Evidence for 800 Ma and possibly older Deformation and Plutonism in Madagascar

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Madagascar occupies a key tectonic position for unravelling tectonic events that occurred during the break-up of Rodinia and the subsequent amalgamation of Gondwanaland. Central Madagascar consists of extensively reworked ~2.5 Ga Archaean crust overlain by a belt of Proterozoic supracrustal rocks, the Itremo Group: a succession of quartzite, pelite and carbonate that has been metamorphosed at sub-greenschist to upper amphibolite-facies in the eastern half of the belt (Moine, 1968). The age of deposition is broadly constrained only between 1855 and ~800 Ma (Cox *et al*., 1998): the maximum age is given by detrital zircons in the Itremo Group and the minimum by the intrusion of 804–779 Ma gabbros and granitoids, which are part of a ~450-km-long belt throughout central and north Madagascar (Handke *et al*., 1999). A second phase of dominantly granitoid emplacement occurred at 570–539 Ma (Tucker *et al*., 1996), and is generally considered to be related to the final stages of Gondwanaland amalgamation.

A major task in Madagascar is to separate the Gondwanaland assembly deformation from earlier tectonic events. A detailed study of the tectonic setting of the ~800 Ma plutons sheds light on the timing and nature of early deformation in the Itremo Group, the presence of which was hinted at by Cox and others (1998), but not documented in detail. We present structural and metamorphic evidence for an early deformational event that was synchronous with greenschist- to lower-amphibolite-facies regional metamorphism. This deformation locally predated the intrusion of ~800 Ma granitic and gabbroic plutons, and is overprinted by high-T–low-P metamorphism in metasediments with peak conditions ≥ 650 °C and ≤ 3.5 kbar during intrusion.

The Itremo map sheet (Moine, 1968) delineates three large ~800 Ma elongate batholiths whose relationship to the supracrustal sediments has been controversial, as many contacts are now tectonic. The plutons range from little deformed to highly strained, the deformation generally being attributed to crustal shortening in the 630–550 Ma interval during Gondwanaland assembly. However, clear intrusive relationships can be observed at several localities along the eastern margin of the Imorona batholith (~1200 km^2) where the 791.4 ± 1.3 Ma porphyritic K-feldspar East Imorona Granite and coeval 793.1 ± 1.5 Ambohitsaony Gabbro (Handke *et al*., 1999) cause contact metamorphism along steep contacts with country rocks. The contacts are parallel to a weak magmatic/tectonic foliation in the granitoid and the aureole contains a weakly foliated actinolite/plagioclase hornfels, with the amphibole both forming and weakly overgrowing the S_1 fabric. In a nearby metapelite, coarse muscovite overgrows a fine-grained foliation of muscovite, biotite and quartz. Some biotite wraps around the coarse muscovite and locally forms a disjunctive secondary cleavage. Fibrolitic sillimanite and tourmaline, both associated with the granitoid intrusion, overprint the S_1 biotite foliation.

At another contact of the granitoid and metapelite, a metamorphic assemblage of muscovite, biotite and quartz forms a well-developed S_1 foliation that also contains fibrolitic sillimanite. This fabric is folded at high angles by open to tight F_2 folds, which locally develop a disjunctive secondary cleavage. The metamorphic growth locally outlasted D_2 as *some* of the sillimanite occurs as random fibrolite crystals and aggregates in both hinges and limbs of F_2 folds. The fibrolite is temporally associated with growth of metamorphic K-feldspar, implying that contact metamorphism occurred above the second sillimanite isograd. Cordierite is also present. Field evidence supports both the high-grade nature and the syn-to-late D_2 timing of contact metamorphism as there is widespread *in-situ* relict melt in the country rock adjacent to the granitoid. The relict melt veins crosscut a pre-existing penetrative fabric in the country rock. Furthermore, the granitoid contains compositionally-layered enclaves of surrounding calc-silicate rocks (skarn), which contain early K-feldspar-bearing melt veins that are folded.

Additional evidence for syntectonic intrusion during D_2, is found in the contact aureole of a continuation of the ca. 792 Ma granitoid. Calc-silicate rocks of the Itremo Group in the aureole are diopside-scapolite-bearing skarns. Several enclaves, up to 50 cm long, are found in the granitoid ~160 m away from the contact. They have sharp boundaries and contain a weak fabric that is both defined and weakly overgrown by actinolitic amphibole. The similarity of the textural relationship and the composition to that of the hornfels suggests that the enclaves also had an Itremo Group protolith. One ~3 m long, foliated enclave forms a rootless, type-3 refolded isoclinal fold. The axial planes of the refold are parallel to a weakly developed foliation in the granitoid, defined by biotite wrapping around weakly aligned porphyritic K-feldspar grains. A felsic vein crosscuts the enclave fabric at high angles and is folded by open folds parallel to the granitoid fabric. Some euhedral prismatic K-feldspar phenocrysts lie at high angles to this weak, macroscopic foliation. Textural relationships in quartz and feldspar indicate only minor solid-state deformation, which occurred at temperatures greater than 500° C.

The relationships in the enclaves and contact aureoles suggest three major conclusions:
1) Intrusion of the ca. 792 Ma granitoid occurred after the formation of a penetrative fabric in the Itremo Group metasediments.
2) Intrusion produced sillimanite and muscovite, and sillimanite, K-feldspar and cordierite assemblages in metapelites, and diopside + scapolite assemblages in calc-silicates, indicating local peak temperatures of at least 650 °C and pressures ≤ 3.5 kbar.
3) The D_2 deformation of the granitoid and the country rock sediments was broadly coeval with intrusion.

The deformation in the Itremo Group platform sediments around ~800 Ma or possibly earlier has implications for late Mesoproterozoic and Neoproterozoic continental configurations. Did Madagascar lie at the edge of Rodinia facing the Mozambique Ocean one billion years ago or did it lie in the interior of a continent that broke up around 800 Ma? The nature of the early deformational event also remains enigmatic. Regionally, stratigraphic overturning of the sedimentary succession indicates the presence of large-scale lower limbs of early recumbent folds that are locally older than the granitoid and gabbro intrusions. More work is needed to establish whether these folds resulted from thickening during early crustal shortening, or from thinning along crustal-scale, low-angle extensional shear zones during continental break-up.

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