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FOLDED CAULDRONS OF THE EARLY PROTEROZOIC LABINE GROUP, NORTHWESTERN CANADIAN SHIELD

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Abstract. Great Bear Magmatic Zone (1.875-1.84 Ga) is a linear belt, 100 km wide by 800 km long, of little metamorphosed volcanic rocks and allied plutons of calc-alkaline affinity. The entire zone was folded shortly after magmatism, and sections many kilometers thick through several cauldron complexes are exposed. Eruptions of rhyolite led to collapse of Black Bear Cauldron in which 1.5 km of tuff ponded. The cauldron then became the locus of fluvial and lacustrine sedimentation followed by augite-plagioclase porphyritic andesite volcanism, both of which also accumulated within the cauldron. Ash flow eruptions of dacite caused collapse of Clut Cauldron which was accompanied by landsliding and avalanching of the cauldron walls. Abundant andesitic and intrusive debris is intercalated with the propylitized intracauldron facies tuff adjacent to the walls and some blocks are as large as 1 km across. Clut Cauldron also became the site for fluvio-lacustrine sedimentation after collapse and was likely resurgent. Resurgence was probably related to the emplacement of a quartz monzonite pluton which occupies the core of the cauldron. Cornwall Cauldron, which is exposed entirely in cross section, contains 1-2 km of intracauldron facies tuff overlain by a complex of dacite lava flows. The cauldron was intruded by a granodiorite-monzogranite pluton probably responsible for resurgence. Data from the area suggest the following: (1) the similarity of early Proterozoic cauldrons to Cenozoic examples indicates that cauldron collapse is a process that has occurred since 1.9 Ga; (2) batholiths beneath ash flow tuff fields are probably composite bodies made up of many individual plutons; (3) most of the plutons are sheetlike in cross section; and (4) cauldron collapse begins as soon as ash flow eruptions, and relief on the cauldron margin becomes large early in the subsidence history.

Introduction

Ever since Williams (1941) published his classic work "Calderas and Their Origin," there has been intensive study of ash flow calderas and related volcanic rocks. This has come about because calderas are sites for economic mineralization (i.e., Creede, Summitville), potential sites for geothermal power (i.e., Valles, Long Valley), located in strategically important areas (i.e., Timber Mountain) and instructive as to the evolution of magmatic systems. Most of the studied calderas and cauldrons are nearly flat lying; their recognition in deformed terranes is more difficult. Thus geologists have speculated about the three-dimensional structure of calderas. For example, what is the nature and relationship to volcanism of magma chambers and resurgent plutons beneath calderas (see Thorpe and Francis, 1979; Lipman et al., 1981)? Are the magma chambers that erupt major ash flow sheets separate plutons, or do they represent cupolas above a batholith of regional extent as suggested by Steven and Lipman (1976)? Do ring complexes such as those found in the Coast Batholith of Peru (Bussell et al., 1976) represent the roots of ash flow calderas? If ring fractures marginal to calderas dip inward, by what mechanism is the room problem solved so that the central block is able to subside? These and many other problems might be resolved by careful study of deformed volcano-plutonic terranes.

This paper describes folded cauldrons located in the northwestern Canadian Shield. They are part of the LaBine Group which is a diverse succession of volcanic and sedimentary rocks that form part of the Great Bear Magmatic Zone, a 1.875-1.840 Ga continental magmatic arc (Hildebrand, 1982; Hildebrand and Bowring, 1984). Most of the rocks in the Great Bear Magmatic Zone are folded so that sections through the crust up to 10 km thick are exposed on individual fold limbs. This makes the area excellent for studying the major features found in calderas such as the topographic wall, structural margin, caldera floor and internal stratigraphy, as well as the more general relationships of plutonism to ash flow volcanism.

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Regional Geology

The LaBine Group is widely exposed in the western part of Wopmay Orogen, an early Proterozoic north trending orogen that developed on the western margin of the Archean Slave Craton between 2.1 and 1.8 Ga (Hoffman, 1973, 1980a). The orogen can be divided into three major tectonic elements whose boundaries parallel the trend of the belt as a whole. From east to west they are Coronation Margin, Great Bear Magmatic Zone, and Hottah Terrane.

Coronation Margin represents an early Proterozoic west facing passive continental margin (Grotzinger and Hoffman, 1983) and overlying foredeep that were imbricated and transported eastward toward the Slave Craton (Tirrul, 1983). In the western part of the belt, continental rise-prism rocks were metamorphosed and intruded by numerous syntectonic peraluminous plutons about 1.885 Ga (Bowring and Van Schmus, 1982).

The Hottah Terrane (Figure 1) forms the basement for much of the Great Bear Magmatic Zone. The terrane comprises deformed and metamorphosed sedimentary and volcanic rocks which are cut by a variety of deformed and undeformed intrusions. Ages of deformed plutons range from 1.914 to 1.90 Ga (Bowring and Van Schmus, 1982; Hildebrand et al., 1983). The supracrustal rocks are older but are of unknown age and provenance. Their metamorphic grade ranges to upper amphibolite facies (McGlynn, 1976; Hildebrand et al., 1983). Hottah Terrane is considered to be a microcontinent, exotic with respect to Coronation Margin and Slave Craton, beneath which attempted subduction of the leading edge of the Slave Craton took place (Hildebrand et al., 1983).

The 800-km-long by 100-km-wide Great Bear Magmatic Zone (Figure 1) comprises a multitude of granitoid plutons, mostly biotite and hornblende bearing, which intrude their own volcanic cover (Hoffman and McGlynn, 1977). It is generally separated

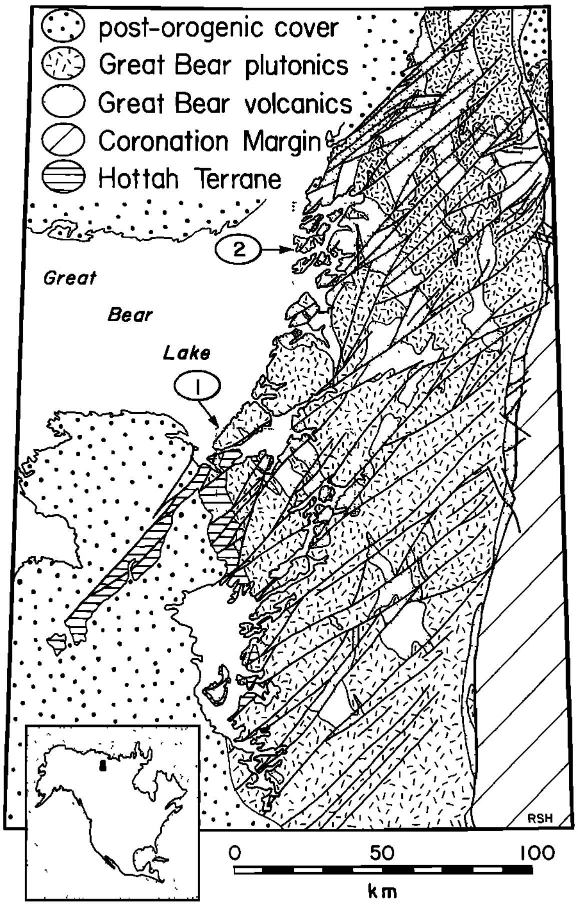

Fig. 1. Geological map of the northern part of the Great Bear Magmatic Zone showing the distribution of volcanic and plutonic rocks, the swarm of postmagmatic transcurrent faults, and the locations of Figures 2 (area 1) and 7 (area 2). This figure is based on field work by P. F. Hoffman (1972-1975), J. C. McGlynn (1973-1975), R. S. Hildebrand (1977-1983), and S. A. Bowring (1980-1983).

from Coronation Margin by a major strike-slip fault, but rocks of the Great Bear Magmatic Zone locally overstep the fault zone and lie unconformably on deformed basement to Coronation Margin. Rocks in the extreme western part of the magmatic zone unconformably overlie polydeformed and metamorphosed rocks of the Hottah Terrane (Hildebrand, 1981).

All of the nonplutonic rocks in the Great Bear Magmatic Zone were termed the McTavish Supergroup by Hoffman (1978, 1982). The supergroup is divided into three groups separated by unconformities: the LaBine Group, Sloan Group, and Dumas Group in ascending order (Hoffman, 1978).

The LaBine Group, of which the three cauldrons described here are a part, is a diverse aggregation, up to 7 km thick, of siliceous to intermediate lava flows, pyroclastic rocks, and associated sedimentary rocks (Hoffman and McGlynn, 1977; Hildebrand, 1981, 1984). This group crops out only along the western margin of the volcano-plutonic belt where it unconformably overlies the Hottah Terrane (McGlynn, 1976; Hildebrand, 1981). U-Pb ages of the group are about 1.87 Ga (Bowring and Van Schmus, 1982).

The LaBine Group is disconformably overlain by the Sloan Group, which consists mostly of thick sequences of densely welded intermediate ash flow tuff and intermediate to mafic lava flows (Hoffman and McGlynn, 1977; Bowring, 1982). Outcrops of the Sloan Group are confined to the central portion of the Great Bear Magmatic Zone. To the east the Sloan Group is unconformably overlain by the Dumas Group, which also lies unconformably on deformed basement to the Coronation Margin. The Dumas Group is a sequence of mudstone, intermediate to siliceous ash flow tuff, and intermediate to mafic lava flows cut by myriads of porphyritic dykes (Bowring, 1982).

Plutonic rocks of the Great Bear Magmatic Zone are mainly hornblende and biotite bearing. On the basis of field relations, they have been roughly divided into four age suites (G_1-G_4: Hoffman and McGlynn (1977); Hoffman (1978)), each with similar compositions. The oldest are sheets and laccoliths of quartz diorite and monzodiorite-monzonite (G_1), informally termed the "early intermediate intrusive suite" (Hildebrand, 1984). They intrude piles of andesite in the LaBine Group. These plutons were generally followed by emplacement of dome-shaped biotite-hornblende quartz monzonite plutons (G_2), some of which are synvolcanic (Hildebrand, 1981). Large discordant biotite granites (G_3), without known extrusive equivalents, were intruded after eruption of the Dumas Group and after the belt was folded. The final plutons to be emplaced were a suite of small, ovoid tonalite to diorite bodies (G_4) found sporadically throughout eastern parts of the zone. U-Pb zircon ages in the belt range from 1.876 to 1.84 Ga (Bowring and Van Schmus, 1982).

All the rocks of the Great Bear Magmatic Zone, except the G_3-G_4 plutons and swarms of siliceous porphyritic dykes, are folded about shallowly plunging axes that trend northwest, except near the extreme eastern and western margins of the belt where they trend north. The folds are en echelon, which led Hoffman (1980a) and Hildebrand (1981) to suggest that they are the product of oblique convergence.

The folds, and even the youngest plutons (G_4) of the magmatic zone, are cut by a swarm of northeast trending transcurrent faults (used in the sense of Freund (1974). Most of these faults are steeply dipping and have right-lateral separation of the order of kilometers. They are part of a larger set of conjugate transcurrent faults found throughout Wopmay Orogen (Hoffman, 1980b).

Cauldrons of the LaBine Group

The LaBine Group is thought to contain parts of at least six cauldrons (Hildebrand, 1981, 1984). This paper discusses only three: Black Bear, Clut, and Cornwall cauldrons. Black Bear and Clut cauldrons are located in the Camsell River-Conjuror Bay area (area 1, Figure 1), and Cornwall Cauldron is found to the north on islands in Great Bear Lake (area 2, Figure 1). The stratigraphy in the two areas is different, and they are separated from one another by major transcurrent faults and younger granitoid plutons; the exact relations between the two are uncertain. Nevertheless, U-Pb zircon ages (S. A. Bowring and W. R. Van Schmus, unpublished data, 1983) indicate that volcanism in both areas was closely contemporaneous.

Black Bear Cauldron

Black Bear Cauldron is the oldest collapse structure known in the Great Bear Magmatic Zone. The cauldron formed upon an older pile of tholeiitic pillow basalts (Bloom Basalt) and marine sedimentary rocks (Conjuror

Bay Formation). These rocks had been uplifted and eroded prior to ash flow eruptions, but the erosion surface is not well enough exposed to discern its nature. Only one major ash flow sheet, Moose Bay Tuff, is known to have been erupted from Black Bear Cauldron, and it ponded to thicknesses in excess of 1 km within the cauldron. The topographic depression remaining after ash flow volcanism ended was filled by fluvio-lacustrine sedimentary rocks of the Terra Formation and intermediate lava flows and breccias, collectively termed the Camsell River Formation. A partial cross section of the cauldron is exposed on the south limb of a regional syncline (Norex syncline; Figure 2) and both the structural and topographic margins are well exposed.

Moose Bay Tuff: an intracauldron ash flow tuff. Subsidence of the Black Bear Cauldron probably began with small-volume ash flow eruptions belonging to the lower member of the Moose Bay Tuff. The tuffs are mostly lithic rich and grade into polymictic breccias containing blocks up to 30 m across in a tuffaceous matrix. Some of the larger blocks are themselves brecciated, suggesting that they have fallen into place. The breccias are interpreted as evidence that at least some increment of subsidence took place concurrent with the initial ash flow eruptions. Between eruptions, some of the low-lying areas were the sites of local lakes or ponds in which finely laminated muds accumulated.

Voluminous rhyolitic ash flow eruptions led to catastrophic collapse of Black Bear Cauldron, and densely welded, lithic-rich Moose Bay Tuff accumulated to about 1.5 km within the cauldron. Generally, the ash flows were deposited so quickly that they welded together without visible partings. Locally, however, the tuff shows characteristics of compound cooling such as interfingering relationships with sandstone, breccias, and intermediate-mafic extrusive rocks (Hildebrand, 1983b). All known exposures of the tuff are intracauldron facies.

The tuff directly overlies precauldron Bloom Basalt northwest of a transcurrent fault that passes from the west side of Moose Bay out into Conjuror Bay (Figure 2) and it thins rapidly to the west until it pinches out. East of the fault the upper part of the tuff is intercalated with 0.5 km of intermediate lava flows, breccia, and lapilli tuff which thin rapidly to the east, so that they are not present in sections 1 km to the east. Beneath the lavas are a few broad channels filled with interbedded airfall tuff, ash flow tuff, and sandstone.

Lithic fragments are abundant in the tuff, locally making up to 50% of the rock. They are generally porphyritic siliceous volcanic rocks, but fragments of metamorphic rock are also common. The average size of lithic fragments decreases upsection from cobbles to pebbles to granules. Large blocks of dacite welded tuff, up to 15 km across, occur near the base of the unit. The upper parts of the tuff are characterized by small (2 cm) flattened pumice fragments, often green to black. In stratigraphically lower parts of the tuff they are not commonly preserved owing to propylitic alteration and recrystallization. The ash flow tuff contains 4-10% broken and embayed quartz phenocrysts (to 3 mm) along with 10-15% shattered 1- to 2-mm phenocrysts of turbid microperthite, probably after sanidine, and tiny anhedral flakes of chloritized biotite in an ultrafine grained groundmass of quartz, feldspar, and sericite.

The tremendous thickness of the Moose Bay Tuff indicates that the tuff ponded within a topographic depression. The dramatic thickness change of the tuff across the transcurrent fault which passes along the western side of Moose Bay suggests that the depression was fault bounded on the west. The disparity in thickness of the tuff across the fault and the presence of coarse breccias intercalated with the earliest eruptions of ash flow tuff suggest that the fault was active as soon as pyroclastic eruptions began and continued to be active throughout ash flow volcanism. This interpretation implies that the fault was later reactivated during transcurrent faulting because it presently separates stratigraphic units younger than the Moose Bay Tuff.

Similar stratigraphic and structural relations are typically found in Cenozoic calderas (Steven and Lipman, 1973, 1976; Lambert, 1974; Lipman, 1975; Bailey et al., 1976; Bailey and Koeppen, 1977; Smith et al., 1970; Byers et al., 1976; Seager, 1973; Elston et al., 1976). Therefore the synvolcanic fault is interpreted to be the main ring fault along which subsidence of the central block of the cauldron took place. The rapid thinning and pinchout of the tuff along the unconformity with older rocks is a buttress unconformity that probably represents the original topographic wall of the cauldron, created as material collapsed from the oversteepened structural margin (Figure 3).

Both the topographic margin and the floor of the cauldron were intruded by a distinctive potassium feldspar-quartz-plagioclase porphyry (Figure 2). The porphyry may appear to be a ring pluton but is considered unrelated to Black Bear Cauldron because it intrudes units much younger than Moose Bay Tuff (see Figure 2). This indicates the need for exercising extreme caution when interpreting ring-shaped plutons in deeply eroded complexes where stratigraphic control is lacking.

Normal and reverse faults located just inside the ring fracture south of Moose Bay (Figure 2) are possibly related to differential subsidence of the central block during collapse. Interestingly, at least two of the fault blocks (Figure 2) appear to have remained high during the faulting. This suggests that an alternative mechanism to marginal tilting (Lipman, this issue) for decreasing the size of the central block subsiding along a ring fault whose radius is decreasing downward, might be to leave large slivers remaining in the cauldron fill deposits (Figure 4). Ultimately, many of the slivers may end up forming megabreccia zones within the cauldron.

Terra Formation: post-collapse fluvio-lacustrine deposits. The Terra Formation comprises up to 200 m of sedimentary and volcanic rocks interpreted as postcollapse fill of the Black Bear Cauldron (Hildebrand, 1984). The formation is exposed only on the southwest limb of Norex syncline from Clut Lake to Conjuror Bay (Figure 2), and it pinches out abruptly at the proposed cauldron margin fault of Black Bear Cauldron (Figure 3). Rapid lateral facies changes are characteristic of the formation as a whole, but in general the lower half is a varied assemblage of mudstone, breccia, limy argillite, and rhyolitic tuff beds; lithic arkose generally dominates the upper half of the formation. The first postsubsidence lava flows within Black Bear Cauldron also occur within the formation and are stubby, aphyric lava flows of rhyolitic composition.

The mudstones are generally finely laminated rocks intercalated with siliceous tuff beds ranging in thickness from a few centimeters to half a meter. Most are composed of ash size material with broken

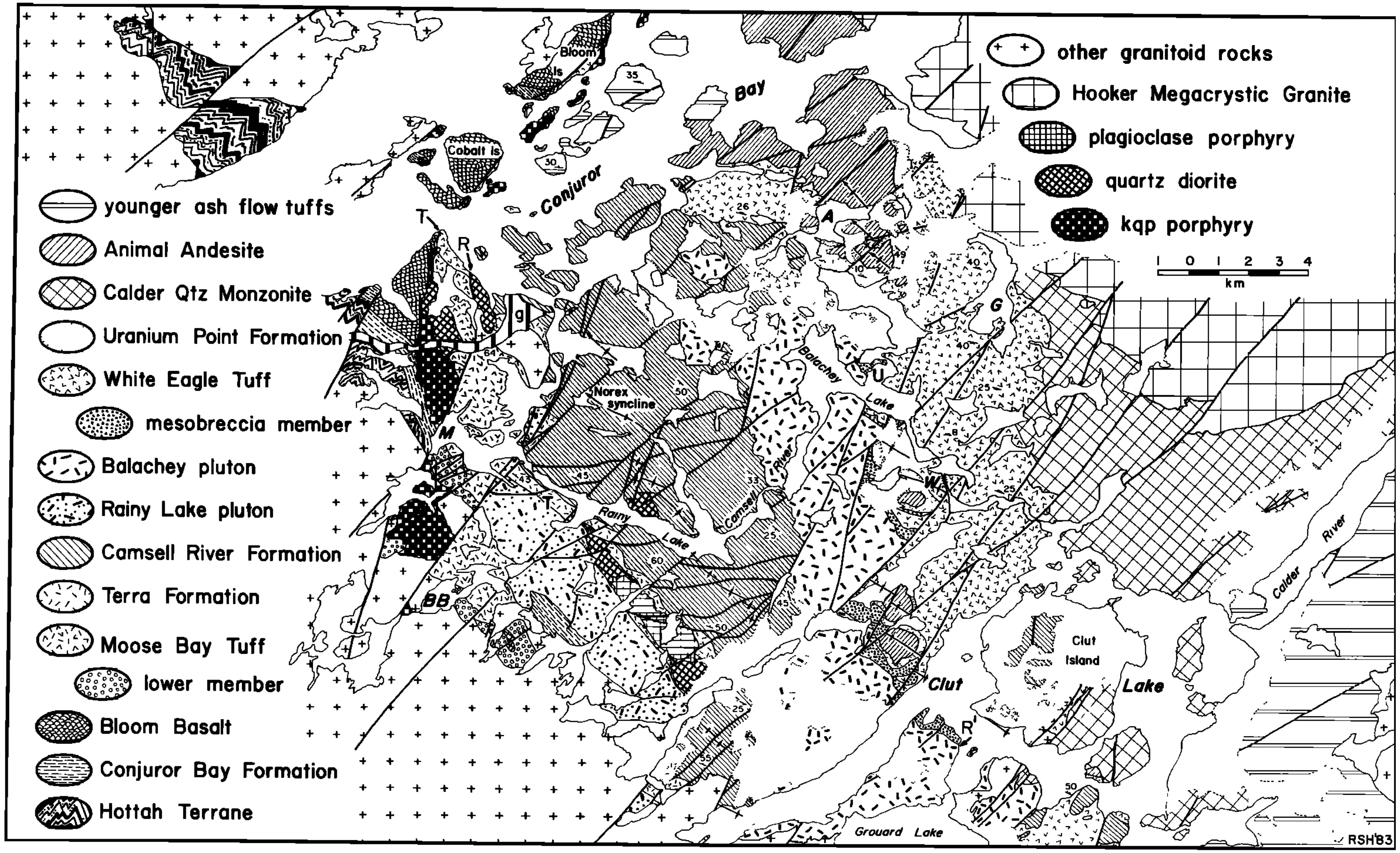

Fig. 2. Geological map of the Camsell River-Conjuror Bay area. T and R refer to topographic and structural margins of Black Bear Cauldron; R1, structural margin of Clut Cauldron; g, postfaulting Gunbarrel Gabbro; A, Animal Lake; BB, Black Bear Lake; G, Ghosty Lake; U, Uranium Point; W, White Eagle Falls.

microphenocrysts of quartz and potassium feldspar, however, normal and reverse size-graded beds of lapilli tuff occur locally. About 20 m of interbedded carbonate and argillite occur in the middle of the formation in a few places. Laminations are crinkly, somewhat irregular in thickness, and average about 1 cm thick. Intercalated with these are beds and lenses of pink weathering rhyolitic tuff, up to 0.5 m thick, and 0.3 m thick beds of fine grained sandstone and crystal tuff, both typically graded. Directly overlying the limy argillite-rhyolite tuff sequence are lenticular beds of completely unsorted breccia. They are thickest (15 m) and most abundant in the northwest, that is, toward the structural margin of the cauldron. Typically, they are clast-supported aggregates containing angular to subrounded fragments, up to 4 m across, of limy argillite-rhyolitic tuff in a dark silty matrix.

The sandstones which dominate the upper half of the formation are mostly volcanogenic, immature, granular to pebbly, and fine to coarse grained. Commonly, there are interbeds, ripups, and drapes of mudstone. Beds of sandstone are lenticular and mostly less than 1 m thick. Sedimentary structures include trough and planar cross-bedding, current ripples, and, where interbedded with mudstone, load features. In places there are paleochannels filled with clast-supported conglomerate comprising rounded to subrounded pebbles and cobbles of chert, andesite, silicified mudstone, siliceous porphyry, and vein quartz in an arkosic matrix containing up to 5% hematite grains. Beds of lithic pebbly sandstone locally contain abundant rhyolitic fragments.

The fine-grained and thinly laminated nature of the lower part of the Terra Formation and interbedded limy argillite-rhyolitic tuff beds, without scours and current structures, indicate that deposition was in relatively quiet water. The rapid lateral facies changes of the formation, its local distribution, and the presence of subaerial units both directly above and below the unit suggest that the formation is nonmarine and probably lacustrine. The upper lithic arkose, with its abundant current-generated structures, conglomeratic lenses and channels, is interpreted to be of fluvial origin.

Because the Terra Formation directly overlies intracauldron facies Moose Bay Tuff and pinches out abruptly at the possible cauldron margin fault northwest of Moose Bay, it is interpreted to have accumulated within the topographic depression of Black Bear Cauldron. Lakes have developed inside most calderas following collapse, and younger examples include the giant Toba caldera (Van Bemmelen, 1949), Creede caldera (Steven and Ratté, 1973), the Kari Kari caldera (Francis et al., 1981), and Kutcharo caldera (Katsui et al., 1975).

The coarse, locally derived breccias of limy argillite-rhyolite indicate that local areas were subject to syndepositional uplift and erosion. The coarse nature of the breccia suggests sudden, significant relief and may have been the result of additional collapse of the central block of the caldera. The fact that the breccia tongues thicken and become more abundant toward the structural margin supports this interpretation.

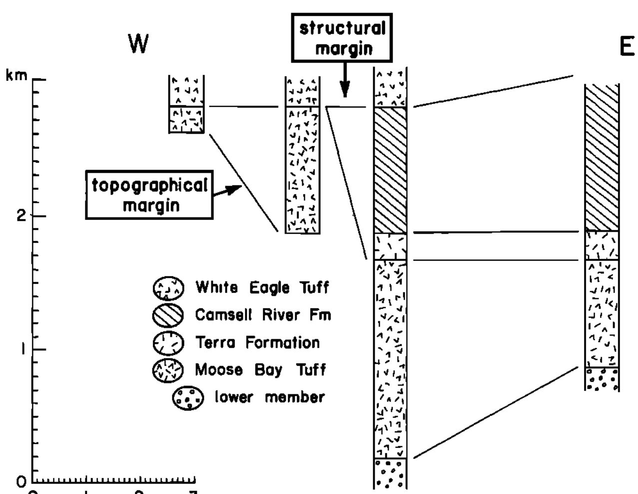

Fig. 3. Stratigraphic sections illustrating thickness variations and abrupt pinch-out of intracauldron fill of the Black Bear Cauldron.

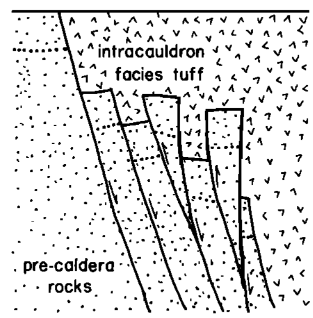

Fig. 4. Diagram illustrating model for cauldron subsidence along an inwardly dipping ring fracture system. In this model the central block of the cauldron behaves as a rigid block and the "room problem" is solved by leaving large slivers of wall rock hanging in the cauldron fill.

Camsell River Formation: post-collapse intermediate volcanism. The Camsell River Formation is a 2-km-thick assemblage of intercalated andesitic to dacitic lava flows, laharic breccia, explosion breccia, andesitic ash flow tuff, sandstone, conglomerate, lapilli tuff, and mudstone that accumulated within Black Bear Cauldron after collapse. Like the Terra Formation, it is not present in sections west of the structural margin of the Black Bear Cauldron (Figure 3).

Andesitic to dacitic lava flows of the Camsell River Formation are characterized by abundant large platy plagioclase phenocrysts that are typically flow aligned. Individual flows are generally 10 to 30 m thick. They are commonly columnar jointed above platy jointed bases, but many flows have autobrecciated margins.

Andesitic ash flow tuffs of the Camsell River Formation are generally less than 10 m thick. They are found at many horizons in the formation, are very discontinuous along strike, and appear to fill paleovalleys. The tuffs are most common in the southeast and generally thin to the northwest.

Laharic breccias are rare in the Camsell River Formation, but where found are generally dominated by andesitic fragments, many of which are larger than 1 m in diameter. Other breccias found in the Camsell River Formation are composed of angular andesitic fragments of various sizes in a fine-grained microbrecciated matrix of similar andesitic material. The breccias are interpreted to be Vulcanian explosion breccias.

Tuff, sandstone, and conglomerate are intimately intercalated and grade into one another laterally. Bedded tuffs range from thin laminations to a few centimeters thick. They occur as normally and reversely graded beds, some with razor sharp contacts and others with gradational contacts. Some beds contain sparse lapilli-size fragments of andesite. Most are strongly altered and contain abundant disseminated sulphides (locally up to 25%). Sandstones and conglomerates are more common in the Camsell River Formation than bedded tuffs. Most contain andesitic debris in beds ranging in thickness from thin laminations to several meters.

Associated with and intruding the Camsell River Formation are two interesting plutons: the Rainy Lake and Balachey Intrusive complexes (Figure 2). They are compositionally and mineralogically zoned sheetlike epizonal plutons which are compositionally and temporally related to the Camsell River Formation (Hildebrand, 1984).

The abundance of lava flows and explosion breccias in the Camsell River Formation is typical of near source facies of intermediate composition stratovolcanoes. However, as no vent regions or feeder dykes were observed and because a large amount of epiclastic material is intercalated with the volcanic rocks, it is most likely that the formation represents material deposited on the flanks of a volcano, perhaps in an environment similar to the large fluvio-volcanic fans of the Peusangan Valley or Mount Talang, Sumatra (Verstappen, 1973).

The occurrence of the formation above cauldron fill deposits, along with its abrupt pinch-out at the proposed cauldron-margin fault, indicates that the formation accumulated within the Black Bear Cauldron after collapse. Postcollapse andesitic volcanism is known from several younger cauldrons. For example, postcollapse andesitic lavas and breccias fill both the Oligocene Platoro and Summitville calderas in the San Juan volcanic field of southwestern Colorado (Lipman, 1975); andesitic stratovolcanoes Atosanupuru and Masu formed after collapse of, and partially fill, the 7 m.y. old Kutcharo caldera, east Hokkaido (Katsui, 1955; Katsui et al., 1975); and four calderas of Kyushu, Japan (Aso, Aira, Ibusuki, and Kikai), each contain stratovolcanoes of pyroxene andesite (Matumoto, 1943).

In most of the cases cited above there appears to be a compositional continuum between the ash flow tuffs, which are mostly dacitic in composition, and the postcollapse andesitic lavas. For this reason, Lipman (1975) suggested that postcollapse andesites represent the lower parts of the same magma chambers from which the ash flow tuffs were derived. However, there is a large compositional gap between andesites of the Camsell River Formation and the rhyolitic Moose Bay Tuff, and no textures indicative of magma mixing were found either in the field or in thin section. Furthermore, plutons such as the Rainy Lake and Balachey plutons are the type of plutons envisaged to have erupted the andesites and, since they are not known to have vented at the surface (Hildebrand, 1984), should preserve compositional zoning if it was present. The plutons are compositionally zoned, but from andesitic to dacitic compositions, not rhyolite, and characteristically they contain only 5-10% interstitial quartz, never present as phenocrysts. Therefore the andesites of the Camsell River Formation are thought to represent a different batch of magma than that which erupted the Moose Bay Tuff.

Although the original extent of the Black Bear Cauldron is unknown, the lack of eruptive vents for the andesites and the probable nongenetic relationship between them and the tuff suggest that the eruptive center may have been outside the cauldron and that the lavas spilled into the topographic depression remaining after collapse.

Clut Cauldron

Collapse of Clut Cauldron followed the emplacement and crystallization of the Rainy Lake and Balachey Intrusive complexes and was caused by ash flow eruptions that produced the White Eagle Tuff. The cauldron is broadly folded, and only about 90 degrees of arc along the southwest part of the complex is preserved. The structural margin is exceptionally well exposed, and interleaved ash flows, chaotic rubble of older rocks, and enormous landslide blocks indicate collapse and rapid filling of the cauldron during ash flow eruptions. Following subsidence related to the eruptions, the topographic depression became the site for local ponds and lakes in which epiclastic and pyroclastic debris of the Uranium Point Formation accumulated as rivers drained adjoining highlands. The oldest known postcollapse lavas overlie the fluvio-lacustrine deposits and are andesitic lavas, breccias, and tuff, collectively termed Animal Andesite (Hildebrand, 1983b). All of the intracauldron deposits were uplifted, or resurgently domed, during intrusion of the Calder Quartz Monzonite, which is a medium-grained, seriate-textured pluton emplaced more or less in the central part of the cauldron.

White Eagle Tuff: cauldron forming ash flow tuff. The White Eagle Tuff is a densely welded ash flow sheet and associated breccias (Hildebrand, 1984). It generally lies unconformably on the Camsell River Formation, but on the mainland south of Conjuror Bay it lies on Moose Bay Tuff (Figures 2 and 3). No complete section of the intracauldron tuff is exposed, but continuous sections on fold limbs are in excess of 1.5 km thick.

The bulk of the White Eagle Tuff is a composite ash flow sheet, composed of densely welded and devitrified ash flows ranging in composition from dacitic near the base of the sheet to andesitic near the top (Hildebrand, 1982). Partially welded tuff is present only at the top and bottom of the unit in thinner preserved sections of outflow facies tuff west of Balachey Lake.

Exposures of ash flow tuff at the southeast end of Clut Lake contain altered and fractured blocks of Camsell River Formation up to 1 km in diameter and a few blocks of Balachey Pluton ranging up to 100 m across. Several large blocks with brecciated margins have many smaller fragments of the same rock type around them. In a crude way the size of the blocks becomes larger in stratigraphically higher sections of the tuff (Hildebrand, 1983b). Elsewhere the tuff generally contains up to 10-20% lithic fragments. Broken phenocrysts of plagioclase, amphibole, biotite, and quartz along with subhedral to euhedral microphenocrysts of magnetite typically make up 25-35% of the rock. In general, the phenocrysts are less than 3 mm in diameter, but a few are as large as 5 mm. Propylitic assemblages are characteristic of all thick sections. In stratigraphically deeper levels of exposure the tuff contains 1-2% quartz, whereas quartz is generally very sparse, if present at all, in the upper parts.

Pumice, typically highly flattened, is present in nearly all exposures but in some thick sections is partially obscured by welding, devitrification, and/or postdepositional alteration. In sections of outflow facies tuff west of Balachey Lake and in the Conjuror Bay area, black fiamme 10-15 cm in diameter and 1 cm thick are very conspicuous.

Mesobreccia member. The informal term mesobreccia member is applied to the thick local

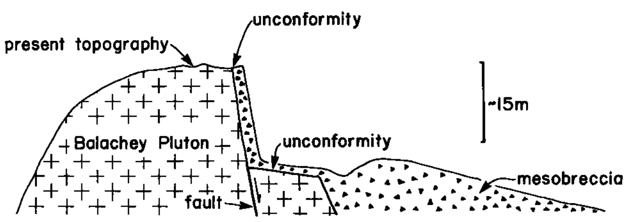

Fig. 5. Cross section of outcrop at Uranium Point illustrating steplike nature of unconformity at Clut Cauldron Margin.

assemblage of breccias along the northeastern margin of the Balachey Pluton (Figure 2). The mesobreccia member interfingers with the ash flow tuff and in many places is gradational with it. In the field the units were mapped on the basis of matrix type. That is, if the matrix was muddy or silty, it was mapped as mesobreccia, but if it was tuffaceous, it was assigned to the ash flow tuff. The stratigraphically lowest part of the breccia is not exposed but presumably it rests on Camsell River Formation, as does the ash flow tuff. The breccia is overlain by the Uranium Point Formation. The unconformity with the Balachey Pluton is mostly subvertical, but locally is roughly horizontal so that the contact is steplike in cross section (Figure 5) and the mesobreccia occurs as wedges that thin away from the unconformity

The mesobreccia is generally an unsorted mixture of clasts (1 cm to 2 m in diameter) and matrix, in places clast supported and in others matrix supported. The breccia is poorly bedded and typically massive (Figure 6), but in places there are graded beds and discrete zones which contain only pebbles and blocks of Balachey Pluton. The dip of these units is presently less than 15° to the northeast.

The clast population varies considerably from place to place. Generally, exposures closer to the Balachey Pluton contain a higher proportion of Balachey Pluton clasts than do those farther from the contact. The other most common clast types are altered fragments of Camsell River Formation. Clast shapes span the entire range from rectangular to spheroid, and both extremes are commonly found adjacent to one another in the same breccia tongues. Some Balachey clasts are nearly perfect quadrilaterals, suggesting that they are still bounded by original joint surfaces.

The abrupt pinch-out of tremendously thick sections of the tuff, coupled with the zones of megabreccia, indicates that most exposures of the White Eagle Tuff represent intracauldron facies tuff. The thin simple cooling units exposed south and west of Animal Lake and in the Conjuror Bay area are not propylitized, contain abundant pumice, and have unwelded or poorly

Fig. 6. Photograph of mesobreccia at Uranium Point. The breccia at this locality is a thin veneer about a meter thick in contact with the Balachey Pluton along a nearly vertical buttress unconformity that is parallel to the plane of the photograph. Note person for scale. Geological Survey of Canada photo 204112.

welded bases. They are interpreted as remnants of the outflow sheet.

The enormous blocks of Camsell River Formation and Balachey Pluton that occur in the tuff south of Clut Lake probably represent material which spalled from the steep cauldron wall during collapse of the cauldron. This, along with the order of magnitude thickness difference between the intracauldron and outflow facies tuff, clearly demonstrates that subsidence occurred simultaneously with ash flow eruptions. The crude inverse grading of blocks may indicate that relief on the wall increased with time. This suggests that ash flow volcanism was not able to keep pace with subsidence or that large volumes of vitric ash were removed from the area by high-level atmospheric transport (see Hildebrand and Bowring, 1984).

The northeastward thinning of the mesobreccia member, coupled with the nearly ubiquitous clasts of Balachey Pluton which become more common toward the intrusion, indicates that the breccia was derived from the southwest. The interfingering relationships of the breccia with the White Eagle Tuff indicate that deposition of the breccia went on contemporaneously with eruption and deposition of the tuff.

As mentioned earlier, the unconformity between the breccia and the Balachey Pluton is presently a nearly vertical buttress facing northeast. When the shallow northeastward dips of the breccia are returned to a horizontal position, the unconformity still dips steeply to the northeast, indicating that the contact remained as a steep scarp during deposition of both the breccia and the White Eagle Tuff.

The above relations are interpreted to indicate that the mesobreccia represents material shed from the southwest wall of Clut Cauldron during collapse of the central block of the cauldron. Similar deposits have been described in Tertiary cauldrons by several workers (Lipman, 1976; Ratté and Steven, 1967; Lambert, 1974).

Uranium Point Formation: postsubsidence fluvio-lacustrine cauldron fill deposits. This formation, dominantly composed of interbedded sandstone, siltstone, mudstone, and pyroclastic rocks, conformably overlies both the mesobreccia and intracauldron facies White Eagle Tuff. The Uranium Point Formation outcrops northeast of the Balachey Pluton (Figure 2) and is a maximum of 80 m thick. It is not present outside Clut Cauldron.

Beds of sandstone-siltstone range in thickness up to 1 m and are composed of angular to subangular volcanic debris. They are generally planar bedded, but locally ripple drift and low-angle cross lamination are present. Siltstones and sandstones are commonly draped with laminations of purplish mudstone. Convolutions are common where there is abundant mudstone. Beds of mudstone range from paper thin laminations to 15 mm thick and are typically continuous on an outcrop scale. Some of the sandstones are pebbly, with a wide variety of typically subrounded to angular volcanic clasts of unknown provenance. Angular chips and flat pebbles of carbonate are common in some beds.

Commonly interbedded with the clastic deposits, especially in the northwest, are crystal and lapilli tuff. These beds are laterally continuous and average about 15 cm thick. Whereas most are probably of airfall origin, some are cross-bedded and rippled, indicating that they were reworked. At the northwest end of Balachey Lake the top of the formation contains ash flow tuff with well-developed eutaxitic structure. The tuff is a simple cooling unit about 30 m thick and is extremely lithic rich, containing about 50% aphanitic volcanic rock chips.

Two common features of the finer units, both clastic and pyroclastic, are the occurrence of synsedimentary normal faults and slump folds . Measurements of both features indicate that slumping was toward the southwest, that is, toward the structural margin of Clut Cauldron (Hildebrand, 1984).

The abundance of fine clastic detritus, coupled with the general lack of current structures, suggests that Uranium Point Formation was deposited in relatively quiet water. The stratigraphic position of the unit above and below subaerial units and its local distribution make a marine origin unlikely; a lacustrine environment is probable. Minor fluvial deposits are represented by cross-bedded, rippled, and pebbly units.

The presence of the formation only inside Clut Cauldron suggests that local ponds and lakes developed in the topographic depression remaining after collapse of the cauldron. Volcanic eruptions from unknown sources periodically deposited pyroclastic units within the lakes. The southwest directed slumping and synsedimentary normal faulting suggest that the central part of the cauldron was uplifted during or shortly after deposition of the Uranium Point Formation. This uplift or resurgence is thought to be related to the emplacement of the Calder Quartz Monzonite more or less in the central parts of Clut Cauldron.

Postcollapse lavas. Andesitic lava flows, breccia and tuff, collectively named Animal Andesite, are the only lavas of the area known to postdate collapse of Clut Cauldron. The lavas are dark, aphanitic to porphyritic rocks containing variable proportions of plagioclase, augite, and pargasite. Many flows contain strongly resorbed quartz xenocrysts ubiquitously armored by coronas of augite (Hildebrand, 1982). Animal Andesite occurs both inside and outside the cauldron, which may indicate that vents were located in both areas or perhaps that there was little relief on the cauldron margin during eruption of the andesites.

The most siliceous samples of Animal Andesite contain similar amounts of SiO_2 as the least siliceous samples of White Eagle Tuff, which suggests that the two were erupted from the same compositionally zoned magma chamber. However, the lavas contain significantly greater amounts of Rb, Zr, and Ba than the tuff (Hildebrand, 1982). This makes it unlikely that the two formations are genetically related by mixing, crystal fractionation of observed phases, or assimilation of quartz and potassium feldspar, inasmuch as none of those mechanisms can increase Rb, Zr and Ba downward in a magma chamber and maintain the same SiO_2 value. Thermogravitational diffusion (Hildreth, 1979) could reproduce most of the observed chemical variations, but further study is needed.

Calder Quartz Monzonite: a resurgent pluton. Hornblende-biotite quartz monzonite and minor monzogranite are exposed in a 100 km^2 wedge-shaped area extending west from the Calder River to Ghosty Lake and south at least as far as Grouard Lake. The unit was named Calder Quartz Monzonite after its exposures west of the Calder River (Hildebrand, 1984).

The southwestern contact of the body is intrusive, cuts only the White Eagle Tuff, and roughly parallels the southwestern margin of Clut Cauldron at a distance of about 8 km. The original extent of the pluton to the north-northeast is unknown because it was intruded by the Hooker Megacrystic Granite (Figure 2).

Seriate quartz monzonite is characteristic of the unit. Subhedral tablets of plagioclase (to 5 mm) are surrounded by potassium feldspar, quartz, and ferromagnesian minerals. Commonly, the plagioclase forms glomeroporphyritic clots containing from three

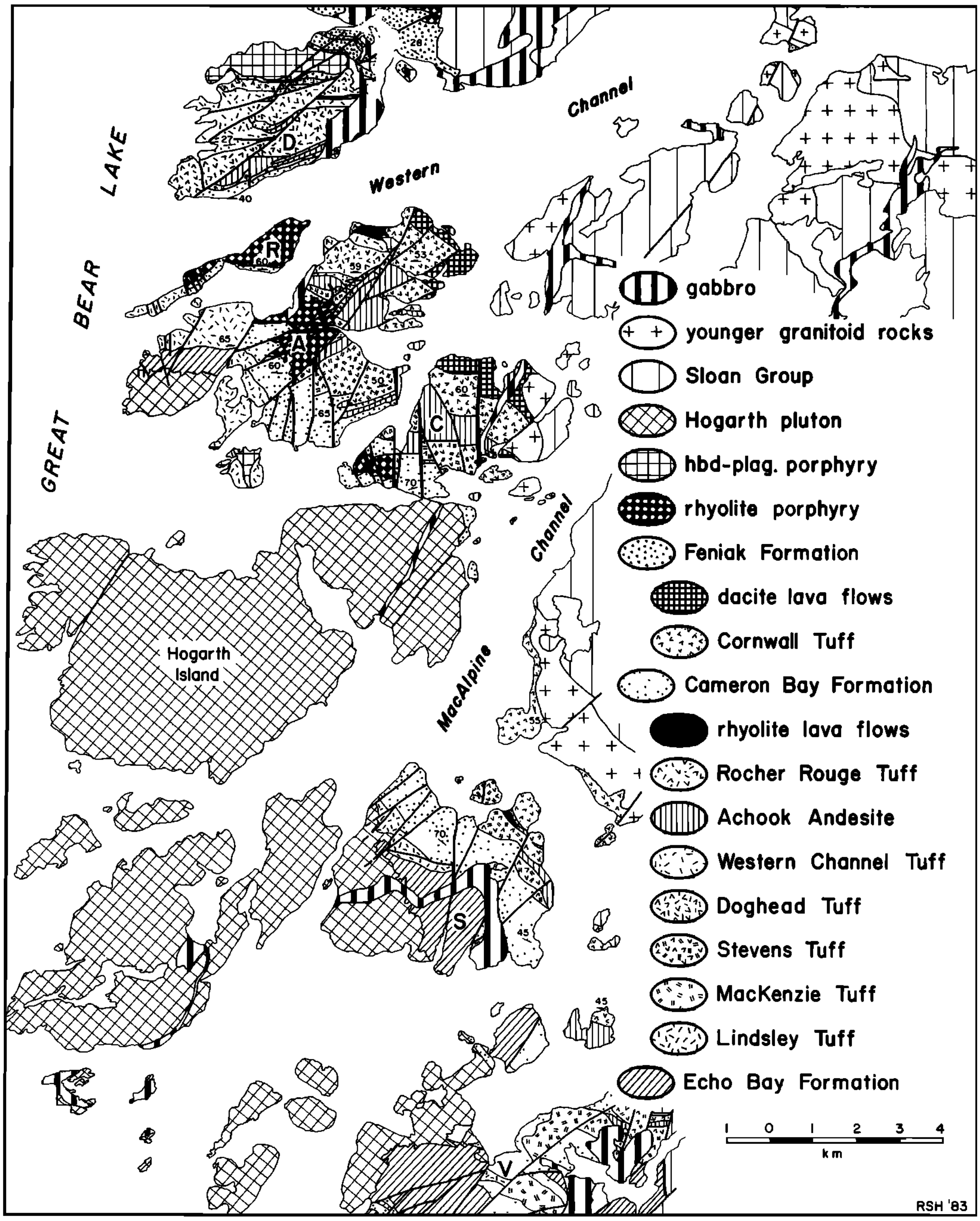

Fig. 7. Geological map of islands in northeastern Great Bear Lake. A, Achook Island; C, Cornwall Island; D, Doghead Point; S, Stevens Island; V, Vance Peninsula.

to six crystals. Biotite is always more common than hornblende, with the combined total ranging from 8% to 15% of the rock. Both often form clots.

Xenoliths of volcanic rocks are generally sparse, but where they do occur they are typically less than 0.5 m across and strongly altered. Compositionally, the Calder Quartz Monzonite is very similar to the White Eagle Tuff (Hildebrand, 1982), although exact matching is ruled out owing to loss of vitric ash during eruption, posteruptive alteration, and alteration of the pluton resulting from interaction with groundwater during cooling.

The compositional similarity of the Calder Quartz Monzonite to the White Eagle Tuff and the fact that the southwest contact of the pluton parallels the margin of Clut Cauldron suggest that it may be a subcauldron pluton. The emplacement of the pluton might then be responsible for the doming or resurgence of the central part of the cauldron suggested by the direction of slumping in the Uranium Point Formation.

Cornwall Cauldron

This cauldron is exposed in cross section as part of a steeply dipping, north facing homocline located on islands along the eastern shore of Great Bear Lake (Figures 1 and 7). It developed from catastrophic ash flow eruptions that cooled to form Cornwall Tuff. The cauldron is particularly interesting because it was intruded by a pluton with a domical roof that uplifted the central parts of the cauldron after collapse.

Cornwall Tuff. Cornwall Tuff is a nonwelded to

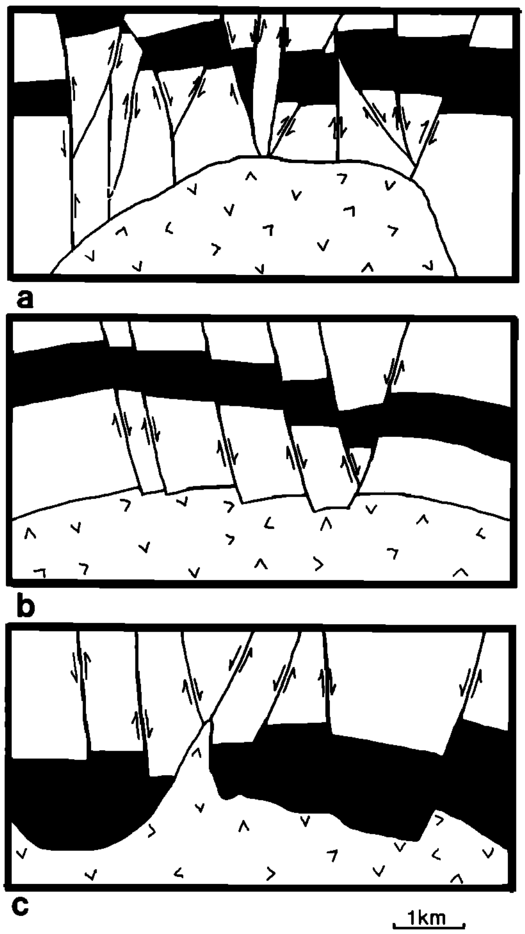

Fig. 8. Comparison of cross sections through the central portions of three large resurgent cauldrons. An arbitrary stratigraphic unit in each has been blackened to show the general doming of rocks above the plutons and the development of the central grabens. (a) map view of the Cornwall Cauldron Complex, (b) Interpretive cross section of Valles caldera (Smith et al., 1970), (c) Interpretive cross section through Timber Mountain caldera (Byers et al., 1976).

densely welded composite ash flow sheet containing 5-15% altered plagioclase, hornblende, quartz, and potassium feldspar phenocrysts. Intracauldron facies tuff is generally greater than 1 km thick and locally could be as thick as 1.8 km (Hildebrand, 1981). It is strongly altered, and major element chemistry shows it to be intensely potassium metasomatized. Locally, the thick sections contain a 4-m-thick, probably lacustrine, stromatolitic dolomite bed, which suggests that the tuff is composed of at least two cooling units. The only exposures of outflow facies tuff occur on Doghead Point (Figure 7) where the Cornwall Tuff consists of three, or possibly four, thin (15 m) cooling units intercalated with a thin sequence of diverse epiclastic rocks.

A 1-km-thick complex of postcollapse dacitic lava flows overlies many of the thick sections of Cornwall Tuff. The lavas are generally highly altered, but where alteration is low are plagioclase porphyritic and locally flowbanded.

Hogarth Pluton. The Hogarth Pluton intrudes volcanic and sedimentary rocks of the LaBine Group and is folded along with them (Hildebrand, 1983a). In its northern exposures it cuts steeply upsection (Figure 7) beneath the thickest sections of the Cornwall Tuff to form a dome-shaped crestal zone in pretranscurrent fault reconstructions. The pluton consists of medium-grained hornblende-biotite granodiorite and monzogranite-quartz monzonite. The granodiorite generally occurs in the upper portions of the pluton, while the monzogranite-quartz monzonite dominates the lower part. Contacts with the wall rock are sharp and alteration is minimal. No miarolitic cavities were found. Xenoliths, of partly digested country rock up to 0.5 m across, are sparse.

A group of block faults that cut rocks of the LaBine Group occurs above the roof of the Hogarth Pluton (Hildebrand,1981). These faults typically have different trends than postvolcanic transcurrent faults or their splays and do not cut the stratigraphically higher Sloan Group except where reactivated by the younger transcurrent faults (Figure 7). The early faults must predate the Sloan Group because one is left laterally separated on Doghead Point by another fault, probably dip slip with west side down, which is overstepped by ash flow tuff of the Sloan Group. The faults are truncated by the Hogarth Pluton near its apex, but at deeper structural levels they penetrate the outer shell of the pluton.

These relations are interpreted to indicate that the faults were active synchronously with emplacement of the Hogarth Pluton and that magma near the margins of the lower part of the intrusion had already crystallized when the uppermost portions of the pluton were emplaced. If this interpretation is correct, then the Hogarth Pluton must predate the Sloan Group. Barring significant pre-Sloan Group erosion of the LaBine Group, the maximum depth of emplacement of the pluton is approximately the stratigraphic thickness between its roof and the LaBine-Sloan contact, about 2.5 km.

The faults are topographically coincident with the thickest parts of the Cornwall Tuff, suggesting that the tuff, faults, and pluton are genetically related. Structural relations above the Hogarth Pluton display striking similarities to resurgent domes of large collapse calderas in other volcanic fields such as Creede caldera (Steven and Ratté, 1973; Steven and Lipman, 1973), Valles caldera (Smith et al., 1970), Long Valley caldera (Bailey et al., 1976; Bailey and Koeppen, 1977), and the Timber Mountain caldera (Byers et al., 1976). Blocks above its roof are jostled and lifted, and there is a group of down-dropped blocks located in the central part of the uplifted zone (Figure 8). Therefore the Hogarth Pluton is interpreted to be a resurgent pluton related to the Cornwall Cauldron. The lack of miarolitic cavities or associated pegmatites in the pluton, which intruded to within a few kilometers of the surface, suggests that the pluton was either exceptionally dry or had already lost most of its volatiles before final emplacement. If the latter is correct, then a possible mechanism for volatile loss may have been voluminous ash flow eruptions which resulted when volatile pressure exceeded the containment capability of the roof.

Discussion

1. The similarity of volcanic rocks and calderas described in this paper to those of the Cenozoic leave little doubt that ash flow volcanism and cauldron collapse are processes which have occurred since at least 1.9 Ga. In fact, there is every reason to expect that with more detailed mapping and study many Archean and early Proterozoic ash flow cauldrons will

be discovered. Potentially, they could assist in our understanding of volcano-plutonic relationships because many will be eroded or exposed at different structural levels. A coherent picture of the evolution of these interesting and economically important magmatic systems will emerge only by careful study of all crustal levels.

2. Steven and Lipman (1976) suggested, on the basis of the associated large negative gravity anomaly, that the San Juan volcanic field, Colorado, is underlain by a single shallow batholith of regional extent above which individual cupolas rose and differentiated, leading to cauldron-forming eruptions. In the Great Bear Magmatic Zone, views 7 to 10 km into the crust are possible owing to folding, and mapping of the north half of the zone has demonstrated that the batholith is a composite one. That is, it is made up of discrete plutons, each of which had its own magmatic history. There is no single body of regional extent; the largest pluton mapped is about 50 km in diameter. Many of the individual plutons of the Great Bear Magmatic Zone are sheetlike bodies 1-4 km thick; even intermediate plutons emplaced within stratovolcanoes are sills up to 2 km thick (Hildebrand, 1984). However, plutons emplaced within cauldrons have a domical roof (i.e., Hogarth Pluton) and may be laccolithic in overall form.

3. Caldera collapse brecccias in Black Bear and Clut cauldrons are intimately intercalated with intracauldron facies tuff, documenting that collapse of the calderas went on synchronously with ash flow eruptions. The association of coarse breccias with the earliest pyroclastic flows of Black Bear Cauldron indicates that cauldron subsidence began at about the same time as ash flow eruptions. The inverse size grading of megabreccia blocks within Clut Cauldron suggests that initial subsidence of the caldera floor was not great but that it quickly increased to over a kilometer and then large blocks were able to spall off the scarp into the cauldron.

4. The existence of several faults at the structural margin of both Black Bear and Clut cauldrons indicates that not all of the subsidence took place along a single fault. The structural margin of Clut Cauldron is a steplike feature with both fault contacts and buttress unconformities. Black Bear Cauldron has one major ring fault and several subsidiary normal and reverse faults. The reverse faults provide a mechanism for decreasing the size of the central block so that it is able to subside along an inwardly dipping ring fault. The faults of small throw might not be found in many cauldrons unless they are deeply eroded or deformed because they have been down-dropped to low structural levels along the main ring fault.

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