Detrital Zircon Geochemistry of the Nacimiento Block, Santa Ynez Mountains, California

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Bachelor of Science in Earth Sciences

By
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Abstract

The long-lived California section of the North American Cordillera is one of the most studied continental margins in the world; however, erosion and deformation in areas along the San Andreas Fault and the Sur-Nacimiento Fault has erased sections of the Cordillera which could provide insight in Cordilleran processes. The lost sections are partially preserved in detrital zircons deposited alongside the arc in fore-arc basins such as in the Toro Formation of the Nacimiento block which represents the coastal central California equivalent to the Great Valley Group, located in the Santa Ynez Mountains. Geochemical analysis of the detrital zircons from the Toro Formation suggests that a previous unmapped fault thrust Tithonian to Valanginian (133.9-152.1 Ma) sedimentary rocks over Albian (100.5-113.0 Ma) rocks. Additionally, a low of U/Yb at 150 Ma, decreasing Yb/Gd with time, and fluctuating Th/U levels with highs during magmatic pulses and lows during lulls correlates with previous work done with similarly aged sandstones in the McCoy Mountains which represents the retro-arc basin. Rising Gd concentration is the driver for the lowering of Yb/Gd while Yb concentrations remained relatively randomly stable which suggest presence of garnet throughout the arc's lifetime and the appearance of titanite with age. Changes of the age distribution of the detrital zircon grains from pre-Cordilleran dominated Tithonian to Valanginian detritus to Cordilleran dominated Albian detritus suggest changes in the drainage networks. All together this study found records of geochemical and physical changes within the arc and physical changes to the Toro Formation on only a portion of the Nacimiento block. Additional studies up section into the Atascadero Formation would uncover additional records of the Cordillera as a whole.

Keywords: Nacimiento block, Salinian block, detrital zircon, REE, Great Valley Group, arc, forearc basin, Santa Ynez Mountain, California

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Lastly, as always, no amount of thanks is enough for my family for their support.

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Goals

Goal: To determine the how the California portion of the North American Cordillera changed with time from detrital zircons from the Toro Formation of the Santa Ynez Mountains

Subgoals:

Collect rock samples from the Toro Formation in Santa Ynez Mountains

Extract zircons from the rock samples

Go to University of California Santa Barbara to use Laser-Ablation Multicollect ICP Mass Spectrometry machine to date the zircons

Process the data for interpretation

List of Figures and Tables

Introduction

The Sierra Nevada magmatic arc and related sections (e.g., Transverse Ranges, Salinian block) in conjunction with the Great Valley forearc basin and the Franciscan mélange records the late California Mesozoic convergence along the western margin of North America (e.g. Hamilton, 1969; Dickinson, 2008). Typically, the existing surface expression of magmatic arcs provides an incomplete record of the whole magmatic system due to erosion of volcanic structures and burial of plutonic structures (Barth et al., 2013). Long-lived magmatic arcs may also dynamically evolve with time due to changes in tectonic and/or magmatic forces. This is the case for the Sierra Nevada and related magmatic arcs, and in particular, the Salinian block portion of the arc and forearc that has been partially excised by the Sur-Nacimiento Fault and transported hundreds of kilometers northwestward by the San Andreas Fault (Jacobson, et al., 2011; Page, 1966). Absent and/or deformed sections of this well-studied magmatic arc present a gap in our knowledge of the evolution of the Sierra Nevada magmatic arc.

One method of studying the missing and deformed portion of the Sierra Nevada magmatic arc is by studying the detrital zircons from the geologic units within the Great Valley forearc basin, the Franciscan mélange and any other sedimentary basins nearby the magmatic arc such as a retro-arc foreland basin. Detrital zircons, which capture information about the age and geochemical composition from the now-eroded rock from which they were derived, can help to piece together the history of the arc (Barth, et al., 2013). Because zircons from sedimentary rocks are derived from a multitude of igneous source rocks, this method provides an integrated view of the arc that is particularly applicable to questions regarding temporal changes (e.g. Triassic v. Cretaceous) and spatial changes (e.g. northern Sierra Nevada v. Southern Sierra Nevada), and that is left under-sampled by studies that focus on the geochronology and geochemistry of single bedrock outcrops alone.

This work examines detrital zircon age and geochemistry from turbidites from the Toro Formation of the Nacimiento block (Seiders, 1983) located within the Santa Ynez Mountains. In addition, the results from the detrital zircons of the Nacimiento block is then compared to detrital zircon data from Barth, et al. (2013) derived from the McCoy Mountain Formation located in a former retro-arc foreland basin (Barth, et al., 2004). Together, these two records will provide higher-resolution record of arc composition and greater insight into the Sierra Nevada evolution.

Geologic Setting

The components of a continental–ocean convergent margin including the magmatic arc, forearc basin and accretionary prism are recorded in California by the Sierra Nevada batholith and related sections, the Great Valley Group, and the Franciscan mélange, respectively (e.g. Hamilton, 1969; Dickinson, 2008). The Sierra Nevada batholith and related sections are a composite of Triassic through Cretaceous (~230–90 Ma) plutons and is a record of the melting in the mantle wedge during the subduction of the Farallon plate (e.g., Chen and Moore, 1982). The arc records three magmatic pulses: *p1* from 240–215 Ma, *p2* from 180–150 Ma, and *p3* from 110–75 Ma that are separated by magmatic lulls *l1* and *l2* (Barth, et al., 2013; Glazner, et al., 1991). The Great Valley Group sedimentary rocks consist of a variety of sediments in the form of turbidites derived from the Sierra Nevada magmatic arc and interior terranes (e.g., Hamilton, 1969; Surpless, et al., 2002), and deposited in the growing forearc basin. Lastly, the Franciscan mélange is a chaotic mixture of coherent blocks of sedimentary rocks (e.g., greywacke, shale) and high-grade metamorphic rocks (e.g., serpentinite, blueschist, and eclogite) within a muddy matrix derived from oceanic crust and sediments from the continent and mixed through a variety of processes in the accretionary prism.

In the central California coast, the convergent margin terranes are correlated with the Salinian block magmatic arc and the Nacimiento block mélange and forearc basin remnants (Barbeau, et al., 2005; Gilbert and Dickinson, 1970; Jacobson, et al., 2011; Seiders, 1983). The Nacimiento block lies southwest, adjacent to the Salinas block with the Sur–Nacimiento Fault separating the two; together these blocks lie southwest of the San Andreas Fault (Seiders, 1983). Beginning between 68 Ma through 75 Ma, either thrusting or sinistral strike-slip displacement on the Sur–Nacimiento Fault gradually removed the western portion of the arc from the Salinan block and the eastern to central portions of the forearc basin from the Nacimiento Block (Jacobson, et al., 2011).

The Toro Formation lies structurally above the Franciscan mélange within the Nacimiento Block, and contains classic thin-bedded turbidites and lenses of pebble and cobble conglomerates (Seiders, 1983; Dibblee and Ehrenspeck, 1993) that rarely preserve fossils. Based on sandstone petrography, Gilbert and Dickinson (1970) have correlated the Toro formation with the lowermost exposures of the Great Valley group of the Sacramento and San Joaquin Valleys, and suggested that it represents the southern extension of the Great Valley Group. Additionally, when the Nacimiento and Salinian blocks are restored to their original pre-San Andreas location, they are placed within the Mojave Desert and the Peninsular Ranges regions east of southern California (Barbeau, et al., 2005; Barth, et al., 2004; Jacobson, et al., 2011). The Toro Formation represents the southern California cordilleran forearc terrain which records the development of the Salinian block and related magmatic arcs such as the Sierra Nevada via the sediments, particularly zircons, derived from the arcs.

Previous geochronological and geochemical research by Barth, et al. (2004, 2013) on detrital zircons from McCoy Mountain Formation in southern California west of the Mojave Desert and Peninsular Ranges region found dates that closely correlate with the magmatic history of the arc. They suggest that changes in the geochemical signatures of the detrital zircons are indicative of regional trends displayed by the arc rocks during the different magmatic pulses and lulls, and are likely related to changes in the tectonic setting of the evolving convergent margin through time (Barth, et al., 2013; Glazner, et al., 1991). In particular, they observed that during the three magmatic pluses, Th/U is higher than during magmatic lulls, whereas Yb/Gd trends toward lower averages with time. Additionally, U/Yb is high in *p*1 and *p*3, with a low at *p*2 (Barth, et al., 2013). The McCoy Mountain is important to this project due to its location. Barth, et al. (2004) suggests that the McCoy Mountain Formation was deposited in a retro-arc behind the Sierra Nevada and related magmatic arcs and has stayed relatively near its source region. Furthermore, Barth (2013) suggested that a forearc location be sampled on a longitudinal transect and compared to retro-arc records such as present in Barth, et al. (2013). The Toro Formation on the Nacimiento Block fits the description and this work is to address this suggestion.

Results

Zircons from seven rock samples from the Toro Formation of the Santa Ynez Mountains were collected for U–Pb analysis, and trace elements, particularly rare earth elements (REEs), analysis (Figure 1, Table 1). Processing methods are outlined in Appendix A. The rock samples were taken from a northeast trending transect that is perpendicular to the northwest strike of the beds that generally dipped 60° to the northeast. Stratigraphic up was determined from cross beds in sample J130711A's collection site (Figure 2a), and indicate that the section should get younger towards the northeast. Several serpentinite diapirs and seams up to 10 m thick are found parallel to bedding within the lower part of the sampled section. The samples are generally very fine to fine-grained greywacke sandstones, although sample J130711C is a slightly coarser medium to coarse grain greywacke. J130711D is the second coarsest with abundant medium sized grains and has fossils within a lens (Figure 2b). The finest grained samples were J130711A and J130711H which are massive very fine grain and laminated very fine sand respectively. No sample was taken from J130711E due to poorly exposed outcrop (Figure 2c).

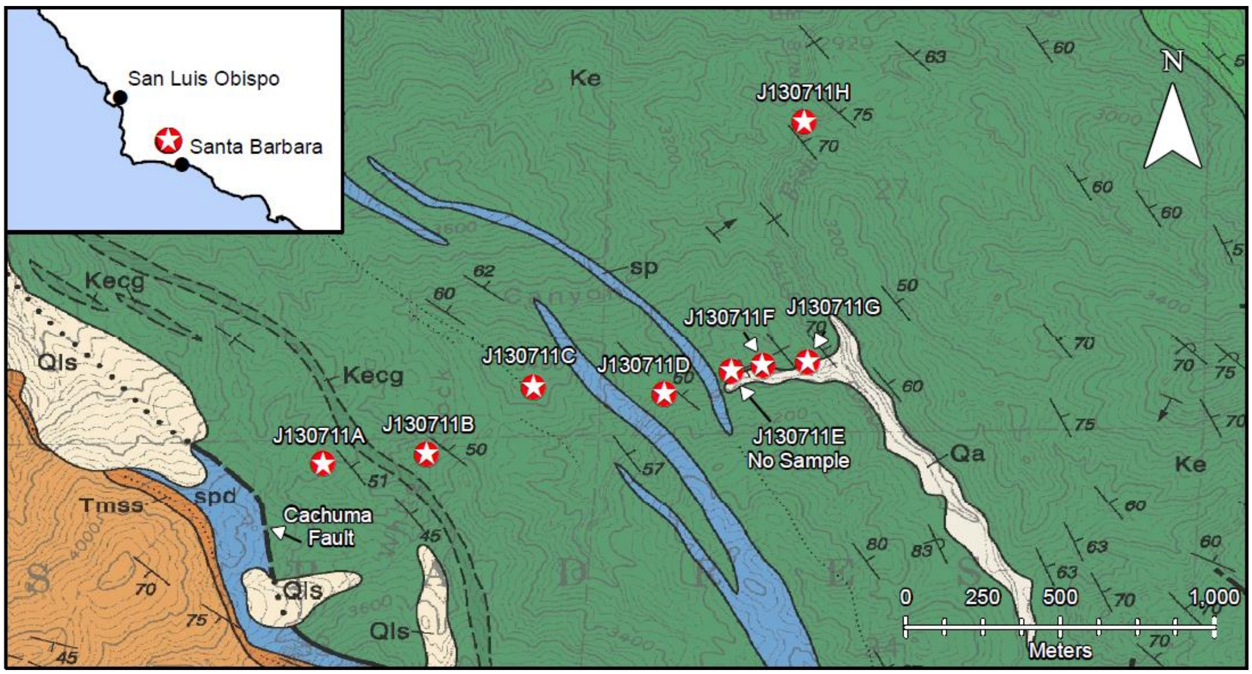

Figure 1. Geologic map of the Santa Ynez Mountains illustrating the locations of the samples. Insert is a regional map for the relative location of the field site. Light green in the upper right corner is Kcgm of the Cachuma Formation, equivalent to the Atascadero Formation. Ke and Kecg are part of the Espada Formation, equivalent to the Toro Formation. Serpentinized rocks are represented by sp and spd. The pale orange is Tm and together with Tmss are Tertiary units. Qa and Qls are Quaternary sediment. Modified from Dibblee and Ehrenspeck (1993).

Table 1. Sample descriptions. Bold indicates the dominant grain sizes in each sample.

Sample	Grain size (mm)	Grain Size	Type	Notes
J130711A	**finer**-0.08	vf	Greywacke	Fine, dark massive, cross beds
J130711B	0.10-**0.15**-0.25	vf-f	Greywacke	Grittier
J130711C	**0.20-0.33**-0.60-1.50	f-m-c	Greywacke	Rusty-pink clasts
J130711D	**0.25**-0.30-0.33	f-m	Greywacke	Fossil
J130711E	**NA**	NA	NA	Poor outcrop. No sample collected
J130711F	**0.15-0.20**-0.25	f	Greywacke	
J130711G	**0.15**-0.20	f	Greywacke	
J130711H	**finer**-0.08-0.10	vf	Greywacke	Laminated

Figure 2a (Top). Cross beds observed in sample J130711A.
Figure 2b (Left). Bivalve fossil found 2 m stratgraphically below sample J130711B.
Figure 2c (Right). J130711E sample location showing poor outcrop with Vincent Zhao for scale.

Zircons were separated from the samples using standard density and magnetic separation tecniques (see Appendix), and mounted in 1” epoxy rounds for laser-ablation split-stream multi-collector ICP analysis at UCSB. The zircons samples were corrected with analyses of zircon standards 91500 (standard age of 1065 Ma, Wiedenbeck, et al., 1995) and GJ1 (standard age of 608.5 Ma, Jackson, et al., 2004), which were analyzed every fifth unknown. Secondary standards SL and Plesovice were also analyzed during each analysis session to ensure accurate results. Fifty-six zircons were analyzed for each of the first six (i.e., J130711A to J130711D, J130711F and J130711G) samples, with seventy-one zircons analyzed for the seventh (i.e., J130711H) sample. Seven grains are greater than 10% discordant were eliminated from further geochemical analysis.

U–Pb ages from all the zircon analyses with special attention to Cordilleran grains were plotted as histograms with a cumulative probability curve superimpose to display both the age measurement and uncertainty of the age measurement (Figure 3). The Toro Formation shows distinct peaks in Mesozoic time (252.2 Ma to 66.0 Ma, Gradstein, et al., 2012) with the prominent peak at 107 Ma (Albian) and lesser peaks at 137.8 Ma, 151 Ma and 161.2 Ma (Late Jurassic to Early Cretaceous). Out of the 234 Mesozoic zircon grains, 212 are younger than 180 Ma, which roughly coincides with the start of *p*2.

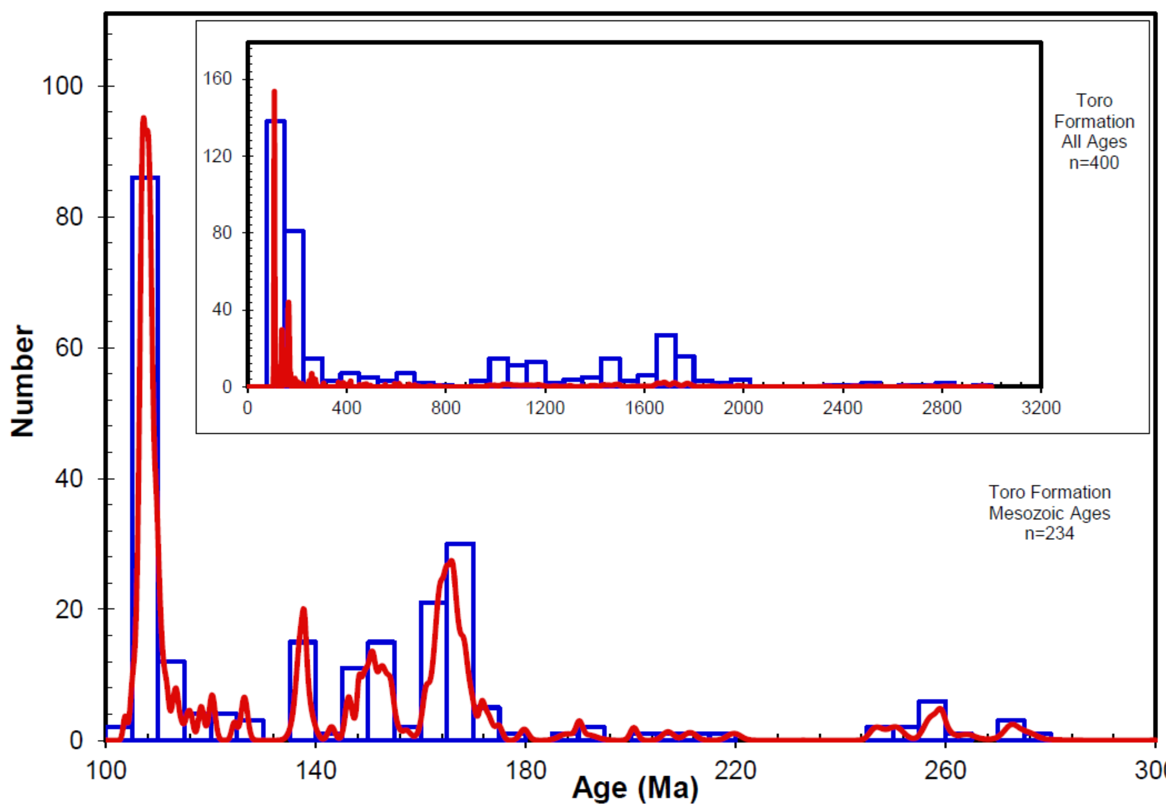

Figure 3. Detrital zircons age histograms for all the samples from the Toro Formation plotted at two time scales to highlight the complete age distribution and the Mesozoic age distributions.

The detrital zircon grains when segregated into Cordilleran (<300 Ma) and pre-Cordilleran (>300 Ma) grains and by sample location to determine maximum depositional ages (i.e., the youngest detrital zircon of the sample) of each sample. The maximum depositional age give us the age of the layer and when ordered stratigraphically, we can determine if they are in chronologic order. The Cordilleran grains were then mapped on a stratigraphic column which shows Tithonian to Valanginian (133.9-152.1 Ma) beds sandwiched between Albian (100.5-113.0 Ma) beds (Figure 4). This suggests an unmapped thrust fault between J130711B and J130711C which placed the Valanginian to Tithonian rocks beds over the Albian beds. Additionally the samples show differences in their major source for their detrital zircons separated by their max depositional ages (i.e., Tithonian to Valanginian versus Albian). Albian samples (J130711A, J130711B and J130711H) consist of 74.5%, 73.2% and 69.0% Cordilleran grains respectively, while Valanginian samples (J130711C, J130711D, J130711F and J130711G) consist of only 45.5%, 42.9%, 53.7% and 47.2% Cordilleran grains respectively. This suggests changes in drainage networks that controlled how much sediment from each source got transported, in the case of this study, pre-Cordilleran detritus (e.g., detrital zircons) got diluted with time. When the pre-Cordillera grain were plotted on histograms (Figure 5), samples J130711A, J130711B and J130711C did not have anything older than 2000 Ma, and sample J130711D did not have grains younger than 700 Ma. As a whole, the samples shows similar peaks that suggests pre-Cordilleran sediment sources remained unchanged. Any changes with the distribution of pre-Cordilleran grains may reflect the limited sample size.

The Cordilleran detrital zircon grains were also simultaneously analyzed for trace elements. Following Barth, et al. (2013), these zircons were sorted by age into 10 Myr time intervals from which average trace element ratios were calculated (Figure 5).

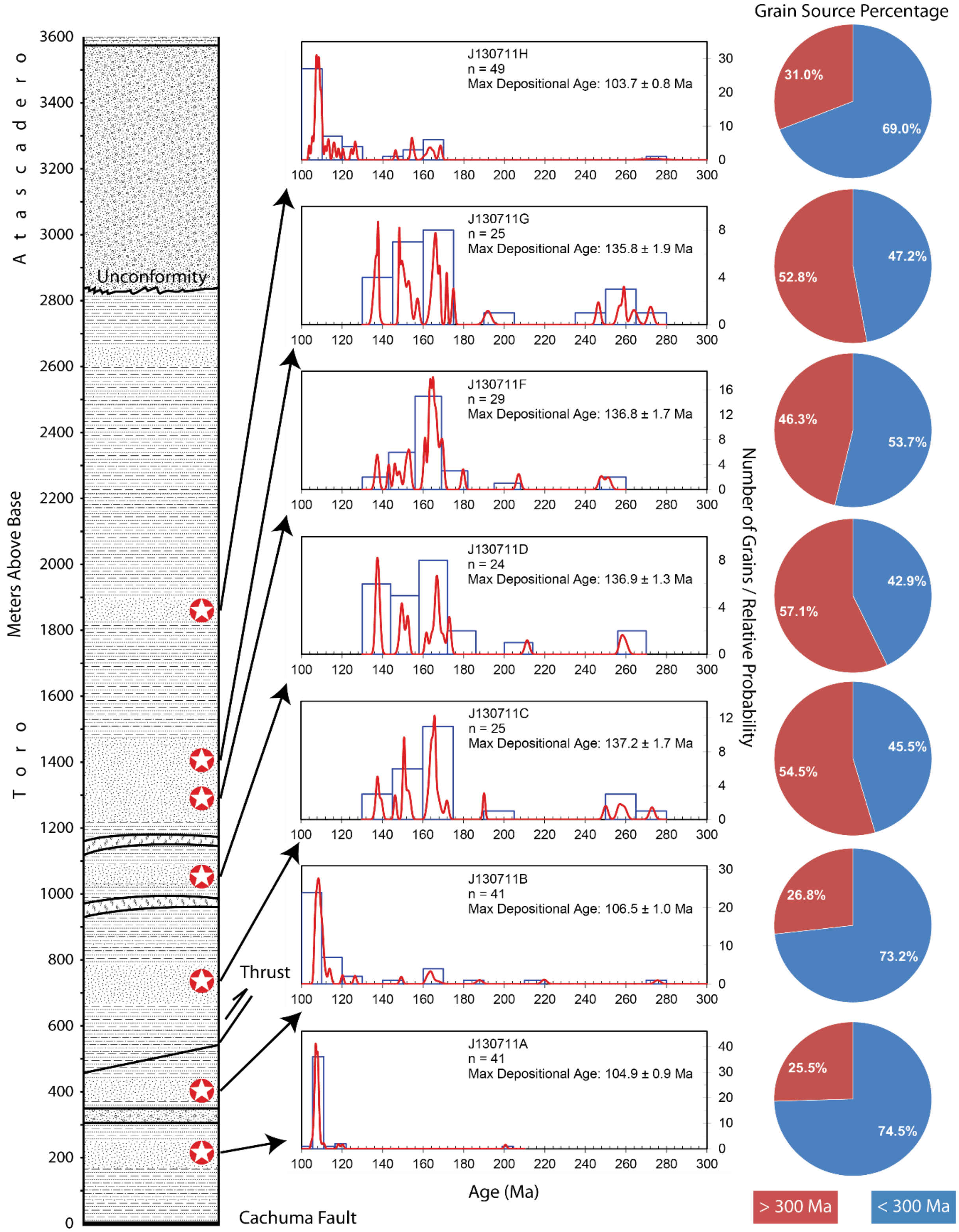

Figure 4. Schematic stratigraphic column of the Toro Formation and the lower portion of the Atascadero Formation with relative locations and Mesozoic detrital zircons age histograms and pie charts for each sample in pie charts, Cordilleran grains (blue) are between 100 Ma and 300 Ma and pre-Cordilleran (red) are older than 300 Ma.

U/Yb peaks at 210 Ma during *l*1 with a local peak at 110 Ma and a low at 150 Ma. Yb/Gd shows a general trend of lower Yb/Gd with time, but shows a significant peak at 200 Ma and a local peak at 270 Ma. When Yb and Gd are plotted against Yb/Gd and age (Figure 7), Yb/Gd is apparently more strongly correlated with variable Gd than with variable Yb. Additionally, although Th/U is generally elevated during p2, lower Th/U is observed from 170 Ma to 160 Ma.

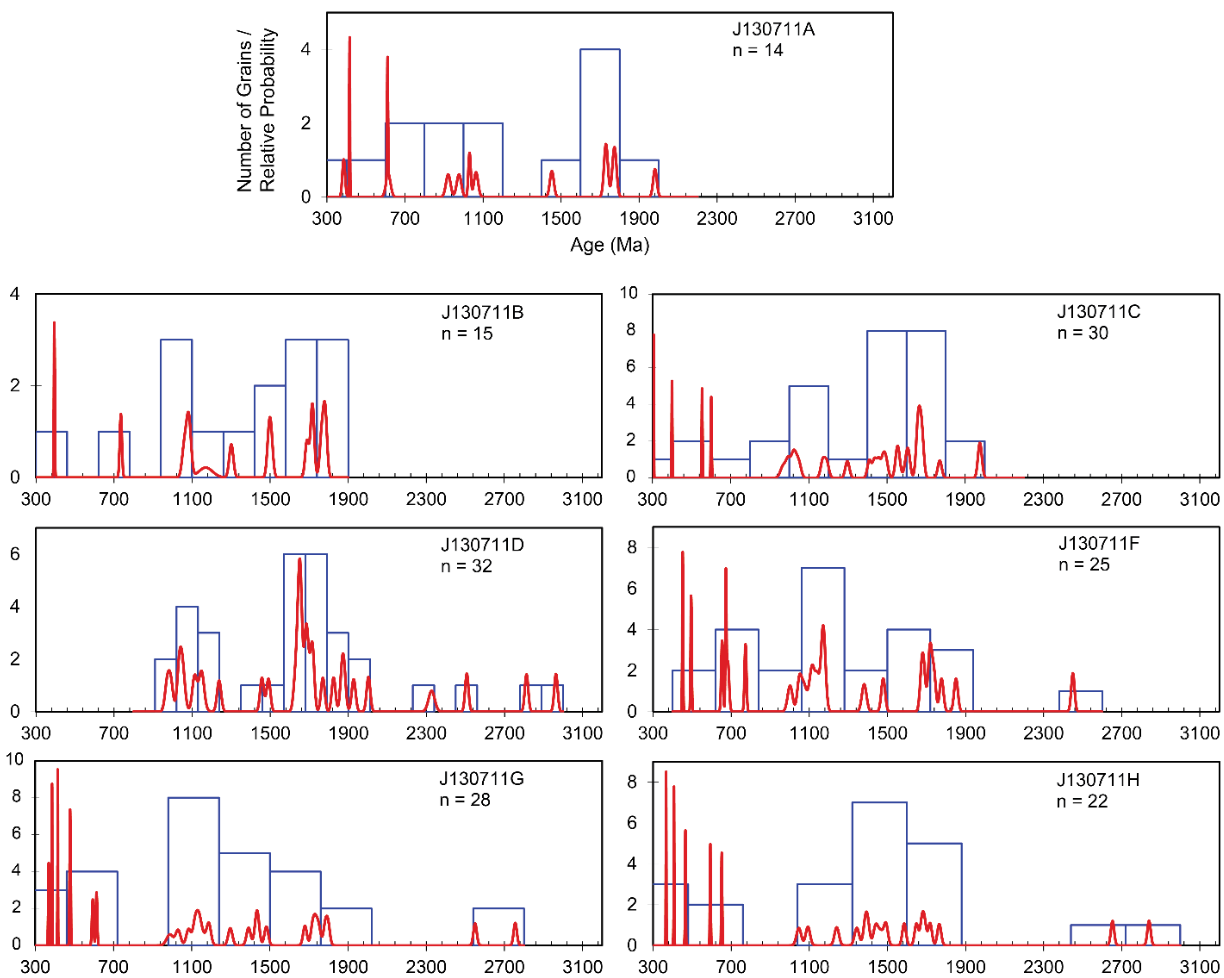

Figure 5. Pre-Cordillera detrital zircon age histograms.

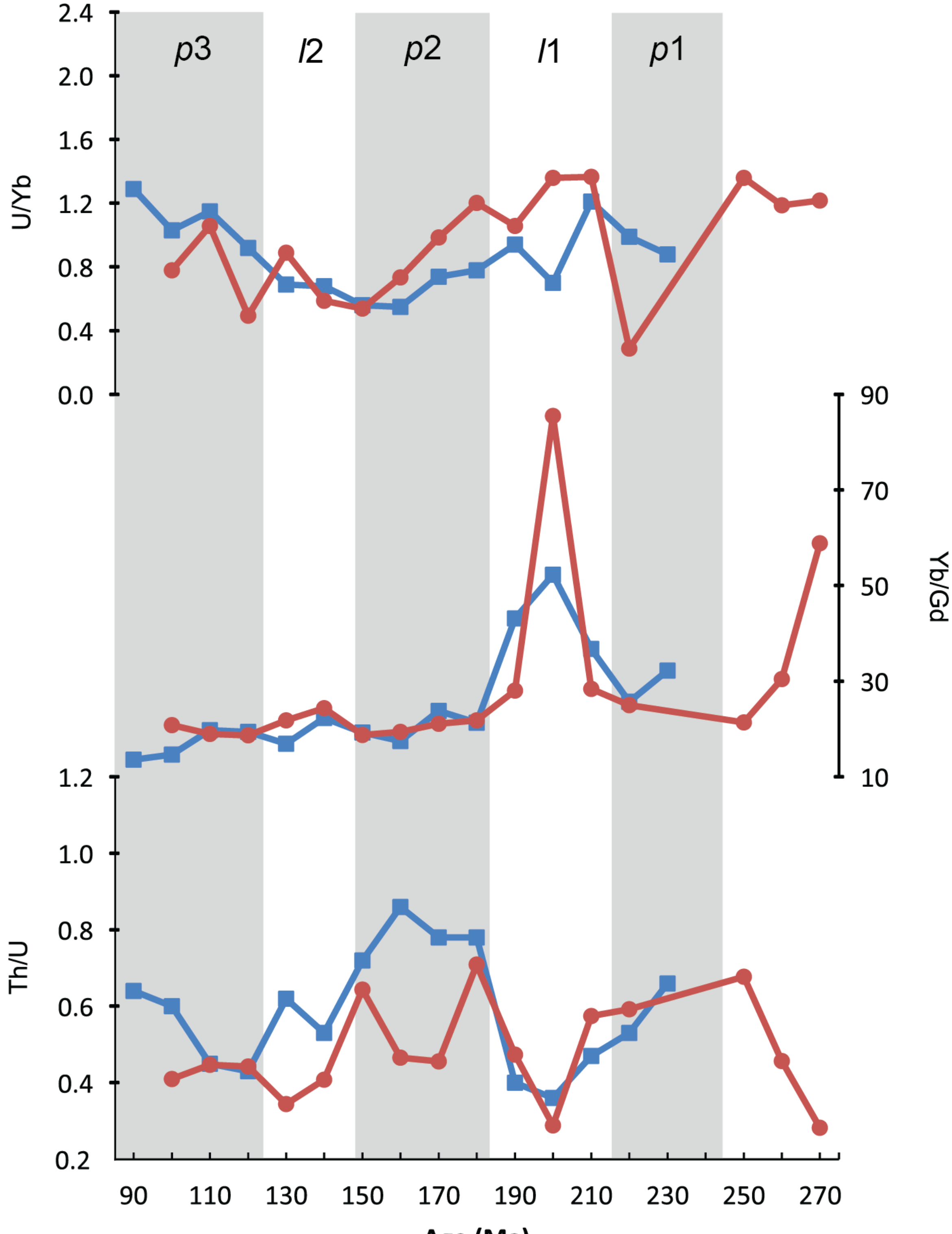

Figure 6. Geochemical composition comparison of the Santa Ynez Mountains detrital zircons (red circle) with the Barth, et al. (2013) McCoy Mountain Formation detrital zircons (blue square). Each square point represents an average composition of detrital zircons in a 10 m.y time window.

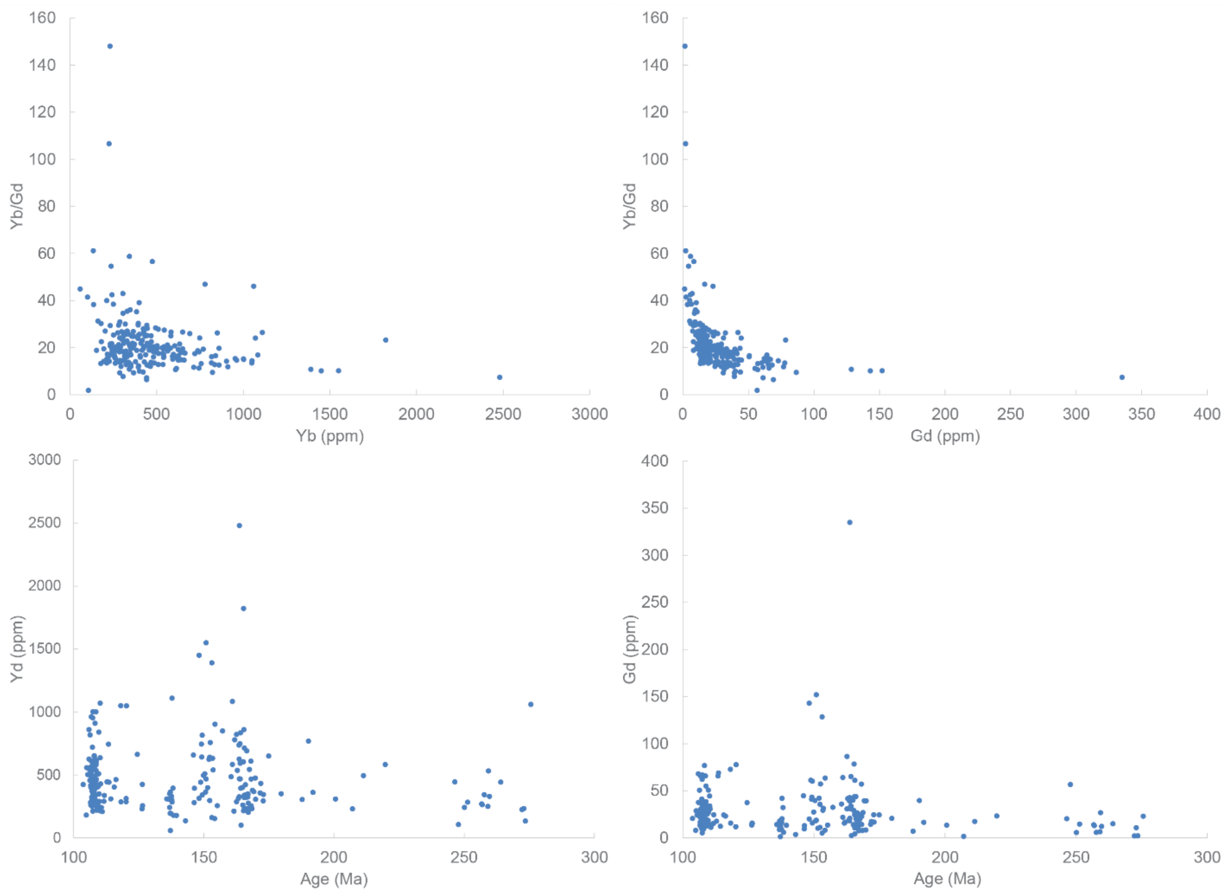

Figure 7. Yb and Gd comparison graphs between Age (Ma) and Yd/Gd in order to determine which element is responsible for the changes in Yb/Gd for the Toro Formation

Discussion

The Toro Formation in the Santa Ynez Mountains is a classic turbidite sequence with interlayered sandstone and mudstone with lenses of gravel beds. The lower portion of the formation has serpentinite belts that were either squeezed through faults or were thrust into place by faults. The unmapped fault between samples J130711B and J130711C may be related to how the serpentinite belts got to where they are or they are part of the more recent deformation by right-lateral slip related to the Hurricane Deck syncline. The age distributions also indicates that there is an apparent depositional hiatus in the forearc between the Valanginian and the Albian that lasted about 30 Myr and starting at roughly 130 Ma. The hiatus roughly correlates to and may be due to the latter part of *l*2.

In the study of magmatic arcs, together the ratios of U/Yb, Yb/Gd and Th/U can be used to explain major geochemical changes with the arc (Barth, et al. 2013). U/Yb is influenced by the presence of slab-derived fluids with high U/Yb being a characteristic signature of influx of slab-derived fluids (Hawkesworth et al., 1993; Pearce and Peate, 1995). The U/Yb low at 150 Ma may related to the apparent hiatus of the arc between the Valanginian and the Albian. Yb/Gd is the relationship between heavy REE (i.e. Yb) and middle REE (i.e. Gd) where a low Yb/Gd implies a melt depleted in HREE due to an increasingly thickened crust with garnet-bearing rocks in the residues (Barth, et al., 2013). The relative stability of Yb levels (Figure 7) suggests that the abundance of garnet in the residue did not change significantly with time. In contrast, the rise of Gd through time suggests MREE being incorporated into the melt and by extension, the zircons, could be related to fractionation of the MREE by titanite. Titanite plays a role in MREE concentration in the melt in the same way that garnet plays a role in HREE concentration in the melt: titanite and garnet preferentially incorporate their respective preferred REE into their crystal lattice. The increase in Gd with time suggests that either titanite was not fractionating in the lower crust as the melt was produced in the early history of the arc, titanite was not crystallizing with the zircons during the later history of the arc, or both. Lastly, Th/U is associated with the presence or absence of an aged lithospheric component—high in Th and$^{208}Pb/^{204}Pb$ —derived from continental sediment and assimilated into the rising arc magma (Hawkesworth et al., 1993, 1997). The peaks during the pulses suggest that aged lithosphere was heavily involved in those pulses. The low at 130 Ma also seems to correlate with the hiatus seen in the Mesozoic age detrital zircon distributions.

Taken as a whole, the patterns in U/Yb, Yb/Gd and Th/U of the detrital zircons from the Santa Ynez Mountains mirrors Barth, et al. (2013) findings for the McCoy Mountain; however, there are two or three periods which differ from their findings.

1. The drop in U/Yb level at 220 Ma.
2. The jump in Yb/Gd level at 200 Ma.
3. The drop in Th/U levels between 150 Ma through 180 Ma.

The drop in U/Yb level and the jump in Yb/Gd level might be more of a product of the lack of detrital zircon data. The period from 180 Ma to 270 Ma have 22 grains compared to the period of 100 Ma to 180 Ma which have 234 grains. A result of this is a lack of data during *p*1 time and being susceptible to extremes in data coming from one or a few zircon grains representing a 10 Myr average. The drop in Th/U levels suggests reduction of Th-rich crustal material.

Lastly, the similarity between the Santa Ynez Mountains and the McCoy Mountain suggest that either the Nacimiento block was adjacent to the southern CA arc prior to San Andreas displacement and therefore the Sur–Nacimiento is a thrust fault, or the arc had regional-scale variations in geochemistry that were consistent along strike and can be correlated temporally.

Conclusion

U– Pb age and trace elements concentrations were measured in zircons extracted from Toro Formation greywackes within the Santa Ynez Mountains. Maximum depositional ages indicate the presence of a previously unmapped thrust fault that placed Valanginian to Tithonian beds over the Albian beds. This thrust fault is most likely related to recent deformation from right-lateral slip due to the fault being parallel to the Hurricane Deck sybcline. Trace element concentrations show similarities to results presented by Barth, et al. (2013) who investigated similarly aged sandstones from the McCoy Mountain. The Toro Formation yields zircons that display three magmatic pulses characterized by higher Th/U than adjacent lulls, and a trend toward lower Yb/Gd with time. Variable Yb/Gd is apparently more closely related to increasing Gd with time, suggesting that factors other than progressive HREE depletion during growth of the continental arc (e.g., Barth, et al., 2013) may be responsible for this trend. Low U/Yb during Jurassic time suggests a reduction of slab-derived fluids within the melt. Future work should be done to complete the transect of the Toro Formation and go continue up section into the Atascadero Formation to record the entire history of the arc through detrital zircon geochronology and geochemistry.

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Appendix

Materials

General
- Air compressor with blower
- Stereo Microscope
- Seven 1000 mL beakers
- Seven 250 mL beakers
- Watch glasses
- Deionized water
- Isopropyl alcohol
- Clean paper
- Cellulose Weighting Paper
- Filter Paper

Collection
- Rock Hammer
- Brunton compass

Coarse Separation
- Steel mortar and pestle
- Rock grinder
- Wire brushes
- Gold pan
- Two plastic tubs
- Heat lamp

Fine Separation
- Frantz Magnetic Separator
- Vacuum pump
- Hand Magnet
- Seven storage vials
- Lithium Metatungstate (LMT)
- Methylene Iodide (MEI)
- Four Buchner funnels and flasks
- Two Separatory Funnels
- Two burette stands
- Two stirrers
- Nitric acid

Mounting
- Mold
- Epoxy
- Sandpaper

Analysis
- Photon Machines Analyte 193nm excimer laser ablation system
- Nu Plasma multi-collector ICP
- Nu AttoM single-collector, high-resolution ICP

Methods

Collection
1. Moving from stratigraphically low to high, select seven outcrops along a transect perpendicular to bedding planes.
2. Collect about one kilogram worth of sample per outcrop while labeling each.
3. Mark the location and the attitude of the bedding planes on a map.

Coarse Separation
A. Grinding
1. Before and/or after each sample, brush, blow and if appropriate, wash off with soap and water, all tools and equipment.
2. Make three separate clean areas (Rock, pea and grinded) laid with clean paper.
3. Break down rocks as needed to fit into mortar and pestle. Brush down each rock.
4. Crush each sample to pea size pieces. Hold in 1000 mL labeled beakers.
5. Grind each sample to 0.10 mm and place back into their beaker and cover.

Methods (Cont.)

Coarse Separation (Cont.)

B. Panning
1. Before and/or after each sample, clean with soap and water each tool and equipment.
2. Make a clean area for panning and for the panned samples under a heat lamp.
3. In about 100 mL batches, wash out the clay and silt size particles with water until water is clear enough to see through. Dump the dirty water to a collection tub.
4. Pan out the less dense particles in a tub filled with water.
5. Pan and concentrate samples till roughly 50 mL worth of sample.
6. Place into 250 mL beakers.
7. Rinse out with deionized water three times.
8. Rinse with isopropyl alcohol.
9. Place under heat lamp to dry.

Fine Separation

A. Heavy Liquids (MEI Optional)
1. Before and/or after each sample, clean with soap and water each tool and equipment.
2. Wrap a hand magnet in paper and use it to remove any magnetic particles.
3. While the stirrer is running, place sample into the heavy liquid for 45 minutes.
4. Carefully pour out the densest minerals out from the separatory funnel into one set of Buchner funnel and flask.
5. Use vacuum pump to suck out sample dry.
6. Place sample onto a watch glass to dry under the heat lamp.
7. Filter out remaining heavy liquid into another set of Buchner funnel and flask to recycle.

B. Frantz Magnet
1. Before and/or after each sample, clean with isopropyl alcohol each tool and equipment. Blow dry with air compressor.
2. Slowly send through the sample through the Frantz Magnet.
3. Send sample through two more times at higher settings.
4. Check sample under microscope.
5. If pyrite abundant, place sample into nitric acid to dissolve pyrites. Rinse with deionized water and isopropyl alcohol and dry.
6. Place finished sample into labeled vials.

Mounting

1. Set sample into the epoxy.
2. Sand down one side till the sample is exposed.

Analyzing

1. Set the epoxy samples into mount.
2. Select at least fifty zircon targets per sample.
3. After every four sample runs, run at least two sets of three control zircon targets.
4. Reduce the data with the Iolite software.
5. Plot and analyze data with Isoplot.