Apatite fission-track dating to deduce exhumation of the Santiago and Silverado Canyon areas, Northern Santa Ana Mountains, California

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Abstract

The Santa Ana Mountains, located in Southern California, contain a number of important sedimentary units, which represent a large portion of the Los Angeles area. However, very little is known about the exhumation age and rates occurring as a result of uplift along the Elsinore Fault. Research conducted by experts in Fission Track analysis demonstrates that uranium contained in certain minerals such as apatite and zircon leaves behind tracks in the crystal lattice of the minerals as it undergoes fission. The tracks remain in the lattice unless the minerals are heated through burial. The ratio between the total amount of tracks that can be produced in a sample and the amount of tracks that have been produced, is used in an equation to determine the years since exhumation has begun. Using this age and the thickness of sediment overlying the sample, it is possible to determine the rate of exhumation. These methods were used in this study to determine the exhumation ages and rates of two samples taken from the Baker Canyon member of the Ladd Formation and the Vaqueros and Sespe Undifferentiated of the Santa Ana Mountains. The average ages of exhumation for the Baker Canyon member and the Vaqueros and Sespe Undifferentiated are 75.2 +/- 5 and 68 +/- 4.2 million years, respectively. It has also been concluded that the Vaqueros and Sespe Undifferentiated was not buried significantly and that the Baker Canyon member has been exhumed at a rate of 0.03mm/year.

Introduction

Very little is known about the Santa Ana Mountains, especially in regards to exhumation rates and burial depths of the strata. The stratigraphy, however, is well documented, and is part of the foundation on which this research project stands. I carried out fission track analysis of two clastic units in the Santa Ana Mountains to determine exhumation rates and time, and burial depths by using strata thicknesses and cross sections combined with the techniques of fission track dating published by Dumitru and others (1996), and Ravenhurst and Donelick (1992). Also, fission track ages of basement rock were obtained from Deanna Hoppe in order to determine if the source material for the clastic units were the basement rocks of the Santa Ana Mountains, or if the source material is elsewhere.

Geologic Background

The northern Santa Ana Mountains (NSAM) reflect the geology of the northern Peninsular Ranges, and therefore are significant in providing evidence for tectonic
activity of the region (Figures 1 and 2). A northwestern onlap of Paleocene strata onto older units records a Tertiary southwestern tilt of the Santa Ana Mountains; the tilting continued through middle Miocene time when the subsidence of the Los Angeles Basin began, and has produced erosional unconformities in upper Miocene, Pliocene and upper Pleistocene strata (Schoellhamer, 1981). The Elsinore fault zone, which bounds the northeast part of the Santa Ana Mountains, has surface features visible along most of the fault zone, and has a slip rate of four to five millimeters per year. (McCulloh, 2000).

The NSAM contain one of the most complete stratigraphic sections (figure 2) of the coastal region of southern California. The core of the Santa Ana Mountains consists of Late Mesozoic calc-alkaline arc-related granitic rocks, which are related to the prebatholithic terrains of the western Sierra Nevada range (Wright, 1991). The basement rock contains Mesozoic granitic rocks, metamorphic rocks of the Bedford Formation, and the Santiago Peak Volcanics. The Jurassic Santiago Peak Volcanics, composed of flow breccia and andesitic flows, are the oldest extrusive igneous rocks of the NSAM (Schoellhamer, 1981). An unconformity separates the basement units from the overlying westward-dipping Upper Cretaceous and Cenozoic clastic deposits (Schoellhamer, 1981)(Figure 3). The maximum thickness of these units total approximately 13,000 feet (Schoellhamer, 1981). These deposits range from organic shale to boulder conglomerates (Schoellhamer, 1981). Along the western edge of this monocline is a north-trending zone of major extensional faults trending to the north, which have offset early Miocene and older strata. A large northwest-plunging syncline containing about 2300 feet of Miocene strata separates this monocline from the Santa Ana Shelf (Figure 2).
Fission Track Dating Background

Fission-track dating is a useful tool to study thermal and burial histories of rocks and to calculate the exhumation rates. Significant amounts of uranium naturally occur in many rock-forming minerals such as apatite, zircon, sphene and volcanic glass. As with any radioactive element, uranium isotope $^{238}$U decays at a constant rate, and does so by alpha particle emission. However, about one out of every 2 million times, a uranium nucleus will decay by spontaneous fission (Dumitru, 1996). The two nuclei formed have mass numbers of about 85 to 105 and 130 to 150, and are highly charged, mutually repelling one another (Dumitru, 1996) at 180 degree angle and in a straight path. The positively charged particles left in the track take electrons from the surrounding crystal lattice, forming ions that repel one another and disrupt the lattice to form a damage zone that is approximately 10 to 20 microns in length and a few angstroms wide (Hurford, 1986). By etching the minerals with the tracks, the spontaneous tracks can be seen and counted using an optical microscope.

Irradiation of the minerals is important to induce fission of the remaining uranium that had not undergone fission naturally. The amount of tracks induced by irradiation depends not only on uranium content, but also on the dose of neutron bombardment by the reactor. The dose is measured by doping a manmade piece of glass with uranium and attaching a external detector that will record the neutron dose in the form of track density ($\rho_d$). Mica (uranium-free) plates sealed over the minerals in epoxy will record the amount of fission tracks induced when exposed to neutron irradiation. The etching process is then used again to reveal the induced tracks in the mica plates, which form mirror-image
prints of the apatite grains on the mount (Dumitru, 1996). The irradiation process induces tracks in the mount as well, but without etching the mount, the tracks remain invisible (Dumitru, 1996). Using an optical microscope, the numbers of both the spontaneous tracks in the apatite grains and the induced tracks in the mica grains are counted in the same location on each to obtain a ratio of spontaneous tracks on the mount to induced tracks on the mica.

The densities of both the spontaneous tracks and induced tracks of a collected sample, along with the determined zeta factor, are used in the following equation to determine apparent fission-track age of a sample:

\[ T = \frac{1}{\lambda_D} \ln \left[ 1 + \lambda_D \zeta \frac{\rho_s}{\rho_I} \rho_d \right] \]

where \( \lambda_D \) is the decay constant, \( \zeta \) is a personal zeta factor, \( \rho_s \) is the density of spontaneous tracks, \( \rho_I \) is the density of induced tracks and \( \rho_d \) is the density of the induced tracks of the standard glass with known uranium content (Ravenhurst and Donelick, 1992). A personal zeta factor is determined by counting the tracks in a sample with a known age to take into account differences in counting methods.

Fission tracks can be partially or completely annealed at 105 +/- 10 degrees Celcius in apatite minerals (Parrish 1983). Complete annealing sets the “clock” back to zero. In apatite, total annealing occurs between 110-135 °Celsius over an exposure time of a few million years. Therefore for total annealing to occur, the rocks must be buried about 3 to 6 km assuming the normal geothermal gradient of 20 to 30 °C/km (Dumitru, 2000). Apatite is the most useful mineral for unroofing and uplift studies because it is
very possible that samples collected at the surface were totally or partially annealed at 3 to 6 km depth, in the Pliocene or Quaternary time.

Exhumation rates can be determined from the fission-track ages of a group of samples collected throughout a stratigraphic section. A total annealing zone (TAZ) in a section, followed by a younger, partially annealed zone (PAZ), indicates that the rocks were being exhumed in that section. The ratio of elevation difference (oldest point in the TAZ to the youngest unit in the profile) to the difference in fission-track age will give an exhumation rate (Ravenhurst and Donelick, 1992).

Fission track length data are used to determine the thermal history of a sequence of rock units. Modeling has demonstrated that rocks that have been subjected to a recent heating event will have progressively shorter track lengths over time, as they are partially annealed (Figure 4). Rocks that have experienced a slow cooling event will have increasing track lengths over time. A past thermal event will give a bimodal distribution of track lengths as shown by path D in Figure 4: longer tracks, followed by shorter tracks during the heating process, and then longer tracks again during unroofing (Ravenhurst and Donelick, 1992). The ratio between conventional track length and track density is normally one to one when little annealing has occurred, but the relationship breaks down with increasing annealing. It is therefore important to use both fission track age and length to determine thermal history (Ravenhurst and Donelick, 1992).

The tracks used to measure track length are those that are just below, and are parallel to subparallel to, the surface of the grain. Those tracks have not been truncated during the grinding and polishing treatment of the grain and still may be visible if the etchant reached them through another intersecting surface track or crack. In addition, the
more parallel the track is to the surface, the more accurate the length measured is. If the track is oblique to the surface, it will appear shorter than it really is (Dumitru, 1996). Because tracks that are oriented parallel to the c-axis anneal slower and etch faster than others (Ravenhurst and Donelick, 1992), when measuring lengths, it is important to measure the angle between the track and the c-axis, to factor in the difference.

The chemistry of the apatite grains sampled can differ significantly and cause inaccurate results. Tracks in grains with more chlorine anneal at temperatures up to 30°C higher than those in more fluorine-containing grains, and tracks are etched faster (Naeser et al, 1990). Therefore, interpretation of burial depth based on apatite fission track data may vary by a kilometer or more if the chemistry of the grains are not analyzed.

**Rocks Sampled for Fission-Track Analysis**

**Baker Canyon Conglomerate Member of the Ladd Formation**

In Silverado Canyon, sample KLM03-2 was collected from the Baker Canyon Conglomerate Member (BCCM) of the Ladd Formation (Figure 5), which is a cretaceous marine, and non-marine, conglomerate and sandstone unit that is approximately 100 feet thick (Popenoe, 1941). Cretaceous molluscs are common in the upper part of the BCCM as casts, molds and shell remnants, and are key indicators of the unit’s age: approximately 90 million years. The cementation and compaction is moderate, and the degree of sorting varies considerably. The pebbles are mostly subangular with a smaller percentage being subrounded. Clasts are mainly andesitic and metasedimentary (Popenoe, 1941). “The proportion of andesites to sediments varies greatly not only along strike but at different levels in the same section (Popenoe, 1941). According to
Popenoe (1941), the clast composition can be dominated by andesites and in other areas andesitic clasts may be almost absent.

According to Schoellhamer (1981), the BCCM can be categorized into upper and lower units. The lower greenish gray, very poorly bedded part and unfossiliferous part is comprised of clasts that are as large as 2 meters in diameter. The clasts are mostly well-rounded and are composed of quartz plutonic rocks and siliceous volcanic rocks. The matrix is sandstone comprised mainly of quartz and feldspar with biotite and lithic fragments. Sandstone beds are rather rare. It is believed that the lower part is non marine in origin (Schoellhamer, 1981).

The upper part of the BCCM is more yellow-brown in color and has smaller clasts. Most of the beds are conglomeratic sandstone with some of the beds being finely laminated. There is better sorting in the upper part of the unit than the lower, and Schoellhamer (1981) interprets the origin as marine.

There is no correlation between the basement plutonic rocks beneath the BCCM and the plutonic clasts within it (Popenoe, 1941), and Popenoe (1941) and Schoellhamer (1981) conclude that the andesitic clasts are derived from the Santiago Peak volcanics. Later evidence demonstrates that the andesitic clasts are not from the Santiago Peak volcanics as thought. The ages of four andesitic clasts from the BCCM were analyzed using U/Pb zircon dating and yielded ages of 109 to 104 Ma which corresponds to a volcanic carapace of the Peninsular Ranges batholith that is now eroded away (Herzig and Kimbrough, 1991 in Abbott et al., 1998).

The locality where I sampled KLM03-2 is in Silverado Canyon just south of the turnoff to Ladd Canyon, on the west side of the road, north of the bridge. The UTM
coordinates are 11S 0440581; 3734179. The strike and dip of the strata are N10W; 40S. According to observations gathered at this locality, and those of Schoellhamer (1981), sample KLM03-2 is assumed to be from the upper BCCM. The unit is moderately resistant to weathering, thickly bedded with minor beds of thinly laminated sandstone. The pebble clasts (≤2.5 cm in diameter) are scattered in a matrix of medium to coarse-grained sandstone, with lenses and bands of clast-supported pebble conglomerates, and lenses of sandstone with no clasts (Figure 6). The degree of rounding is subangular to subrounded. Trough cross-bedding is present and molluscs such as scallop and clam fossil shells, casts and molds are found on the east side of the road in the cliff side. A rough analysis of 100 random clasts indicates that the majority of the clasts are andesitic with minor amounts of metamorphosed sedimentary pebbles. The composition of the matrix is as follows: 50% quartz, 30% lithic fragments, and 20% feldspar. The grains are angular to subrounded, with moderate to poor sorting, and silica cement.

It may be suggested that the combination of marine fossils, lenses and bands of conglomerate material with the coarse to medium grained sandstone on top, and trough-cross bedding indicate that the formation is full of turbidite deposits. The high amount of andesitic clasts suggests that this unit formed in a forearc basin.

**Vaqueros and Sespe Undifferentiated**

The late Eocene to early Miocene marine Vaqueros commonly overlies the nonmarine Sespe formation, however in many locations such as the Santa Ana Mountains and San Joaquin Hills to the south, the formations interfinger. More of the undifferentiated Vaqueros and Sespe formations are exposed in the Santa Ana Mountains.
than any other Mesozoic or Tertiary unit (Schoellhamer, 1981). The formations are predominately reddish stained sandstone, but with a closer look, the majority of the beds are light gray or tan. The Vaqueros and Sespe Undifferentiated is divided into three sections by Schoellhamer (1981): Basal conglomerate, sandstone and conglomeratic sandstone, and upper conglomerate.

The concentration of the unit description will be on the sandstone and conglomeratic sandstone because this was the section sampled. According to Schoellhamer (1981), beds are reddish to gray and buff feldspathic sandstone with numerous isolated pebbles and cobbles. Lenses of conglomerates are also present. In areas the sandstone is a “clayey feldspathic biotitic coarse-grained to conglomeratic sandstone, with a few brownish-red earthy sandstone layers…(Schoellhamer, 1981).” This description depicts the northeastern area of Schoellhamer’s map, however it also seems to describe the lithology of where KLM03-6 was collected.

The Vaqueros/Sespe Undifferentiated is both marine and nonmarine, as a result of the non-marine Sespe interfingering with the marine Vaqueros Formations. The Sespe is considered non-marine because of it’s red color (an indicator of an arid environment) and the lack of marine fossils. The vaqueros has marine fossils. The age of the Vaqueros/Sespe Undifferentiated is thought to be between the Eocene and Miocene (Schoellhamer, 1981).

The sample was collected (Figures 5, 7 and 8) on the northeast corner of Jamboree and Irvine Park Drive by the water line valves and fire hydrant (UTM coordinates: 11S 0429683; 3739630). The exposure is poor, and a local sandstone unit has a strike and dip of (N18W; 20S). The rest of the exposed outcrop not covered by
vegetation was severely weathered, probably mainly due to foot-traffic. The yellow/tan, thin to thickly bedded sandstone collected is medium to coarse-grained, poorly cemented by calcite, moderately sorted, and poorly compacted (Figure 8). The grains are angular and consist of 75% Quartz, 20% Feldspar and 5% Biotite.

**Methods**

**Sample Preparation**

The collected samples were sent to Apatite to Zircon, Inc. in Idaho to be pulverized and the minerals separated using gravimetric and magnetic techniques. Upon return, the apatite minerals were set in an epoxy of one part hardener to five parts araldite. The mixture was stirred slowly for about five minutes, cautiously preventing the formation of air bubbles. Apatite grains were then placed in the wet epoxy spread in an area of 1 × ¾ inch on 2 × 1-inch slides and prodded to ensure the grains sank below the surface of the epoxy. The slides were then placed on a hot plate for 20 to 30 minutes to dry.

After a day of drying the samples were ground and polished. Two grinding wheels were used: one with 320 grit and the other with 620 grit sandpaper. First the samples were ground for only a few seconds and checked under the microscope. If the grains were not well exposed, the slides were ground for a few more seconds, and so on until the grains were sufficiently exposed in the epoxy. The slides were then ground upside down, in the same manner, on the 620 grit paper to remove the rainbow-shaped scratch marks from the first wheel. The slides were washed thoroughly in a beaker of water and dish soap to remove the grit.
The polishing wheel was set up with a Metcloth polishing cloth, and the solution used was 10:1 deionized water to 0.3 micron alumina paste. The polishing wheel was set at the highest speed and the cloth was saturated with the deionized water and then added alumina solution before polishing began. Polishing required ample pressure applied to the slide as it was moved in a circular motion, opposite to the spin direction of the wheel. Each polishing session was for 30 seconds at a time and after three sessions the slide was checked under the microscope to check for any remaining scratch marks. If so, the slide was polished again. Once the polished slide was devoid of most scratches, it was washed and dried.

The mounted grains of apatite were broken into rectangular pieces 18 x13mm and then etched with 5 N nitric acid for 20 seconds at an ambient temperature of 23 degrees Celcius. This was done by dipping each mount in the nitric acid with tweezers, swirling for 20 seconds, immediately plunging the mount into a beaker of deionized water to rinse, and then submerging it in a second beaker of water to soak.

For each sample a sheet of mica was cut and taped to the face of the mount. Scotch Magic tape was affixed to the side of the mica that had the sample number scratched into it, and making sure the mount was perfectly clean, the mica was pressed snugly on top. Great care was taken to make sure the tape was stuck securely to the mount before using an exacto knife to cut the edges of the tape flush with the mount. The dosimeter glasses (CN-5) that were to be sent with the samples were prepared with mica sheets like the grain mounts.

The samples were then loaded into triga tubes to be sent to the reactor. Careful notes were taken to keep track of the order of sample placement in the tubes. A
dosimeter glass was placed at each end, and halfway through, the triga tubes. The mounts were stacked so that a piece of black rubber spacer separated the micas from two adjoining mounts. Each set of five or six mounts was compressed together and wrapped with scotch tape. The stacks were then placed in proper order inside a polyethylene tube with a cut off end of another tube as a lid to make the tube waterproof. The whole tube was then placed inside a triga tube.

After irradiation, tape was carefully removed from the micas by soaking in water overnight. The micas were then soaked in 48% hydrofluoric acid, in a Teflon beaker, for 18 minutes to etch the induced tracks caused by irradiation. Using Teflon tweezers, the micas were removed, rinsed in a beaker of deionized water and soaked in a second beaker of deionized water for a few minutes before rinsing in ethanol and drying in the oven. The grain mounts and micas were then glued onto slides using Sally Hansen’s Hard as Nails clear nail polish, with fission track side up.

**Zeta Calibration**

The standard samples used for calibrating a zeta factor were three irradiated samples from the Durango and Fish Canyon formations. Two slides from Durango and one from Fish Canyon in irradiation CSUF A1, and one slide each of Durango and Fish Canyon from irradiations CSUF A2 and A3 were counted; a total of seven age standards.

FT Stage 3.12B Fullerton was the program used in conjunction with a Olympus BX50 microscope and FT Stage Systems Digitizing Tablet. Grains selected for counting were those that were oriented with the C axis parallel or oblique (but not perpendicular) to the slide. Each grain, as viewed under the scope, was sketched (Appendix, see notes) and the spontaneous and induced tracks were counted. Twenty grains were counted from
each slide to get the best statistical representation, and the zeta factor was calculated on a spreadsheet for each grain. The sums/average of the zetas yielded a total zeta for the slide. Zeta factors are calculated using the equation (Dumitru, 1996):

\[
\zeta = \frac{1}{\lambda_t} \left[ \exp (t_{\text{std}} \lambda_t) - 1 \right] \left[ \rho_i / (g \rho_s) \right] (1 / \rho_d)
\]

where \( \zeta = \) zeta;

\( \lambda_t = \) the known decay constant for \(^{238}\text{U} \) \((1.551 \times 10^{-10} \text{ yr}^{-1})\);

\( t_{\text{std}} = \) known age of the sample (Fish Canyon: 27.9 ma; Durango 31.4 ma)

\( \rho_i = \) induced track density measured in tracks/ cm\(^2\) (induced fission of \(^{235}\text{U}\))

\( \rho_s = \) spontaneous track density measured in tracks/ cm\(^2\) (from natural fission of \(^{238}\text{U}\))

\( \rho_d = \) track density measured from the dosimeter

\( g = \) geometry factor of the external detector method \((0.5)\), which compensates for the probability that about half of the grain has been removed from the grinding in the preparation of the sample, so only about half as many induced tracks will form on the detector.

The zeta factors from the seven slides were then averaged to obtain a simple average. In addition a program called “ZetaAge” by Mark Brandon at Yale, was used to calculate a global weighted mean with a standard error. The same track-counting process used for calibrating a zeta factor was used for counting tracks in the samples.

**Measuring Track Lengths**

In order to determine if annealing had occurred, horizontal, confined track lengths were measured. This was done using the optical microscope, digitizing tablet, laser diode and drawing tube. First, the orientation of the c-axis of the grain measured was recorded.
The laser diode, seen through the drawing tube, was placed at two points parallel to the long side of the etch pits on the grain (which is parallel to the c-axis), and using a specific command on the digitizing tablet, was recorded. Then, the laser diode, was placed on each end of the track and recorded by the digitizing tablet. The length, in µm, and acute angle between the track orientation and the c-axis was displayed in the FT Stage program.

The chemistry of the grains was determined by measuring etch pit widths. Using the above procedure, the diode was placed on each side of an etch pit and recorded on the digitizing tablet.

**Results**

The mean ages calculated for KLM03-2 and KLM03-6 are 75.2 +/- 5 and 68 +/- 4.2 million years, respectively. The individual grain ages can be viewed on Tables 1 and 2. The grain-age distribution (Figures 9 and 10) for KLM03-2 and KLM03-6 shows the ages for the sampled grains to be between about 39 and 121 million years and 45 and 116 million years, respectively, with half of the grains being between about 63 and 92 million years and 59 and 72 million years, respectively. The probability of chi-squared values, indicating the probability of the grains to be from a single population, for both KLM03-2 and KLM03-6, are 0.0 for both.

The track length averages for KLM03-2 and KLM03-6 are 9.5 and 12.6 microns, respectively (Table 3 and 4). Sample KLM03-2 has a broad length distribution ranging between 4.45 and 14.6 microns (Figure 11) with a standard deviation of 2.2. Sample KLM03-6 has better defined, sharp peak of narrower distribution, and longer track
lengths: between 7.91 and 17.85 microns. The standard deviation is only 1.4 (Figure 12).

Dpar values are similar in both samples, and in a scatter plot of the age vs. dpar the trendlines in both graphs have similar slopes of 0.005 microns per million years for KLM03-2 (Figure 13) and 0.004 microns per million years for KLM03-6 (Figure 14). The slopes of the trendlines are shallow and the trendlines are not very representative of the points plotted, which is indicated by the low R^2 values of 0.16 and 0.31 for KLM03-2 and KLM03-6, respectively.

**Discussion**

*Baker Canyon Member*

The wide age range of 39 to 121 Ma for the individual grains of KLM03-2, and a probability of chi-squared value of 0.0, indicate that the grains are from different populations. Grain chemistry was examined to determine if the grains came from different sources with their own unique thermal histories. High fluorine content in apatite causes tracks to anneal at lower temperatures than those with more chlorine, and therefore would cause the grain to appear to have come up through the PAZ more recently than it actually did. In the dpar measurements it is expected that the smaller dpar values (smaller etch pit widths) are recorded in grains with more fluorine, and therefore should be correlated with a younger age. When the measured dpar values of each grain were plotted against the ages of each grain, the dpar R-squared value of 0.16 (Figure 13) indicates that the best fit line is not very fit. A value of 1.0 indicates a perfectly fit line. The best-fit line with a slope of 0.005 indicates that there is some correlation between age
and dpar values. The lack of a highly representative best-fit line and a slight slope of the line suggest that the chemistry of the grains is not well correlated to the age of the grains, and therefore the chemistry differences cannot completely explain the wide age distribution.

The depositional age of the Baker Canyon member (89-91 Ma) is older than the fission track age of 77.1 Ma, indicating that some track annealing took place. The track lengths measured were annealed at varying degrees (Figure 11). The average track length from KLM03-6 of 9.5 microns is almost half the length of a un-annealed track. The standard deviation of 2.2 indicates that 66% of all track lengths fall within 2.2 microns on either side of the average, creating a slightly skewed, bell shaped curve. Path B of Figure 5 demonstrates that a bell shaped histogram of track lengths suggests that a sample was slowly buried deep enough to partially anneal some of the tracks, but not deep enough to anneal all of the tracks.

The sample was buried to at least the PAZ which is about 2 km, so the Baker Canyon member had to have at least 2,000 meters of material deposited on top of it at some point. Indeed, today the Baker Canyon member has approximately 2,700 meters of deposits between it and the Vaqueros and Sespe Undifferentiated.

**Vaqueros and Sespe Undifferentiated**

The wide age range of 45 to 116 m.a., and a probability of chi-squared value of 0.0 indicates that the sample may be composed of grains with different chemical compositions. However, upon examination of the dpar of the grains, the values were similar to those of KLM03-2. The dpar R-squared value of 0.31 (Figure 14) indicates that the best fit line is poorly fit. The best fit line with a slope of 0.004 microns per
million years indicates that there is a slight correlation between age and dpar. In this case, as well as with KLM03-2, the chemistry is not sufficient to completely explain the age distribution of the sample grains.

The depositional age (20–30 Ma) is younger than the fission track age of 68.7 m.a. This indicates that the sample has not been annealed; rather, the older age recorded by the fission tracks represents when the grains that compose the sample were leaving the PAZ. The sample as a whole was not buried deep enough to anneal the tracks much.

In this situation, track length analysis was important to determine the amount of annealing that took place. The average track length is 12.6 and the standard deviation is 1.4 (Figure 10). The average track length is still shorter than the un-annealed track, however significantly longer than the tracks in sample KLM03-2. The standard deviation also indicates that 2/3 of the tracks fall within only 1.4 microns of the average rather than the 2.2 microns of KLM03-2. The histogram is similar to histogram A of Figure 9 by Ravenhurst (Figure 13) where the majority of the tracks are long. This figure indicates that the sample was not buried enough to significantly anneal many of the tracks.

Proposed geologic and thermal history

The Mesozoic batholiths of the western United States formed during the subduction of the Pacific Plate beneath the North American Plate (Gilluly, 1963). The Southern California Penninsular batholith is part of this group and was formed during the Jurassic around 100 Ma according to Hoppe (personal communication). In addition to the batholiths, volcanic arcs formed and were deposited after the batholiths during the late Jurassic or early Cretaceous (Schoellhamer, 1981), among these being the Santiago Peak volcanics (Figure 15a).
The Baker Canyon member of the Ladd Formation was deposited during the early Cretaceous between 89 and 91 Ma (Schoellhamer, 1981) as a result erosion of the batholith and volcanic deposits (Figure 15a). The Baker Canyon member most likely was deposited in a forearc basin depositional environment and was subsequently buried by about 2,700 meters of sediment over the next 60 million years or so (Figure 15b).

Approximately 37 Ma the East Pacific Rise, part of the Pacific Plate, was subducted beneath the North American Plate, but due to its buoyancy, coastal and southern California were lifted up and exposed (Figure 15c). This triggered erosion and exhumation. The eroded material was deposited in the form of the non-marine Sespe and marine Vaqueros Formations (Dickinson et al, 1987) around 20-30 Ma (Schoellhamer, 1981). Shortly after, in the Miocene, the Elsinore-Whittier Fault became active (Burrato and Yeats) and began to uplift the Santa Ana Mountains. This caused further exhumation and tilting of the beds to the south (Figure 15d).

In this manner, the sampled part of the Baker Canyon member was exhumed from the partial annealing zone to the surface, and the Sespe and Vaqueros Undifferentiated was never buried deep enough to cause much annealing to take place.

**Conclusion**

Fission track ages were obtained for each sample as a starting point to help us see the time since the rocks began exhumation. Dpar measurements were used to determine that chemical compositions of the grains could not completely explain the wide range of ages for each sample. Track length measurements were used to ascertain the amount of annealing, and from that the minimal amount of burial that the rock had to experience.
Further work is needed to constrain the burial amounts, and repeated fission-track dating would be useful to get a more representative age for each sample.

References


Figure 1. Regional map of the Santa Ana Mountains and surrounding area, showing the primary geomorphic and tectonic features. EF= Elsinore Fault, WF= Whittier Fault (Wright, 1991)
Figure 2. Regional geologic map of the Santa Ana Mountains showing lithologic units (Morton et al, 1981).
Figure 3: Geologic Map of a portion of the Northern Santa Ana Mountains along the Santiago and Silverado Canyons (Morton and Miller, 1981). Sample locations are indicated. North is towards the upper left-hand corner, one inch equals about a mile.
Figure 4. Photograph of the sampled Baker Canyon Member, KLM03-2, showing the lenses and bands of andesitic clasts.
Figure 5. Photograph of the sampled location for KLM03-6
Figure 6. Photograph of the sampled outcrop for KLM03-6
Figure 7. Histogram and line graph of the grain-age distribution for KLM03-2, where x-axis represents million of years.

Figure 8. Histogram and line graph of the grain-age distribution for KLM03-6 where x-axis represents age in millions of years and y-axis represents number of tracks.
Figure 9. Histogram showing the number of tracks per measured track length for KLM03-2

Figure 10. Histogram showing the number of tracks per measured track length for KLM03-6
Figure 11. Scatter plot showing the correlation between grain age and dpar value for KLM03-2
Figure 12. Scatter plot showing the correlation between grain age and dpar value for KLM03-6

The equation of the best-fit line is $y = 0.004x + 1.5065$ with $R^2 = 0.3076$. The data points and the linear regression line are shown on the graph.
Figure 13. Graph of temperature vs. time with resulting track length histogram for rocks with varying thermal histories (Ravenhurst, et al, )
Figure 14. Generalized stratigraphic column showing relative sample stratigraphic ages and stratigraphic thicknesses (Schoellhamer, 1981).

**KLM03-6**
Stratigraphic age: 30-20 m.a.

**KLM03-2**
Stratigraphic age: 91-89 m.a.
Figure 15. Drawing to demonstrate the onlap sequences
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<th>rhoS (x10^6 cm^-2)</th>
<th>rhoI (x10^6 cm^-2)</th>
<th>rhoD (x10^6 cm^-2)</th>
<th>rhoS/rhoI</th>
<th>FT age</th>
<th>+/-</th>
<th>SUM1</th>
<th>SUM2</th>
<th>FT age</th>
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Chi-squared= 40.6008  
This value has a 0.5 term in it, but don't know why

P(Chi-square)= 0.000%

Need to figure out how to compute P(chi-sq). Excel does it as long as use 2x the Chi-square above.
Chi-squared value based on Green (1981) - see comp book notes (Armstrong 9/97-)
Must make sure # degrees of freedom are right (num-1)
### TABLE 2
Calculated Ages for Each Grain Counted in Sample KLM03-6

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<tr>
<th>Grain #</th>
<th>NS</th>
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<th>Area units (×10⁶ cm²)</th>
<th>rhoS</th>
<th>rhoI</th>
<th>rhoD</th>
<th>rhoS/rhoI</th>
<th>FT age</th>
<th>+/-</th>
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| Pooled-> | 2453 | 8085 | 1612 | 1.521712159 | 5.01550868 | 1.301 | 0.30340136 | 69.4 | 3.0 |
| Mean->   | 68.7  | 2.7   |

Chi-squared= 42.7176 This value has a 0.5 term in it, but don't know why
P(Chi-square)= 0.000

Need to figure out how to compute P(chi-sq). Excel does it as long as use 2x the Chi-square above.
Chi-squared value based on Green (1981) - see comp book notes (Armstrong 9/97)
Must make sure # degrees of freedom are right (num-1)