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MESOPROTEROZOIC RAPAKIVI GRANITES WITHIN THE COLUMBIA SUPERCONTINENT CONTEXT

Abstract: Mesoproterozoic rapakivi granites are found in the East European shield, central and western US, Amazonian craton, Labrador and Greenland. The suite was emplaced between 1.7 and 1.3 Ga, several hundred Ma after the orogenic peak that gave place to the amalgamation of Columbia supercontinent. For this reason, those granites were called anorogenic. The present paper tries to replace the granite generation within the context of a supercontinent and it examines the relations with the underlying mantle convection. Continent convergence implies a downwelling flow (antiplume) in the mantle, above which the convergent poloidal flow anchors the supercontinent. With time, it is replaced by a toroidal motion (shear) that makes the supercontinent spins. During this motion, heat is still delivered to the base of the continental lithosphere. Archean heterogeneities in the lithosphere thickness concentrate heat toward the juvenile suture zone. Intrusions and shear start at 1.57 Ga in Fennoscandia, and pass to Amazonia (1.53 Ga), western US (1.48-1.43 Ga) and Labrador (1.3 Ga) in a clockwise sense. They reflect progressive heating of the plate while moving over the heat source. Heat diffuses through the lithosphere, explaining the time span (300 Ma) before magmatism starts, and the long time (20-60 Ma) for a single intrusion to build up. Hence, the basal crust must achieve 1200-1300°C before producing anorthosites. Subsequent heating of the crust produces the other observed types of granites. Their emplacement time indicates a progressive diffusion of heat within the crust. Owing to the temperature gradient, diapirs develop. They give their thin (5km) and square shape (100 km) to the intrusions with a large spacing (100-150 km). Shear zones oblique to the orientation of late topaz-bearing granites progressively develop, reflecting sinistral strike-slip.

Keywords: rapakivi granites, Proterozoic, Columbia supercontinent, mantle convection

INTRODUCTION

During the Mesoproterozoic (1.6-1.3 Ga) rapakivi granites intruded a wide region (7000 by 1500 km) from the East European Craton to Laurentia, including Greenland and Amazonia. They are usually considered as being “anorogenic” since they were emplaced more than 200 Ma after the orogenic peak (Rämö, Haapala 1995). Numerous points have been identified that characterize the Proterozoic rapakivi granites and their magmatic suite:

- large intrusive area that encompasses ancient shields and very young crust;
- only a few, in Greenland are found within an Archean material;
- all intrusions develop a long time (from 200 to 400 Ma) after the peak of convergence;
- no polarity in age is clearly reflected in the distribution of dates within a province;
- the average intrusion ages are 1.57 Ga in Fennoscandia, 1.54 Ga in Amazonia, 1.48 Ga in middle US, 1.43 Ga in western US and 1.33 Ga in Labrador*;*
- this defines a global time shift;
- the granitic magmas show a wide range in composition, with SiO_2 spanning 55 - 78 %;

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- all magmas present a large mantle (~50%) component;
- granites are associated with anorthosite, mangerite and charnockite, or AMCG suite;
- the intrusions remobilise young juvenile crust with a residence time less than 200 Ma;
- the massifs are generally large, up to 100-200 km in diameter;
- no preferred shape, or grain, for individual massifs is evidenced in most provinces
- the more evolved facies (topaz bearing granite) in a pluton present an elliptic shape;
- the massifs are very thin (3 to 8 km, as a maximum);
- a large spacing (100 to 150 km) exists between individual plutons;
- successive intrusions that build up a single massif last a long time (20 to 60 Ma);
- incoming magma batches are less and less evolved over time;
- the interval between magma pulses that form a single pluton is about 5-8 Ma;
- the ascent proceeds whilst the magma retains a large (up to 40%) crystal content;
- the pressure and temperature conditions reflect isothermal decompression;
- granitic magma intrusion takes place at 450-650 °C;
- the surrounding crust is generally hot (550 to 700 °C) in the amphibolitic facies;
- contact metamorphism is either lacking or poorly developed around plutons;
- crust remains hot (> 500 °C for resetting Ar-Ar ages) from 1.6 to1.4 Ga;
- cooling finally develops over a very short time interval close to 1.4 Ga;
- anorthosite formation requires 1.1-1.3 GPa, or 30-36 km, - the base of the crust;
- the temperature of anorthosite formation is about 1300 °C;
- rapakivi textures are generated by isothermal decompression;
- temperature estimates for granite formation are 780 – 720 °C;
- whilst the AMCG suite is restricted to Proterozoic, rapakivi textures occur at any time;
- bimodal magmatism*:* ilmetite-granites eastward, magnetite-bearing magmas westward;
- large-scale tectonic context of anorogenic granites is poorly constrained;
- when present, ductile shear zones are identified;
- most identified shear zones are conjugated and dextral in their present geometry;
- global sinistral strike-slip deformation of the whole plate;
- sinistral deformation progressively affects all regions in a clockwise sense;
- sediments that would attest large topography erosion or mantle swell generally lack;
- the sedimentation, when existing, reflects internal basin, with few marine connections;
- sedimentary series close to intrusions developed high-grade metamorphism;
- sedimentary series far from the intrusions are cold (greenschist facies);
- both types of Proterozoic sedimentary series are separated by a piece of Archean crust;
- the convergence of continents lead to the formation of Columbia at about 1.9-1.8 Ga;
- no apparent large motion in latitude of Fennoscandia and Laurentia from 1.7 to 1.2 Ga;
- both cratons remain within about ± 30° from the Equator during 500 Ma;
- Columbia never get really dismembered before Rodinia re-assembly.

Those specific points indicate that a large scale mechanism should be at the origin of the magmatism. Its should be connected to deeper processes, certainly with the mode of mantle convection.

REPLACING THE MAGMATISM IN A SUPERCONTINENT CONTEXT

Proterozoic rapakivi granites have been described in wide areas, extending over 7000 km, and large time span occurring during about 200 Ma. They profoundly differ from all other types of granites as they are presently observed worldwide (Vigneresse 1999).

However, the formation of the rapakivi texture (Sederholm 1891) is not addressed in the present paper. It corresponds to specific conditions of magma mixing and ascent (Eklund, Shebanov 1999). Examining the specific conditions of the Proterozoic rapakivi granites formation indicates that the long time delay after the tectono-metamorphic peak, the long time a single pluton is built and the thermal state of the surrounding sedimentary sequences point to a global event. It should be examined into a global context, actually Columbia supercontinent that amalgamated at 1.9-1.8 Ga (Zhao *et al.* 2002). The settings should also involve the mantle conditions, hence the convection pattern.

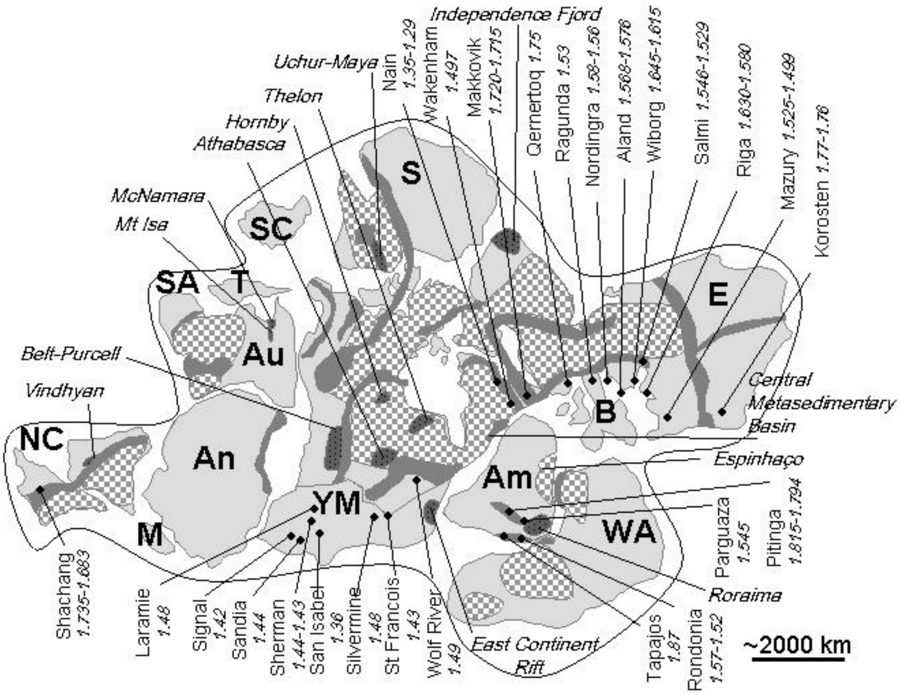

Fig. 1. Map showing a reconstruction of Columbia supercontinent at about 1.6 Ga, as redrawn from Zhao *et al.* (2002). Former orogenic belts that fit together are in dark grey, whereas the Archean nuclei are in squared grey. Major rapakivi granites are indicated with their name and age in vertical letters. The few sedimentary basins (doted dark grey) associated to the period (1.7 – 1.3 Ga) are with horizontal names. Letters refer to shields*:* Siberia, Greenland, Fennoscandia, East European, Amazonia, North-America, Australia, Antarctica, Tasmania, South-Africa, South-China, North-China, India, Madagascar, Yavapai- Mazatzal and West-Africa.

Previous models involved a thickened or thinned crust (Grocott *et al.* 1999; Nyman *et al.* 1994). However, the few occurrence of large scale tectonics and sedimentary basins do not support this model (Ericksson *et al.* 1998). A crustal overturn (Anderson, Bender 1989) or crustal tongue (Duchesne *et al.* 1999) may apply to one region, but cannot explain the large scale magmatism and age differences between provinces. A plume hypothesis (Anderson, Bender 1989) fits with the chemistry of mantle-derived magmas. However, an ascending divergent plume contradicts the convergent motion leading to the amalgamation of a supercontinent.

The adopted reconstitution for Columbia supercontinent (Zhao *et al.* 2002) is based on a geometric fit between former orogenic belts (Fig. 1). There are no reliable paleomagnetic poles in Laurentia between 1750 and 1500 Ma (Buchan *et al.* 2001), but both Laurentia and Fennoscandia were close to the Equator (Elming *et al.* 2001). The differences between Columbia and Rodinia reconstructions appear very subtle (compare Zhao *et al.* 2002 and Karlstrom *et al.* 2001). It suggests that the time of about 800 Ma spent between the aggregation of Columbia (1.9-1.8 Ga) and that of Rodinia (1.0 Ga) has not given place to a large splitting and divergence amongst Laurentia, Fennoscandia and Australia. The most effective separation took place along the future Grenville Front.

In this model (Zhao *et al.* 2002), the exact positions of Laurentia, East European Craton and Yapavai-Mazatzal platelets are correct to a first order. The East European Craton may be refined by spinning on itself to adjust some geometric constrains. The position of Amazonia seems also correct. The position of the external plates (Australia, Antarctica, India, Siberia) seems more problematic. However this has less importance since Proterozoic rapakivi granites have not been found there. Restricting the time window to 50 ± 20 Ma also restricts the region where the granites can be observed, but it suggests a global trend that varies in place with time. First, a bulk polarity in ages of rapakivi granites formation is observed that goes from Fennoscandia (1.57 Ga), Amazonia (1.54 Ga), central US (1.48 Ga), western US (1.43 Ga) and Labrador (1.33 Ga). Second, those regions align on an ellipse and magmatism develops in a clockwise sense. It documents an anticlockwise rotation of the plate over the heat source. Finally, in each region, the position of the local shear zones and the orientation of the late facies (topaz-bearing granites) when existing, define a sinistral shear deformation, with corresponding extensional joints and conjugated shear zones. The global pattern reflects a progressive shearing of the supercontinent, with anticlockwise rotation, inducing sinistral shear and jog opening (Fig. 2).

SUPERCONTINENT AND MANTLE CONVECTION

The amalgamation of a supercontinent supposes that a convergent flow exists that contributes to continent convergence. It corresponsds to a downwelling cell, i.e. a poloidal mode. The associated toroidal mode (Tackley 2000) represents the net rotation of the plates. This is is similar to the decomposition of deformation into a convergent/divergent strain and a shear strain (Ramsay, Huber 1983). Downwelling zones of mantle convection act as local attractors toward which continents converge (Peltier *et al.* 1997).

A supercontinent forms by successive aggregation of smaller ones under such a converging flow (Fig. 2). It amalgamates Archean cratons surrounded by younger accreted belts. The deep keel of those Archeran nuclei excite the first order toroidal motion, i.e. the net rotation of the lithosphere (Tackley 2000). Under this tangential motion, the supercontinent spins up to split under strike-slip. However, heat is still delivered at the surface and it takes a long time (300 Ma) for heat to diffuse through a 100 km thick lithosphere (Carlslaw, Jeager 1959). It corresponds to the time delay observed between the orogenic peak and magmatism. Progresively, the supercontinent spins and magmatism develops in a clockwise sense. It starts at 1.57 Ga in Fennoscandia, passing to Amazonia (1.54 Ga), then to middle US (1.48 Ga), to western US (1.43 Ga) and 1.33 Ga in Labrador. Associated local shear zones are observed that are dextral, as conjugated shear zones with oblique elliptic shapes of the late topaz-bearing granites.

It takes a very long (20 to 50 Ma) time to build a single pluton compared to that generally admitted (about 10 ka) for commmon plutons (Petford *et al.* 2000). This results from the progressive heating and melting of the crust. Magmatic episodes are calibrated in pressure and temperature according to experimental petrology (Creaser *et al.* 1991; Longhi *et al.* 1999) and in time (Amelin *et al.* 1997; Morgan *et al.* 2000; Dörr *et al.* 2002). The base of the crust (1.1-1.3 GPa) must complete 1200-1300 °C before reaching the temperature conditions of anorthosite production (Longhi *et al.* 1999). The pressure conditions correspond to a crustal thickness of 36 km, thus leading to a thermal gradient of 33 °C/km in the crust.

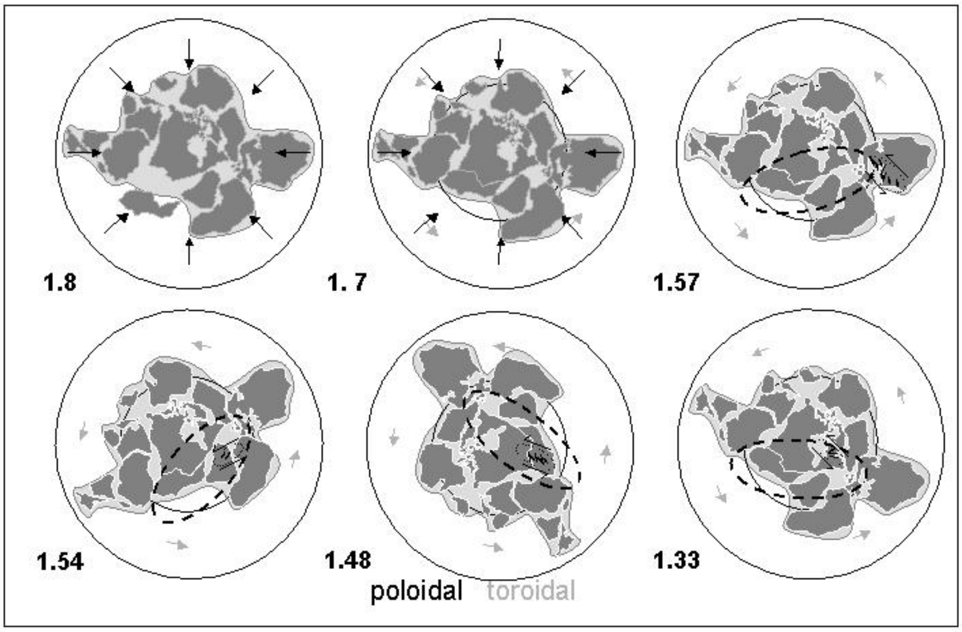

Fig. 2. Cartoon showing the assumed position of the supercontinent and development of strike-slip deformation. Poloidal flow is in black arrows, and toroidal flow in grey arrows. Late granitic bodies are represented in black, with their actual orientation, as well as the local shear zones. They define a sinistral shear. The large ellipse in dotted black indicates the progressive advance of magmatism with time.

In the Salmi massif, Russia, six successive magmatic episodes have been reported lasting 17 Ma (Amelin *et al.* 1997). Anorthosites are the first intrusive rocks. Gabbro-norite and monzonite follow. The former, a two pyroxene and plagioclase rock, cannot be found in the mantle, attesting crustal formation (Wiszniewska *et al.* 2002). The early Salmi wiborgite and pyterlite form the large rapakivi granite before the main biotite granite and the late Salmi pyterlite. Olivine gabbro and amphibolite-bearing granite are the late intrusions. The biotite granite forms at 500 MPa and about 800 °C (Patiño Douce 1996). In this example, each magmatic episode has a probable duration of 2.7-3.4 Ma with intervals of 3.5-5.0 Ma (Amelin *et al.* 1997). They develop in 17 Ma over 400 °C and 800 MPa, or 23 km in depth. It corresponds to a high thermal gradient (33 °C/km) and progressive advancing front of melting in the crust, leading to a diapiric ascent of the magmas.

The isothermal decompression that manifests through the rapakivi texture (Eklund, Shebanov 1999) also reflects a mechanism driven by the magma density. The viscosity contrast between magma and its surrounding joint to the large thermal gradient suggest development of Rayleigh-Taylor instabilities. A thin (< 5 km) source layer of magma with high crystal content (10^7 Pa.s) induces instabilities spacing above 100 km, matching the actual spacing between massifs. Diapirism is confirmed by numerical models for a younger (930 Ma) anorthosite massif in Rogaland, Norway (Barnichon *et al.* 1999).

DISCUSSION AND CONCLUSIONS

The magmatism that developed during the Proterozoic appears to be a very specific event. It has no other equivalent on that scale later in time. The occurrence of rapakivi texture in granites points to mixing and rapid decompresion of magmas. It has no relation in its genesis with the worldwide occurrence of a magmatic suite, delayed by about 300 Ma after the orgenic peak. Specific conditions were required that lead to a delayed magmatism compared to the orogenic peak. However, there is no reason to consider those granites as „anorogenic".

A supercontinent with old Archean cratons and very juvenile crust is a first requisite. The keel of the old craton acted as an heat refractor (Mimouni, Rabinowicz 1988) to focus heat toward the juvenile crust, that finally melts. With time, heat focusing ceratinly loss intensity, whic couldexplain the shift from ilmenite- to magnetite-bearing granites (Anderson, Bender 1989). Hence the later indicates a less participation of the mantle, with an increase amount of crustal component.

Occurrence of anorthosites and associated suite, as those found around 900 Ma, after the amalgamation of Rodinia (review in Tobi, Touret 1985) could reflect a similar behavior. However, the presence of contrasted Archean and juvenile crust is important for the process develops.

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