# Instructor Guide

# “ZirChron” Virtual Zircon Analysis App

## Access:

Use a web browser (e.g. Safari, Chrome, Firefox) to access the app at:

[**http://www.boisestate.edu/earth-isotope/education-and-outreach/zirchron-virtual-zircon-analysis/**](http://www.boisestate.edu/earth-isotope/education-and-outreach/zirchron-virtual-zircon-analysis/)

Click on any photo banner to explore versions of the app for different types of rocks. You can ‘print’ the browser window to a pdf at any time to save a record of your experiments.

## Background and Overarching Learning Goal:

*By the end of this set of activities, students should be able to evaluate a radioisotopic age and its uncertainty based upon the collection of data, the application of statistics, and the interpretation of geological and analytical sources of complexity and bias.*

This application was developed to promote a deeper understanding of the science of geochronology, including the integration of crystal-scale relative dating principles with numerical dating via radioisotope measurements. We felt that an integral aspect of developing this understanding was practical experience with the ***decision-making*** that goes into the selection of samples for analysis, and the subsequent interpretation of the result isotopic ages from those samples. The U-Pb decay system in zircon is particularly amenable to this practice, as we can apply different methods—both *in situ* laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) and high-precision chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-IDTIMS)—to the same crystals, and link the resulting radioisotopic ages to the textures within crystals revealed by cathodoluminescence (CL) imaging.

The application presents the student with a set of images of zircon crystals from a single sample, illustrating their internal zone and complexities. Two modules—LA-ICPMS and CA-IDTIMS) are available, with the same set of crystals illustrated for analysis in each. The exercises are designed around the ability of the student to ***conduct a virtual experiment*** by clicking on either labeled laser ablation “spots” (in the LA-ICPMS module) or individual crystals (in the CA-IDTIMS module) to obtain a set of radioisotopic ages. These ages are illustrated in both tabular and graphical formats, to allow the student to visual the distribution of data, and assess the relative similarities and differences between the data using common statistical tools.

Relative dating principles used in geological mapping and interpretation (e.g. superposition, crosscutting relationships, and principle of inclusions) are often taught as distinct from the application of radioactive decay and numerical dating. In fact the practice of radioisotopic dating—particularly using the U-Pb zircon chronometer—is informed by the same relative dating principles applied at the crystal scale. The internal zoning structures of individual crystals capture unconformities, cross-cutting relationships, inclusions all within a framework of superposition of younger on older growth zones. These observations can and should inform the selection of samples for dating—this application puts the powerful ***integration*** of the two branches of geochronology into the students’ hands.

Statistics plays an important role in ***calculating*** and ***assessing*** radioisotopic ages. We chose to focus on a single chronometer (238U decay to 206Pb), and to emphasize the numerical and graphical results of adding new analyses to each experiment. With each spot or grain selection, the empirical probability density function of the data set (obtained by summing the individual normal distributed data points) is calculated and illustrated (orange curve) along with the corresponding histogram (binned frequency graph) of the data set. These two graphical representations can be contrasted during the exercise. The probability density function can also be compared to a theoretical normal distribution of the data set (red curve), which assumes that the zircon population has a single true value estimated by the arithmetic mean and standard deviation of the data set. This assumption can be evaluated by visual comparison, or more quantitatively using the probability of fit statistics described below.

The most common model used to interpret a group of radioisotopic ages—the ***inverse-variance weighted mean age*** and the ***standard error*** of the mean—is also tabulated above the graph, along with the ***probability of fit*** statistic, and the ***Mean Squared Weighted Deviations (MSWD)*** statistic. The probability of fit statistic has an expectation value of 0.5 for a single-valued normal distribution of data; lower values indicate increasing scatter of the data away from this ideal normal distribution. For example, values of <0.05 indicate that one or more analyses lie outside of two standard deviations of the mean value. Similarly the expectation value of the MSWD for a single-valued normal distribution is 1; values >1 indicate increasing scatter of the data away from this ideal normal distribution.

These statistical concepts of distributions and probabilities may be new and complex material for some students, however the application provides an intuitive visual representation of these concepts by capturing how a choice made by the student translates into a change in the distribution of ages. Little background is required other than a familiarity concepts of the mean, the standard deviation, and the normal “bell-shaped curve” distribution. For more advanced classes, background statistical information is provided in an accompanying file ([ZirChron Stats Background](http://earth.boisestate.edu/isotope/files/2014/10/ZirChron-Stats-Background.pdf)).

In this instructor guide we provide some ideas for promoting effective exploration and class discussion, keyed to each of the questions posed in the [ZirChron Student Exercise](http://earth.boisestate.edu/isotope/files/2014/10/ZirChron-Example-Exercise.docx). The following activities can be used in a scaffolded manner. A high school or lower division undergraduate course may use the first two activities, while an upper division undergraduate or graduate course might use all four activities. The first two activities will easily fill a one hour class period. The activities can also be launched as partially or completely online assignments, for example utilizing message boards to facilitate communication between students.

Finally, we note how key statistical concepts promoted by this activity fully emerge when individual student results are compiled in real time in front of the class. This can be facilitated for example via a prepared GoogleSheet linked in a learning management system that allows students to input their results efficiently for immediate viewing and analysis.

## Specific Learning Objectives:

**By the end of this set of activities, students will be able to:**

* Apply relative dating principles at the crystal scale
* Describe the statistical distribution of the crystal ages including means, modes and outliers
* Form hypotheses that relate the statistical distribution of crystal ages to the physical characteristics of those crystals
* Form hypotheses about the geologic and/or analytic processes that could account for the distribution of crystal ages in a population
* Compare and contrast the LA-ICPMS and CA-IDTIMS analysis techniques with respect to precision and accuracy
* Describe the decisions that are made to determine the geologic age of a rock sample from a set of crystals

## Activity #1: Probability

### Select only 10 spots on the zircon crystals to analyze by laser ablation U-Pb analysis.

*Ask the students to save the results of their experiment by ‘printing’ the browser window to a pdf file.*

### Questions to answer:

1. What were your criteria for selecting your 10 spots?

*One of the strengths of the application is the linkage between the relative time concepts that can be analyzed from the zircon CL images (e.g. superposition of younger growth zones on older zones, crystal resorption features corresponding to growth unconformities, associated cross-cutting relationships, and cores of older zircons included within younger grains), and the numerical ages extracted from both in situ and isotope dilution analyses. Students can initially work in a forecasting mode, by establishing criteria based upon the images to predict which zircon crystals will yield the most precise and accurate crystallization age for the hosting igneous rock. The initial selection of spots might be done individually, with subsequent discussion in pairs or small groups.*

1. What was the range of ages you measured in those spots?

*One of the strengths of the application is the linkage between the relative time*

1. What was the weighted mean age with uncertainty of your 10 spot analyses?

*Each student or small group of students will have an immediate experimental result that can be compared to others. This can be facilitated relatively simply by having students compile their maximum age, minimum age, weighted mean age, and 2 uncertainty on a whiteboard, or more flexibly by compiling those parameters in a spreadsheet (or a GoogleSheet linked in a course management system) in front of the class. This compiled list provides an opportunity not just to identify the phenomenon of outliers, but also to assess how sensitive the mean value is to those outliers. The students have done a Monte Carlo simulation of sorts, and thus the results of their many experiments could be used to establish a measure of “external” reproducibility of the mean value.*

1. How would you describe the probability distribution of the spots you analyzed?

*Most data sets will exhibit outliers, asymmetry in the probability density functions, or even multiple modes.*

1. Is the probability distribution of your spots consistent with the model of a single age population as illustrated by the normal distribution?

*This question leads the student to the first direct comparison of their ‘real’ data set to a statistical model of the normal distribution, first visually and then drawing attention to the probability of fit statistics. Students can immediately assess the sensitivity of the probability of fit statistic by adding or subtracting outliers from their data set, either individually or in pairs or small groups.*

1. Are there any correlations between numerical outliers or the shape of the probability distribution and the physical characteristics of the crystals?

*Here the class can be queried for the relative time concepts that can be analyzed from the zircon CL images (e.g. superposition of younger growth zones on older zones, crystal resorption features corresponding to growth unconformities, associated cross-cutting relationships, and cores of older zircons included within younger grains), and whether those criteria can explain any of the anomalous numerical ages obtained in their initial selection.*

1. Based upon this experiment, how would you change your strategy for determining the most accurate age of the zircon population?

*Students can now transition into working in a hindcasting mode, hypothesizing on the features of the zircon images that might produce complexities in determining a precise and accurate crystallization age for the hosting igneous rock. This discussion might be facilitated in pairs or small groups.*

## Activity #2: Reproducibility

### Clear your selections, and then select only 10 spots on the zircon crystals to analyze by laser ablation U-Pb analysis with the goal of determining the most accurate age of the zircon population.

*Ask the students to save the results of their experiment by ‘printing’ the browser window to a pdf file.*

### Questions to answer:

1. What were your criteria for selecting the new set of spots, and how do those criteria differ from the criteria you used in exercise 1?

*Students can now directly test their hypotheses developed at the end of Activity #1. This question allows students to reflect on the results of Activity #1 and use their learned knowledge to improve their performance, establishing a more ‘expert’ opinion in the process.*

1. What was the weighted mean age with uncertainty of your new set of 10 spot analyses?

*A second compiled list (again a GoogleSheet linked in a course management system works well for this) at the front of the class will facilitate quantitative comparison of the two activities.*

1. Where you successful in avoiding outliers?

*The compiled lists will facilitate quantitative assessment of the ability to predict and eliminate outliers.*

1. Considering both of your experiments, what geologic or analytical processes could account for a range of ages in a zircon population, including outliers?

*Older outliers are most commonly attributed to the geological process of crystal inheritance—the incorporation of older zircon crystals from basement rocks or earlier volcanic or plutonic rocks, which are incompletely dissolved and/or isotopically reset upon incorporation into the host magma. Inherited cores may have irregular resorption features, differing CL brightness, or differing zoning patterns compared to the dominant magmatic zircon. Younger outliers or tails on the probability distributions may be attributed to open system behavior, or Pb-loss occurring after crystallization of the zircon and facilitated by the accumulation of radiation damage to the crystal lattice during radioactive decay. Pb-loss may thus be correlated to CL-dark crystals or zones, since U content is inversely proportional to CL brightness (U and Th substitution and radiation damage inhibit CL emission).*

**Activity #3: Precision versus accuracy**

### Clear your selections (“Select None”) and then select 1, 4, 9, 16, and 25 spots, each time recording the weighted mean age and error in the table below. You may choose to exclude outliers as you select your spots.

*Ask the students to compile the results of each of these selections in the table.*

### Questions to answer:

1. How does the *precision* in the weighted mean age of your spots change with the number of analyses (e.g. compare to your results in Activity 2)?

*The standard error of the weighted mean, which is displayed above the graph as spots are selected, is a statistic that estimates the variance of the estimated mean value of the population. As such it implicitly assumes that the sample has a single mean value and that random errors are normally distributed. The standard error of the mean also decreases with the inverse of the square root of the number of measurements, thus the precision of the weighted mean age apparently improves with higher N.*

1. Can you write a formula for this relationship?

*This question presents a challenge for students to use the empirical data they have collected to discover the relationship between the standard error of the mean and the standard deviation of the data being averaged. Ask students to identify the variables: the standard deviation (****sd****) of an individual date, the number of analyses (****N****), and the resulting standard error (****se****) of the weighted mean for each selection. Then write up the* ***se*** *on the left side of an equality and the* ***sd*** *on the right side; challenge students to see (from the pattern of results in their table) a factor that relates the two quantities:*

***se = sd / sqrt(N)***

3-3. How could you assess the *accuracy* of your calculated age for the zircon population?

*In choosing their own sets of spot analyses, the students have done a Monte Carlo simulation of sorts, and thus the results of their many experiments could be used to establish a measure of accuracy as the “external” reproducibility of the mean value (see also section 1-3). Referencing the compiled lists at the front of the class the students can assess whether the variation between each of their age experiments is greater or less than the standard error of their individual ages.* ***Note that this measure of accuracy may be robust to random errors and outliers, but may not be sensitive to systematic errors that would bias entire data sets; this phenomenon can be explored in Activity #4.***

## Activity #4: Comparing LA-ICPMS versus CA-ID-TIMS methods

### Clear your selections, move to the CA-IDTIMS page of the app, and then select only 10 single zircons to analyze by CA-IDTIMS U-Pb analysis.

*Ask the students to save the results of their experiment by ‘printing’ the browser window to a pdf file.*

### Questions to answer:

1. Describe your criteria for the selection of single grains to analyze by CA-IDTIMS? How were these criteria informed by your LA-ICPMS analyses?

*This is the third opportunity for students to state and reflect on their criteria for choosing samples to date—they are well on their way to being experts!*

1. How would you describe the probability distribution of the spots you analyzed? How does it compare to your LA-ICPMS results?

*The CA-IDTIMS data sets may also exhibit outliers and asymmetry in the probability density functions, generally to older ages. The scarcity of anomalously young ages is due to the chemical abrasion method, which partially dissolves the crystals prior to analysis, eliminating open-system portions of the crystals, i.e. Pb-loss.*

1. Are there any correlations between the numerical outliers and the physical characteristics of the crystals? Are there correlations of numerical outliers between the two methods (LA-ICPMS and CA-IDTIMS)?

*The students may be prompted to examine a number of features, including: a) do the grains with “cores” (either truncated or with different CL intensity) yield older ages? b) do the older outliers in the LA-ICPMS data also provide older CA-IDTIMS ages?*

1. What was the weighted mean age with uncertainty you interpreted from your set of 10 grains? How does your CA-IDTIMS result compare to your LA-ICPMS result?

*A compiled list at the front of the class will facilitate quantitative comparison between CA-IDTIMS and LA-ICPMS across all of the student experiments.*

1. Compare and contrast the LA-ICPMS and CA-IDTIMS analysis techniques in terms of precision and accuracy.

*The increased* ***precision*** *of the CA-IDTIMS technique is apparent from the smaller standard deviations of each analysis, the lower standard error of the mean, and the smaller ranges (max to min). Similar to question 3-3, the results of many experiments could be used to establish a measure of* ***accuracy*** *as the “external” reproducibility of the mean value. Referencing the compiled lists at the front of the class the students can assess whether the variation between each of their age experiments is greater or less than the standard error of their individual ages.*

1. What geologic or analytical processes might account for any apparent bias between the CA-IDTIMS and LA-ICPMS results?

*The students will likely find that the weighted mean ages for the CA-IDTIMS and LA-ICPMS data sets do NOT overlap within error, which points out a systematic error between the two methods. This observation provides an opportunity to collect ideas about sources of systematic error, which can include both analytical and geological sources. This is a key discussion point to draw in ideas of inheritance, which might bias CA-IDTIMS to older ages, versus Pb-loss, which might bias LA-ICPMS to younger ages. The students can assess both of these mechanisms by examining whether grains with cores actually give older CA-IDTIMS ages, or whether CL-dark (high-U, damaged) zones generally give younger LA-ICPMS spot ages.*

### Wrap up questions: These reflection questions could be assigned outside of class.

1. Compare relative dating principles that you might use in the field (e.g. superposition, crosscutting relationships, and principle of inclusions) with observations you used to describe the internal structures of individual crystals.
2. Describe and defend an experiment that you would undertake (including crystal selection criteria, analytical methods, numbers of analyses) to accurately determine the crystallization age of a rock from a sample of zircon crystals.
3. How has your thinking about geochronologic ages reported in the literature changed as a result of these activities?