U/Pb ages of Eocene and younger rocks on the eastern flank of the central Cascade Range, Washington, USA.

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Table of contents Page

List of Figures: Page

List of Tables and Graphs:

ABSTRACT

Geological units located on the eastern flanks of the central Cascade Range, the Summit Conglomerate of Natapoc Mountain, Sugarloaf Peak, Basalt Peak, Horse Lake Mountain, Pole Ridge, Wenatchee Dome at the Cannon mine, and the Wenatchee Formation east of the Columbia River, have not been well dated or constrained by high precision U/Pb techniques. Zircons separated from samples were submitted and prepared for U-Pb isotopic dating; analyses were performed by isotope dilution-thermal ionization mass spectrometry (ID-TIMS) at the Massachusetts Institute of Technology (MIT). Sixty-five dates were obtained from samples taken from igneous, sedimentary, and volcanic units from the region in and around the eastern flanks of the Cascade Range. The units sampled with results intrude crystalline basement or uncomformably overlie deformed lower Tertiary rocks. I compared those results where possible to previous work. The results reveal a robust post-Eocene tectonic history and contain evidence of late Oligocene, Miocene, and Pliocene volcanism. Specifically, the andesite of Natapoc Mountain dates to the early Pliocene at 3.981 +/- 0.053Ma. The Basalt Peak intrusion at the north intersection of the Coulter Creek and Entiat Faults dates to the late Oligocene at 27.42 +/- 0.017Ma; Sugarloaf Peak east of the Ential fault at the Eocene/Oligocene boundary at 36.0 +/- 0.43 Ma and the Wenatchee Dome intrusion through Eocene Chumstick Fm. at 44.447 +/- 0.027Ma. The results of this study represent the newest high-precision zircon U-Pb geochronology dates for the samples tested.

INTRODUCTION

The Cenozoic development of the fault-bounded Chiwaukum Structural Low (CSL) in the central Cascade Range of Washington State e.g., (Cheney and Hayman, 2009a, 2009b), was followed by an extensive period of intrusion, sedimentation and erosion. The Chumstick Formation and the younger volcanic and sedimentary units are particularly significant in understanding the geological evolution of the region. Important units that overlie both crystalline basement and Chumstick Formation have conflicting F/T and K/Ar dates with unacceptably large margin for errors (Naeser, 1983), and many important units have no precise dates (Cameron, 1981,1996). Works by Tabor, et al. (1984, 1987), Gresens (1983), Naeser et al., (1976, 1979) and Margolis (1989) all reported dates that constrain the geological history of units found in this study area (Fig 1). New precise dates help answer questions about complex geological timing and unconstrained structural relationships.

To settle open questions about the geological history of the region analyses of zircons were obtained from nine locations (13 individual samples) utilizing U/Pb Chemical Abrasion/Thermal Isotope Mass Spectrometry (CA/TIMS) empirical analysis by Bowring Geo-chron Labs (2011) and numeric analysis after McLean (2011) are reported. A total of sixty-five new U/Pb Thorium corrected concordia dates are included in this study (see appendix A).

STUDY AREA

The study area contains the fault bounded structural low as described by Cheney and Hayman (2009) set between Chiwaukum schist of the Lake Wenatchee area and the Swakane Biotite Gneiss east of the Columbia River. The study area is roughly a 40 km by 100 km parallelogram that trends northwest to southeast that includes all of the Chiwaukum Structural Low (CSL). A detailed outline of the study area is shown in Fig 1.

GEOLOGIC SETTING

Cascade Range

The Cascade Range is an anticline; the Miocene Columbia River Basalt Group in the Walpapi sequence highlights its south to southwest plunge in an antiformal map pattern (Cheney, 1994). A crystalline core of pre-Cenzoic age rocks abound in the north; south of Mt. Stuart younger Cenozoic sedimentary and volcanic rocks gradually become more extensive as the system continues southwestward into Oregon and northern California. The Straight Creek fault (SCF) is an Eocene dextral strike-slip system splitting the Cascade Range north-south with 90km of offset (Johnson, 1985) . Middle to late Tertiary regional exhumation of Creteaous and younger plutons occurs throughout the range.

Early Neogene exhumation and uplift dominates the regional geological processes seen today in the Chiwaukum Structural Low (CSL). Tertiary and younger sedimentary units of sandstones and conglomerates extend into the central and southern areas of the state. The Coulter Creek and Chumstick fault systems strike generally north/south with younger northwest trending dextral strike-slip faults cutting Cenozoic sedimentary and plutonic units (Cheney and Hayman, 2009).

The eastern flank of the central Cascade Range includes four major Cenozoic unconformity-bounded sequences (UBS) (Cheney, 1994, 1997). The UBS sequences of Eocene and younger continental sediments are some of the thickest alluvial sequences in North America (Evans 1984). Geologic and stratigraphic patterns show clear faulting; dextral strike-slip, normal, reverse, and oblique-slip, that demonstrate significant variation in Tertiary tectonically driven geological processes. Cheney and Hayman (2009) provided evidence that periods of reactivated high-angle reverse faulting creating structural lows that have been deformed by post-Miocene folding.

The Chiwaukum Structural Low and the surrounding region contain an amalgam of units representing volcanic island arcs, deep ocean sediments, tectonic terranes of metamorphosed ancient continental blocks, and basalts of deep marine origin, basalts of sub-aerial origin, proximal sediments, submarine fans, volcanic flows, tuffs, ash and glacially derived sediments. The relationships between the major faults to the north and west demonstrate strike/slip movements dated to the mid- Eocene (Miller and Bowring, 1990) that fostered the standard transtensional structural model of the region, which until recently was presumed correct without challenge. Cheney and Hayman (2009) present evidence that instead of a long uninterrupted period of filling and erosion late in the Eocene, the Chumstick Formation has structural clues that indicate an erosive history punctuated by occasional deposition from the early Eocene that supposes that the structural low is an erosional remnant of earlier Cenozoic deposition.

The Chumstick Formation is an arkosic sedimentary deposit of mudstone, sandstone, with inter-bedded tuffs, and conglomerate layers with clasts up to several meters. The formation is punctuated by volcanoclastic tuffs, dikes and sills (McLean, 2010). The sandstones, conglomerates and the shales reflect the two predominant fluvial and lacustrine depositional systems called the Chiwaukum Graben (after Willis, 1953; Gresens et al., 1981 ; Tabor et al., 1983, 1987; Johnson, 1985; Evans, 1994).

Metamorphosed supra-crustal rocks extending from the Columbia River westward to Sugarloaf Peak along the Entiat fault produced discordant F/T and K/Ar dates from the biotite-quartz feldspars and zircons sampled in the fault zone. Tabor et.al. (1987) reported correctly that very few dates have been published for post-metamorphic units in the CSL. To correct this deficiency, samples were collected from several levels of Natapoc Mountain, specifically from the summit andesite and the lower unit of volcanic deposits that lie unconformable on the Chumstick Formation. Both of these facts highlight issues that are addressed in this paper.

METHODS

Field mapping and sampling

The study areas are extensively forested with more than kilometer of strato-topography that is highly incised creating steep walled canyons. All major areas that have undergone erosion also have large volumes of fill from glacial and alluvial sediments, with upland areas partially covered with loess obscuring contacts. Regardless, there are enough appropriate fresh exposures in all cases to have high confidence in the identity of samples recovered from regional units. Mapping of the various sample sites was accomplished over a period of summer field seasons, from 2007 to present day.

Isotopic chronology/ U/Pb / zircons

Isotopic U/Pb analysis of nine samples to ascertain certain ages was carried out by quantitative analysis of the ratios between uranium and lead quantities via measuring the available levels present in zircon crystals separated from samples using generally accepted scientific processes. Zircons then undergo a chemical abrasion process to reduce Pb leakage and then were analyzed using an ISOTOPX at MIT geo-chronology labs, Mattinson (1970, 2005) Bowring et al. (2012).

The Uranium-Lead analyses were performed in exceptional clean-room conditions and carried out by isotope dilution-thermal ionization mass spectrometry (ID-TIMS) at the Massachusetts Institute of Technology (MIT) Sam Bowring Geochronology lab. Zircons for U-

Pb dating were separated from my 13 and samples dissolved using the chemical abrasion (CA) method (Mattinson, 2005), modified for single grain dating. Uranium (U) and Lead (Pb) isotopic analyses were carried out on a VG sector 54 IsotopX thermal ionization mass spectrometer (TIMS). All data reduction and error propagation was done using the U-Pb Redux software package (Bowring et al. 2011, McLean et al. 2011). ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ratios were corrected for initial exclusion of ^{230}Th from the ^{238}U decay chain using the model Th/U of the zircon, calculated from the ^{208}Pb/^{206}Pb ratio.

XRF composition analysis

XRF compositional geo-chemistry analysis was performed at Washington State University Geo-Lab of the 13 samples using in house standards. Table in Appendix C lists all results. Specific empirical information regarding the procedures, methodology, and integrity of the results are detailed in appendix C.

Geo-Chron Methodology

High precision isotopic ages from zircons were separated from 13 samples obtained from ten locations on the eastern flank of the central Cascade Range in Washington State. Zircons analyzed by CA-TIMS using the Bowring Geo-chronological lab located at The Massachusetts Institute of Technology via method standard by Bowring et al., (2006). Results for 9 of the 15 samples reported below by specific sample site. A summary of the all the concordia Th corrected U/Pb results are listed in Table 1 in Appendix A.

DISSCUSSION of RESULTS

ame and Lithology	Sample #	NA27 Location	Formal Description	Pubishied date	New Date	Significance	Cites
Summit Conglerate of Natapoc Mountain fm. Phenocrystic Andesite	LAG-506	10 T 0671935 5290729	Page (1939) Whetten (1976) Laravie (1976) Tabor et al. (1987)	No date	3.981Ma +/- 0.053 MSWD = 0.15 N=3	Previously undated Pliocene era volcanism	Page (1939) Tabor et al., (1987)
Natapoc at basal contact W/ Chumstick Arkosic Sandstone	LAG-615	10 T		No date			
Pole Ridge Shale Sandstone	LAG-604	10 T 0666217 5302725	Tabor et al. (1987)	45.5Ma via fiss track From Chumsti In Stratigraphi relationship	91.880Ma +/- 0.046 MSWD = 0.44 N = 4	Indeterminate	Evans, (1977)
Sugarloaf Peak Clino-Pyroxene Andesite	LAG-548	10 T 0685050 5292007	Page (1958) Gresens (1976)	No date	36.85 Ma +/- 0.43 No pref. Extreme Range N=3	Date for the Oligocene age flow related to Cenozoic intrusives	Laravie, (1973)
Basalt Peak Hornblende Andesite	LAG-603	10 T 0668380 5315690	Tabor et al.(1987)	No date ……	27.422 Ma +/- 0.017 MSWD = 0.25 N = 3	Previously undated litho and petrological relationship to other units In area.	Tabor (1987) Cheney and Hayman (2009)
Horse Lake Mountain Hornblende Andesite	608	10 T 0603995 5251945	Gresens (1976)	25.2Ma Fission Trk	Not Concordant Table 1 Apdx	youngest dextral N/S Constrains slip on 3 syste Leavenworth/Coulter/Entia Systems	Naeser, (1983)
Wenatchee Blue Grade. Shale/arkosic sandstone		10 T 0704133 5261076	Gresens (1976)	34.4 +/- 9.0Ma Zircon F/T Naeser(1978)	49.22Ma +/- 0.06 K/Ar	Indeterminate	Hauptman (1983) Gresens, (1976) (1983)
Wenatchee Dome (Cannon Mine) Rhyo-dacite	ESC-13148	10 T 702150 5252325	Margolis(1986)	~~ 45.4Ma K/Ar	44.447Ma +/- 0.027 MSWD = 0.74 N = 4	Defines lower limit of Dextral SE/NW strike/slip Crosscuts Chm Fm. new precise date.	Margolis(1986) Cameron(1981),(2007)
Tip Top Biotite-Gneiss	LAG-559	10 T 0685050 5256690	Cheney (1994)	No	290.548Ma +/- 0.077 MSWD = 0.15 N = 4 Discordant: ~90.7Ma	Indeterminate	Cheney (2001,2003) Cheney and Hayman (2009)

TABLE 1.

Location map of study area and sample sites

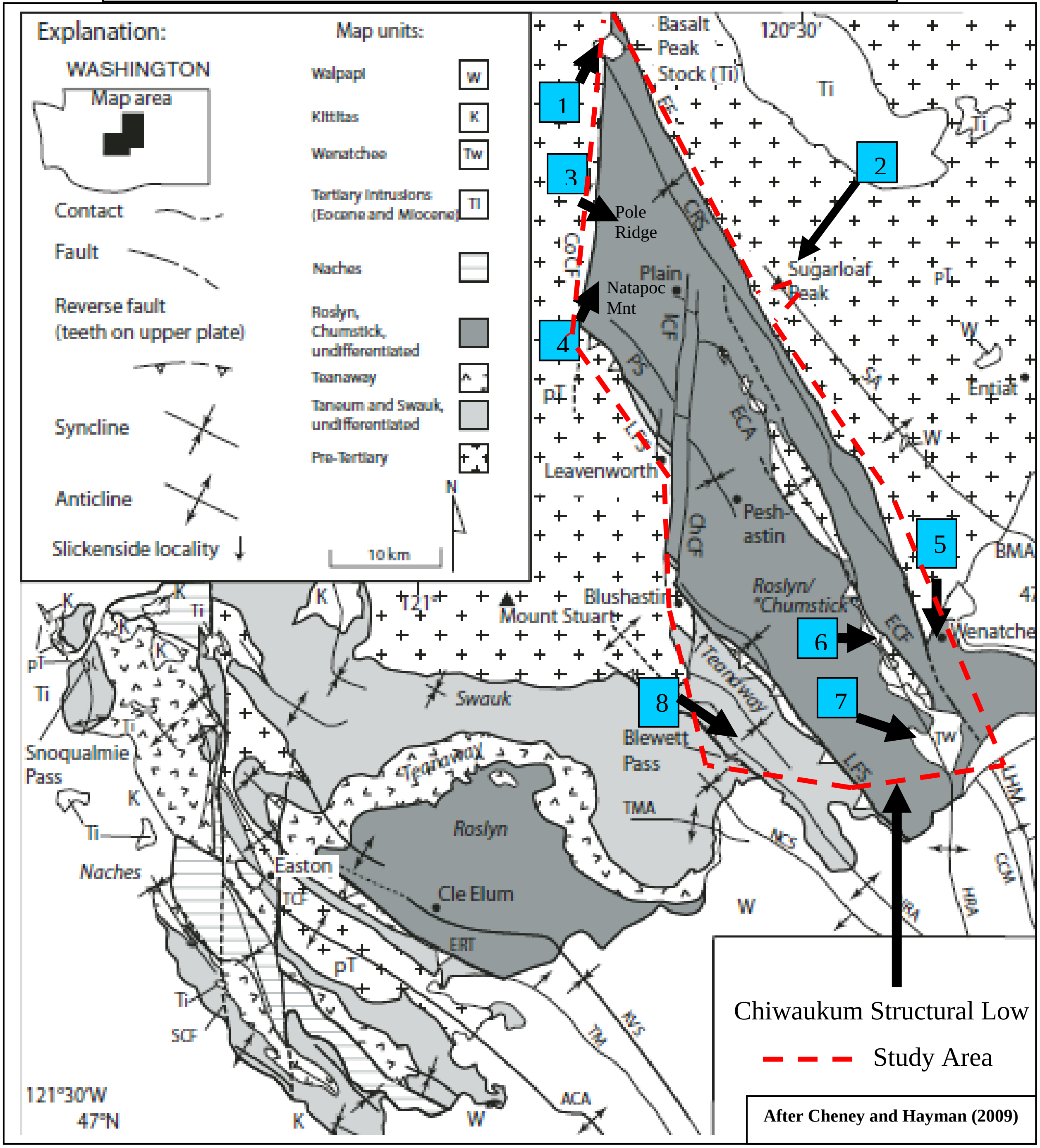


Figure 1.

Locations of all sample sites that results where are reported. Study area defined by dashed line. 1. Basalt Peak 2. Sugarloaf Peak (two locations) 3.Pole Ridge 4. Natapoc Mountain (4 locations) 5. Blue grade Wenatchee Fm. 6. Wenatchee Dome (Cannon Mine) 7. Horse Lake Mountain 8. Tip Top. Abbreviations are: ACA—Ainsley Canyon antilcline; BMA—Badger Mountain anticline; ChCf—Chiwawa River syncline; ECA—Eagle Creek anticline; ECF—Eagle Creek fault; EF—Entiat fault; ERT—Easton Ridge thrust ; HRA—Hog Ranch anticline; ICF—Icicle Creek fault; KVS—Kitittas Valley synclind; LFS—Leavenworth fault system; LHM—Laurel Hill monocline; NCS—Naneum Creek syncline; NRA—Naneum Ridge anticline; SA—Swakane Creek anticline; SCF—Straight Creek fault; TCF—Tucker Creek fault; TM—Taneum monocline; TMA—Table Mountain anticline.
NAD locations in table 1.

Summit Conglomerate: Natapoc Mountain

The Summit Conglomerate from Page (1939), Whetten and Laravie (1976) and later called the Natapoc Mountain formation by Laravie, (1976) is approximately 20km west of Leavenworth and 4km southeast of Lake Wenatchee (Fig 1). The Summit Conglomerate was formally described, but without dates by Page (1939). Laravie further differentiates the lower unit as the Natapoc Mountain formation capped by a phenocrystic andesite (Whetten, per.Comm.,1976). The modern description is mapped as the Summit Conglomerate by Whetten and Waitt (1977) and Tabor (Tabor et al, 1987) as a formal unit Qtup.

I will refer to the rocks on Natapoc Mountain as the Natapoc Mountain formation after Laravie (1976). The formation irregularly crops out from an elevation of1270m to the 1335m summit. The Natapoc Mountain formation is composed of a Pliocene upper unit that crops out at the summit and lower unit consist of undetermined age uncomformably overlying the Eocene Chumstick. The lower unit a poorly sorted and poorly indurated debris flows, both texturally and compositional immature. Multiple volcanic, debris and laharic flows repeat in a series of matrix and clast supported poorly bedded deposits. There is a ten to one ratio of volcanic to crystalline clasts in two reverse graded deposits that are nearly horizontal. This unit is composed of light-gray to buff- white fine-grained sandy tuffaceous debris flow. The lower unit from 0.0m to 9.5m (fig 2)is a reversely graded bed that contains large rounded boulders of volcanic rocks as much as 2 meters in diameter, interspersed with reverse graded fine to pebble sized matrix. Below is a measured schematic stratigraphic column of the exposed lower unit of the Natapoc Mountain formation section where two of the three repeated flows are identified in Fig 2.

NATAPOC MOUNTAIN SCHEMATIC STRATIGRAPHIC COLUMN

Measured from 1270m to 1292m above mean sea level

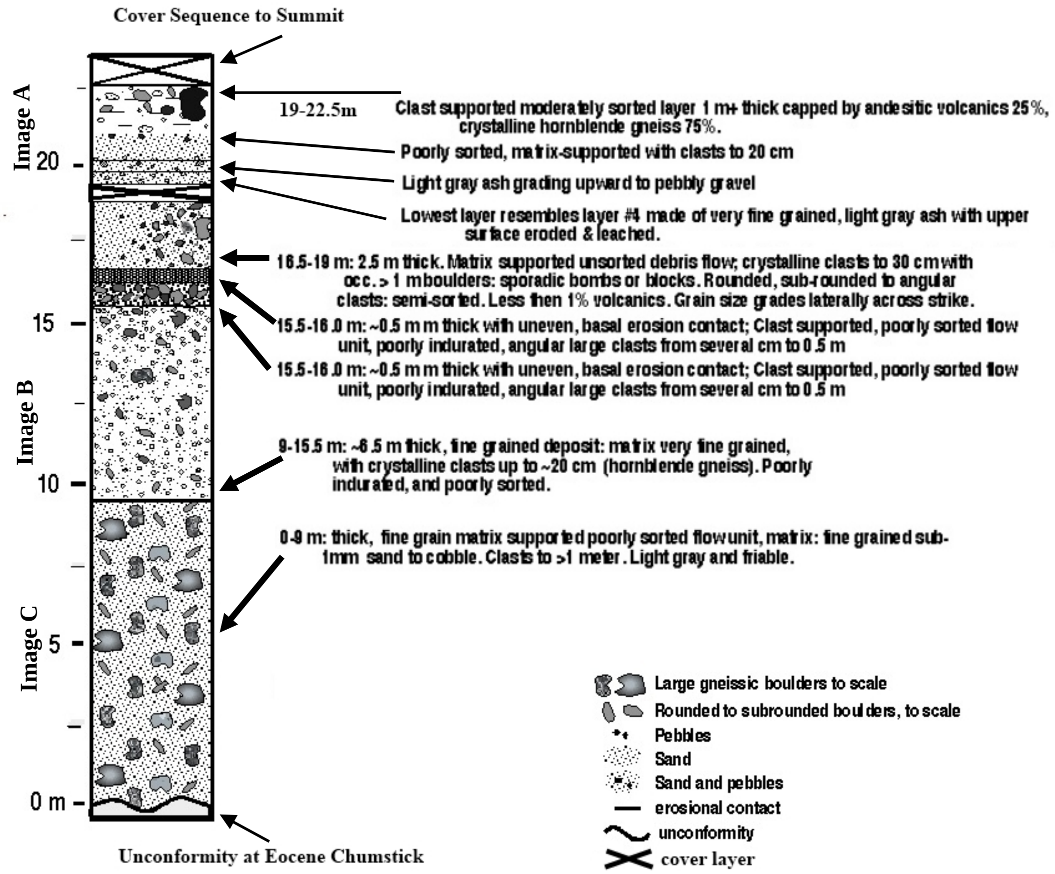


Fig 2.

Natapoc Mountain stratigraphic column of the lower unit at the unconformity with the Eocene Chumstick.

Three areas from the Natapoc Mountain fm. S.S.W. exposure.

Refer to Fig (2) schematic stratigraphic column.

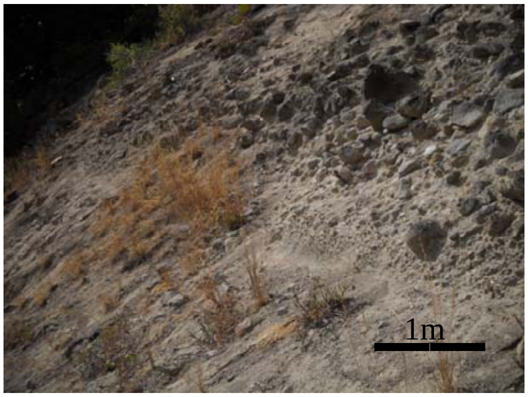


Image A**: Reverse graded in a clast-supported volcanic flow.**

Image B**: Series of reverse graded matrix supported debris/ lahar flows.**

Image C: **Large crystalline and volcanic clastic matrix supported debris flow.**

Three meters of the upper unit of the Natapoc Mountain formation crops out on the summit of Natapoc Mountain. The upper unit is composed of dark gray phenocrystic vuggy andesite, weathered to a highly pitted and wrinkled black surface. The contact between upper and lower units is obscured by vegetation. U/Pb analysis yielded a preferential concordia Th- corrected result for sample #506 Natapoc fm. summit andesite at 3.981 +/- 0.053/0.13/0.13 Ma, MSWD= 0.15, n=3. U/Pb results from the individual zircons separated from the summit andesite sample # 508 [z-1, 2, 5, z-1a, 2a] are tightly grouped from 4.12 Ma to 3.96 Ma +/- 0.15 to +/- 0.09 Ma.

The lower unit of the Natapoc Mountain formation.

Below the summit is a series of volcanic and laharic debris flows. The stratigraphic column (Fig 2) is evidence that a series of related volcanic eruptions and lahars, which appear to be byproducts of proximal extrusive or eruptive events across a planar landscape by presumably the same events that created the capping andesite at the summit. The contention is supported by the presence of early-Creteaous 158 +/- 0.30 Ma [z3] and older dates obtained from the zircons at the angular unconformity with the Chumstick Formation. The older ages obtained from five zircons separated from (sample #615) presumed to be of fluvial detrital origin deposited across the unconformity pre-dating most of the deposition of the Natapoc Mountain formation at the summit of Natapoc Mountain. Without confirmed dates from any of the discrete layers present in the lower unit, this hypothesis will necessarily have to wait for confirmation. In contrast to my contention, Whetten reported by personal communication to Laravie dates of 40.6 to 47.3Ma

(1976) taken from the ‘lower unit’, that are in conflict with dates of a coeval unit of the underlying Chumstick at Natapoc, reported in this paper and the date obtained from the Wenatchee Dome at 44.2Ma and Pole Ridge at +92Ma. Further the lithological and compositional immaturity of the lower unit suggests a younger depositional date. Also supporting this contention is the fact that the lower unit is nearly horizontal: it does not dip to the west-southwest with the underlying Chumstick Fm. as one would expect if it were close to the same age or reflect the later regional dip to the east from the uplift sequence that began post-Columbia River Basalt Group deposition (Byerly and Swanson, 1978) and (Cheney and Hayman, 2009).

Dates from zircons from sample #615 taken at the basal contact with the Chumstick unconformity were not concordant with any previous dates from the area. Samples from several beds of the lower unit between 1270m and 1292m failed to produce testable zircons.

Chemical XRF comparisons to the chemical composition of the upper unit at the Natapoc summit are shown in a LeBas classification diagram, see Graph 1, along with all the samples that have reported in dates in this paper. Tabor and Haugerud (2012) and Whetten and Waitt, (1979) describe ‘Qtup’ upland gravel type deposits of unknown age as remnants of ridge capping angular volcanic rocks; descriptions from all authors are consistent with the upper unit of the Natapoc Mountain formation at the summit of Natapoc Mountain. Pliocene volcanic rocks of Natapoc Mountain are correlative with distal Cascade Range undated volcanic rocks described by Hildreth (1980), Conrey et al. (2002), Tabor (1982), wherein the authors report undated poorly sorted deposits that crop out in the Wenatchee Heights area east of the City of Wenatchee.

The geological map of Tabor et al. (1987) shows deposits of coeval units to the Natapoc Mountain andesite throughout the western part of the CSL. To confirm published descriptions in Tabor's et al. (1987), samples from a location west of Dirty Face Peak contact with the Leavenworth fault zone were submitted for analysis and those results are reported below. My attempts to find the mapped coeval deposits similar to the Natapoc Mountain summit andesite from the proximal locations taken from the Tabor et al. geologic map (1987) were not successful.

Basalt Peak and Horse Lake Mountain

Tabor et al. (1987) mapped and described the biotite-hornblende-plagioclase porphyritic dacite at the 1906m summit elevation of Basalt Peak. Cheney and I mapped a 100m thick exposure of volcanic rocks weathered to a light gray/buff complexion, with large hornblende crystals that intrudes both part of the Chumstick Fm. and Mad River gneiss at the northernmost extent of the Coulter Creek Fault (sum.2009). The field map published by Cheney and Hayman (2009) shows that the Basalt Peak intrusive complex intrudes both the Coulter Creek and Entiat Fault systems at the their northernmost intersection. Sample #603 (Basalt Peak) [z1,2,4] yielded a weighted mean Th corrected concordia date of 27.422 +/- 0.017/0.022/0.037 Ma, MSWD = 0.25, n=3. The new date from the Basalt Peak intrusion defines a lower age limit to strike/slip offset activity of these two fault systems.

Gresens (1973), described the Horse Lake Mountain Intrusive (HMI) complex which contains two sills which follow from Chappell (1936) and Bayley's (1965) descriptions of the Twin Peaks in which all three authors differentiate a porphyritic light gray/blonde/buff-colored hornblende-rich high silica-andesite from #2 Canyon in the (HMI) complex. Gresens and Chappell described chloritic alteration in rocks from in the same area where sample #608 was collected, noting that hornblende phenocrysts are in abundance, pyramidal to (10mm+) found in hand samples. New dates from Horse Lake Mountain at Number Two Canyon are close to the Basalt Peak sample and date within the margin of error: sample #603 (Basalt Peak [z2]) of 27.42Ma +/- 0.03Ma and the HMI complex F/T date of 25.2Ma +/- 0.02 (Naeser, 1983). The comparison of the two newest dates suggests that all three areas may be related to a single or series of igneous extrusive events in the early Miocene.

Sample number #608 (Horse Lake Mnt. andesite) [z1] dates to 75.51Ma +/- 0.07 and [z2] to 163.5 +/- 0.56 Ma. The result is indeterminate and further tests are required to see if a U/Pb date confirms the earlier K/Ar dates reported from similar samples tested by Tabor et al. of 25.1 +/- 0.03 Ma to (1983 report and map-1331) and the dates ranging between 24.9 +/- 0.04 Ma and 29.4 +/- 2.1 Ma, (Gresens, 1983, pp. 39 Table #4).

Basalt Peak and Horse Lake Mountain samples have similar lithology and composition; see Graph #1 and XRF chemistry in appendix C. Basalt Peak and the Horse Lake Mountain Intrusive complexes also share similar lithology and composition with Old Gib (Cater, 1967). Further, Cater described the Horse Lake Mountain intrusive complex rocks as similar in composition and lithology to the distal dacite volcanic rocks located north of the Chelan Quadrangle and contended that they are related to the same igneous activity. New dates for all these areas would be necessary to test this theory that all are closely related to the same volcanic episode.

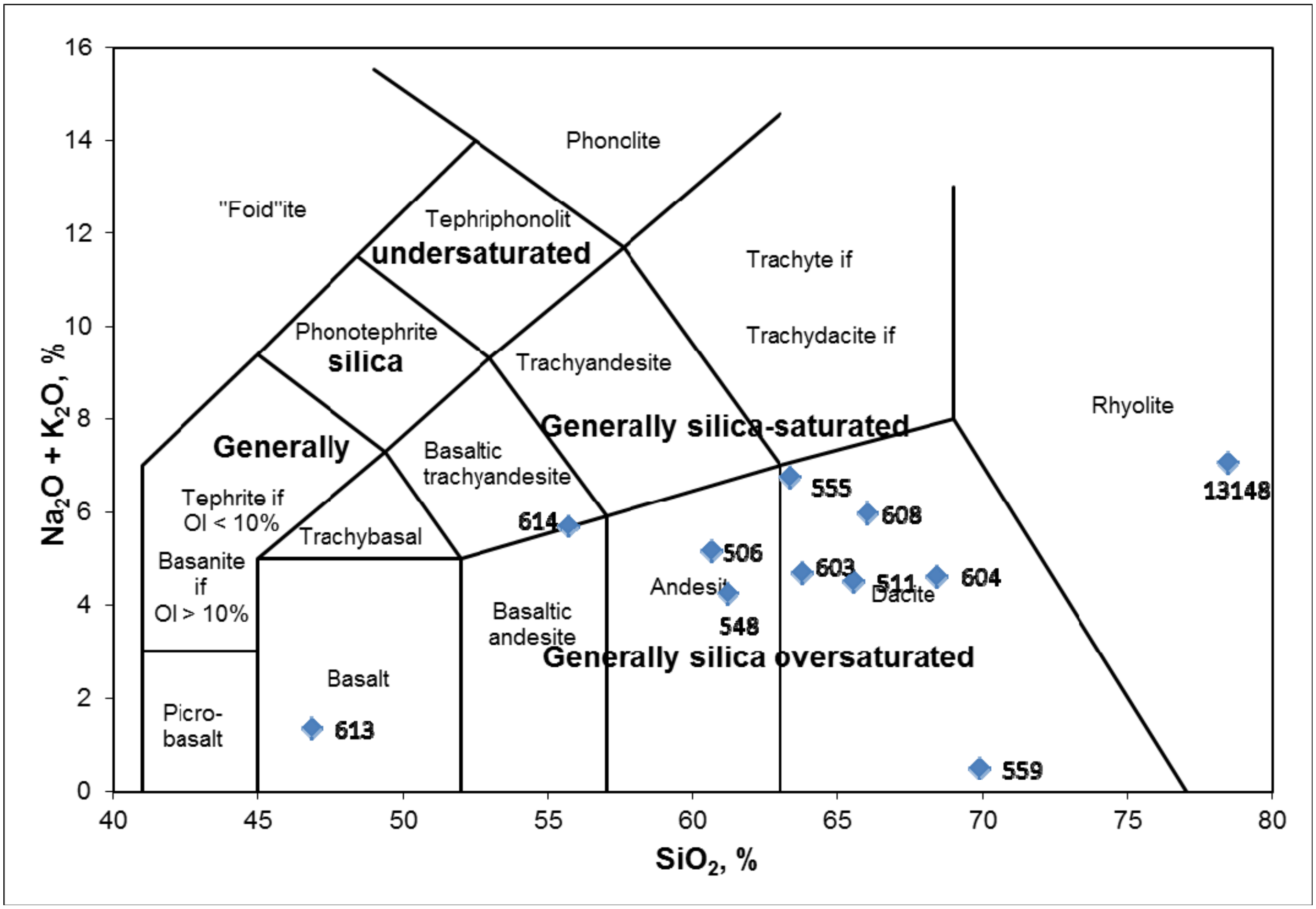
Sugarloaf Peak

Sugarloaf Peak is located 12km northeast of Leavenworth Washington on the east side of the Entiat fault. The 1846m summit is capped by a 20m thick deposit of hypersthene clinopyroxene andesite in with highly developed columnar jointing. Laravie (1976) described the andesite as either a flow uncomformably overlying the pre-Upper Cretaceous basement or a sill intruding an existing unconformity between crystalline basement, sediments and sedimentary rocks.

Page observed (1939) the Sugarloaf andesite to occupy 2/3 of a square mile on Sugarloaf Peak. It is an eroded lava cap dipping less than 10 degrees to the southwest that points to detached outliers located approx 475m below the main outcrop. He writes the Sugarloaf andesite 'is not overlain by younger deposits…its age is in doubt' with no visible basal contact (p. 76). Continuing this question, Laravie observed that the interpretation of the deposit as a flow or sill is dependent on obtaining a date and the examination of the apparent offset from the Entiat fault scarp (1976).

New dates span from 36 +/- 0.43 Ma to the Proterozoic at 1.622 Ga +/- 4.82 Ma; the extreme range between sample #548 [z1 – z3] precludes a 'preferential' date choice and MSWD calculation. The full data set of results is presented in Table 1, Appendix A. The incorporation of these zircons into the andesite, coupled with the strong columnar jointing indicative of sub-aerial cooling support the interpretation that it was originally deposited as a flow. Samples of displaced down-dip talus did not yield testable zircons. Finding volcanic rocks coeval with this distinctive andesite will help to complete the history of slip on the Entiat Fault

Lebas Diagram, Chemical Classification Igneous Samples



Sample #	Name	X SiO2%	Y Na2O + K2O%
511	Natapoc mid	65.47	4.72
506	Natapoc summit	60.56	5.39
555	Natapoc SE 3000'	63.30	7.01
604	Pole Ridge	68.34	4.84
603	Basalt Peak	63.72	4.91
608	Horse Lk. Mnt.	65.95	6.25
548	Sugarloaf	61.13	4.45
13148	Wnt Dome	78.38	7.35
613	Wnt Blue Grade	46.81	1.46
559	Tip Top Pk.	69.82	0.58
614	Sugarloaf Basalt	55.65	5.95
506	Natpooc and 2nd	60.51	5.40

Graph #1: Classification after LeBas and others (1986)

Pole Ridge

Several outcrops described by Tabor et al. (1987) as coeval deposits to the Summit Conglomerate of Natapoc Mountain (USGS Map 1661- map symbol ‘Qtup’) were mapped in local upland areas of unknown age. They consist of moderately sorted to poorly sorted river gravels that sparsely cap ridges or erosion surfaces (Tabor, 1987). Sample #604 was taken from an outcrop that was mapped by Tabor as ‘Diamictite’ and ‘upland gravels’; but it closely resembles the dark green flaggy shale interspersed with medium grained sandstones of the Chumstick Formation (Gresens, 1977) and (Cheney and Hayman, 2009).

Sample #604 obtained 2 km west of the Dirty Face Pluton yielded a Th corrected concordia date of 91.880 +/- 0.064/0.064/0.12 Ma, MSWD = 0.44, n=4. The date from a mapped location of Tabor (1987) had mapped this location as a unit coeval with the Natapoc Mountain formation. However, this result suggests the area is instead part of the upper member of the Chumstick Formation. The Ten Peak and Dirty Face plutons as described by Willis (1950), and Van Driver (1967), who reported a K/Ar ratio date of 93 Ma. The results from this sample average date of 91Ma, suggesting systematic fluvial sediment transport of these detrital zircons as one theory to explain their presence.

Wenatchee Blue Grade cut:

The Blue Grade cut is described as a group of meter-scale bedded bluish colored shale and arkosic sandstones that lies uncomformably over significant areas of Chumstick Formation west of the Columbia River and overlies Swaukane gneiss east of the river, Gresens (1976 and 1983). The samples were obtained from a deposit that crops out in a quarry cut at 800m elevation located NE of the City of Wenatchee see Fig 1.

Tabor et al. (1983) dated areas the Wenatchee Formation west of the Columbia River to the middle Oligocene to the middle Eocene. Cheney and Hayman (2009) refer to the Nahahum Canyon deposit that is distinctive and continuous along the northeastern side of the CSL, west of the Columbia River and is overlain by the Wenatchee Formation. These two observations when coupled together create some discrepancy. Both Chappell (1936) and Gresens (1973) distinguished the Wenatchee Formation west of the Columbia River from the underlying Nahahum Canyon Chumstick of sandstone and shale. (Tabor et al., 1983, p. 12) also subdivided the Wenatchee Fm. into several ‘fairly continuous members’ that they did not evaluate for age.

Tuffaceous beds from the Wenatchee Formation west of the river yielded F/T ages on two zircons of 33.4+/-1.4 Ma and 34.5 +/- 1.2Ma plus a F/T on a apatite of 39.8+/- 9.0Ma (Tabor et al.,1983). My new large sampling taken from the Blue Grade cut obtained from east of the Columbia River produced a range of new dates of 49.2 +/- 0.06 Ma [z15] to 212 +/- 0.08 Ma [z11]. The newest dates do not confirm two of the dates from the zircon and apatite F/T results of Gresens, et al. (1981) and Tabor et al. (1983, Table 1, nos. 22 and 24), but do confirm a single F/T date of 49.1 +/- 2.3Ma (no. 23) and the F/T apatite (no.24) that has an uncomfortably large margin for error. Therefore there is partial disagreement with the analysis of palynomorph biozones of the late Eocene to early Oligocene by Newman (1981) and Hauptman (1983) of the Wenatchee Formation west of the Columbia River when compared to the Blue Grade cut to the east.

Without further sampling and testing from the Blue Grade Cut, no further conclusions regarding the Gresens (1983) subdivisions found east of the Columbia River are offered in this paper.

Wenatchee Dome (Cannon Mine)

The Wenatchee Dome is located east of the City of Wenatchee and cuts the surface trace of the Eagle Creek fault in several places along strike. The rhyodacite outcrop intrudes a mineralized arkose deposit that cuts older Eocene Chumstick Formation (Cameron, 1996; Margolis, 1989). It was mined throughout the late 20th century. Zircons separated from sample #13148-10 yielded concordia date of 44.447 +/- 0.027/0.035/0.059 Ma, MSWD = 0.74, n=4.

The new high-precision date is important as this unit intrudes the Eagle Creek fault trace though the Chumstick Fm. Coeval areas with similar lithology that may contain unrecognized mineralization could be identified throughout the area using these new dates. This date defines a lower age limit to fault movement in the Eagle Creek fault system. The result confirms the newest date for the Chumstick Fm. from the Wenatchee Dome intrusion.

CONCLUSIONS

- The dates of the Natapoc Mountain formation are early Pliocene and are strong evidence of the area’s volcanic history that may be linked to other episodes of regional volcanism.
- The Summit Conglomerate of Whetten and Tabor et al. (1987) is separated into two units, upper and lower, based on the difference between the summit andesite and the lower unit of clastic debris flows of unknown age.
- Pole Ridge dates were indeterminate to the extent that the results do not reveal the relationship to the areas mapped by Tabor et al. (1987).
- Basalt Peak dates constrain the dextral slip on the Coulter Creek (Leavenworth fault systems) and the Entiat Fault systems. The new date for this intrusive unit coupled with previous petrological descriptions suggests a relationship with both Old Gib and the Horse Lake Mountain complex.
- At Sugarloaf Peak the new date constrains the upper limit of the Oligocene age deposit and suggests that the deposit is the result of an extrusive volcanic flow.
- The Wenatchee Dome date is the newest U/Pb result for the Chumstick Formation. The date for the intrusion defines the lower limit of local dextral dip slip activity on the Eagle Creek fault.
- The date from the Blue-Grade member from the Wenatchee Formation both confirms and is in contrast to previous published dates, and creates a need for more testing to

constrain the stratigraphic relationship of similar deposits found west of the Columbia River.

- The study area is heavily influenced by punctuated tectonic episodes that appear responsible for the patterns of deposition/uplift and exhumation/erosion observed between relatively young volcanic deposits found high on steep slopes of the eastern flank of the Central Cascades. The new high precision dates from this paper facilitate review of many previously unconstrained tectonic and depositional processes.

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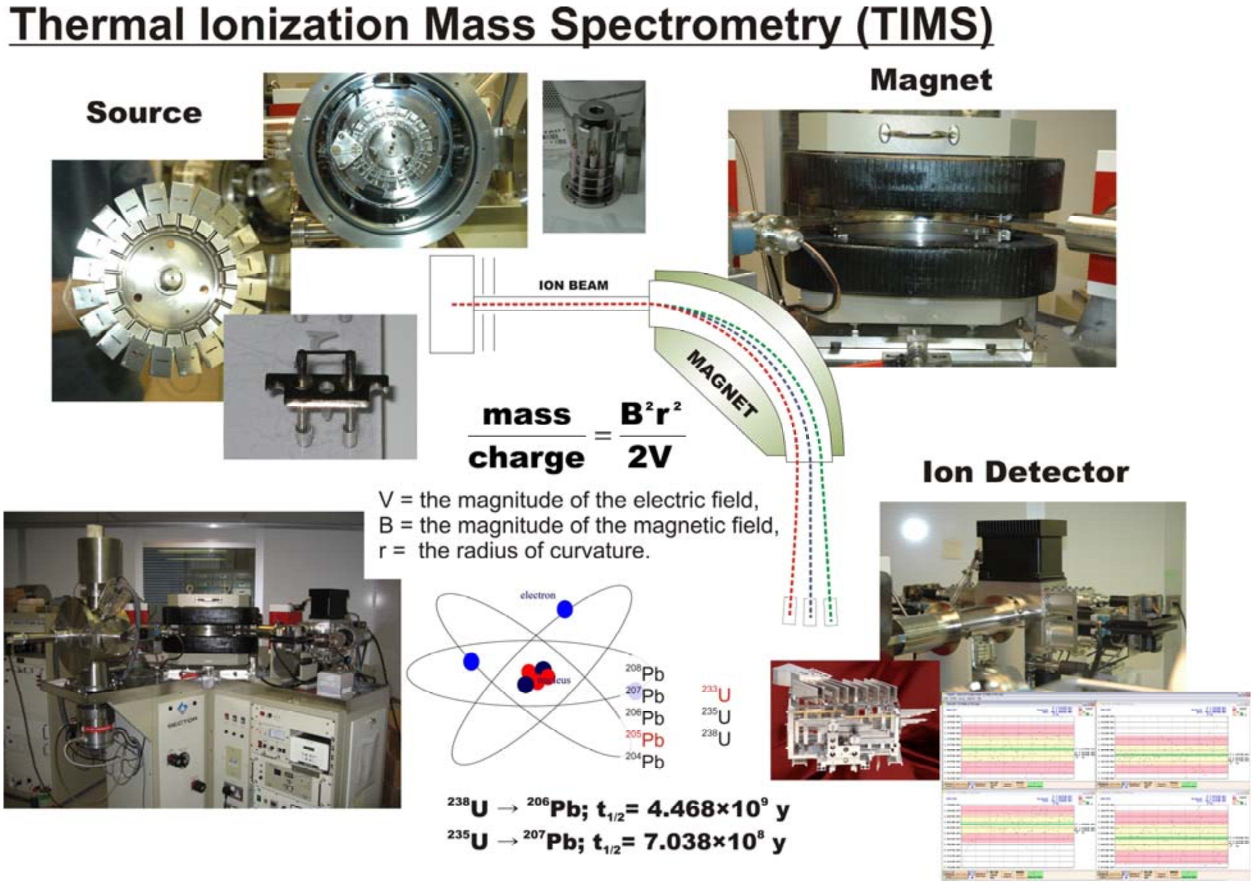
Appendix A



U-Pb isotopic analyses were carried out by isotope dilution-thermal ionization mass spectrometry (ID-TIMS) at the Massachusetts Institute of Technology (MIT). Zircons for U-Pb dating were dissolved using the chemical abrasion method (Mattinson, 2005), modified for single grain dating. Prior to dissolution, zircons were annealed at 900ºC for 48 hours. Individual grains were then loaded into teflon micro-capsules with 29 N HF, placed in Parr acid digestion vessels, and leached at 180–210ºC for 12-14 hours. Each leached grain was subsequently transferred to a clean teflon beaker for rinsing. Following removal of the HF solution, grains were rinsed in H_2O, placed in an ultrasonic for 15-20 minutes in ~7 N HNO_3, fluxed on a hot plate for 1 hour in ~7 N HNO_3, and then re-rinsed in H_2O prior to loading. The rinsed grains were loaded into cleaned teflon microcapsules, spiked with the EARTHTIME ^{205}Pb-^{233}U-^{235}U tracer (ET535) and dissolved in ~29 N HF in Parr acid digestion vessels held at 210ºC for 48 hours. Following digestion, sample solutions were converted to 6.2N HCl, then 3.1 N HCl, and U and Pb were separated on anion exchange columns (Krogh, 1973).

U and Pb Isotopic analyses were carried out on a VG sector 54 thermal ionization mass spectrometer (TIMS). Samples were loaded in silica gel (Gerstenberger and Haase, 1997) onto out-gassed Re filaments. Pb isotopes were measured by peak-hopping on the Daly detector and fractionation corrected based on repeat analyses of NBS 981 using the isotopic composition of Baker et al. (2004). U isotopes were measured statically on Faraday cups and fractionation corrected using the ^{233}U-^{235}U double spike. All measured ^{204}Pb was assumed to be from laboratory blank, which was subtracted using Pb isotopic ratios determined by repeat analyses of spiked total procedural blanks. All data reduction and error propagation was done using the U-Pb Redux software package (Bowring et al. 2011, (McLean et al. 2011). ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ratios were corrected for initial exclusion of ^{230}Th from the ^{238}U decay chain using the model Th/U of the zircon, calculated from the ^{208}Pb/^{206}Pb.

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Appendix B.

Complete table of U/Pb isotopic results

	Composition				*Isotopic Ratios*							*Dates [Ma]*						
Fraction	Th/U $^{(a)}$	Pb* $^{(b)}$ [pg]	Pbc $^{(c)}$ [pg]	Pb*/Pbc $^{(d)}$	^{206}Pb/^{204}Pb $^{(e)}$	^{206}Pb/^{238}U $^{(f,g)}$	±2σ [%]	^{207}Pb/^{235}U $^{(f)}$	±2σ [%]	^{207}Pb/^{206}Pb $^{(f,g)}$	±2σ [%]	^{206}Pb/^{238}U $^{(g,h)}$	±2σ [abs.]	^{207}Pb/^{235}U $^{(h)}$	±2σ [abs.]	^{207}Pb/^{206}Pb $^{(g,h)}$	±2σ [abs.]	Corr. coef.
13148-10: Zircon																		
GPS:	**Wenatchee Dome Gold Mine**																	
z1	0.34	4.5	0.37	12.34	790.4	0.00692	0.198	0.045	1.24	0.046974	1.134	44.42	0.09	44.49	0.5	47.9	27.1	0.59
z2	0.45	1.9	0.34	5.68	362.9	0.00693	0.301	0.045	3.64	0.047008	3.378	44.52	0.13	44.61	1.6	49.6	80.7	0.90
z3	0.35	2.2	0.46	4.81	317.8	0.00694	0.204	0.045	2.67	0.047454	2.536	44.58	0.09	45.09	1.2	72.1	60.3	0.67
z4	0.33	3.1	0.41	7.59	493.6	0.00692	0.095	0.045	2.02	0.046803	1.981	44.43	0.04	44.34	0.9	39.2	47.4	0.43
z5	0.25	6.8	0.33	20.19	1313.1	0.00692	0.093	0.045	0.64	0.046762	0.588	44.46	0.04	44.33	0.3	37.1	14.1	0.61
506: Zircon																		
GPS:	**Natapoc Mountain Summit Andesite**																	
z1	0.53	0.1	0.40	0.21	31.1	0.00062	4.094	0.004	52.17	0.047887	49.355	4.01	0.16	4.16	2.2	93.7	1168.9	0.73
z2	0.69	0.2	0.33	0.51	47.3	0.00062	1.806	0.004	27.18	0.044124	25.937	3.99	0.07	3.82	1.0	103.8	637.8	0.73
z3	0.02	1.7	0.31	5.48	396.2	0.01474	0.313	0.098	1.85	0.048457	1.719	94.32	0.29	95.36	1.7	121.6	40.5	0.49
z4	0.52	4.2	0.67	6.17	388.0	0.01484	0.150	0.100	1.69	0.048871	1.588	94.93	0.14	96.74	1.6	141.6	37.3	0.69
z5	0.08	0.1	0.23	0.32	39.9	0.00061	2.342	0.004	34.48	0.046174	32.767	3.96	0.09	3.96	1.4	6.7	788.8	0.77
z1s*	0.65	0.1	0.39	0.00	31.0	0..000639	3.600	0.005	42.00	0.060308	40.000	4.12	0.15	5.40	2.3	615.0	860.0	0.77
z2s*	0.75	0.2	0.32	1.00	48.0	0.00063	1.600	0.004	24.00	0.050587	23.000	4.04	0.07	4.40	1.1	222.0	540.0	0.75
548: Zircon																		
GPS:	**Sugarloaf Peak**																	
z1	0.20	8.0	0.30	26.43	1673.5	0.28629	0.322	4.151	0.42	0.105214	0.212	1622.94	4.62	1664.46	3.4	1717.2	3.9	0.87
z2	0.14	10.2	0.54	18.75	1269.0	0.01638	0.090	0.108	0.56	0.047946	0.540	104.76	0.09	104.38	0.6	95.5	12.8	0.33
z3	0.71	36.1	0.45	79.70	4566.4	0.00573	1.172	0.037	1.19	0.046853	0.157	36.85	0.43	36.91	0.4	40.7	3.8	0.99
559: Zircon																		
GPS:	**Tip Top Mnt.**																	
z2	0.41	10.7	0.56	19.20	1195.9	0.01413	0.604	0.093	1.14	0.047874	0.892	90.47	0.54	90.56	1.0	93.0	21.1	0.63
z4	0.45	10.4	0.34	30.37	1861.6	0.01428	0.169	0.094	0.62	0.047852	0.545	91.37	0.15	91.40	0.5	92.0	12.9	0.56
z5	0.26	18.5	0.45	41.47	2672.1	0.01414	0.139	0.093	0.69	0.047845	0.605	90.54	0.12	90.58	0.6	91.6	14.3	0.70
z6	0.35	8.4	0.54	15.60	990.6	0.01423	0.125	0.094	0.98	0.047919	0.931	91.08	0.11	91.24	0.9	95.3	22.0	0.45
z7	0.32	17.0	0.50	33.66	2132.8	0.01423	0.106	0.094	0.47	0.047818	0.443	91.08	0.10	91.05	0.4	90.3	10.5	0.37
z8	0.34	9.2	0.44	20.92	1324.6	0.01414	0.145	0.094	0.72	0.048030	0.608	90.53	0.13	90.91	0.6	100.7	14.4	0.82
z9	0.40	276.6	5.22	52.98	3279.7	0.01432	0.499	0.094	0.79	0.047848	0.562	91.63	0.45	91.63	0.7	91.8	13.3	0.70
z10	0.29	26.9	0.67	40.21	2568.8	0.01415	0.168	0.094	0.36	0.048026	0.314	90.59	0.15	90.95	0.3	100.6	7.4	0.50
603: Zircon																		
GPS:	**Basalt Peak**																	
z1	0.30	10.9	0.39	27.80	1775.8	0.00426	0.106	0.027	0.62	0.046505	0.601	27.41	0.03	27.37	0.2	23.9	14.4	0.27
z2	0.33	6.5	0.33	19.91	1266.7	0.00426	0.103	0.027	0.77	0.046620	0.702	27.42	0.03	27.45	0.2	29.8	16.8	0.68
z3	0.26	7.3	0.27	27.43	1772.7	0.00428	0.148	0.027	0.68	0.046563	0.585	27.54	0.04	27.53	0.2	26.9	14.0	0.73
z4	0.28	5.9	0.33	17.81	1150.0	0.00426	0.123	0.027	1.04	0.046560	0.982	27.43	0.03	27.42	0.3	26.7	23.6	0.55
z5	0.33	13.5	0.66	20.33	1293.6	0.00427	0.133	0.027	0.85	0.046441	0.764	27.47	0.04	27.39	0.2	20.6	18.4	0.69
604: Zircon																		
GPS:	**Pole Ridge**																	
z3	0.41	10.0	0.30	33.38	2064.3	0.01437	0.109	0.095	0.57	0.047796	0.532	91.98	0.10	91.87	0.5	89.2	12.6	0.40
z4	0.35	8.6	0.32	26.72	1681.5	0.01437	0.125	0.095	0.74	0.047856	0.649	91.99	0.11	92.00	0.6	92.2	15.4	0.74
z5	0.31	23.8	0.35	67.54	4278.4	0.01436	0.146	0.095	0.30	0.047847	0.244	91.90	0.13	91.90	0.3	91.7	5.8	0.61
z6	0.27	5.5	0.86	6.41	425.9	0.01451	0.154	0.097	1.73	0.048282	1.635	92.88	0.14	93.65	1.5	113.1	38.6	0.66
z7	0.35	24.8	0.50	49.35	3094.1	0.01434	0.148	0.095	0.45	0.047885	0.372	91.81	0.13	91.88	0.4	93.6	8.8	0.63
z8	0.31	7.9	0.99	7.98	520.9	0.01449	0.166	0.096	1.44	0.048232	1.351	92.76	0.15	93.44	1.3	110.7	31.9	0.58
z9	0.39	11.9	0.31	38.68	2401.3	0.01436	0.094	0.095	0.54	0.047791	0.480	91.90	0.09	91.79	0.5	88.9	11.4	0.68
z10	0.33	19.1	0.35	55.10	3468.9	0.01435	0.073	0.095	0.32	0.047917	0.303	91.88	0.07	92.00	0.3	95.2	7.2	0.36
608: Zircon																		
GPS:	**Horselake Mountain**																	
z1	0.57	10.3	0.41	25.10	1511.0	0.01178	0.094	0.077	0.71	0.047559	0.689	75.51	0.07	75.57	0.5	77.4	16.4	0.33
z2	0.45	4.2	1.08	3.83	253.9	0.02569	0.349	0.176	3.96	0.049784	3.899	163.50	0.56	164.89	6.0	184.9	90.8	0.21
613: Zircon																		
GPS:	**Wenatchee Blue Grade Cut**																	
z1	0.34	33.3	0.47	70.48	4419.1	0.00768	0.140	0.050	0.26	0.047094	0.213	49.31	0.07	49.40	0.1	54.0	5.1	0.56
z2	0.27	4.4	0.39	11.26	735.4	0.01031	0.255	0.067	1.36	0.047289	1.312	66.09	0.17	66.03	0.9	63.8	31.3	0.28
z3	0.38	1.1	0.23	4.74	311.2	0.01494	0.336	0.098	3.81	0.047812	3.586	95.60	0.32	95.38	3.5	90.0	85.0	0.70
z4	0.25	1.6	0.30	5.44	367.1	0.01379	0.356	0.091	2.68	0.047761	2.585	88.32	0.31	88.29	2.3	87.4	61.3	0.34
z5	0.35	1.8	0.42	4.33	287.6	0.01697	0.287	0.113	3.60	0.048423	3.431	108.45	0.31	108.95	3.7	120.0	80.9	0.61
z6	0.53	1.4	0.45	3.09	201.7	0.01422	0.343	0.094	4.23	0.047990	3.979	91.03	0.31	91.32	3.7	98.8	94.1	0.75
z7	0.25	6.7	2.38	2.81	198.1	0.01382	0.296	0.091	3.90	0.047998	3.693	88.45	0.26	88.83	3.3	99.2	87.4	0.72
z9	0.64	3.8	0.49	7.64	459.1	0.01554	0.627	0.103	3.06	0.048263	2.732	99.38	0.62	99.89	2.9	112.2	64.5	0.59
z11	0.45	8.1	0.27	30.29	1852.0	0.03343	0.345	0.230	1.00	0.049826	0.889	212.00	0.72	209.94	1.9	186.9	20.7	0.48
z12	0.35	5.6	0.52	10.70	684.8	0.02069	0.345	0.138	1.47	0.048394	1.325	132.03	0.45	131.32	1.8	118.6	31.2	0.52
z13	0.37	6.3	0.35	17.85	1124.0	0.00769	0.165	0.050	1.15	0.046792	1.000	49.39	0.08	49.17	0.6	38.6	23.9	0.94
z14	0.26	2.8	0.25	11.51	753.1	0.02020	0.293	0.136	2.20	0.048652	2.057	128.95	0.37	129.06	2.7	131.1	48.4	0.54
z15	0.43	6.1	0.32	19.01	1177.4	0.00766	0.115	0.050	0.95	0.047304	0.914	49.22	0.06	49.53	0.5	64.6	21.8	0.36
615: Zircon																		
GPS:	**Natapoc Mountain Basal**																	
z1	1.12	15.3	0.51	29.84	1562.7	0.03922	0.103	0.276	0.45	0.050960	0.486	247.97	0.25	247.11	1.0	239.0	11.2	-0.21
z3	0.39	9.2	0.30	31.14	1949.6	0.02492	0.192	0.170	0.55	0.049364	0.463	158.68	0.30	159.09	0.8	165.1	10.8	0.57
z5	0.17	6.7	0.33	20.17	1313.1	0.05739	0.074	0.651	0.32	0.082205	0.285	359.75	0.26	508.79	1.3	1250.4	5.6	0.52
z6	0.11	5.6	0.36	15.84	1070.6	0.03182	0.840	0.273	1.18	0.062150	0.815	201.94	1.67	244.84	2.6	679.3	17.4	0.72
z7	0.20	4.3	0.62	6.99	470.3	0.02644	0.268	0.226	1.27	0.062083	1.172	168.23	0.44	207.16	2.4	677.0	25.1	0.45

Blank composition: ^{206}Pb/^{204}Pb = 18.41 ± 0.24; ^{207}Pb/^{204}Pb = 15.41 ± 0.145; ^{208}Pb/^{204}Pb = 37.61 ± 0.565

(a) Th contents calculated from radiogenic ^{208}Pb and the ^{207}Pb/^{206}Pb date of the sample, assuming concordance between U-Th and Pb systems.

(b) Total mass of radiogenic Pb.

(c) Total mass of common Pb.

(d) Ratio of radiogenic Pb (including ^{208}Pb) to common Pb.

(e) Measured ratio corrected for fractionation and spike contribution only.

(f) Measured ratios corrected for fractionation, tracer, blank and initial common Pb.

(g) Corrected for Initial Th/U disequilibrium using radiogenic ^{208}Pb and Th/U [magma] = 2.8

(h) Isotopic dates calculated using the decay constants λ_{238} = 1.55125E-10, λ_{235} = 9.8485E-10 (Jaffey et al. 1971), and for the ^{238}U/^{235}U = 137.818 ± 0.045 (Hiess, J. et al. 2012)

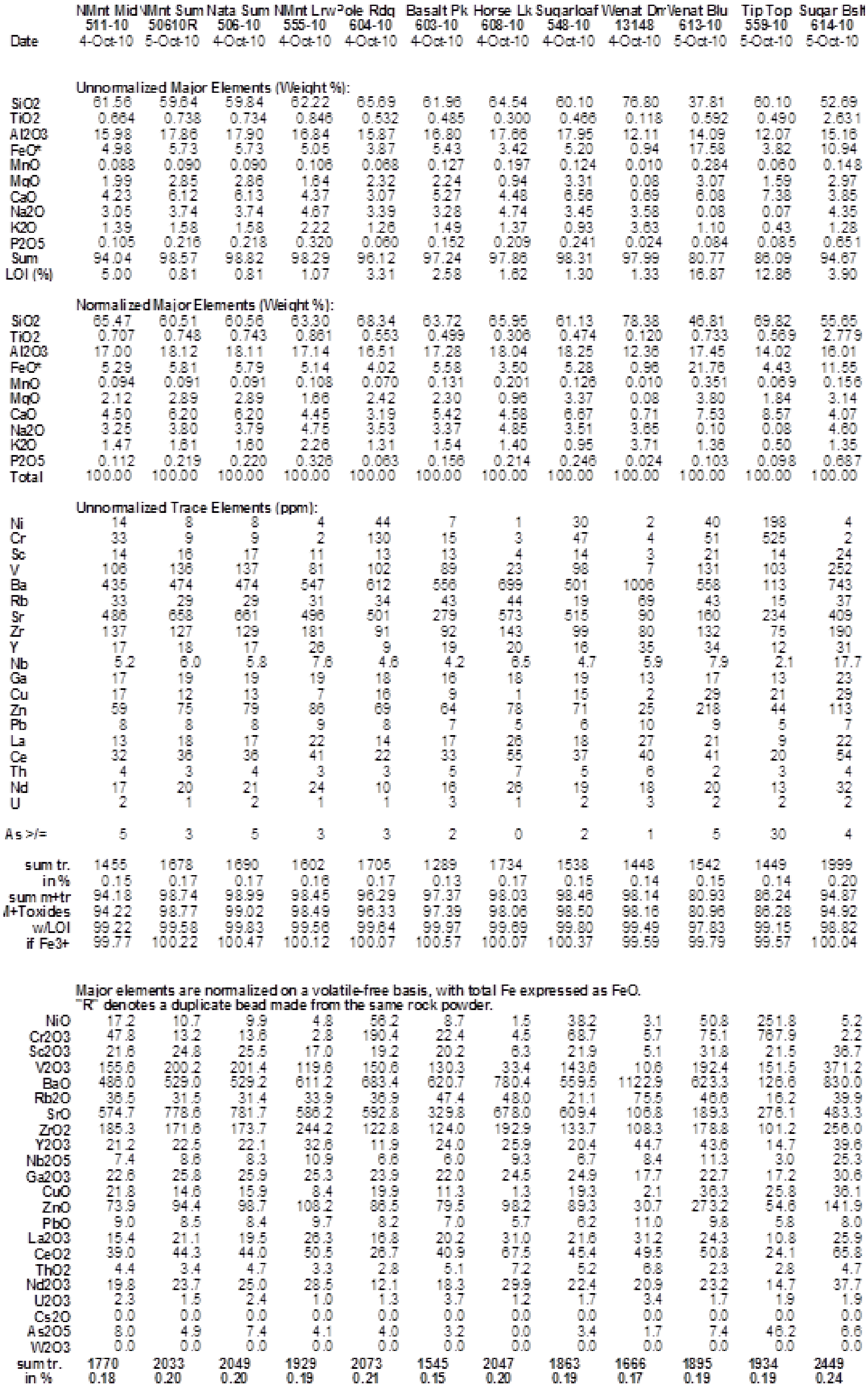
(s*) Supplemental results post first run

Appendix. C.

The concentrations of 27 elements in the unknown samples are measured by comparing the X-ray intensity for each element with the intensity for two beads each of nine USGS standard samples (PCC-1, BCR-1, BIR-1, DNC-1, W-2, AGV-1, GSP-1, G-2, and STM -1, using the values recommended by (Govindaraju, 1994) and two beads of pure vein quartz used as blanks for all elements except Si. The 20 standard beads are run and used for recalibration approximately once every three weeks or after the analysis of about 300 unknowns. The intensities for all elements are corrected automatically for line interference and absorption effects due to all the other elements using the fundamental parameter method. Operating conditions (Table 2) are unremarkable and the values used for the standards are listed in Table 5.

The precision and accuracy of a low (2:1) Li-tetraborate fused bead technique by X-ray fluorescence analysis for 27 major and trace elements is demonstrated by comparison to accepted values of standard samples and to values acquired by other techniques in other laboratories.

XRF results

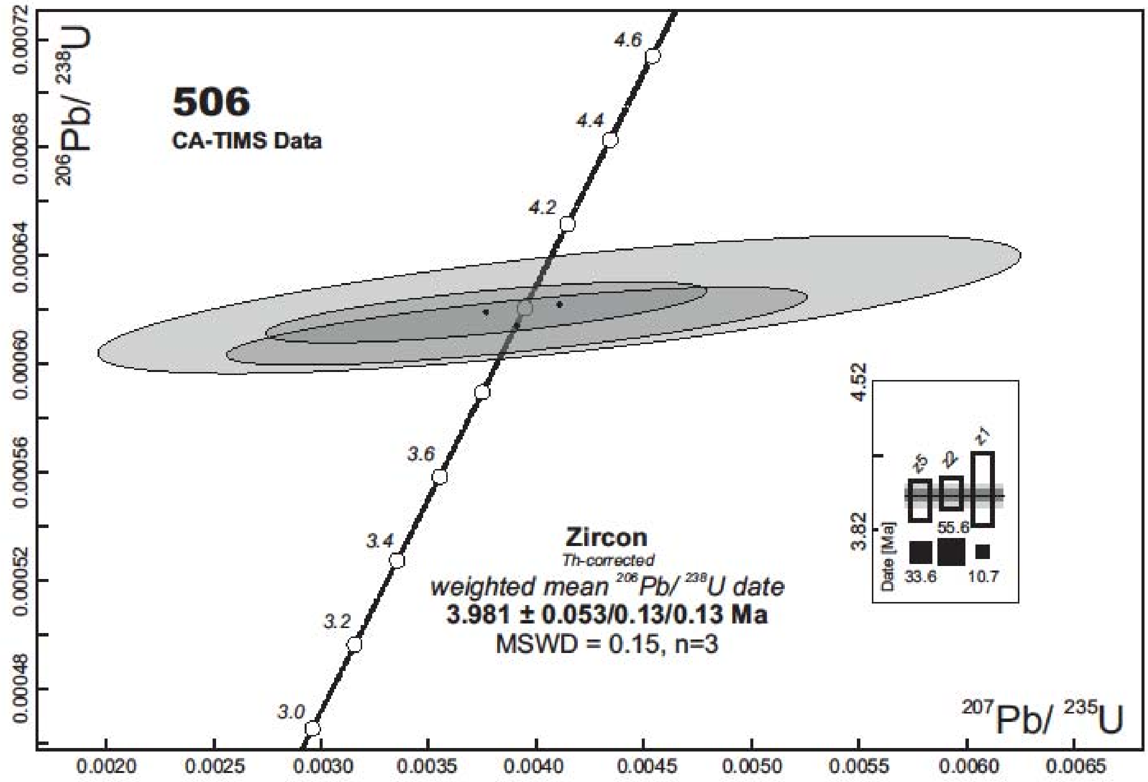


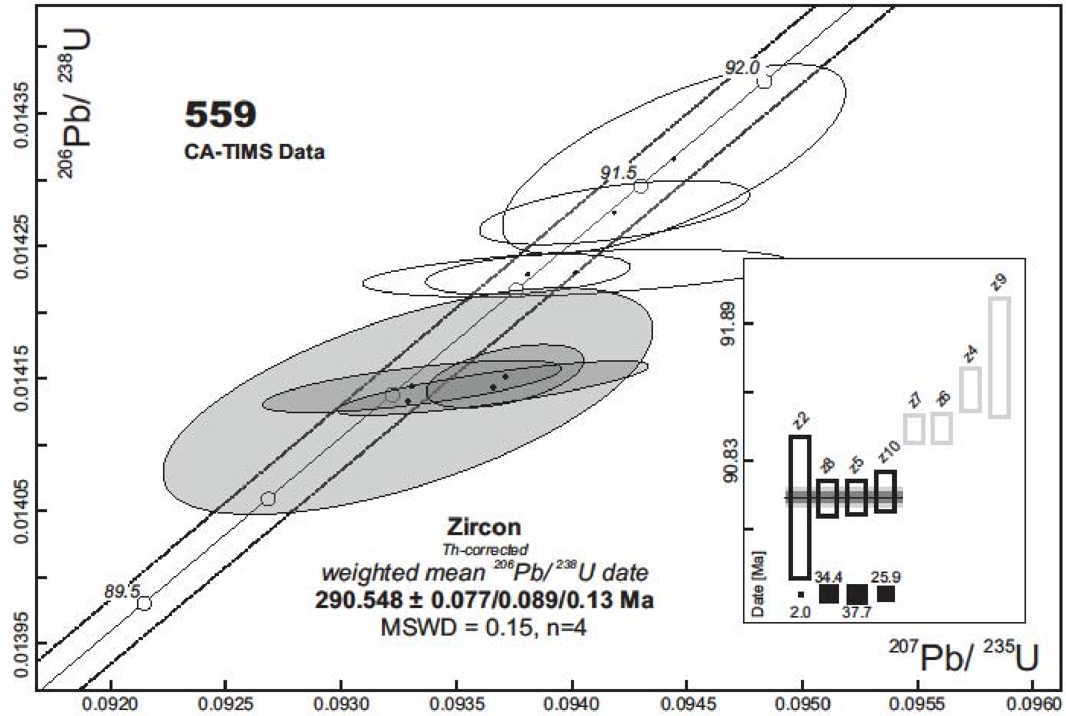
	NMnt Mid	Mnt Sum	Nata Sum	NMnt Lrw	ole Rdg	Basalt Pk	Horse Lk	Sugarloaf	Wenat Dr	Venat Blu	Tip Top	Sugar Bsl
	511-10	50610R	506-10	555-10	604-10	603-10	608-10	548-10	13148	613-10	559-10	614-10
Date	4-Oct-10	5-Oct-10	4-Oct-10	4-Oct-10	4-Oct-10	4-Oct-10	4-Oct-10	4-Oct-10	4-Oct-10	5-Oct-10	5-Oct-10	5-Oct-10
	Unnormalized Major Elements (Weight %):											
SiO2	61.56	59.64	59.84	62.22	65.69	61.96	64.54	60.10	76.80	37.81	60.10	52.69
TiO2	0.664	0.738	0.734	0.846	0.532	0.485	0.300	0.466	0.118	0.592	0.490	2.631
Al2O3	15.98	17.86	17.90	16.84	15.87	16.80	17.66	17.95	12.11	14.09	12.07	15.16
FeO*	4.98	5.73	5.73	5.05	3.87	5.43	3.42	5.20	0.94	17.58	3.82	10.94
MnO	0.088	0.090	0.090	0.106	0.068	0.127	0.197	0.124	0.010	0.284	0.060	0.148
MgO	1.99	2.85	2.86	1.64	2.32	2.24	0.94	3.31	0.08	3.07	1.59	2.97
CaO	4.23	6.12	6.13	4.37	3.07	5.27	4.48	6.56	0.69	6.08	7.38	3.85
Na2O	3.05	3.74	3.74	4.67	3.39	3.28	4.74	3.45	3.58	0.08	0.07	4.35
K2O	1.39	1.58	1.58	2.22	1.26	1.49	1.37	0.93	3.63	1.10	0.43	1.28
P2O5	0.105	0.216	0.218	0.320	0.060	0.152	0.209	0.241	0.024	0.084	0.085	0.651
Sum	94.04	98.57	98.82	98.29	96.12	97.24	97.86	98.31	97.99	80.77	86.09	94.67
LOI (%)	5.00	0.81	0.81	1.07	3.31	2.58	1.62	1.30	1.33	16.87	12.86	3.90
	Normalized Major Elements (Weight %):											
SiO2	65.47	60.51	60.56	63.30	68.34	63.72	65.95	61.13	78.38	46.81	69.82	55.65
TiO2	0.707	0.748	0.743	0.861	0.553	0.499	0.306	0.474	0.120	0.733	0.569	2.779
Al2O3	17.00	18.12	18.11	17.14	16.51	17.28	18.04	18.25	12.36	17.45	14.02	16.01
FeO*	5.29	5.81	5.79	5.14	4.02	5.58	3.50	5.28	0.96	21.76	4.43	11.55
MnO	0.094	0.091	0.091	0.108	0.070	0.131	0.201	0.126	0.010	0.351	0.069	0.156
MgO	2.12	2.89	2.89	1.66	2.42	2.30	0.96	3.37	0.08	3.80	1.84	3.14
CaO	4.50	6.20	6.20	4.45	3.19	5.42	4.58	6.67	0.71	7.53	8.57	4.07
Na2O	3.25	3.80	3.79	4.75	3.53	3.37	4.85	3.51	3.65	0.10	0.08	4.60
K2O	1.47	1.61	1.60	2.26	1.31	1.54	1.40	0.95	3.71	1.36	0.50	1.35
P2O5	0.112	0.219	0.220	0.326	0.063	0.156	0.214	0.246	0.024	0.103	0.098	0.687
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	Unnormalized Trace Elements (ppm):											
Ni	14	8	8	4	44	7	1	30	2	40	198	4
Cr	33	9	9	2	130	15	3	47	4	51	525	2
Sc	14	16	17	11	13	13	4	14	3	21	14	24
V	106	136	137	81	102	89	23	98	7	131	103	252
Ba	435	474	474	547	612	556	699	501	1006	558	113	743
Rb	33	29	29	31	34	43	44	19	69	43	15	37
Sr	486	658	661	496	501	279	573	515	90	160	234	409
Zr	137	127	129	181	91	92	143	99	80	132	75	190
Y	17	18	17	26	9	19	20	16	35	34	12	31
Nb	5.2	6.0	5.8	7.6	4.6	4.2	6.5	4.7	5.9	7.9	2.1	17.7
Ga	17	19	19	19	18	16	18	19	13	17	13	23
Cu	17	12	13	7	16	9	1	15	2	29	21	29
Zn	59	75	79	86	69	64	78	71	25	218	44	113
Pb	8	8	8	9	8	7	5	6	10	9	5	7
La	13	18	17	22	14	17	26	18	27	21	9	22
Ce	32	36	36	41	22	33	55	37	40	41	20	54
Th	4	3	4	3	3	5	7	5	6	2	3	4
Nd	17	20	21	24	10	16	26	19	18	20	13	32
U	2	1	2	1	1	3	1	2	3	2	2	2
As >/=	5	3	5	3	3	2	0	2	1	5	30	4
sum tr.	1455	1678	1690	1602	1705	1289	1734	1538	1448	1542	1449	1999
in %	0.15	0.17	0.17	0.16	0.17	0.13	0.17	0.15	0.14	0.15	0.14	0.20
sum m+tr	94.18	98.74	98.99	98.45	96.29	97.37	98.03	98.46	98.14	80.93	86.24	94.87
l+Toxides	94.22	98.77	99.02	98.49	96.33	97.39	98.06	98.50	98.16	80.96	86.28	94.92
w/LOI	99.22	99.58	99.83	99.56	99.64	99.97	99.69	99.80	99.49	97.83	99.15	98.82
if Fe3+	99.77	100.22	100.47	100.12	100.07	100.57	100.07	100.37	99.59	99.79	99.57	100.04

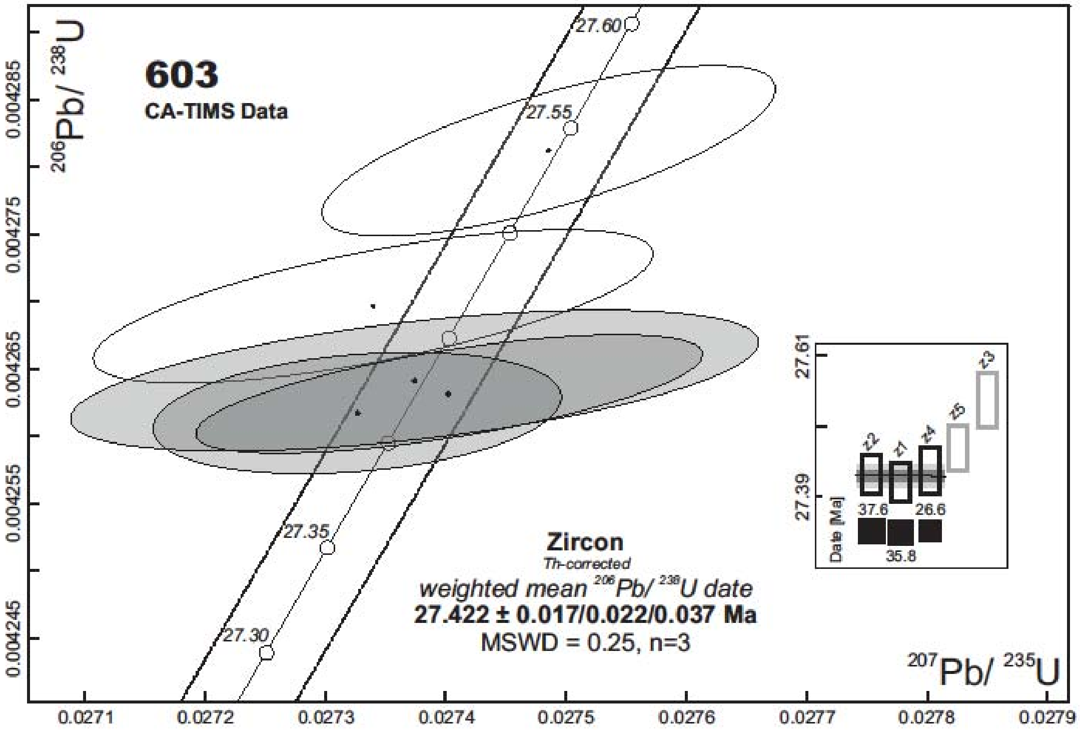
Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO.
"R" denotes a duplicate bead made from the same rock powder.

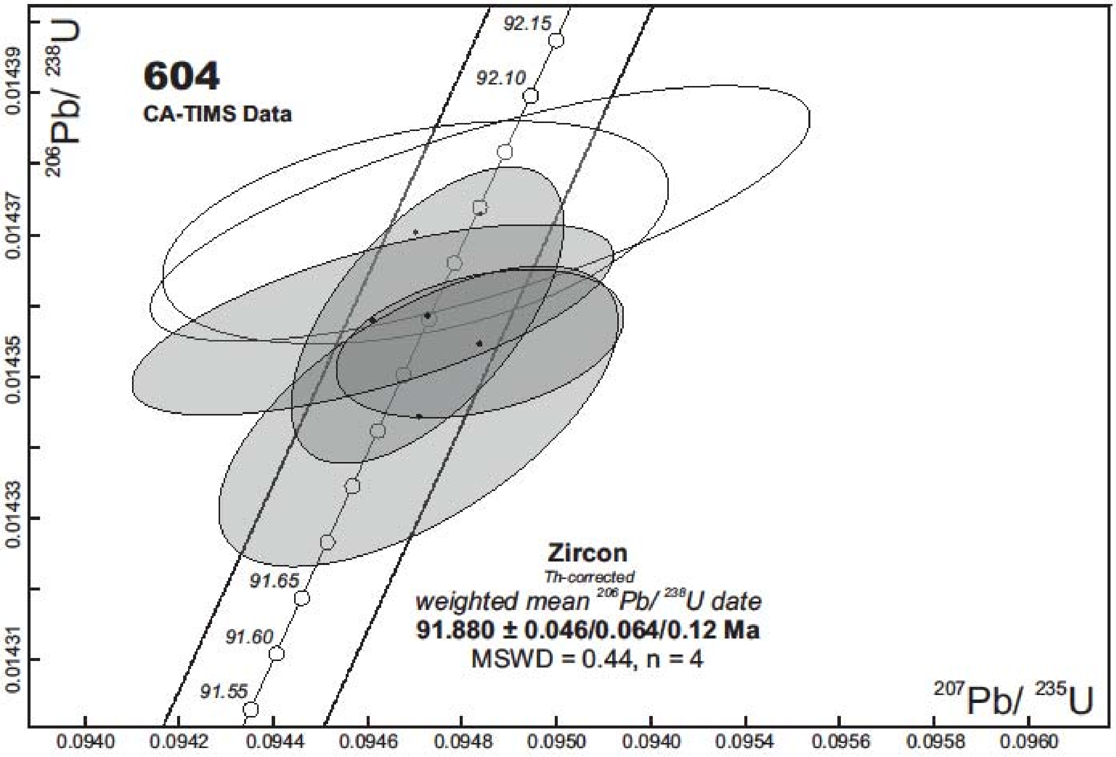
NiO	17.2	10.7	9.9	4.8	56.2	8.7	1.5	38.2	3.1	50.8	251.8	5.2
Cr2O3	47.8	13.2	13.6	2.8	190.4	22.4	4.5	68.7	5.7	75.1	767.9	2.2
Sc2O3	21.6	24.8	25.5	17.0	19.2	20.2	6.3	21.9	5.1	31.8	21.5	36.7
V2O3	155.6	200.2	201.4	119.6	150.6	130.3	33.4	143.6	10.6	192.4	151.5	371.2
BaO	486.0	529.0	529.2	611.2	683.4	620.7	780.4	559.5	1122.9	623.3	126.6	830.0
Rb2O	36.5	31.5	31.4	33.9	36.9	47.4	48.0	21.1	75.5	46.6	16.2	39.9
SrO	574.7	778.6	781.7	586.2	592.8	329.8	678.0	609.4	106.8	189.3	276.1	483.3
ZrO2	185.3	171.6	173.7	244.2	122.8	124.0	192.9	133.7	108.3	178.8	101.2	256.0
Y2O3	21.2	22.5	22.1	32.6	11.9	24.0	25.9	20.4	44.7	43.6	14.7	39.6
Nb2O5	7.4	8.6	8.3	10.9	6.6	6.0	9.3	6.7	8.4	11.3	3.0	25.3
Ga2O3	22.6	25.8	25.9	25.3	23.9	22.0	24.5	24.9	17.7	22.7	17.2	30.6
CuO	21.8	14.6	15.9	8.4	19.9	11.3	1.3	19.3	2.1	36.3	25.8	36.1
ZnO	73.9	94.4	98.7	108.2	86.5	79.5	98.2	89.3	30.7	273.2	54.6	141.9
PbO	9.0	8.5	8.4	9.7	8.2	7.0	5.7	6.2	11.0	9.8	5.8	8.0
La2O3	15.4	21.1	19.5	26.3	16.8	20.2	31.0	21.6	31.2	24.3	10.8	25.9
CeO2	39.0	44.3	44.0	50.5	26.7	40.9	67.5	45.4	49.5	50.8	24.1	65.8
ThO2	4.4	3.4	4.7	3.3	2.8	5.1	7.2	5.2	6.8	2.3	2.8	4.7
Nd2O3	19.8	23.7	25.0	28.5	12.1	18.3	29.9	22.4	20.9	23.2	14.7	37.7
U2O3	2.3	1.5	2.4	1.0	1.3	3.7	1.2	1.7	3.4	1.7	1.9	1.9
Cs2O	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
As2O5	8.0	4.9	7.4	4.1	4.0	3.2	0.0	3.4	1.7	7.4	46.2	6.6
W2O3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
sum tr.	**1770**	**2033**	**2049**	**1929**	**2073**	**1545**	**2047**	**1863**	**1666**	**1895**	**1934**	**2449**
in %	**0.18**	**0.20**	**0.20**	**0.19**	**0.21**	**0.15**	**0.20**	**0.19**	**0.17**	**0.19**	**0.19**	**0.24**

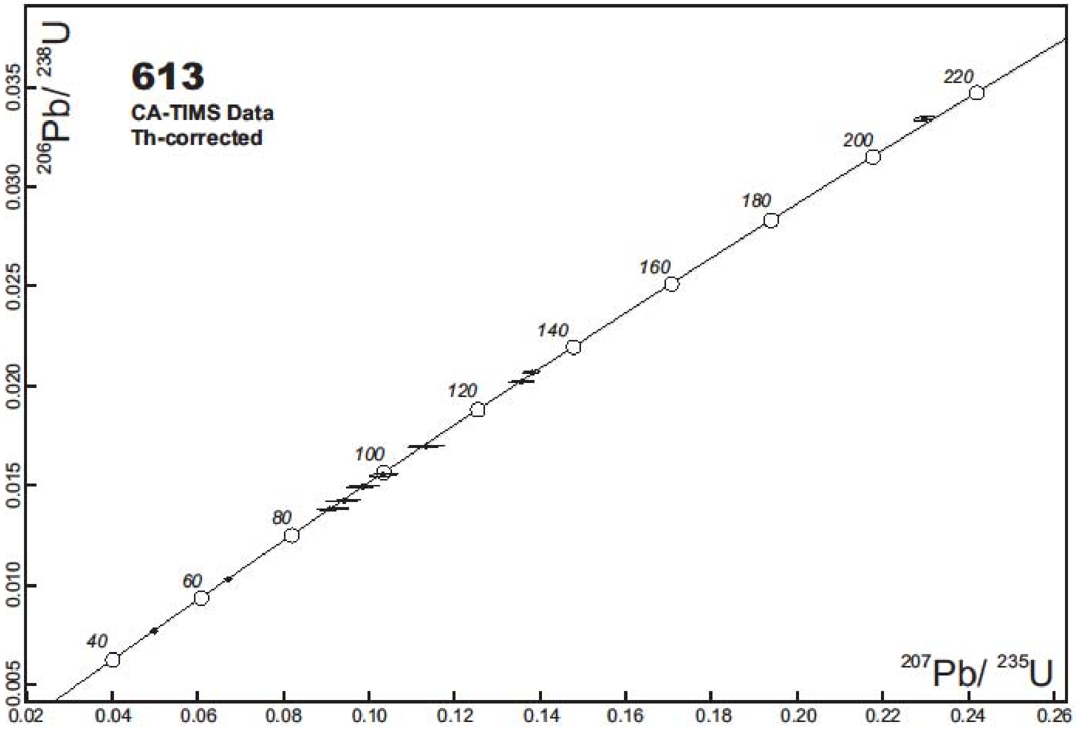
Appendix D. CA/TIMS data graphs:

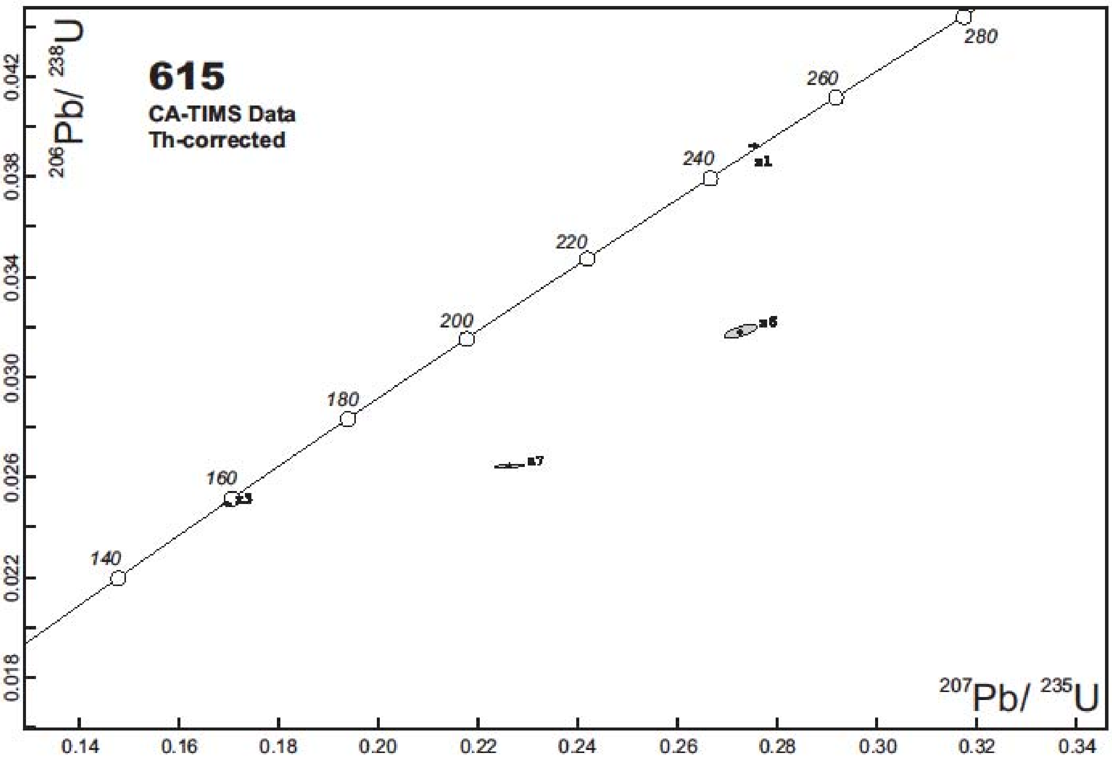

506
CA-TIMS Data
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
0.00072
0.00068
0.00064
0.00060
0.00056
0.00052
0.00048
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
0.0050
0.0055
0.0060
0.0065
4.6
4.4
4.2
3.6
3.4
3.2
3.0
Zircon
Th-corrected
weighted mean $^{206}Pb/^{238}U$ date
3.981 ± 0.053/0.13/0.13 Ma
MSWD = 0.15, n=3
4.52
3.82
Date [Ma]
z5
z2
z1
55.6
33.6
10.7

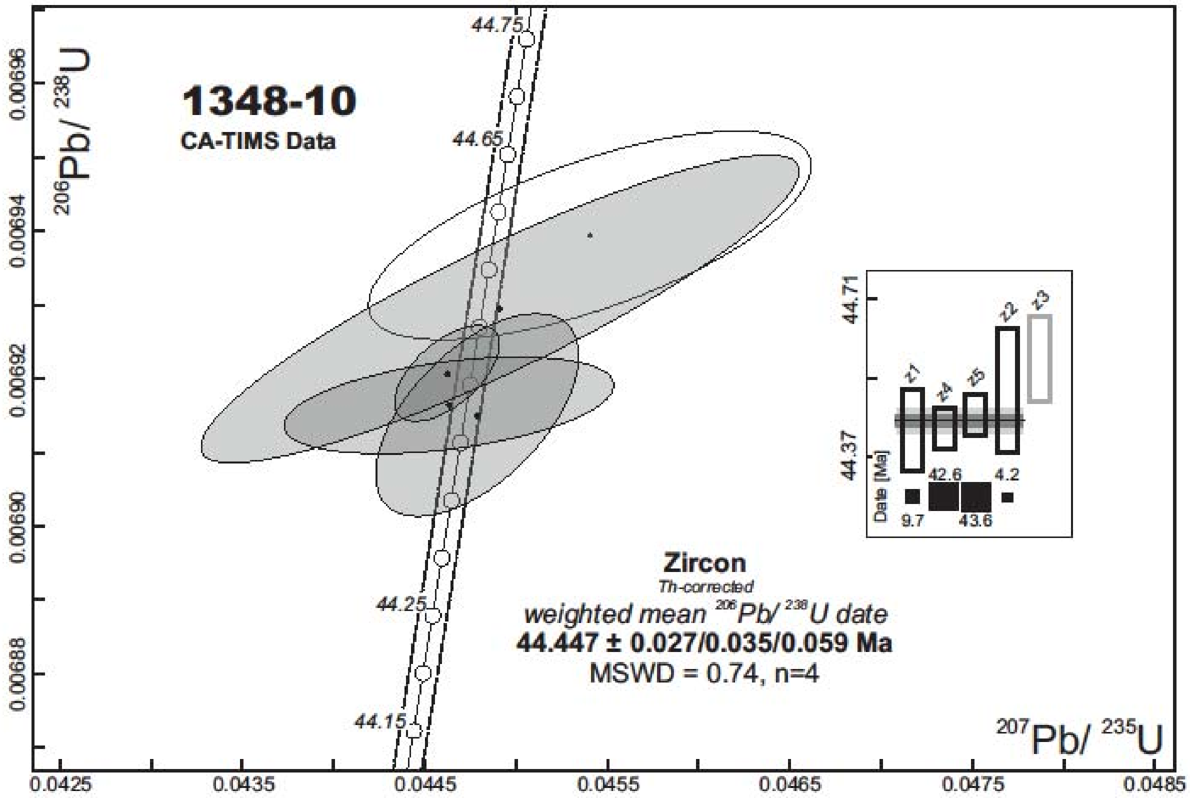

559
CA-TIMS Data
206Pb/238U
0.01435
0.01425
0.01415
0.01405
0.01395
92.0
91.5
89.5
Zircon
Th-corrected
weighted mean 206Pb/238U date
290.548 ± 0.077/0.089/0.13 Ma
MSWD = 0.15, n=4
207Pb/235U
0.0920
0.0925
0.0930
0.0935
0.0940
0.0945
0.0950
0.0955
0.0960
Date [Ma]
91.89
90.83
z2
z8
z5
z10
z7
z6
z4
z9
34.4
25.9
2.0
37.7


603
CA-TIMS Data
27.60
27.55
27.35
27.30
Zircon
Th-corrected
weighted mean ^{206}Pb/ ^{238}U date
27.422 ± 0.017/0.022/0.037 Ma
MSWD = 0.25, n=3
^{206}Pb/ ^{238}U
^{207}Pb/ ^{235}U
0.004245
0.004255
0.004265
0.004275
0.004285
0.0271
0.0272
0.0273
0.0274
0.0275
0.0276
0.0277
0.0278
0.0279
27.61
27.39
Date [Ma]
z2
z1
z4
z5
z3
37.6
35.8
26.6


604
CA-TIMS Data
^{206}Pb/ ^{238}U
0.01439
0.01437
0.01435
0.01433
0.01431
92.15
92.10
91.65
91.60
91.55
Zircon
Th-corrected
weighted mean ^{206}Pb/ ^{238}U date
91.880 ± 0.046/0.064/0.12 Ma
MSWD = 0.44, n = 4
^{207}Pb/ ^{235}U
0.0940
0.0942
0.0944
0.0946
0.0948
0.0950
0.0940
0.0954
0.0956
0.0958
0.0960


613
CA-TIMS Data
Th-corrected
^{206}Pb/ ^{238}U
^{207}Pb/ ^{235}U
40
60
80
100
120
140
160
180
200
220
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26


615
CA-TIMS Data
Th-corrected
^{206}Pb/ ^{238}U
^{207}Pb/ ^{235}U
140
160
180
200
220
240
260
280
z1
z6
z7
z3
0.018
0.022
0.026
0.030
0.034
0.038
0.042
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34


1348-10
CA-TIMS Data
$^{206}Pb/^{238}U$
0.00696
0.00694
0.00692
0.00690
0.00688
44.75
44.65
44.25
44.15
Zircon
Th-corrected
weighted mean $^{206}Pb/^{238}U$ date
44.447 ± 0.027/0.035/0.059 Ma
MSWD = 0.74, n=4
$^{207}Pb/^{235}U$
0.0425
0.0435
0.0445
0.0455
0.0465
0.0475
0.0485
44.71
44.37
Date [Ma]
z1
z4
z5
z2
z3
42.6
4.2
9.7
43.6