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VOLCANOLOGICAL CONSTRAINTS ON ARCHEAN TECTONICS P. C. Thurston and L.D. Ayres, Ontario Geological Survey, Toronto, Ont., Canada, M5S 1B3; Dept.of Earth Science, Univ.of Manitoba, Winnipeg, Man., Canada. R3T 2N2.

Terranes within Archean shields can be classified as granite-greenstone megabelts, contemporaneous sedimentary megabelts (1) and basement enclaves within either of the above (2,3). Stratigraphic and geochronological work in the Superior Province has shown the granite-greenstone megabelts represent proximal volcanism, sparse deep water clastic sedimentation, and late alluvial fan-submarine fan sedimentation(4). The sedimentary megabelts represent stratigraphically equivalent deep water sedimentation of wacke-pelite couplets (5), submarine fan conglomerates and minor distal facies volcanism(6). Basement enclaves include meta-igneous and metasedimentary gneiss and fragmented metavolcanic relics with poorly preserved primary textures.(2,7).

Greenstone belts of Australia have been subdivided into >3 Ga platform-phase greenstones and <3Ga rift-phase greenstones (8). Platform phase units are basal komatiite flows and tholeiitic flows with an upper unit of minor pyroclastics. Volcanism in the platform phase is typified by abundant pillowed amygdular flows, overlain by minor airfall tuff and relatively distal debris flow volcaniclastic units. Sedimentary units include chert, quartzite, and stromatolitic carbonates with minor wackes, indicative of shallow water platform sedimentation (9). Examples in the Superior Province, generally about 3 Ga old (10) include quartz-rich wackes in the lower sequence at North Spirit Lake in the Sachigo Subprovince (11), quartzites with fuchsite clasts in the lower sequence of the Wabigoon Subprovince at Armit Lake (12), and carbonate-rich sediments in the Lumby Lake greenstone belt (13) within the Wabigoon Diapiric Axis basement enclave (3). Volcanologically one can conclude from the thickness of the shallow water volcanic rocks and sediments that accumulation took place on a shallow platform (9) and as well, large scale subsidence kept pace with the rate of accumulation of volcanic rocks.

Rift-phase greenstones are relatively deep water amygdule-poor, pillowed tholeiites succeeded upward by vesiculated pillowed flows and calc-alkaline pyroclastic and volcanoclastic units (8). Considering the maximum water depth for pyroclastic erutions (14) and the thickness of pyroclastic sections in many rift-phase greenstone belts, Ayres (15) has suggested many Plinian eruption columns became subaerial. Classically (15) most Archean pyroclastic units were considered to have been deposited subaqueously. Recent studies have shown however that many Archean pyroclastic units were deposited subaerially (16,15). Sedimentologic studies of rift-phase greenstones show some deep-water clastic deposits(17), but increasingly shallower water deposits (alluvial fan) at stratigraphically high levels. The structural pattern in rift-phase belts is alternating synclinoria and anticlinoria either breached by diapirism or sheared out (8). Most Superior Province greenstone belts younger than 2.9-2.8 Ga (18) are probably rift-phase based on the following. a)structural style with synclinoria dominating with only rare dome and basin structures. b) Quartz-rich and carbonate rich sedimentation is scarce in the Abitibi (4), kWabigoon(20), and younger (<2.9Ga) sequences of the Uchi (18) and Sachigo (11,18) Subprovinces. c) Volcanism is typified by bimodal tholeiite-rhyolite sequences (21) with shoaling upward attributes (18,4). Evidence for small scale operation of rift-related volcanism is seen in the Six Mile Lake cycle at Sturgeon Lake (22) where a tholeiitic basalt-calcalkaline rhyolite sequence 2755 Ma (23) is rich in incompatible elements relative to later sequences and is cut by abundant mafic dikes assumed to feed the uounger (2718Ma) (24) cycles related to wide-scale rifting.

A survey of volcanic cyclicity (20) reveals the following types of cycles within the Superior Province. (+=fractionation relation; -=no fractionation KOM =komatiitic; TH=tholeiitic; CA=calc-alkaline; ALK=alkaline magma clans

1)KOM Perid Kom +dacite

2)KOM Perid.kom - TH bas + rhy - -CA bas + rhy -ALK

3)TH bas + andes - Th andes - Ca dac +rhy

4)TH bas + andes - Ca bas + rhy - ALK

5)CA bas + rhy

6)TH bas - CA dac + rhy - THbas

Increasing stratigraphic height to the right in each entry.

Cycle types 3,4, and 5 above were formerly thought to represent fractionation sequences,but recent work has shown that many are bimodal(21). The fact that the above cycle types are bimodal has profound volcanologic and petrogenetic implications in that the bimodalism is not simply the paucity of intermediate composition magmatic liquids. Trace element geochemistry and field evidence suggests, when corrected for unerupted volume in zoned magma chambers,and loss of vitric fines in high level winds during Plinian eruptions are made, preserved volumes of felsic volcanics in the Archean represent $\pm$ 15% of the original felsic magma (21). In effect, we concluded that Archean bimodal volcanism represents subequal volumes of mafic and felsic magma which are involved in greenstone belt volcanism.

Determination of paleoenvironment (above), eruption type, eruption rate, magma chamber size and type, developmental processes, and the life span of individual volcanoes places many genetic constraints on greenstone belt tectonics. In mafic sequences subequal volumes of pillowed and massive flows (18) suggest eruption by sheet flow processes (25) dominate over eruption from shield volcanoes (18). In felsic sequences the volumetric dominance of ignimbrites (21) and the notion that sedimentary basins contain large amounts of tephra suggest Plinian eruptions were dominant in the Archean. Many Plinian eruptions produced subaerial deposits on local volcanic islands (18.19,15). Vulcanian eruptions are subordinate, they produce less widespread deposits - examples include the Skead Group (26) and the Lake of the Woods area (27). This eruption type is often the result of less volatile-rich magmas relative to Plinian systems (28) interacting with near-surface water. The deposits are generally less widespread in extent than many Plinian deposits.

Eruption rates of Archean volcanoes can be determined in an approximate and indirect fashion. Sheet flows (25) a greater mean flow thickness than in Phanerozoic analogues (18) and the presence of lava plains (29) in Archean mafic sequences suggest a more rapid eruption rate than in Phanerozoic analogues (30). Phanerozoic ignimbrite systems have volumes in the 10^1-10^2 km^3 range (31) with exceptional examples in the 10^3-10^4 km^3 range (31,32). Phanerozoic felsic volcanoes had a life-span generally not exceeding 1.5 Ma (18) but many Archean felsic edifices apparently existed for 10-20 Ma(18).

The preserved volume of felsic ignimbrites (recalculated to compensate for unerupted material and loss of vitric fines, but ignoring compaction) suggests existance of felsic magma chambers on the order of 10^3 km^3 (21) rivalling those of the largest Phanerozoic systems (28,29). When integrated with data on the lifespan of Archean volcanoes of 10-20 Ma, Archean felsic eruption rates were large, but not as large as those seen in Archean mafic systems.

Volcanological and trace element geochemical data can be integrated to place some constraints upon the size, character and evolutionary history of Archean volcanic plumbing, and hence indirectly, Archean tectonics. The earliest volcanism in any greenstone belt is almost universally tholeitic basalt. Archean mafic magma chambers were usually the site of low pressure fractionation of olivine, plagioclase and later Cpx$\pm$ an oxide phase during evolution of tholeitic liquids (33 and references therein). Several models suggest basalt becoming more contaminated by sial with time (33,34). Data in the Uchi Subprovince shows early felsic volcanics to have fractionated REE patterns (33)followed by flat REE pattern rhyolites. This is interpreted as initial felsic liquids produced by melting of a garnetiferous mafic source followed by large scale melting of LIL-rich sial (33). Rare andesites in the Uchi Subprovince are produced by basalt fractionation, direct mantle melts and mixing of basaltic and tonalitic liquids(33). Composite dikes in the Abitibi Subprovince (35) have a basaltic edge with a chill margin, a rhyolitic interior with no basalt-rhyolite chill margin and partially melted sialic inclusions. Ignimbrites in the Uchi (16) and Abitibi (36) Subprovinces have mafic pumice toward the top. Integration of these data suggest initial mantle-derived basaltic liquids pond in a sialic crust, fractionate and melt sial. The inirial melts low in heavy REE are melts of mafic material, subsequently melting of adjacent sial produces a chamber with a felsic upper part underlain by mafic magma.
Compositional zonation of the overlying felsic magma develops with time (31), resulting in Plinian eruption through roll over (37) or volatile supersaturation(38).

Numerous arguments suggest widespread volcanism-related subsidence kept pace with the rate of eruption: a) The preservation of felsic sequences rather than the rapid erosion common in Phanerozoic terranes (39) b)Minimum water depth for pyroclastic activity (14) vs preserved stratigraphic thickness of subaqueous pyroclastic units (15)i.e. sections are much thicker than maximum water depth for eruption - therefore subsidence occurred. c) Lateral extent of 30-50 km for stromatolitic carbonates (40) in the Uchi subprovince, lateral extent of 30-50 km for shallow water silicified evaporites (41) and lateral extent and high eruption rate for shallow water environment mafic plains would have rapidly become subaerial unless subsidence kept pace(18). Isostatic calculations (42,43) suggest lava plain eruptions produce lesser crustal loading than central vent eruptions and less isostatic subsidence. Models involving sialic substrate to lava plain systems produce (42) sufficient subsidence to just maintain volcanic piles at sea level. Therefore we conclude a) subsidence kept pace with volcanism, b) subsidence was regional in extent, c) it is difficult to envision a sagduction style of subsidence (44) producing subsidence over a large area consistent with the great areal extent of the main contributor to the subsidence- the mafic lava plains. Subsidence was more rapid during mafic volcanism slowing during felsic volcanism.

The great volumes of Archean rhyolites and bimodal nature of rift-phase volcanism mitigates against an island arc or back-arc basin analogue where rhyolite is scarce (39 and references therin). Both continental arcs and continental rifts have sufficient volumes of felsic volcanism to compare to greenstone belts. The sediment-filled grabens associated with the Rio Grande Rift (45) offer a possible modern analogue as do the continental intra-arc depressions (39).

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