Magma evolution in the Halls Creek Orogen; insight from geodynamic numerical modelling and geochemical analysis

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SUMMARY

In this work two plausible tectonic scenarios for the Halls Creek Orogen are examined using a 2D thermo-mechanical-petrological numerical experiment based on I2VIS code. The initial constraints for the model setup are appropriate to the inferred tectonic environment for the protoliths to the Tickalara Metamorphics in an intra-ocean subduction or ocean-continent subduction/collision. These numerical models allowed us to examine a range of conceptual models for the different geodynamic settings for the Halls Creek Orogen through time. With this approach, we determined experiments with specific physical parameters that are compatible with the geology observed in the Halls Creek Orogen. Finding the model most compatible with observed geology can help to reveal geological processes which are not observable without the aid of geodynamic simulation. The results indicate that the geology of the Halls Creek Orogen is best represented by the ensialic marginal basin scenario. A further aspect of the numerical models is the degree to which they reveal magmatic activities which lead to the generation of key lithological units during the tectonic evolution of the Halls Creek Orogen. Development and closure of a marginal basin and the role of collisional magmatism are important parts of tectono-thermal evolution of the Halls Creek Orogen. The numerical models predict magma sources through time, linked to the tectonothermal evolution of the region. Hf-isotopic evolution patterns from the region have been used to verify and improve the models as this isotopic system is able to chart the influence of crust and mantle in melts through time. Lu-Hf data from zircon grains indicate a substantial juvenile melt addition in c. 1865-1840 Ma linked to marginal basin development in the Halls Creek Orogen.

Key words: Halls Creek Orogen, Paleoproterozoic tectonics, geodynamic numerical modelling, hafnium isotopes

INTRODUCTION

Precambrian geodynamics remains a controversial issue, because of the scarcity of natural observational data related to the physical-chemical state of the early Earth. Further progress in understanding Precambrian geodynamics requires cross-disciplinary efforts with a special emphasis placed upon quantitative testing of existing geodynamic concepts and extrapolating back in geological time using thermo-mechanical codes which have been validated for present day Earth conditions. Taking into account the fundamental scarcity of observational constraints, modelling can play an important role in developing and testing geodynamic hypotheses aimed at explaining the evolution of the Earth (Gerya, 2011, 2014; Gorczyk et al., 2013).

The Halls Creek Orogen (HCO) is a well-exposed Paleoproterozoic orogenic belt, extending along the eastern Kimberley Craton margin. This orogen can provide insights into the collision of the Kimberley Craton with the Diamantina Craton during the amalgamation of the Nuna Supercontinent. However, there is some uncertainty as to how the Halls Creek Orogen developed in the Paleoproterozoic (Griffin et al., 2000; Sheppard et al., 1999). The 1865 Ma Tickalara Metamorphics seem to be a key unit within the Halls Creek Orogen for solving this uncertainty. The formation of the protolith sedimentary and igneous rocks of the Tickalara Metamorphics in the Central Zone have been described as either forming in (1) an oceanic island arc setting above an easterly dipping subduction zone outboard of Kimberley Craton, or in (2) an ensialic marginal basin located closer to the margin of Kimberley Craton above a west-dipping subduction zone (Figure 1). Kohanpour et al. (2017) conducted a series of 2D thermo-mechanical-petrological numerical experiments based on the I2VIS code (Gerya and Yuen, 2003) to determine the probable geodynamic setting of the Halls Creek Orogen. The initial constraints for the setup of the models was provided by the two possible inferred tectonic environments for protoliths to the mafic, felsic and sedimentary rocks of the Tickalara Metamorphics (Griffin et al., 2000; Sheppard et al., 1999). The results of numerical models indicate that the geology of the Halls Creek Orogen is best represented by two models of the ensialic marginal basin scenario.

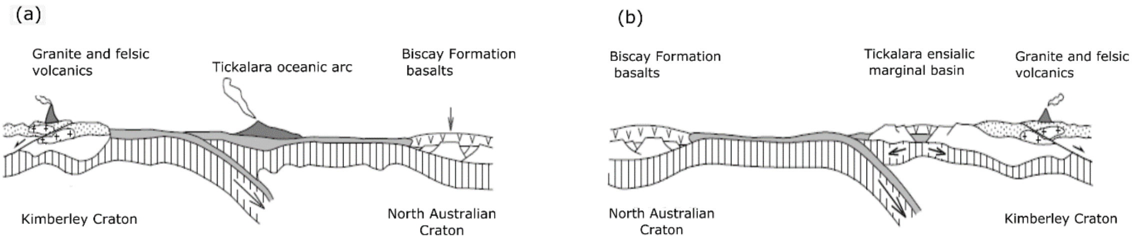

Figure 1. Possible tectonic setting for basalts in the Tickalara Metamorphics: (a) Oceanic island setting; and (b) marginal/back-arc basin (From Sheppard et al., 1999)

Results of the two models (Model I and II) are presented here. Both these models show structures and lithologies consistent with geophysical and geological data collected from the Halls Creek Orogen, and interpretations proposed by Griffin et al. (2000) and Sheppard et al. (1999). The two presented models include active continental margin experiments that predict arc basin development followed by collision of continental blocks and associated magmatism. The results indicate that the most plausible process that replicates the inferred Paleoproterozoic tectonic evolution of the Halls Creek Orogen and the major geological features can be induced by west-dipping subduction at the margin of Kimberley Craton. A further interesting aspect of the numerical models is the degree to which they predict development of a back arc basin and compositional evolution of magma chemistry due to collisional process. In considering two possible tectonic scenarios with different magmatic evolution, zircon U-Pb Lu-Hf isotopes provide supporting information to evaluate the numerical models as they record both the timing and relative roles of new mantle addition into the crust and also the process of crustal reworking. In this study, U-Pb and Lu-Hf isotopes are used as a tool to further constrain the geodynamic models as specific tectonic environments may be expected to have characteristic Hf evolution patterns.

METHOD AND RESULTS

To examine the conceptual range of tectonic models applicable to the Halls Creek Orogen, 33 2D petrological-thermomechanical numerical experiments were run by Kohanpour et al., 2017. The models are based on the I2VIS code using conservative finite differences method with a non-diffusive marker-in-cell techniques to simulate multiphase flow (Gerya and Yuen, 2003). The details of initital setup based on the current conceptual models of Halls Creek Orogen were explained by Kohanpour et al. (2017). The numerical models used in this work aim to simulate the process of ocean subduction followed by continental collision in an active continental margin and intra-ocean setting to envisage the possible tectonic settings of the Tickalara Metamorphics as a volcanic arc or an ensialic marginal basin, and Sally Downs Supersuite as a collisional magmatism. These models explored plate behavior, and generation of magma during the tectonic evolution of the Halls Creek Orogen.

In the conceptual model of intra-ocean subduction model (Figure 1a), east-dipping subduction has formed towards an overriding North Australian Craton. Retreat of the subduction zone and then reversal of subduction polarity followed until the collision of the Eastern and Central zones (Griffin et al., 2000; Sheppard et al., 1999). However, the numerical model shows a parallel advancing subduction zone without any polarity reversal which is comparable with neither the proposed tectonic evolution of the Halls Creek Orogen nor geological features mapped in the Eastern Zone. Therefore, the intra-ocean subduction experiment is not examined further here. The two models of active continental margin (ensialic marginal basin) scenario (Figure 2 and 3) consistent with the conceptual tectonic evolution of the Halls Creek Orogen including oceanic crust subduction, development of an arc basins, and later collisional tectonics are presented here.

Model I shows development of a prolonged extensional regime in the early stages, leading to the formation of a wide back-arc basin (Figure 2b-c), which is postulated to be the tectonic setting for deposition of the Tickalara Metamorphics protoliths. Decompression melt may cause the intrusion of ultramafic rocks in the Halls Creek orogen (Figure 2d). Subduction was terminated by the collision of continental crust including the combined Western and Central zones at the margin of the Kimberley Craton with the North Australian Craton. Collision results in a period of compression and closure of the newly formed basin (Figure 2e). The final phase of the collision was marked by the intrusion and suturing of all three zones of the Halls Creek Orogen by magmatism (Figure 2f).

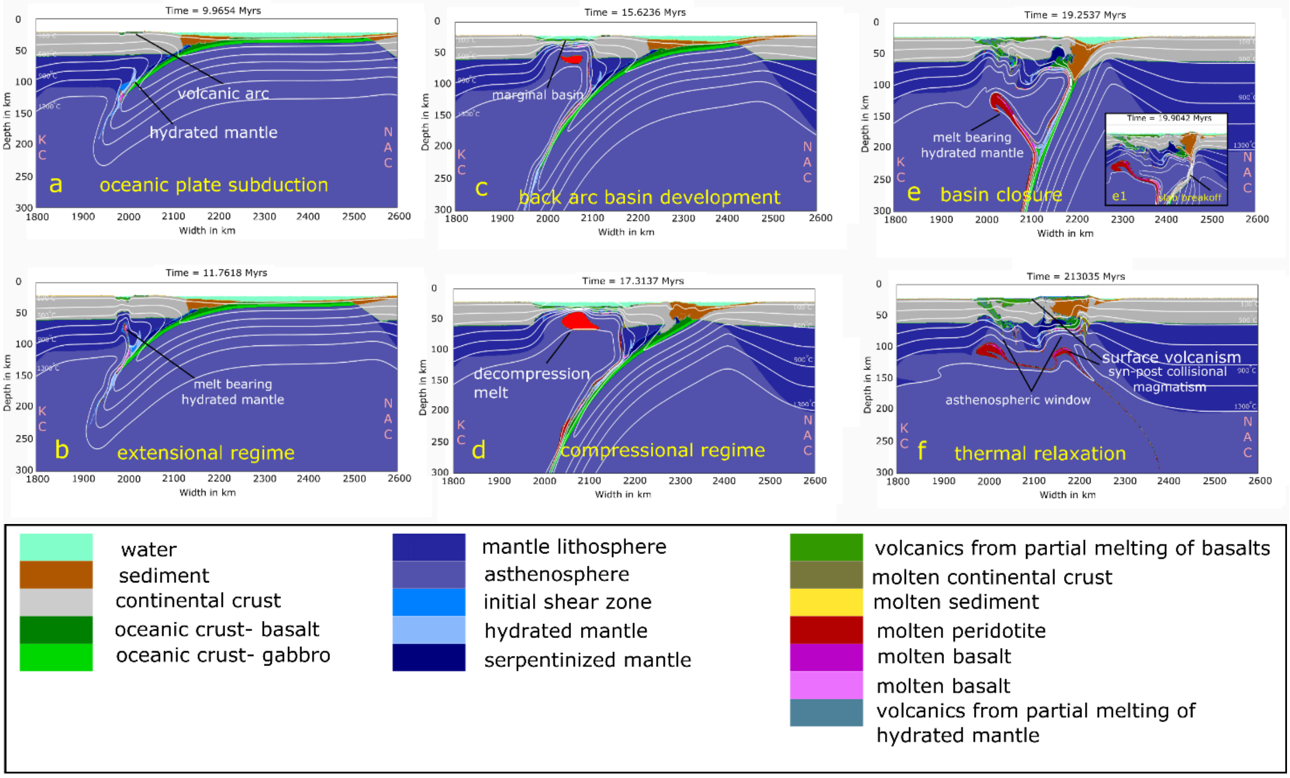

Figure 2. Dynamic evolution of Model I (active continental margin scenario with 600 km wide oceanic plate and 2 cm/y convergence rate for 16Myrs) in time represented by composition with colour codes and white line isotherms

Model II led to a different evolution in the marginal basin scenario. In this model the magmatic arc and intra-arc basin developed for a short period because of strong coupling of a subducting slab (North Australian Craton) and overriding plate (Kimberley Craton) and shortening of continental crust in this experiment (Figure 3a-b). During the relaxation period, subducted continental crust comes in contact with hot mantle as a result of a Moho temperature increase, undergoes melting and subsequently forms a dome-like chamber of melt-bearing continental crust at the bottom of the overriding plate (Figure 3c-f). The magma chamber causes magmatism and upwelling of mantle lithosphere in the centre of the orogeny (Figure 3e-f).

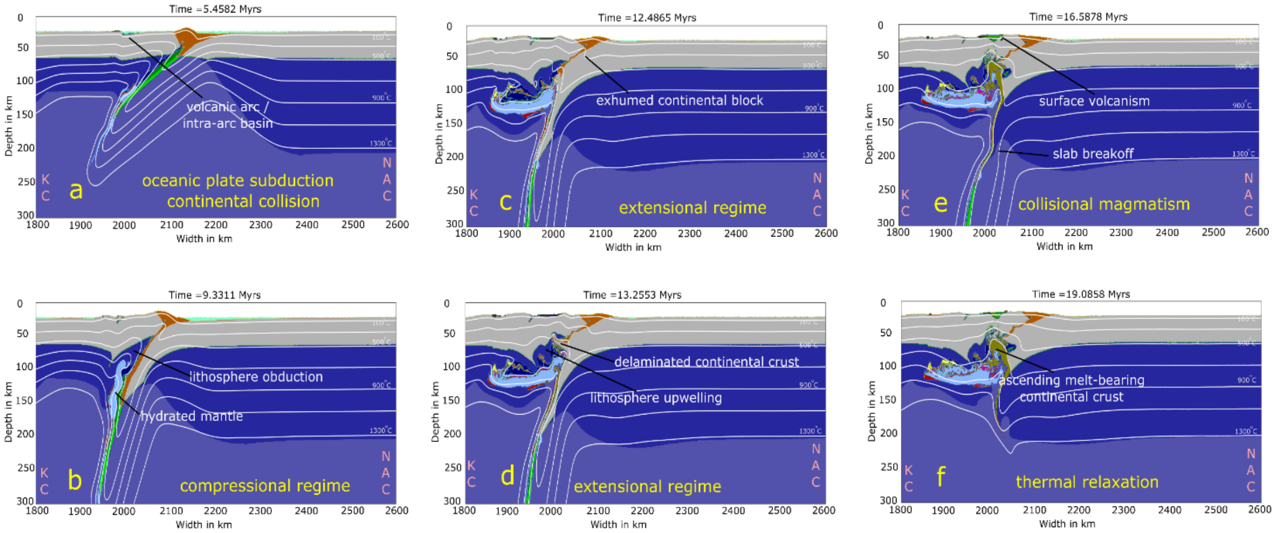

Figure 3. Dynamic evolution of Model II (active continental margin scenario with a 200 km wide oceanic plate and 4 cm/y convergence rate for 12Myrs, and rock composition represented with colour codes as described in Figure 2

The magmatic evolution of the Model I is presented in Figure 4. In the first 15 Ma, melt production is mainly derived from partial melting of the subducting ocean crust. The main melting peaks are observed at around 16 Ma and 19 Ma. The first period of extensive melting at 16 Ma is caused by extension and opening of the back-arc basin. Decompression melting of mantle material is the major source of magmatism in the region (Figures 2c-d and 4), which is accompanied by a slight increase in lower crust melt production. The second episode of extensive melting occurs at about 19 Ma, which is associated with the flux of wet mantle melt during the period of collision (Figures 2e-f and 4). After 20 Ma the volume of melt becomes constant because of thermal relaxation. By the end of the experiment at 21.3 Ma, total melt in the region comprise 60% mantle input, 28% oceanic crust and 10% lower crust.

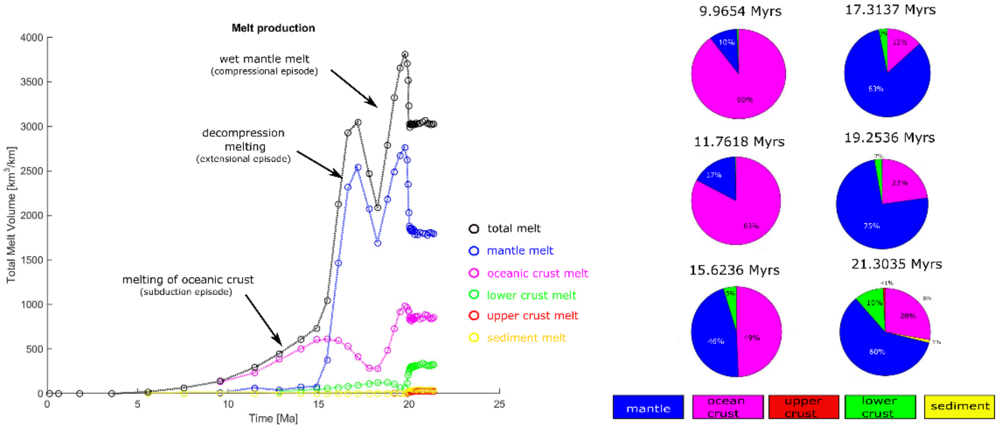

Figure 4. Magmatic evolution of Model I in terms of magmatic addition (km^3/km) and magmatic composition

In Model II, melt production was mainly derived from partial melting of the subducting ocean crust in the first 8 Ma (Figure 5). At 8-12 Ma, before initiation of extension, melt-bearing hydrated mantle caused most of the magmatism. The release of compressional forces which led to exhumation of the subducted continental crust and heating of the Moho, in turn caused partial melting of the lower crust as the major source of magmatism in the region (Figures 3e-f and 5). After 17 Ma the volume of melt reached a constant state because of thermal relaxation. When thermal relaxation was faster than tectonic relaxation, extensive melting occurred at the Moho (Figures 3f and 5). By the end of the experiment at 19 Ma, of the total melt in the region, 50% was derived from the lower crust, 16% from oceanic crust, 15% from sediments, 11% from upper crust, and 8% from the mantle.

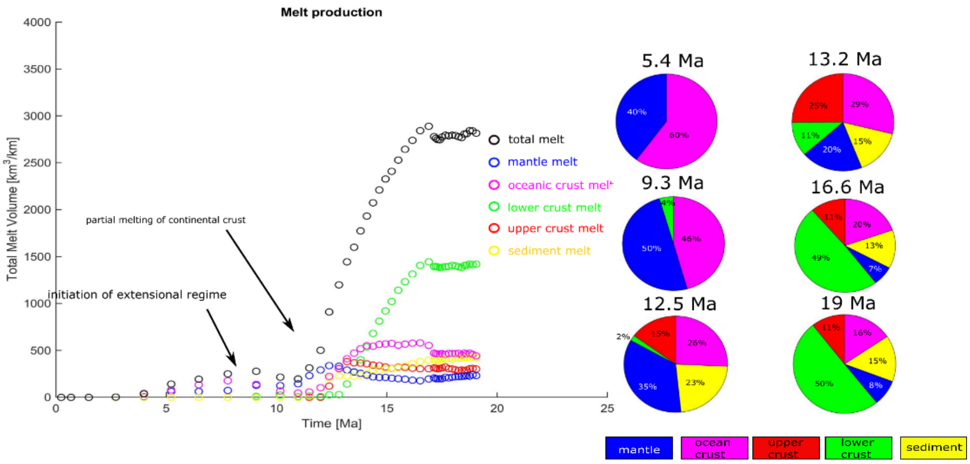

Figure 5. Magmatic evolution of Model II in terms of magmatic addition (km^3/km) and magmatic composition

The results in each model predict the development of arc basins, which is followed by continental collision and collisional magmatism. The main differences are continent coupling and slab pull which had a significant influence on the magmatic evolution, especially on the development of a back-arc basin and on the source of collisional magmatism in the two models. For constraining the geodynamic models, Lu-Hf isotopes measurements on previously dated zircons used to determine the crustal evolution. Processes of crustal reworking and juvenile mantle input can operate independently or together, and could produce distinctive patterns of isotopic changes through time in magma source regions (Collins et al., 2011; Kirkland et al., 2011). Hf-evolution trends can provide information about the timing of juvenile mantle input or reworking of older crust (Kirkland et al., 2013). We use time-constrained isotopic datasets to identify the main periods when mantle material was introduced into the crust of the Halls Creek Orogen, and periods when recycling of old crust, or mixing between old reworked crustal segments and juvenile additions from the mantle prevailed.

Based on the results of numerical models, unique Hf evolution patterns can be expected reflecting either juvenile input or reworking, or a combination of these processes. For example, in a situation where two cratonic blocks were sutured through oceanic crust subduction, Hf evolution pattern would be expected to show mixing trends between addition of juvenile mantle melt and crustal reworking. In contrast, rifting of continental margin would be expected to show a predominantly juvenile input trend (Kirkland et al., 2011). Figure 6 present the εHf for zircon grains from the Central Zone of the Halls Creek Orogen. Zircon Lu-Hf data for a range of intrusive rocks yield εHf arrays in which crystallisation ages between 1.6 and 1.9 Ga correspond with Lu-Hf T^2_{DM} of 1.2 and 2.6 Ga. The Lu-Hf results define 3 main fields: Field 1 which includes c. >1870Ma detrital zircons is dominated by reworking of continental crust; Later magma with c. 1870-1840 Ma crystallisation age, i.e. Field 2, influenced by increasing input of juvenile melt, and Field 3 encompasses data with c. 1840-1800 Ma crystallisation age lies along an apparent mixing of juvenile and reworked sources. In the younger grains c. <1800Ma, increasing input of juvenile material happened.

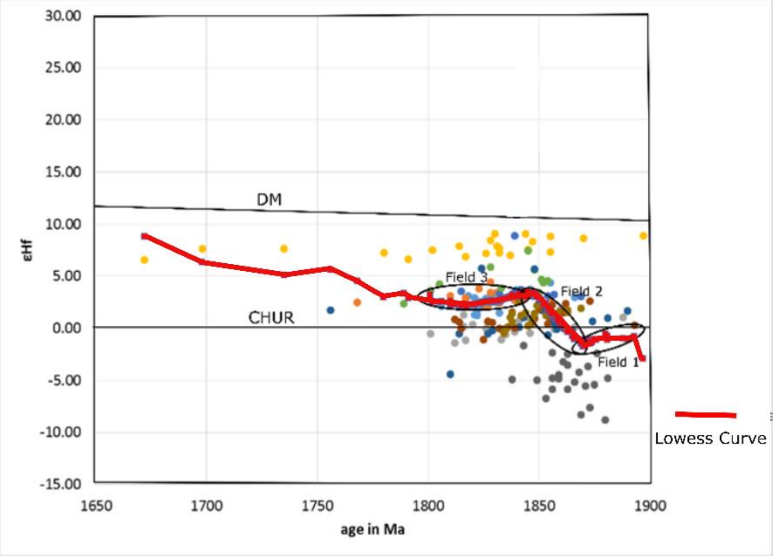

Figure 6. εHf-evolution diagram for zircon grains from the Central Zone of the Halls Creek Orogen. Fileds 1, 2, and 3 are discussed in the text

Based on geodynamic numerical models and the Lu-Hf evolution plot, the tectonic evolution of the Halls Creek Orogen is best explained using Model I as summarised in Figure 7. At c. 1865 Ma, initiation of subduction beneath the Kimberley Craton margin produced a magmatic arc with the evolved Hf signature of Tickalara Metamorphics. Continued convergence and slab pull during 1865- 1840 Ma resulted in marginal basin development which resulted in mafic-ultramafic intrusion with input of juvenile mantle melts to the crust. Asthenosphere upwelling, decompression melt and heat flow during this period resulted in elevated geothermal, melt production and high temperature metamorphism. Tectonic switching during the Halls Creek Orogeny at c.1835Ma, compressed and closed the marginal basin. Collision of Kimberley and North Australian cratons and crustal thickening may have resulted in mixing juvenile input and reworking continental crust as magmas penetrate thick buyout continental crust.

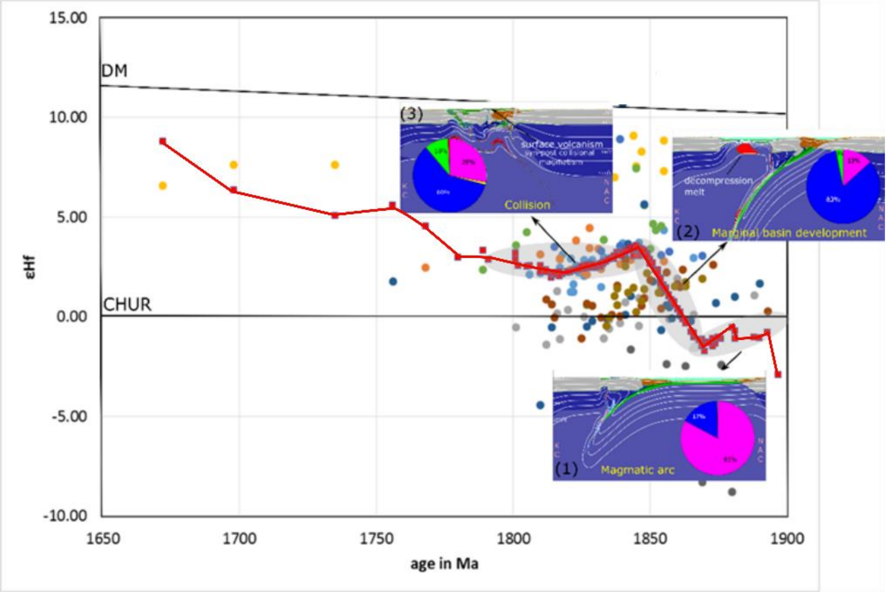

Figure 7. Geodynamic model of the Halls Creek Orogen based on the numerical models and Hf evolution pattern

CONCLUSIONS

The tectonic evolution of the Halls Creek Orogen provides an important insight into the operation of plate margins during the Proterozoic history of Australia. Useful insights into the evolution of the Halls Creek Orogen can be extracted from the numerical models to reveal possible scenarios for the tectonic of a Precambrian orogen. Numerical models with an active continental margin setup show the development of a back arc basin for deposition of the protoliths to the Tickalara Metamorphics and successfully replicate the geological evolution of the Lamboo Province. Development and closure of a back arc and the role of asthenospheric upwelling are important parts of the tectono-thermal evolution of the Halls Creek Orogen as illustrated in the active continental margin experiment whivh presented in Model I and II. Temporal variation of Hf isotopic values in intrusive rocks is used to track the introduction of juvenile or reworked material into magmas over time which may be reflective of the broad scale geodynamic environment. Results obtained by numerical experiments and Hf isotopes suggest that a sequence of three tectonic regimes which is consistent with Model I have occurred in development of the Halls Creek Orogen: (1) subduction of oceanic crust and formation of magmatic arc; (2) marginal basin development in an extensional regime combined with subsequent decompression melting and asthenosphere upwelling; (3) collision of the North Australian Craton and newly formed Kimberley Craton margin which resulted in compression and basin closure. In the final stage, detachment of a subducted slab triggered the opening of an asthenospheric window under the collision zone and initiation of extensional regime, and syn- to post-collisional magmatism leading to suturing of the North Australian and Kimberley cratons.

This study demonstrates that better understanding of Precambrian geodynamic requires cross-disciplinary efforts. Numerical modelling experiments provide an indication on the source of magmatism, which can be compared to observed isotope evolution patterns. Conversely, geochemistry and isotope studies can provide useful insights for the geodynamic numerical modelling to constrain lithospheric thickness, plate velocities, etc. Such linking of datasets provides a more robust framework to understand Precambrian tectonics.

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