Apatite Fission-Track Thermochronology, Northern Range, Trinidad (and Paria Peninsula, Venezuela) Abstract

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Abstract

The Northern Range of Trinidad is an east-west trending mountainous exposure of metamorphic rocks located in the Caribbean-South American plate boundary zone. With a maximum elevation of ~1km, the Northern Range is the only place in Trinidad were metamorphic rocks have been exhumed to the surface. Prior to ca. 10 Ma the Caribbean plate was obliquely converging relative to the South American plate and began creating the geologically young mountains that we see today. However, ca. 5-10 Ma, the Caribbean plate shifted from oblique convergence to dextral shearing (strike-slip faulting), and near Trinidad is currently moving at ~20mm/year toward N86°E ± 2° with respect to the South American plate. Using apatite fission-track methods, we test whether the Northern Range rocks were exhumed before or after this shift in plate motion to better understand the processes by which they were exhumed (unburied). Samples were collected over the past decade, and then the fission-track analysis was performed at Apatite to Zircon Inc. in the summer of 2008. We studied apatite fission tracks in fifteen samples: fourteen from the Northern Range, and one from the Paria Peninsula in Venezuela. All samples gave reset fission-track ages, between ~4 Ma and ~20 Ma. We recognize a spatial pattern in the ages: older fission-track ages (ca. 13 to 18 Ma) are located in the eastern Northern Range and younger fission-track ages (ca. 5 to 6 Ma) are located in the western Northern Range. The younger fission-track ages in the western Northern Range postdate oblique convergence of the Caribbean plate motion relative to South America. The older fission-track ages in the east predate the shift in plate motion. Inverse modeling using the HeFTy program also shows that exhumation occurred at a faster rate (ca. 15°C/m.y.) in the west than in the east (ca. 5°C/m.y.). Our interpretation is that a thick, buoyant crustal root is present in the western Northern Range and this resulted in isostatic uplift and associated erosion, exhuming rocks of the western rocks long after oblique convergence (transpression) shut off.

1. Introduction

The Northern Range (NR) of Trinidad is a geologically young, east-to-west-oriented belt of mountains made up of exhumed (unburied) metamorphic rocks that is located in the Caribbean-South American plate boundary zone (Fig. 1). This belt continues to the west as the Cordillera de la Costa, Paria Peninsula, Venezuela (Cruz et al., 2007). Currently, the Caribbean plate slides past the South American plate near Trinidad at ~20mm/year toward N86°E ± 2° (Weber et al., 2001a). Based on the regional geology, Pindell et al. (1998) suggested that oblique convergence occurred between these two plates prior to 10 Ma. Our study aims to test whether the Northern Range metamorphic rocks were exhumed during the early period of oblique convergence or more recently during post-10 Ma transform motion. In general the thickening that accompanies convergence and shortening produces tall mountains that get buoyed up by deep crustal roots. Crustal roots, once formed, wear away very slowly via erosion off the top of the mountains and once formed, crustal roots can buoy up modest topography long after crustal thickening occurred.

We present a study of the thermal history (thermochronology) of the Northern Range rocks using apatite fission-track methods. Samples were collected over the past decade (by JW) as part of a long-term study of the Northern Range and Paria Peninsula (e.g. Weber et al., 2001b; Cruz et al., 2007). Our apatite fission-track analysis was done at Apatite to Zircon Inc., Viola, Idaho (supervised by RD), with one of us (CD) working as a visiting student researcher, learning and assisting with the mineral separation. Fission tracks were studied for fifteen samples: fourteen from the Northern
Rock uplift is a term that describes the movement of rocks toward the Earth’s surface (Platt, 1993). Surface uplift refers to the upward movement of the Earth’s surface. Finally, the term exhumation refers to the unburial of rocks. Exhumation occurs only when rock uplift is greater than surface uplift (England and Molnar, 1990; Ring et al., 1999), and is in fact the difference between these two values (i.e. exhumation = rock uplift – surface uplift). Here, we study the timing and rates of exhumation across the Northern Range to test whether there are east-to-west differences in exhumation rates and magnitudes across the range, and to assess whether and how metamorphic rock unburial is related to the plate tectonic scenario discussed above.

We determined that Northern Range apatite fission tracks were reset during the Neogene, between ~4 Ma and ~20 Ma, dating their passage through ~120°C. We also recognize a spatial apatite fission-track pattern within the range: younger fission-track ages (ca. 5 to 6 Ma) are located in the west; older fission-track ages (ca. 13 to 18 Ma) are located in the east. Rates at which rocks were exhumed also differ between ~15°C/m.y. in the west to ~5°C/m.y. in the east. We question whether these changes occur along a fault or are gradual.

2. Apatite fission-track thermochronology methods

Fission tracks are micrometer-sized damage zones of a crystal lattice caused by the spontaneous nuclear fission of the isotope 238U (Fig. 2). Nuclear fission is a process in which a heavy, unstable nucleus splits into smaller fragments that are energetically ejected. Spontaneous fission is a naturally occurring process in heavy nuclides (atomic mass > 230). Minerals such as apatite contain enough 238U and crystalline lattice to make them a perfect media for spontaneous nuclear fission that leaves a permanent record (Tagami and O’Sullivan, 2005). Fission-track analysis is most commonly performed on minerals of apatite and zircon, but may in principle be performed on any uranium-bearing minerals. Analysis requires a dual measurement of fission-track age and track length (Barbarland et al., 2003). Fission-track ages reflect the concentration of uranium within samples, the number of tracks present per unit area, and the amount of time given for the tracks to accumulate. Track length is important for understanding rock time-temperature histories (Barbarland et al., 2003). Chlorine content is another important parameter to measure because it exerts significant control on track annealing rates.

Thermochronology is the use of radiogenic dating to constrain the thermal history of rocks and minerals. Over the past few decades apatite fission-track analysis has become an important tool to constrain the low-temperature (<120°C) thermal histories of igneous, metamorphic, and sedimentary rocks in a wide range of geological settings (Donelick et al., 2005). Within particular settings, distinct thermal histories occur. The types of geologic problems that can be addressed include: measuring timing and rates of uplift and exhumation, timing and rates of tectonic events, absolute age dating of volcanic deposits, and long-term landscape evolution (Donelick et al., 2005).

Once the uranium concentration of a sample is determined, the spontaneous fission-track density in that sample is an indication of the time that the sample crystallized or cooled through its closure temperature; this has been fairly confidently estimated to be ~100 ± 20°C for apatite (Wagner and Van den Haute, 1992; Donelick et al., 2005; Weber et al., 2001; Cruz et al., 2007), but does depend on cooling rate (Bruhn et al., 2005). With temperatures elevated to >100 ± 20°C apatite fission tracks begin to anneal by shortening until they exceed their closer temperature, when the tracks are reset and disappear completely (Bernet and Spiegel, 2004; Tagami and O’Sullivan, 2005). Annealing temperatures vary depending on the minerals involved, and fission tracks in apatite anneal between the temperatures of 120 and 60°C. The temperature region between 120 and 60°C is referred to as the partial annealing zone (PAZ) for apatite (Donelick et al., 2005). The simplest interpretation of a single apatite fission-track age is that it represents a single point in the upward journey of a sample as it is exhumed to the surface.

3. Apatite fission-track analysis

3.1. Mineral separation procedures

The methods used and described here are explained in greater detail in Donelick (2005). Minerals were first disaggregated by crushing the rock into sand-sized grains. The most effective way to do this is by first breaking a large sample with a rock-crusher or hammer, then running the sample through a jaw-crusher (Fig. 3a) several times until sand-sized sediment is obtained. Next, the sand-sized particles were sieved through a 300 micron cloth (Figs. 3b,c) leaving the <300 micron sediment for further density separation.

After crushing the rocks and sieving the sediment, the fine <300 micron material was washed using a wash bucket and regular tap water (Fig. 3d). The purpose of this step is to wash out most of the fine mud and clay particles. This was done by placing the material into the wash bucket and rinsing with tap water, followed by decanting off the muddy water. Washing was repeated as many times as needed until the water was clear. After all of the fine particles were removed, we decanted one final time and emptied the remaining coarse sediment into an aluminum pan, where it was stored in a safe environment and left to dry overnight.

The next mineral separation used heavy liquid separation, specifically an inorganic compound called lithium metatungstate (LMT). The LMT has a SG of 3.0 g/cm³ and apatite has a specific gravity between 3.15-3.20 g/cm³. The common minerals found in high abundance in most rocks, e.g. feldspars and quartz, have specific gravities less than 3.0 g/cm³. Equal amounts of sediment and LMT (Fig. 3e) were mixed into two beakers and stirred to loosen and mix the material. Then, the mixture was centrifuged at 2,000 rpm (Fig. 3f). After centrifuging the first time, we stirred the top half of the mixture and centrifuged again to make sure that materials were properly separated. After centrifuging, the light minerals (SG<3.0, e.g. quartz &
feldspar) sat on the surface of the mixture and the heavy minerals (SG>3.0, e.g. apatite) settled to the bottom. We then decanted off the light minerals and rinsed the heavies with distilled water several times. Finally, we emptied the remaining mineral grains into a small Petri dish and let them dry (Fig. 3g). Using a binocular microscope the remaining mineral grains were assessed for the amount and quality of apatite present.

Our final mineral separation used magnetic separation methods. We used a Frantz Isodynamic magnetic separator (Fig. 3h) and split the magnetic minerals from the nonmagnetic minerals. After separation, the nonmagnetic grains, including apatite, were set into an epoxy-only, polished grain mount (Fig. 3i).

3.2. Track length & age-measuring procedures

After the apatite grains were mounted and polished, the mounts were etched. Etching the polished surfaces of the mineral grain revealed spontaneous fission tracks in the crystals, providing accessibility for optical observations—counting and track length measurements. Tracks were enhanced by chemically etching the polished slide in 5.5 N HNO₃ at 21°C for 20s (Donelick et al., 2005; Jonckheere et al., 2007). Once etched, the mounts were placed under a high-powered >1000 X magnification microscope, where fission tracks were located and counted. With the additional use of a computer and a digitizer (Fig. 3j), the locations of the individual grains within the mount were recorded and saved to an external disk. When the grain mount is later placed under the laser ablation microprobe attached to an inductively coupled plasma spectrometer (LA-ICP-MS) (Fig. 3k), these coordinates are uploaded into a computer so that the grains can be easily found by the microprobe. The microprobe needs to know the exact coordinates of each grain within the mount so that it can accurately measure the concentration of Uranium, which is then used to calculate the age of the sample (Cox et al., 2000). The basic equation used to calculate the fission-track age is written:

\[
t = \frac{1}{\lambda_D} \ln \left( \frac{\lambda_D}{\lambda_f} \frac{N_s}{238U} + 1 \right)
\]

where \( N_s \) is the number of spontaneous fission tracks present in the sample, \( ^{238}\text{U} \) is the number of \(^{238}\text{U} \) atoms in the sample, \( \lambda_D \) is the total decay constant for \(^{238}\text{U} \), and \( \lambda_f \) is the spontaneous-fission decay constant for \(^{238}\text{U} \) (Bruhn et al., 2006).

The next procedure used was Californium-252 radiation (Fig. 3l). \(^{252}\text{Ca} \) is a very strong neutron emitter, releasing 170 million neutrons per minute. Grain mounts are placed in a vacuum chamber, beneath a \(^{252}\text{Ca} \) source where they are bombarded with neutrons. The purpose of the technique is to re-etch the spontaneous fission tracks, which enhances the number of fission tracks available for length measurement, and to create induced tracks.

4. Track length Modeling

Once track length distributions and ages were determined, these data were analyzed using a forward modeling program called HeFTy (http://www.geo.utexas.edu/scientist/ketcham.htm). The purpose of this step is to create theoretical annealing models that give a range of acceptable time-temperature histories and a best-fit history. We use starting constraints of 20°C surface temperatures, and 150 – 67 Ma depositional ages of to calibrate the HeFTy model parameters.

5. Results

Our new sample locations and apatite fission-track age results are given in Figure 5 and Table 1. Ages are given with two sigma (=2σ) uncertainties. Apatite fission-track ages from fifteen samples are shown, with two of the samples used as a composite (T-97-MACQ1+2), and one from the Paria Peninsula, Venezuela (PP-022). All samples yielded fission-track ages between ~4 and ~20 Ma, dating their upward passage through ~120°C. We recognize a spatial pattern in the ages obtained, with younger fission-track ages (ca. 5 to 6 Ma) in the west and older fission-track ages (ca. 13 to 18 Ma) in the east. Our single sample from Paria Peninsula, Venezuela, yielded an apatite fission-track age of 20.3 ± 1.3 Ma.

Figure 6 compares the relationship between east-west sample location using local Universal Transverse Mercator (UTM) coordinates in meters and fission-track age in Ma. UTM sample coordinates are given by eastings (east-west) and northings (north-south), both of which have a precision of ± a few meters. The black trend line shows the two groupings of fission-track ages and how they change across the range. The few samples that had extremely poor apatite yields show the largest uncertainties (e.g. RCS 91-6 and M2). In the west, fission-track ages are < 10 Ma. In the east (ca. >716000 easting) fission-track ages are > 10 Ma. The break in ages (at ca. 716000 easting) is a sharp thermal discontinuity that may represent a fault or exhumed isotherm.

Results from HeFTy model runs are shown in Figure 7; we use these to compare time-temperature histories for representative samples from the western and eastern Northern Range. The lightly shaded area in the plots represents “acceptable fits” and the dark shaded areas shows “good fits.” The heavy dark lines represent the “best fit” time-temperature histories.

The modeled time-temperature history for samples in the western Northern Range (Figs. 7a,b) illustrates rapid exhumation prior to 10 Ma. Figure 7a (T-97-Maq-1&2; our composite sample) shows that starting at ~100°C this rock cooled to 20°C at a rate of ~15°C/m.y. The sample has a calculated fission-track age of 4.97 ± 2.49 Ma. Figure 7b (sample WM-1) shows a similar cooling history, with a rate of exhumation ~15°C/m.y. and a calculated fission-track age of 5.45 ± 1.42 Ma. Difference between the modeled histories for the two samples is that HeFTy was able to model a longer, clearer history for WM-1 than for T-97-Maq1&2.

Time-temperature models for example eastern samples are given in Figures 7c and 7d. Figure 7c illustrates that sample T-97-TOC-1 reached its annealing temperature (120°C) at ~19 Ma. By the time this sample reached surface temperatures (20°C), cooling rates completely leveled out and the sample is modeled to have sat at surface conditions for the next ~7 m.y. The calculated/modeled age of T-97-TOC-1 is 16.6 ± 5.5 m.y. Figure
7d illustrates that sample T-97-TB-253 reached its annealing temperature at ~15 Ma and was exhumed to ~30°C at a rate of ~10°C/m.y. At this point in its journey the rate of exhumation decreased to ~1.1°C/m.y. Sample T-97-TB-253 has a calculated age of 13.7 ± 4.0m.y.

6. Discussion and conclusions

Fission-track ages in the Northern Range of Trinidad generally increase from west-to-east. This pattern is not necessarily expected based on the general west-to-east migration of the Caribbean plate relative to South America. An eastward-younging fission-track age distribution might be expected instead (Cruz et al., 2007). Furthermore, a major question arises regarding how only plate tectonic processes could drive exhumation in the region. Most of our fission-track ages postdate the aforementioned ~10 Ma shift from oblique plate convergence to dextral shearing in Caribbean plate motion. Pure lateral shearing alone can not account for the exhumation of metamorphic rocks (Platt, 1993; Ring et al., 1999). This argument, together with our results, allow us to rule out plate tectonics as the sole driving force for the exhumation. We conclude that the exhumation of metamorphic rock in the western Northern Range is the result of surface erosion that was coupled to a buoyant crustal root that formed during pre-10 Ma oblique convergence and resulted in long-lived isostatic and erosional exhumation (Cruz et al., 2007).

A significant difference also exists between the time-temperature histories for the two regions (Fig. 7). The eastern samples have old fission-track ages and rates of exhumation that slowed down significantly at about 10 Ma, and samples in the east were essentially exhumed by 9-10 Ma. Samples from the west show rapid exhumation over the entire post-10 Ma period. We conclude that a well-developed crustal root is present beneath the western Northern Range and has buoyed up this part of the range well after the pre-10 Ma phase of oblique plate convergence (and transpression) ended. On the other hand, the eastern Northern Range probably has a less well-developed (thinner) crustal root, and exhumation there seems to have stopped when oblique plate convergence stopped.

Acknowledgements

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References Cited


Track Age Determination Attempt. Impact Tectonics, p. 447-466.

Additional References


Figure 1. Map showing the location of the North American, Caribbean, and South American plates, and the island of Trinidad. Currently, the Caribbean plate moves ~eastward at a rate of ~20mm/year relative to the South American plate.
Figure 2a. Etched spontaneous fission tracks within an apatite crystal. 

Figure 2b. Etched spontaneous fission tracks within an apatite crystal. 
http://faculty.plattsburgh.edu/mary.rodentice/research/Fission_Track.html
Figures 3a-f. Mineral separation procedures. (a) Jaw crusher used to crush samples. (b) 300 micron sieve cloth. (c) Sieved material ≤ 300 microns. (d) Washing the fine-grain mud and clay particles. (e) Heavy mineral separation using lithium metatungstate (LMT). (f) Centrifuge.
Figures 3g-l. (g) After centrifuging and rinsing, air drying the remaining sediment in a small Petri dish. (h) Frantz Isodynamic magnetic separator. (i) Grain mounts that used epoxy-only. (j) High power microscope, coordinate system digitizer, and computer. (k) LA-ICP-MS. (l) Californium-252 source.

http://epsc.wustl.edu/geochronology/frantz.htm
Figure 5. Map of Northern Range, Trinidad, showing the locations of samples used in this study.

Figure 6. Apatite fission-track ages determined in this study plotted against UTM eastings. All error bars represent 2σ level errors. The vertical line at ~716000 easting represents a thermal discontinuity where older FT ages (east) are in contact with younger FT ages (west). This could be either a fault or an exhumed isotherm.
## Summary of AFT Data (Northern Range, Trinidad and Paria Peninsula, Venezuela)

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Table 1. Summary of samples, locations, and apatite fission-track ages.
Figures 7a-b. HeFTy models – western Northern Range samples. (a) T-97-Macq-1&2. (b) WM-1. Track length distributions (right) are observations; time-temperature histories (left) are models.
Figures 7c-d. HeFTy models – eastern Northern Range samples. (c) T-97-TOC-1, (b) T-97-TB-253. Track length distributions (right) are observations; time-temperature histories (left) are models.