom of a crater), these landforms are circular. An example is the Wahanga dome, Mt. Tarawera, New Zealand (Cole, 1970). On slopes of more than a few degrees, flow in the coulée is dominated by the topography rather than the hydrostatic head. Examples include Pu'u Wa'awa'a, Mt. Hualalai, Hawaii, and Ruawahia, New Zealand (Fig. 2D). On very steep slopes the lava will undergo brittle fracture, and movement will be concentrated in imbricated shear planes, concave towards the vent, called *rampart* structures. One example is a post-glacial flow at Landmannalaugar, Iceland, which ran down a steep hill. The same effects can also be seen where a flow has moved against a steep slope of its own making, such as a basal breccia "bowl" which has trapped lava inside.

All the domes described above are termed *endogenous* because their growth is internal, like the inflation of a ballon. *Exogenous* domes are built up by the addition of lava squeezed out through cracks in the surface.

Flow banding in domes is generally parallel to the dome margins, becoming more irregular near the surface. Jointing is usually either parallel to the margins or radial. Breccias are common, and result from the following processes:

(a) rupture of the skin of a dome because of expansion due to endogenous growth;
(b) rupture of the skin of a dome because of thermal contraction;
(c) collapse of a dome which has grown gravitationally unstable;
(d) flow brecciation, particularly in the basal zone;
(e) fragmentation during explosive eruption of gases.

Breccias range from modest talus aprons at the feet of domes (Fig. 2C) and coulées, to the bowl-shaped structures, mentioned above, which comprise the bulk of some domes.

Most domes have complex histories. Two examples illustrate this point.

Santiaguito is a horseshoe-shaped volcano, somewhat like the present Mt. St. Helens. The crater is filled with an active complex of domes and coulées, comprising at least 26 units, which has been extruded intermittently since 1922. The complex

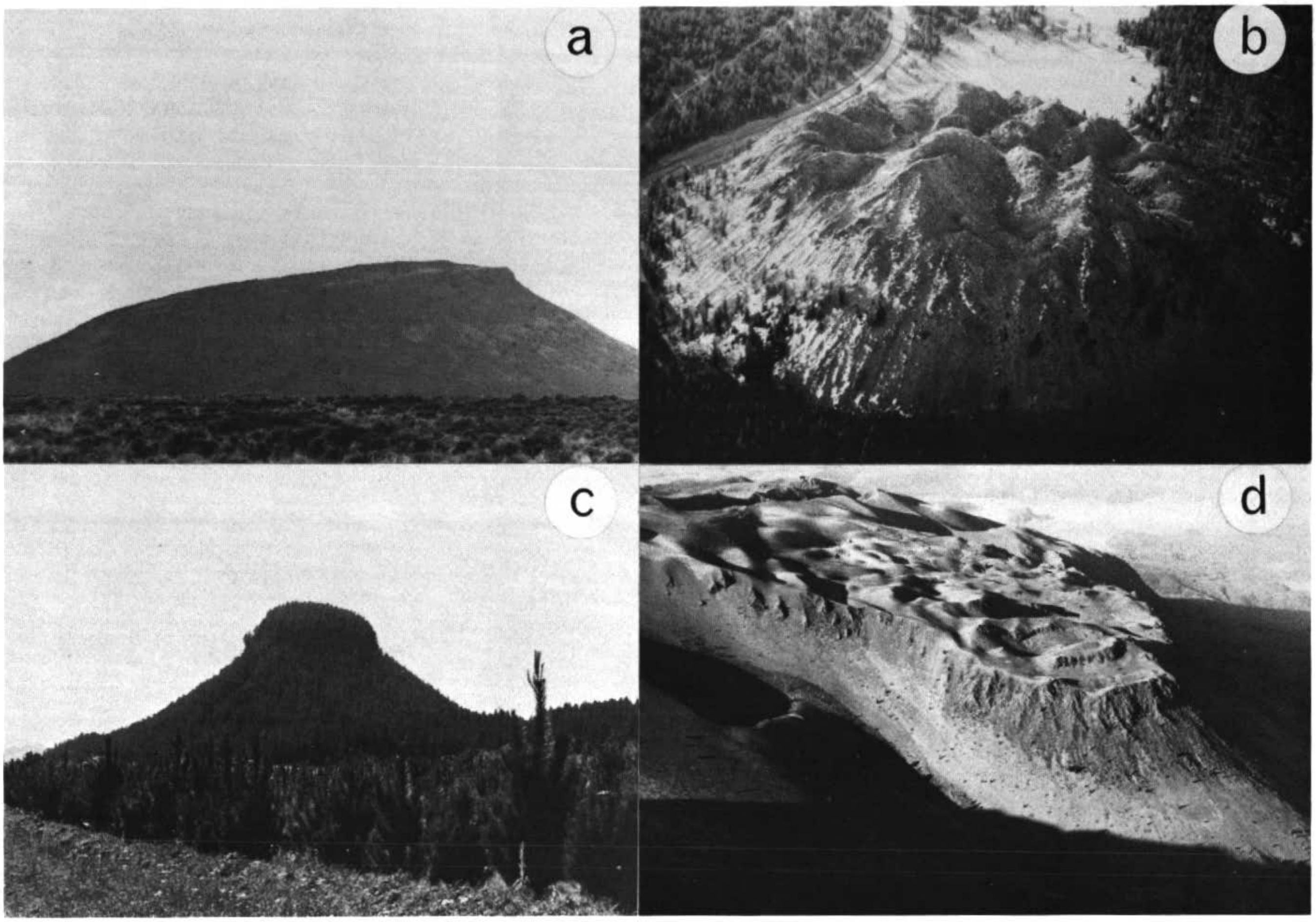

**Figure 2** *domes of siliceous lava.*
*2A: Middle Butte, eastern Snake River Plain, Idaho, looking southwest. This hill is composed entirely of stratified basalts, which dip to the south at about 10°. These basalts resemble those of the surrounding Snake River Plain. Spear (1977) has interpreted Middle Butte as a trap-door-like structure above a plug of silicic magma. 2B: Wilson Butte, a rhyolitic dome, about 650 m in diameter and 150 m high, part of the Mono-Inyo chain of craters and flows, Mono County, California. 2C: Pohaturoa, a rhyolitic dome about 270 m high, near Atiamuri in New Zealand's Taupo Volcanic Zone. Note the talus apron surrounding the dome. 2D: A coulée, part of the Ruawahia rhyolitic extrusion, Mt. Tarawera, Taupo Volcanic Zone. The front of the flow is about 200 m high, and the maximum width of the flow is 850 m.*
*(All photos by R. Goldie)*

is composed of dacite (dacites are commonly richer in crystals and contain a smaller proportion of volatile constituents than rhyolites). Fumarolic activity is concentrated in a single vent which issues periodic phreatic eruptions. One dome has the form of a poached egg. The yolk is represented by a plug of lava which has grown both by exogenous and by endogenous processes. Jointing in the plug is columnar and inward-dipping. The white of the egg is represented by a crumble breccia which formed by spalling of the skin of the plug and by collapse of exogenous spines.

The Archaean Millenbach QFP ("quartz-feldspar porphyry"), near Noranda, must be one of the world's best documented volcanoes (although most of the documentation is presently unpublished). Geologists with Corporation Falconbridge Copper have logged 3,629 diamond drill intersections of the QFP and have carefully mapped about 13 km of underground workings within it. The QFP has the form of a ridge which is conical in cross-section (Fig. 4) and like a whale's back in longitudinal section. The maximum thickness is 250 m.

The elongated nature of the QFP does not appear to be the result of topographic control, as with the Pu'u Wa'awa'a. In fact, the shape of the ridge reflects a subjacent fissure, 2.2 km long, from which the QFP was extruded via 3 or more vents.

Because most of the QFP is a massive, featureless rock, many details of its formation have been determined indirectly. For example, the presence of inter-QFP exhalative sediments and the occurrence of massive sulphide lenses indicate that the Millenbach QFP is a composite dome, composed of at least two separable flow-units in the Millenbach mine and as many as 4 flow-units in an area approximately 1.5 km to the southwest. In places these exhalites were laid down on rugged, steep slopes that were subsequently tilted and steepened as a result of internal "swelling" of the rhyolite as the dome grew endogenously. To the untrained eye, these chemical sediments look like discontinuous veinlets. Geologists at Falconbridge Copper, however, have shown that the "veinlets" represent filling of the matrix of a monolithologic breccia on top of a flow unit.

A cross-section of one end of the QFP ridge shows a great scour-like irregularity (Fig. 4) interpreted as the scar of a slump which was generated when the dome had grown too steep to support itself. In the area which was once below the scar there is a deposit of porphyritic felsite breccia, up to 30 m. thick, interpreted as the remains of the slump.

## The Formation of Intermediate to Felsic Pyroclastic Rocks

Fisher drew upon observations made on Quaternary volcanoes to describe pyroclastic flows and their products; Thurston reviewed occurrences of subaerial intermediate to felsic pyroclastic rocks in the Superior Province of the Canadian Shield.

In recent years some of the greatest advances in volcanology have come in our understanding of pyroclastic processes and products. The terminology has been in a state of flux and is now confusing to those who have not been closely following developments in the field. Most volcanologists now recognize three primary modes of transport of pyroclastic fragments: ballistic transport ("pyroclastic fall"), transport in a fluid moving in a laminar fashion ("pyroclastic flow") and transport in a turbulent fluid ("pyroclastic surge"). The most important secondary mode of transport is the debris flow, or lahar. Our seminar concentrated on pyroclastic flows and surges.

*Pyroclastic flows* are dense, hot mixtures of gases and solids. The course of a pyroclastic flow, like that of a lava flow, is strongly controlled by topography. During

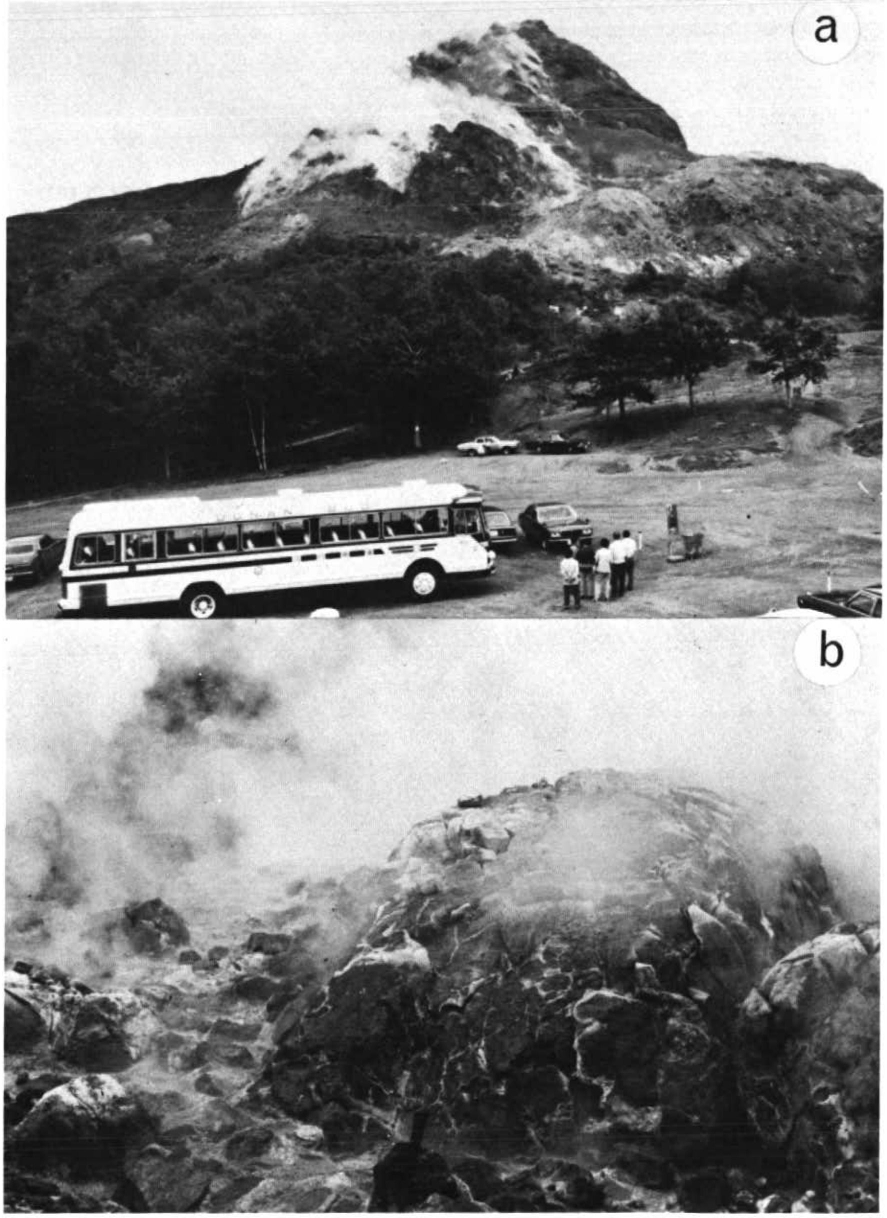

**Figure 3** *Showa Shinzan, southern Hokkaido, Japan.*
*3A: Showa Shinzan: a felsic dome which rose to a height of about 440 metres in less than two years. (Photo by S.D. Scott, July 1977.)*
*3B: "Turtle Rock": a finger of dacite lava slowly oozing out of the top of the Showa Shinzan dome. The finger is being hydrothermally altered, including the deposition of sulphur. Steam temperatures are 575°C. (Photo by S.D. Scott, April 1977.)*

their travels, pyroclastic flows lose their volatile constituents and eventually "freeze" when their viscosity becomes too high to permit further movement. The term *ignimbrite* is now used by many workers for the product of any pumiceous pyroclastic flow, whether those products are welded or not. Some workers would restrict the term to the products of large eruptions: many such large pyroclastic flows probably originate in the collapse of eruption columns. Fisher recommends that the term *nuée ardente* be restricted to the small pyroclastic flows which result from the collapse of hot lava flows or domes.

*Pyroclastic surges* are of two types: cold and hot. Cold, or *base surges* are the result of the phreatomagmatic explosions generated when surface water meets magma. Hot, or *ground surges,*result from the collapse of eruption columns or by entrainment of air in a pyroclastic flow. (Note that the term "ground surge" was formerly applied to all pyroclastic surges.)Pyroclastic surges are a dilute suspension of solids in a gas, and are less constrained by topographic obstacles than are pyroclastic flows. Indeed, a ground surge generated from a pyroclastic flow (by elutriation or by gravity segration) may eventually become detached from its parent and move independently. Surges of this type may be termed *ash cloud surges.*

Sparks *et al.* (1973) introduced a facies model (c.f. Walker, 1979) for the typical products of a single pyroclastic eruption sequence. The model has been modified by other workers. In its present incarnation, a "typical" pyroclastic sequence is thought to consist of a basal fall deposit overlain successively by a cross-bedded ground surge deposit, then an inversely-graded pyroclastic flow deposit, then a fine ash deposit (the *coignimbrite ash)* and, in some cases, a lava flow. The pyroclastic flow deposit is the most voluminous part of the unit, and thickens away from the source for as much as several tens of km: the other deposits thicken towards the source. The Sparks *et al.* sequence represents the emptying of a magma chamber from the top down. The fact that ground surge deposits are generally found *below* pyroclastic flow deposits close to their source suggests that ground surges are generated at vents much more commonly than from subjacent pyroclastic flows.

The two eruptions of Mt. Pelée, Martinique in May 1902 produced hot pyroclastic flows which were channelled through a small, preexisting notch in the crater wall. As each pyroclastic flow moved downhill, it continuously separated by gravity into a block-and-ash flow (underflow) beneath an ash cloud surge. The routes of the surges deviated from those of the block-and-ash flows. The flows deposited poorly-sorted breccias, with blocks up to several metres across. Only gas escape structures hint that these breccias were primary products of volcanic eruptions, rather than debris flows. The surges left more extensive, bedded deposits capped with accretionary lapilli.

Archaean subaerial volcanic rocks are more common than is generally suspected. In the Superior Province, geologists have demonstrated the existence of subaerial rocks in the Uchi-Confederation Lakes greenstone belt, the Favourable Lake and Lang Lake belts (Buck, 1978; Thurston, 1979; 1980). Subaerial rocks also may be present in the Blake River Group of the Abitibi belt. The best known ones are in the Uchi-Confederation Lakes greenstone belt (Figs. 5 and 6). These rocks conform closely to the model of Sparks *et al.* (1973) and are stratigraphically equivalent to a suite of subaqueous volcanic rocks.

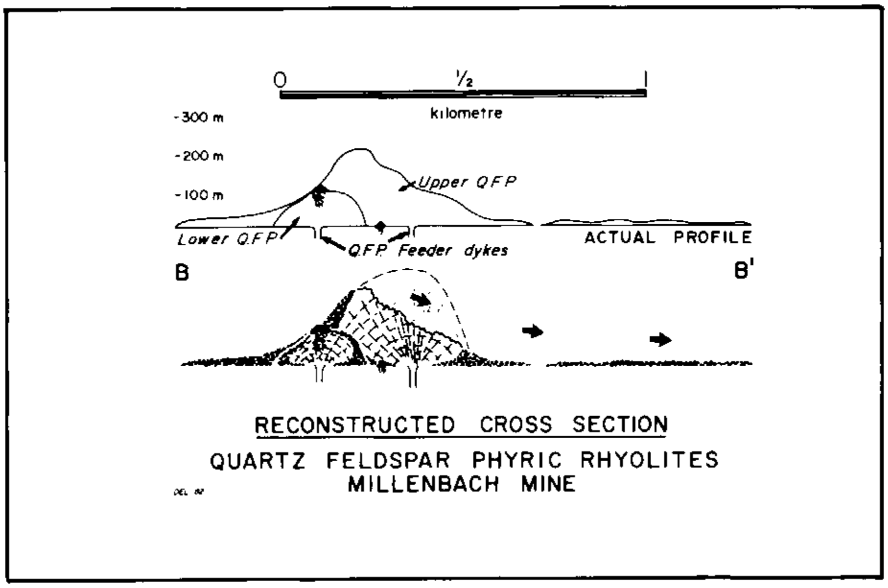

**Figure 4** *Transverse cross-section through the "Q.F.P." of the Millenbach mine, Noranda, Québec (Comba, C.D.A. and H. Gibson, in preparation). B-B' is a NW-SE section through the Millenbach QFP at the Millenbach mine.*

Thurston described how the products of subaerial pyroclastic flows and surges can be distinguished from those of subaqueous flows, according to the following criteria:

| | *Subaerial* | *Subaqueous* |
|---|---|---|
| Bedding: | poorly bedded | bedded; chaotic bedding near vents |
| Grading: | normal | well developed; reverse or normal |
| Fragment Sizes: | bigger | smaller |
| Sorting: | sorted | poorly sorted |
| Welding: | common | uncommon, poorly developed |
| Vapour-phase Recrystallization: | present | absent |

(after Thurston, 1981)

Note that welding is uncommon, but not absent in subaqueous rocks.One would expect subaqueous welding to be more common in pyroclastic flows than in surges because a turbulent surge would readily become mixed with the surrounding, cold water. On the other hand, the entrainment of a little water (a few percent) into a pyroclastic flow could *facilitate* welding by lowering the viscosity (Sparks *et al.*, 1980).

## Relationships Between Volcanism and Structural Geology

Hodder discussed calderas and related structures; Comba, Gibson and Scott addressed the relationships between lineaments and volcanism. Muir presented some cautionary tales: he showed structures formed in areas of modern volcanism which, in ancient rocks, could be misinterpreted as indicating profound tectonic disturbances.

*Calderas* are circular or arcuate volcanic depressions. Their diameters are greater than those of any single vent, even though they may host only a single volcanic centre. Calderas form by collapse. *Hawaiian-type calderas* are generally thought to originate by withdrawal of subjacent magma during a flank eruption (although Goldie, 1979, has suggested that a contributing factor may be consolidation of a volcanic pile with abundant voids). *Krakatoan-type calderas* are excavated out of composite cones by giant explosive eruptions. Crater Lake, Oregon, was long thought be of this type, but the absence of material from the hypothetical cone of Mt. Mazama has convinced many geologists that this caldera is of Hawaiian type. *Valles-type calderas,* well described in the classic study of Smith and Bailey (1968), have undergone repeated periods of inflation, eruption and collapse.

A *cauldron* is a large depression which results from passive subsidence into a magma reservoir (batholith?). There is little associated volcanism.

A *volcano-tectonic depression* is a linear, fault-bounded structure which may be hundreds of kilometres long. These structures become partially filled with volcanic debris, mostly pyroclastic.

Although Goldie suggested that the Méritens Unit of the Flavrian pluton may be the remains of a ring-dyke in the Noranda area, the syn-volcanic fractures which so far have been mapped elsewhere in the Superior Province have linear or othogonal patterns. Either calderas were rare in Superior Province rocks, or the evidence for them has been destroyed. Certainly some modern calderas have superposed rectilinear fractures.

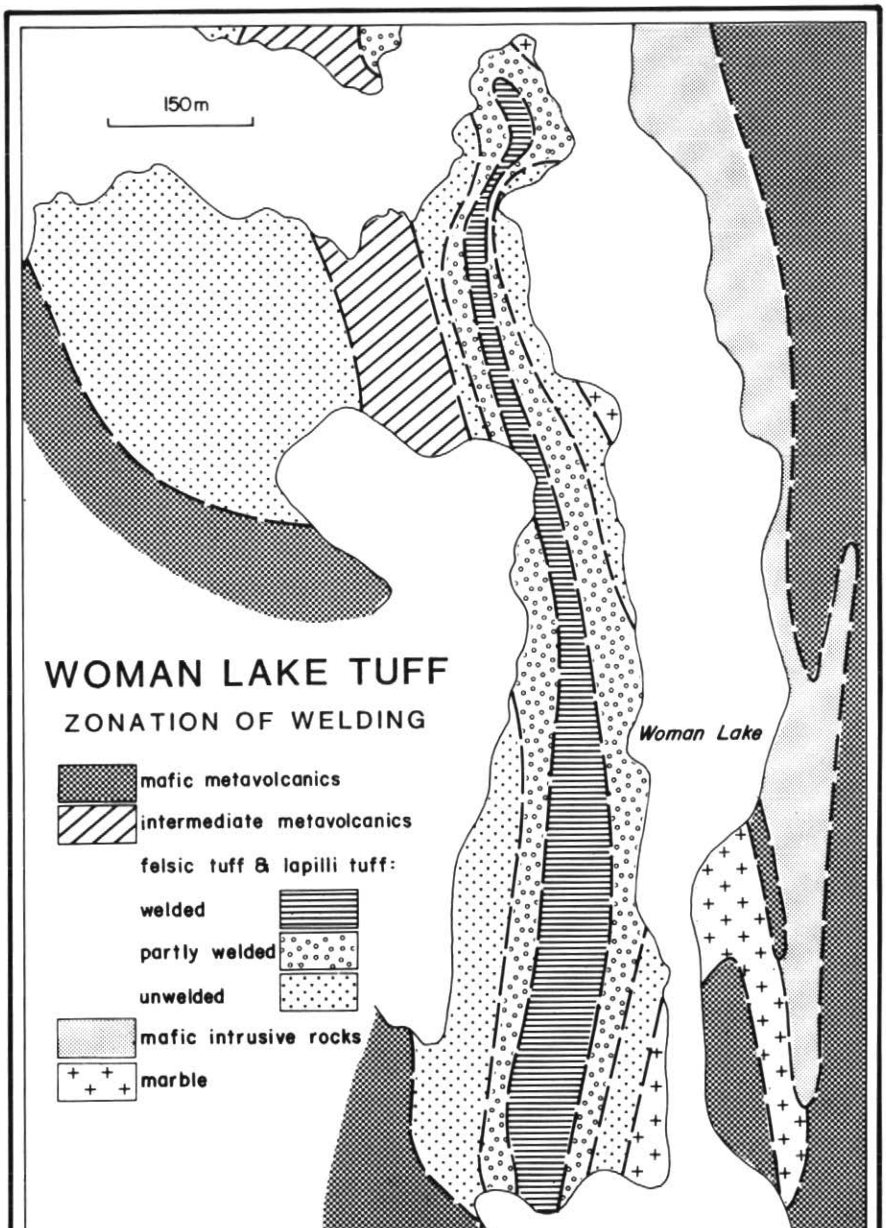

**Figure 5** *The southern most 2 km of the Woman Lake tuff, Uchi-Confederation Lakes greenstone belt, northwestern Ontario. The unit is subdivided on the basis of the degree of welding (after Thurston, 1980).*

According to Muir, the major reasons why geologists could misinterpret volcanic structures in Precambrian terranes, and postulate faults and folds that do not exist, are as follows:
(a) incomplete or poor exposure; (b) the ubiquity of syn-volcanic faulting; and (c) post-depositional tectonic adjustment related directly to the history of the volcanic complexes or to Archean-style deformation.

Muir illustrated these potential problems by describing some small-scale unconformities found in exposures of modern, subaerial volcanic and related rocks. Some of these examples included:

1) The island of Hawaii, where lava flowing down fault scarps has often frozen in place to produce deposits with initial dips of about 90°.
2) Ubehebe crater, Death Valley, California, where sharp discontinuities resulted from the filling of a volcanic explosion crater (Fig. 7A).
3) Pyroclastic flows and airfall deposits on St. Vincent, West Indies, where successive discontinuities result from two modes of deposition with intervening periods of erosion (Fig. 7B).
4) Sediments and airfall deposits in Guatemala, where plastically deformed, slumped soft sediments are overlain by undeformed layers of "mantle bedding". These strata are in turn overlain by layers which failed by brittle slumping. Some of the underlying material was sucked up into the resulting fractures, producing "veinlets". These "veinlets" were further filled by precipitates from ground water solutions (Fig. 7C).
5) Pyroclastic and fluviatile deposits on St. Vincent, where at least four depositional events can be identified in dissected deposits (Fig. 7D).
6) A variety of deposits on St. Vincent where contrasting environments juxtapose, within a small area, lava flows, pyroclastic flows, fluviatile deposits, talus deposits, detrital fans, beach deposits and unspecified subaqueous deposits (Fig. 7E).

Structures such as schistosity planes, minor folds and boudins can be formed by plastic deformation under conditions of high-grade metamorphism. However, they are also formed by plastic deformation during the last stages of consolidation of bodies of viscous lava!

### The 1980 Activity of Mt. St. Helens

There are differing interpretations of what happened at each stage during the eruption of Mt. St. Helens. Rose's version is presented here.

In the mid-1970s the United States Geological Survey prepared a map depicting its assessment of the volcanic hazards in the vicinity of Mount St. Helens. The Survey delineated hazard zones by studies of Recent deposits, which included radiocarbon dating.

In early 1980, a plug of magma was rising inside Mount St. Helens, producing an asymmetrical bulge which eventually could be perceived by the naked eye. By late March the plug had moved sufficiently close to the base of the zone of groundwater circulation to generate a series of phreatic eruptions. Prompted by this activity, geologists formulated a set of possible scenarios for the eventual climactic eruption. As it turned out, most of the scenarios did not envisage an eruption as violent as the one which occurred. However, the precautions taken on the basis of the scenarios and the hazard map undoubtedly saved the lives of many sight-seers. That it occurred on a Sunday probably also saved the lives of more than 2,000 loggers.

On the morning of May 18, the bulge on the side of the cone began to shake like jelly. The bulge then collapsed to form a massive avalanche or debris flow. An underlying plug of magma was thus exposed. In response to the sudden relief of pressure the plug, and the hot, wet rocks which surrounded it, exploded. The explosive blast was directed horizontally, resulting in a ground surge which overran the debris flow. The ground surge subsequently climbed and went over ridges several hundred metres high. The debris flow produced a megabreccia consisting of chunks of the old cone, up to hundreds of metres in diameter, in a heterolithic matrix. (Fisher's field work in 1982 suggests that the debris flow also climbed ridges.)The surge produced a thin-bedded ash deposit.

Less than six minutes after the debris flow was detached, Mount St. Helens began to eject a powerful vertical eruption column. This vertical eruption continued for at least nine hours and formed a cloud which extended to at least 24 km above the vent. The blast entrained air, producing inward-rushing winds which actually reversed the flow of part of the ground surge.

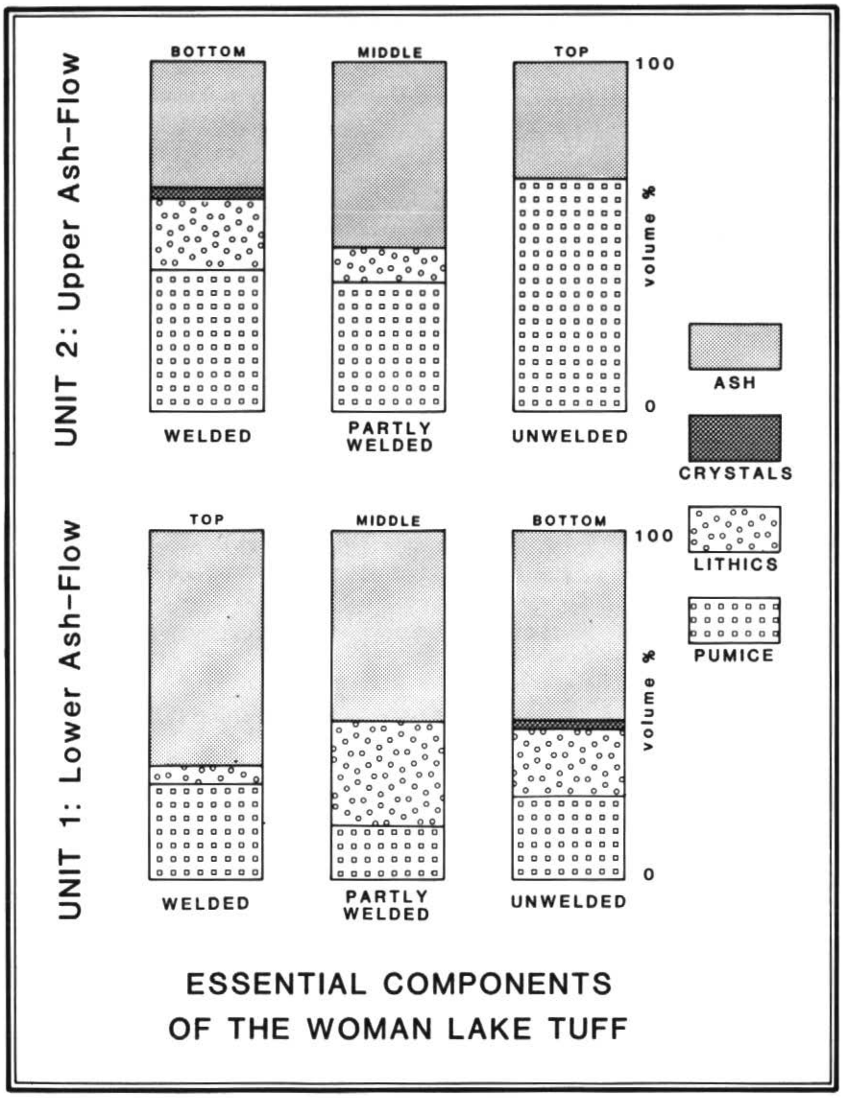

**Figure 6** *Summary of modal data for each of the sub-units of the Woman Lake tuff (after Thurston, 1980). Note: these are not stratigraphic sections. The vertical axis represents volume percentages*

Although radar imagery could distinguish individual "puffs" within the Plinian cloud, isopachs of the resulting airfall deposits show a regular decrease in thickness with distance from the vent—with one puzzling exception. There is a secondary peak in ash thicknesses near the town of Ritzville, Washington, about 350 km. down-wind from the vent. Although the reasons for the Ritzville bulge are not clear—aggregation of particles? via electrostatic forces? water?—the phenomenon was repeated in subsequent Plinian eruptions.

In the remainder of 1980, Mt. St. Helens produced a series of progressively smaller Plinian eruptions. Each eruption produced dacitic pumiceous pyroclastic flows, several metres thick, with post-emplacement effective viscosities of about 1,000 poise, according to Wilson and Head (1981). This is very similar to the viscosity of basaltic lava. In fact, the shapes and dimensions of the "frozen" pyroclastic flows greatly resemble those of channelled basaltic flows. Levées, interdigitated flows, flow ridges and "pahoehoe" toes, about 1 m thick, are all present: the startling differences are that the Mt. St. Helens flows are fragmental and white!

Some of the pyroclastic flows are welded near the vent, and had a measured rest temperature of about 700°C. Even when "frozen", the pyroclastic flows remained partly inflated for weeks. For example, the surface of a flow would "splash" when a rock was thrown into it. The fluidization was probably maintained by de-gassing of shards.

A dome complex, which may grow to be similar to that at Santiaguito, has begun to form in the throat of Mt. St. Helens. The dome currently has the form of an inverted bowl and is expanding exogenously.

One of the most important lessons of the May 18 eruption has been in the assessment of volcanic hazards. The deposits left by ground surges are thin and unimpressive except where they thicken in stream valleys. Prior to the eruption, therefore, many geologists lacked an appreciation of the nature and effects of ground surges. One of those who *was* aware of their danger was David Johnston. Tragically, Johnston was killed in May 1980 when a ground surge surmounted a ridge previously mapped as a "low hazard zone".

### Further Reading

A month after the Discussion Group seminar, Lorne Ayres, of the University of Manitoba, ran G.A.C. Short Course 2,

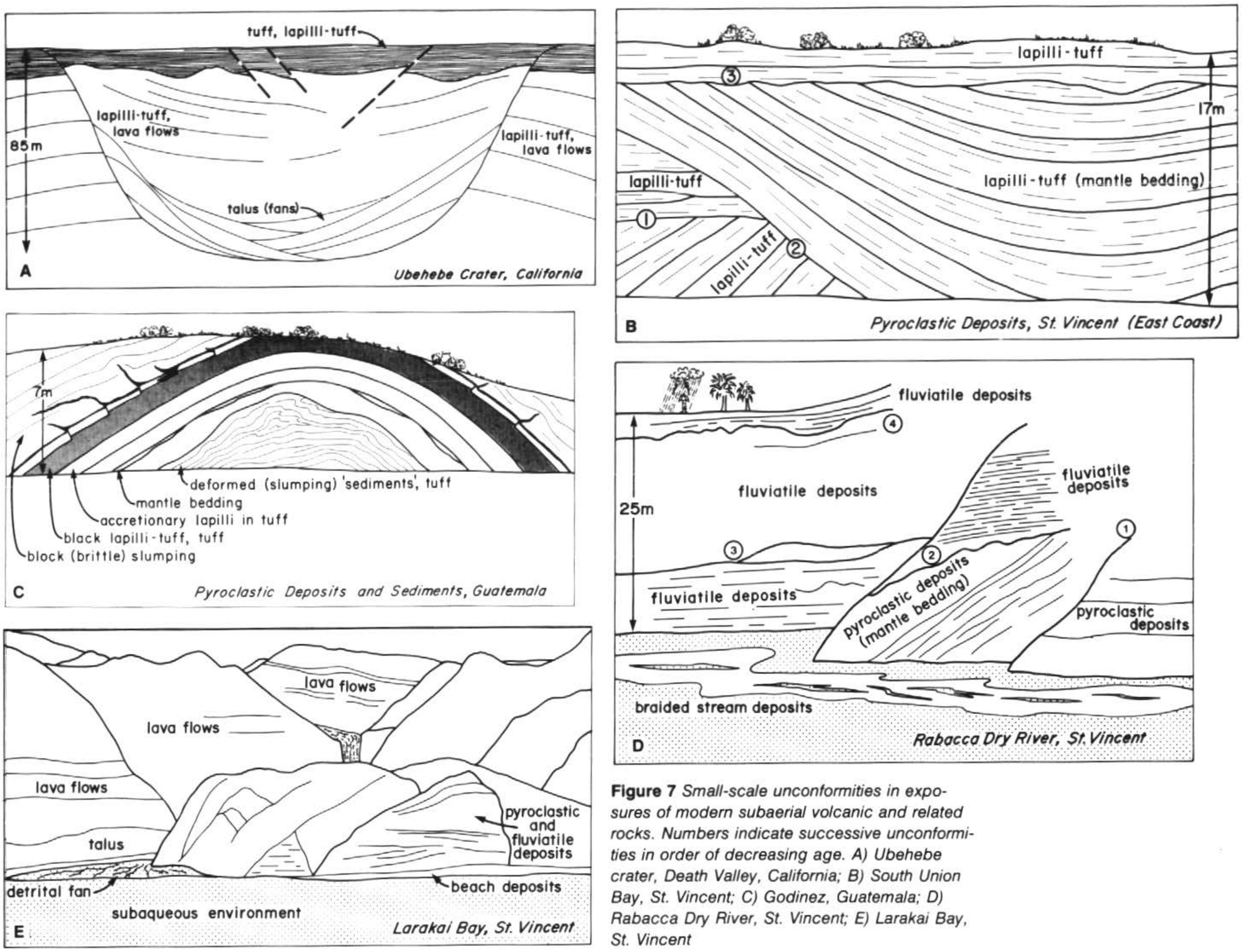

**Figure 7** *Small-scale unconformities in exposures of modern subaerial volcanic and related rocks. Numbers indicate successive unconformities in order of decreasing age. A) Ubehebe crater, Death Valley, California; B) South Union Bay, St. Vincent; C) Godinez, Guatemala; D) Rabacca Dry River, St. Vincent; E) Larakai Bay, St. Vincent*

entitled "Pyroclastic volcanism and deposits of Cenozoic intermediate to felsic volcanic islands with implications for Precambrian greenstone belt volcanoes". Contributors were Ayres, Fisher, Self and Sigurdsson. The notes of the course cover many of the topics dealt with in this report. The most comprehensive account of the 1980 activity of Mt. St. Helens is U.S.G.S. Professional Paper 1250: "The 1980 eruptions of Mt. St. Helens, Washington".

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