MUCCAN BATHOLITH, EASTERN PILBARA, WESTERN AUSTRALIA

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INTRODUCTION

The Muccan Batholith is located in the northeastern part of the Archaean Pilbara Craton, Western Australia (cf. Figure 1). The granites, forming the main lithology, are not well exposed and mostly covered by Quaternary sediments.

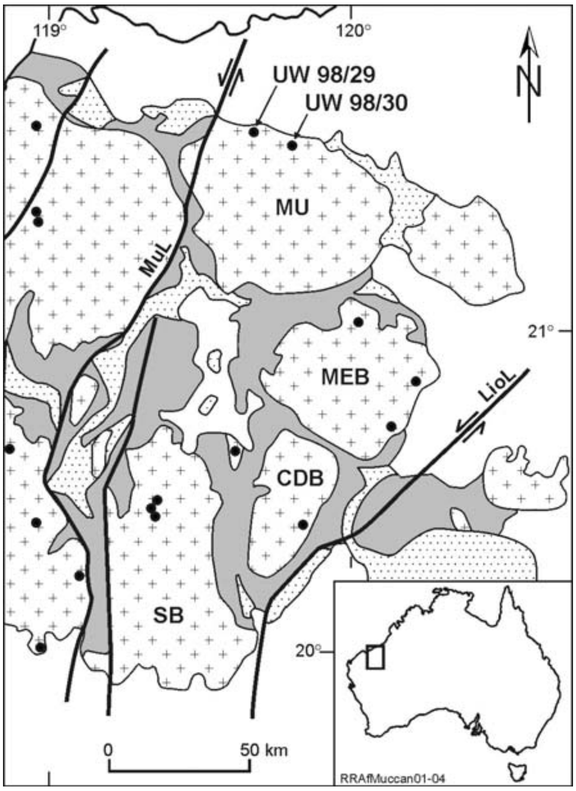

Figure 1. Location of AFT samples from Muccan Batholith, eastern Pilbara. CBD=Corunna Downs Batholith, MEB=Mount Edgar Batholith, MU=Muccan Batholith, SB=Shaw Batholith, LioL=Lionel Lineament, MuL=Mulgandinna Lineament.

The antiquity of rocks in Western Australia combined with the relatively low relief of the landsurface has led to the notion that the landscape is also very old. Fairbridge and Finkl (1980) suggested that the surface of the West Australian Shield has not effectively been lowered by erosion since Mesoproterozoic time, while Stewart *et al.* (1986) reported that a mid-Cambrian, valley-fill conglomerate from the Davenport Range, Northern Territory, central Australia formed an undisturbed depositional surface that could still be discerned and, moreover, had been continuously sub-aerial since that time. However, Neoproterozoic and Phanerozoic tectonism has been recorded from different parts of Western Australia (e.g. Veevers, 2000) but little direct evidence for this activity is available.

Low temperature thermochronology, the use of temperature sensitive geological dating methods, such as apatite fission track (AFT) dating, has been used to reconstruct the thermal histories of rocks. This method has proved to be an important tool with a wide range of applications, particularly in revealing the timing and magnitudes of upper crustal tectonism and its consequences for landscape evolution. Within the upper crust, temperature can often be used as a proxy for depth so that reconstructed cooling histories may be taken as a record of rock movement towards the surface. For the apatite fission track system the temperature record is most sensitive in the range ~110-60º C (e.g. Gleadow *et al.*, 1983; Laslett *et al.*, 1987), which typically equates to ~2-5 km of crustal depth, depending on the geothermal gradient. Because of the wide temperature susceptibility of fission tracks in apatite the data obtained can be used to model thermal histories of samples. Using thermal histories and assuming that cooling in the near-surface environment in the areas investigated is dominated by tectonic and erosional denudation, then the long-term denudation record of an area can be deduced. This potentially provides important information on long-term landscape evolution and regolith development.

APPROACH

Fission track analysis is based on the accumulation of radiation damage in uranium-bearing minerals (e.g. apatite, zircon and sphene) due to the spontaneous nuclear fission of ^{238}U. The linear damage zones, called fission tracks, result from the passage of highly energetic fission fragments through the crystal lattice. Following a simple chemical etching procedure, fission tracks can be observed as cylindrical-like holes under an optical microscope. Knowing the concentration of ^{238}U in the mineral grain, the track concentration and the decay constant for ^{238}U, it is possible to calculate an apparent fission track age. Several factors can influence a fission track age, e.g. the chemical composition of the apatite grains and the thermal history experienced by the sample.

Tracks are produced continuously through time and in apatite for example, on average, have an initial etchable mean length of ~16±1 µm and a diameter of ~1-2 µm. When exposed to elevated temperatures though, the radiation damage forming the tracks is gradually annealed (or repaired) and eventually disappears, progressively resetting the record of the fission track clock to zero. Annealing thus has important implications for the fission track age calculation – shorter tracks have a lower probability of intersecting the polished grain surface and therefore the track density will be reduced and the apparent fission track age will be lower. This effect became quite obvious when samples from drillholes were dated and it was observed that the fission track ages decreased to zero with increasing depth (Naeser and Forbes, 1976). The most pronounced annealing temperature of fluorine-rich apatite (the common type of apatite in most rocks studied) ranges between ~110–60º C (Gleadow and Duddy, 1981), but below ~60º C the kinetics of track annealing are very sluggish.

Laboratory experiments on track annealing characteristics have been extrapolated to longer time scales (Crowley *et al.,* 1991; Duddy *et al.,* 1988; Gleadow *et al.,* 1986; Laslett *et al.,* 1987), thus allowing for the application of apatite fission track thermochronology to geological problems. A detailed account of such applications is contained in reviews by Wagner and Van den Haute, 1992; Gallagher *et al.,* 1998; Van den Haute and de Corte, 1998 and Gleadow *et al.,* 2002.

The information derived from apatite fission track thermochronology can provide crucial and unique geological constraints, e.g. the timing and rate of orogenic events, rift shoulder uplift at passive continental margins or the determination of the amount and magnitude of regional denudation, which can be integrated over time to yield denudation rates (Gallagher and Brown, 1999a; Green, 1986).

In this study we use apatite fission track data from the Muccan Batholith to model thermal histories numerically using a genetic algorithm (Gallagher, 1995). Assuming that changes in palaeotemperature can be linked to the effects of burial and denudation, the results can be combined with heat flow data and further interpreted to reconstruct the amount of material that overlay the present landsurface, denudation rates and palaeotopography (Brown *et al.*, 2000; Gallagher and Brown, 1999a, 1999b). Figure 2 shows the inferred relationship between the different inputs and outputs that are involved in this process.

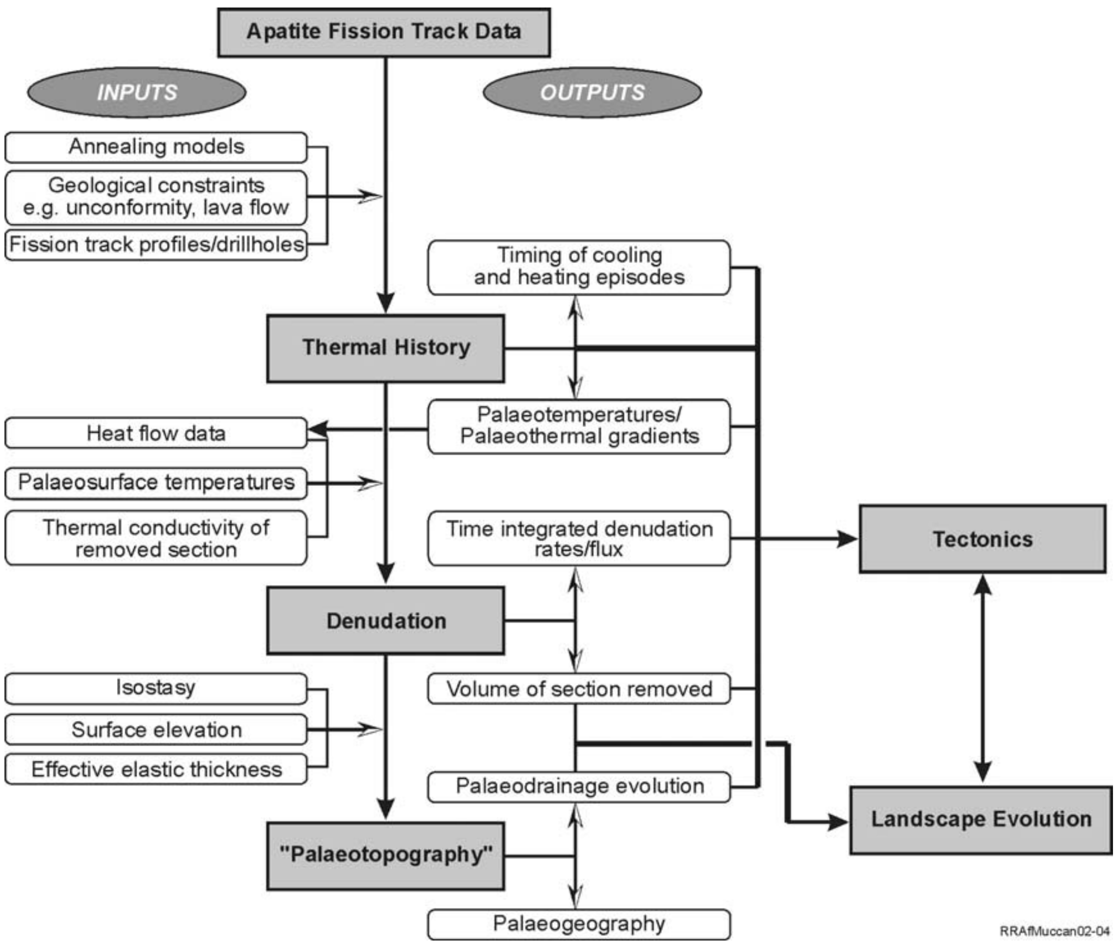

Figure 2. Flow diagram showing the sequence of steps and inputs which can be used to derive geologically useful parameters (outputs) from AFT data. Sources of error are cumulative so uncertainties increase with each step away from the AFT data (modified after Kohn *et al.*, 2002).

PHYSICAL SETTING

Geology

The Pilbara Craton, located north of the Yilgarn Craton and the Proterozoic units of the Capricorn Orogen is surrounded by Phanerozoic basins to the west, north and east. The granitoids constituting much of the craton are mostly surrounded by greenstones and there is still much debate as to whether the Pilbara Craton is an amalgamation of Archaean terranes as for the Yilgarn Craton or whether it was formed by solid–state diapirism (Smithies *et al.,* 1999; Zegers, 1996). Recently, Van Kranendonk *et al.* (2002) have suggested that the Pilbara Craton was formed by phases of granitoid plutonism intercalated with phases of microplate tectonics. Recognition that the eastern part of the Craton is older than the western part and that tectonic styles differ between them has led various workers to propose a subdivision of the Pilbara Craton into various tectonostratigraphic domains (Krapez and Eisenlohr, 1998; Van Kranendonk *et al.,* 2002).

U/Pb zircon ages from the Muccan Batholith range between 3470-3244 Ma and indicate formation of the granitoid complex over that time (Nelson, 1998). Apart from the Mount Shaw and Mount Edgar batholiths, which reached amphibolite facies (Zegers, 1996), most rocks in the Pilbara area were affected by greenschist facies metamorphism. Structurally, the craton is dissected by NNE-trending lineaments such as the Mallina and the Mulgandinnah Lineament (Zegers *et al.,* 1999), the latter of which passes through the north western part of the Muccan Batholith.

A few Phanerozoic sequences, mainly Permian and Jurassic/Cretaceous sediments, outcrop in the northeast and east of the craton, but most of the Muccan Batholith is covered by 10-40 m of Quaternary alluvial sediments and sands. The geology of the Muccan Batholith is detailed on the 1:250,000 geological sheets PORT HEDLAND-BEDOUT ISLAND (SF 50-4) (1982) and YARRIE (SF 51-1) (1983) and more recently on the MUCCAN geological sheet 1:100,000 (1999). The De Grey River alluvial plain runs WNW-ESE across the Muccan Batholith. The average elevation ranges between 100-300 m above sea level and the landscape is mostly planar, with the only relief being created by a few granite outcrops, dykes and quartzite ridges. To the east, the Great Sandy Desert continues with its broad aeolian sand plain and dunes.

Climate

Climate in the field area is mostly semi-arid in the interior and precipitation in the Pilbara reaches about 250-300 mm per year (Hickman, 1983). The northwest coast of Western Australia is usually passed by cyclones staying approximately 100–200 km off the Pilbara coast. Occasionally they veer inland, causing torrential rain accompanied by heavy winds reaching velocities of ~180 km/h and causing considerable damage to settlements and townships.

Vegetation

The semi-arid climate with low rainfall restricts the variety and distribution of flora in the study area. In dry inland areas only drought resistant shrubs and prickly grasses such as spinifex survive, whereas the riverbanks, depending on water abundance, may be flanked by a confined variety of eucalypts. Since the vegetation mostly depends on hydrological conditions of the area the relationship between flora and geology is negligible (Hickman, 1983).

DATING

Two samples from the Muccan Batholith were dated by the AFT method and both samples yielded apparent ages ~236-250 ± 10 Ma with mean horizontal confined track lengths of 12.8-13.2 ± 0.2 µm. Both samples were collected from the northern part of the exposed batholith and are in general agreement with AFT data from a regional study of the eastern Pilbara (Weber, 2002).

Figure 3 shows the modelled thermal histories of the samples from the Muccan Batholith, which indicate a general cooling in the Late Carboniferous-Early Permian from temperatures >110º C to 80º C. The samples continued to cool slowly throughout the Triassic and reached temperatures of ~60º C during Early Jurassic time. Assuming a geothermal gradient of 18±2º C km^{-1} then cooling of ~50º C (from 110-60º C) suggests denudation of ~2.5-3.1 km for the present day surface over that time span. The assumed geothermal gradient is based on present day heat flow measurements in the Pilbara ranging from 40-50 mW m^{-2} (Cull, 1982; Morgan, 2000) and assuming an average thermal conductivity of 2.5 Wm^{-1} $ºC^{-1}$. According to the temperature sensitivity of the AFT thermochronometer the thermal history of the samples is less well-constrained since mid-Jurassic time. However, sometime between mid-Jurassic to the Present the samples cooled by a further ~40º C (assuming a surface temperature of 20°C). Based on the assumption that the cooling is mainly due to erosion then we can estimate that the equivalent of a further 2.0-2.5 km of overlying material was eroded from the Muccan Batholith during this period.

Assuming the geothermal gradient range cited above then average denudation rates of 20-26 m $m.y.^{-1}$ apply for the Muccan Batholith area during the Late Carboniferous-Early Permian to Early Jurassic, and <10-15 m $m.y.^{-1}$ average denudation rates since ~180 Ma. However, it is emphasised that it is not possible to know, especially for the second stage of cooling, if this material was removed episodically or slowly and continuously over time.

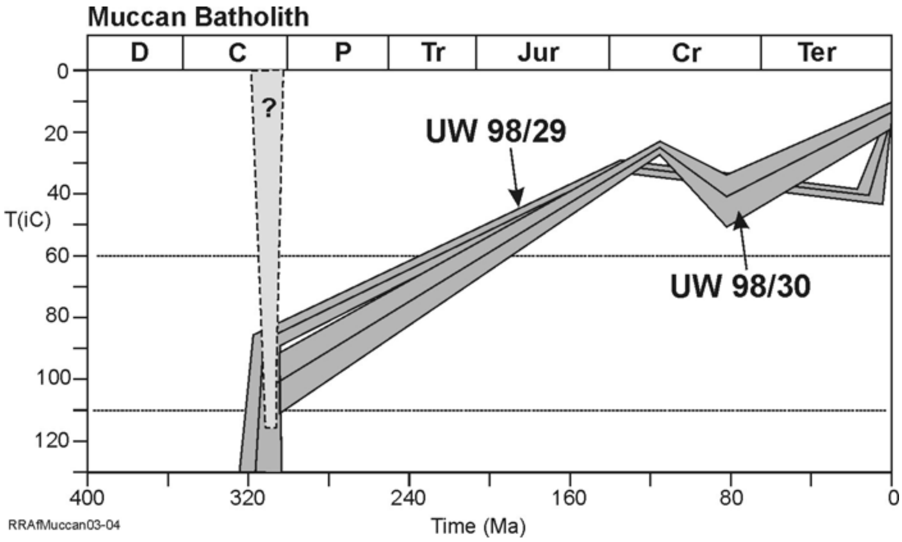

Figure 3. Modelled thermal histories for the Muccan Batholith based on two AFT data from Weber, 2002. The black line shows best-fit thermal history with grey envelope showing the range of other successful models. Dashed lines delimit the temperature boundaries of the zone in which most track annealing occurs in apatite.

LANDSCAPE EVOLUTION

The AFT results show that the present day outcrops of the Muccan Batholith have not been exposed since the Mesoproterozoic, but indeed probably resided at a depth of between ~4.5-5.6 km prior to Late Palaeozoic cooling. The batholith is assumed to have cooled mainly through denudation during the Late Palaeozoic and Mesozoic. The question of how long the batholith rocks at the present day surface have been exposed is, however, not possible to determine using the AFT approach. Another method, apatite (U-Th)/He thermochronology (e.g. Farley and Stockli, 2002), which has a lower closure temperature range between ~80º-40º C, may be a more suitable method to investigate this question further.

Playford (2002) identified Early Permian glacial striae on Precambrian rocks at Carawine Pool, ~100 km east of the Muccan Batholith, where striated Proterozoic pavement is unconformably overlain by Permian fluvio–glacial deposits of the onshore Canning Basin. This implies that present day surface rocks in the eastern Pilbara have been exposed since Late Carboniferous-Early Permian time. The thermal histories obtained from the AFT data, however, can only be reconciled with these Permian glacial striae, if we assume that the rocks were at the surface in the Late Carboniferous-Early Permian, then buried >3 km by overlying sediment and then slowly denuded in Late Permian and Mesozoic time. This alternative explanation is shown by the dotted line in Figure 3. The burial of the present day surface has to be sufficient for the AFT ages to be totally annealed and therefore reset, otherwise the thermal history models do not suggest a burial event.

A further possibility is that the glacial striae may be older than suggested by Playford (2002), possibly Late Carboniferous or older (Walter and Veevers, 2000).

Our data from the Muccan Batholith area support previous studies carried out in other Australian crystalline terranes (e.g. Kohn *et al.*, 2002) which argue that a process of burial and exhumation has contributed significantly to ensuring the subaerial preservation of ancient Australian landforms.

REGOLITH EVOLUTION

The present day landsurface of the Muccan Batholith may have been exposed at the surface in the Palaeozoic or earlier and last evolved some time after the Early Jurassic. The present landscape developed mostly in the Cainozoic, with low relief and most of the batholith being covered by Quaternary alluvial sediments of the De Grey River drainage area. Large parts of the batholith are also covered by rock fragments, which overlie the granitic basement rocks. This regolith cover probably only forms a thin veneer ~10-40 m thick (Hickman, 1983). Weathering and denudation rates of the granitic basement are now low due to the low precipitation and semi arid climate in this area.

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