Using Online Igneous Geochemical Databases for Research and Teaching

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Course Overview

This course introduces participants to the use of large on-line geochemistry databases. The goal of the course is two-fold: (1) it aims to enable users to interact with and understand these databases, their components, and technologies, and (2) it aims to broaden awareness and understanding of the opportunities and benefits that Geoinformatics can offer to teaching and research. The course is intended to offer a blend of education opportunities in the use of geochemical databases as well as background knowledge about Geoinformatics, relational databases, and data reporting. The course will give students, teachers, and researchers training on the practical use of four related data management systems for igneous rock geochemistry through a variety of exercises and short lectures to explore and explain how these systems work.

Overview of Geoinformatics

This section provides context for the geochemical databases as part of the broader development of Geoinformatics and Cyberinfrastructure.

CYBERINFRASTRUCTURE

Science and engineering increasingly rely on a rapidly evolving infrastructure of digital information and computing resources that capitalizes on recent advances in computing and related information technology. This infrastructure has been termed *cyberinfrastructure*. Cyberinfrastructure is viewed as a new paradigm for doing research: *"Coupled with continuing improvements in microprocessor speeds, converging advances in networking, software, visualization, data systems and collaboration platforms are changing the way research and education is accomplished."*[1] Cyberinfrastructure is considered "essential, not optional" to advance science and engineering.

The National Science Foundation recently established a new *Office for Cyberinfrastructure* (OCI), which "coordinates and supports the acquisition, development and provision of state-of-the-art cyberinfrastructure resources, tools and services essential to the conduct of 21st century science and engineering research and education"[2]. The NSF has taken leadership in the development of cyberinfrastructure in the US, supporting a wide range of research activities to develop new technologies and methodologies that contribute to the construction and expansion of cyberinfrastructure capabilities across disciplines. The NSF supports many community-driven efforts, from sensor networks to virtual observatories to digital data collections, that are considered the 'seeds of cyberinfrastructure'. Prominent examples are: The Network for Earthquake Engineering Simulations (NEES), the Grid Physics Network (GriPhyN), the National Virtual Observatory (NVO), Science Environment for Ecological Knowledge (SEEK), the National Ecological Observatory Network (NEON), the Linked Environments for Atmospheric Discovery (LEAD), and the Geosciences Network (GEON).

Both the potential power and the challenges of cyberinfrastructure lie in the integration of the many relevant and mostly disparate resources to provide a platform that can on the long term empower the modern scientific research endeavor. Many technical, disciplinary, organizational, political, and cultural barriers still need to be overcome before

[1] NSF Special Report 'Cyberinfrastructure', http://www.nsf.gov/news/special_reports/cyber/index.jsp
[2] NSF Office of Cyberinfrastructure web site at http://www.nsf.gov/od/oci/about.jsp

cyberinfrastructure will reach its full potential and fulfill its promises, but its impact is increasingly visible through first implementations.

GEOINFORMATICS

Many people think of Geoinformatics as the application of computer technologies and methodologies to scientific results with spatial-temporal coordinates. But *Geoinformatics* is a much broader endeavor. Envisioned as the cyberinfrastructure for the Earth Sciences, it corresponds to a distributed, integrated digital information system and working environment that provides innovative means for the study of the Sun-Earth system and other planets through the use of advanced information technologies. Geoinformatics is an emerging science and technology frontier built on a broad range of disciplinary activities. These activities range from major research and development efforts in both the earth and the computer sciences developing new approaches and technologies for data discovery, integration, visualization and analysis, to small, domain-specific projects that develop data collections (databases) and data analysis tools that serve the needs of individual communities such as geochemistry, sedimentology, or structural geology.

Geoinformatics is and will at an increasing rate provide new, cross-disciplinary approaches for accomplishing Geoscience research. It broadens the dissemination and application of scientific data and knowledge and permits more efficient use of resources including data, samples, and computing resources. Virtual institutions and collaboratories enhance collaborations. Sensor networks generate and make accessible in real-time vast amounts of observational data, from the oceans, the continents, the atmosphere, and from space. High-performance computer grids will enable the next generation of earth system modeling.

Geoinformatics also offers powerful new methods and solutions for Geoscience education, making accessible cutting edge research results and large, global data sets for incorporation into instructional activities and training of young scientists. Easy and fast access to large data collections as well as appropriate tools for data analysis and visualization allow students to address large-scale complex problems within formerly unimaginable timeframes that fit their course schedules, develop their ability to use scientific methods, and teach them how to critically evaluate the integrity and robustness of data and their consequent interpretations.

DIGITAL DATA COLLECTIONS

At the heart of Geoinformatics are data. Many key components of Geoinformatics – information and knowledge discovery, data integration, modeling, and visualization - present new, more efficient and more effective ways for taking advantage of data to generate new knowledge, but require data to be accessible in digital form. Without digital data, Geoinformatics has nothing to run upon. The importance of digital data collections has recently been emphasized by the National Science Board's report on long-lived digital data collections[3]: *"It is exceedingly rare that fundamentally new approaches to research and education arise. Information technology has ushered in such a fundamental change. Digital data collections are at the heart of this change. They enable analysis at unprecedented levels of accuracy and sophistication and provide novel insights through innovative information integration."*

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[3] *Long-lived Digital Data Collections: Enabling Research and Education in the 21st Century*; NSB report to the National Science Foundation, September 2005; http://www.nsf.gov/pubs/2005/nsb0540/

Data in the Earth Sciences come in many forms, and in varying quantities. In many domains of the Earth Sciences, large amounts of observational or computational data are generated that automatically stream into digital data management systems, e.g. remote sensing data from satellites or ground motion data from seismographic stations. These can be fairly easily integrated into the Geoinformatics framework. In other areas, especially in which data volumes are rather small and are being produced by individual researchers in the field or in the lab, for example geology and geochemistry, data have until now been accessible only through the published literature, or have not been accessible at all, but only their interpretation. These data have in general been seriously underutilized. In order to maximize the application of these data types and make them accessible within the Geoinformatics system, new approaches to data publication and data management need to be planned and implemented including the creation of digital data collections that capture both legacy data and new data. This process generally entails a difficult cultural change towards more open data sharing, and emphasizes the roles and responsibilities of each investigator in the development of a functional cyberinfrastructure for the Geosciences.

In order for Geoinformatics to become (and remain) a valuable resource for scientists, educators, and students, their active involvement in all aspects of this endeavor is essential. Geoscientists need to contribute to Geoinformatics by communicating their needs, scientifically guiding the design of systems and system linkages, providing constructive feedback on usability and utility of systems, and reporting problems, as well as helping to educate system engineers and IT developers in relevant geoscientific concepts, methods, and data. As data authors (investigators who produce and publish data) and data users, they need to take on new responsibilities for the data that they produce and that they use in their research or teaching, respectively. Highest priority among these responsibilities is compliance to standards for format, documentation (metadata), quality control, access/publication, and citation of data that need to be defined by the community.

GEOCHEMISTRY AND GEOINFORMATICS

Geochemical data are a prominent example of an underutilized resource in the Earth Sciences. For over a century, chemical data for natural samples have been archived and published in paper journals, widely dispersed and difficult to find and compile. Over the past three decades, data volumes have increased exponentially due to the advent of automated instrumentation such as the electron microprobe or ICP-MS. Rather than developing alternative data management infrastructures capable of dealing with the expanding quantity of geochemical data, there was erosion in the amount of primary data published. This resulted in a loss of much data and thus the opportunity for more critical data evaluation and application of new data analysis methods. Additionally, data no longer appear in only a handful of journals, but are scattered across a large number of journals published worldwide. This has created a situation where only selected primary data are published, and what sees print is spread so widely distributed as to be nearly impossible for any single investigator to see or aggregate.

In the mid-1990's, two geochemical database projects started independently at nearly the same time, GEOROC at the Max-Planck-Institute in Germany, initially focused on data for ocean island basalts and convergent margins volcanics, and PetDB at the Lamont-Doherty Earth Observatory of Columbia University, focused on data for ocean floor igneous and metamorphic rocks. A third database project joined them a few years later, NAVDAT, the database for North American volcanic rocks. These projects maintain and operate relational databases for igneous rock geochemistry that are accessible online via dynamic, interactive web interfaces. The special feature of these databases is their integrative approach. Instead of cataloging entire datasets as done in data libraries, each individual value of a dataset is stored and described, so that each individual value is searchable and can be integrated with related values into new, customized datasets. The igneous rock databases had a revolutionary impact on the use of geochemical data in research and education. In spite of their recent arrival on the scene, they have already been used intensely in many studies as the source of data used to develop and test new hypothesis regarding chemical and mineralogical composition of Earth's mantle, the generation and evolution of continental and oceanic crust, melt transport , and global geochemical seawater budgets. PetDB alone has been cited in more than 100 papers since 2002. As stated by one of the investigators using these databases: *"…Within about 5 minutes of logging on for the first time, I was staring at an EXCEL file that had all the REE on basalt glasses from the EPR from 10°N to 20°S. And the answer to my La/Sm question. I am very impressed, we are looking at the future of geochemistry."*

Information Technology Aspects of Geoinformatics

This section reviews the principles of databases and current practices in information technology (IT) and the Internet. We discuss the basics of data transfer between databases as well as visualization of data for teaching and research. Lastly, we describe the sorts of supporting data needed to make these systems useful and complete.

SOME BASIC DATA ABOUT DATABASES

The foundation of a geoscience's cyberinfrastructure is the data communicated and explored. For this reason, the data along with all supporting information are entered into a database. In short, any database is an organized set of related information stored in a computer system using a combination of software and hardware that allows for speedy access and search.

Flat databases (or flat files) are probably most familiar to educators and researchers. This is simply a single table containing values arranged in rows and columns (fields). This is exactly the sort of table that appears in publications as well as the "Excel" worksheet used by most workers (although the latter may contain embedded calculations and functions that relate one cell to others). A typical flat table is shown below in Figure 1.

Sample Name	IGSN	206_204Pb	207_204Pb	208_204Pb	Age	87Sr_86Sr
12-2-01E	JDW000001	19.017	15.656	39.017	13.37	0.708286
12-4-01A	JDW000002	18.920	15.638	38.934	12.81	0.707199
12-5-01B	JDW000003	18.457	15.577	38.181	4.5	0.705294
12-5-01C	JDW000004	18.601	15.634	38.456	4.04	0.705647

Figure 1. Portion of a geochemical data table containing isotopic and age data.

Connected with these data is a host of valuable information pertaining to the values. For example, how and in what lab the analyses were made, what sort of standards were measured at the same time, the sample location, and other important facts are typically contained within the body of a published text. In addition, information such as location, age, rock name, and other chemical values may be contained within the paper or in additional tables. For example, expanding on the data fields in this table, we could get the supporting information shown in Figure 2. This added information is critical to understanding the basic values, but in most publications is contained within the body of the text or in a footnote to a table. This information is commonly referred to as metadata.

In any database, all information must be included for every sample and be available for search and output. As can be seen by comparing figures 1 and 2 and considering that there may well be other tables and other methods for different values, such a full representation becomes unwieldy to impossible to implement in a single flat file. It is also obvious that much of the information in Figure 2 is redundant: all the values for the lab, standard, normalization, and method are the same. Data of this sort is amenable to a relational database approach.

Sample Name	87Sr_86Sr	Lab	Standard Value (NBS 987)	Normalization (86Sr/88Sr)	Method
12-2-01E	0.708286	Univ. Kansas	0.71025	0.1194	TIMS
12-4-01A	0.707199	Univ. Kansas	0.71025	0.1194	TIMS
12-5-01B	0.705294	Univ. Kansas	0.71025	0.1194	TIMS
12-5-01C	0.705647	Univ. Kansas	0.71025	0.1194	TIMS

Figure 2. Typical associated information for the Sr isotopic values in Figure 1.

A relational database is one that contains the data not in a single table, but in multiple tables related by a common field or "key" that carries from one table to the next (although there is seldom one single key that goes between all the tables). In this way, a value that is repeated is present in the database only once, and is referenced using the key (Figure 3). This allows for very efficient storage of data and simple retrieval and referencing from one table to the next.

Item Measured	Value	**Method Number**
87Sr_86Sr	0.708286	**1**
SiO2	61.7	**2**
Fe2O3T	3.86	**2**
MgO	2.34	**2**

Method Number	Lab Number	Standard Value	Standard Name	Normalization	Normalization Ratio	Method
1	Univ. Kansas	0.71025	(NBS 987)	0.1194	(86Sr/88Sr)	TIMS
2	Univ. Kansas	Not Given	Not Given	Not Given	Not Given	XRF

Figure 3. Two tables showing a key formed by the values in Method Number. These tables contain data from a single sample in the figure above. Although the Method Number is repeated multiple times in the first table, it appears only one time in the second table. The two tables are related by the Method Number.

Many relational databases are complex in that they contain 10's or even 100's of individual tables that are related by a series of keys most of which are only repeated once between two tables. These databases are very efficient in that they are organized so that items applying to multiple values are not repeated in storage (this is referred to as database normalization). A large number of tables can make the database difficult to understand and to read for normal, non-technical users. The arrangement of data and relations from table to table is called the database schema. The schema is a representation of the items in a table and the identification of a key that carries from one table to the next (Figure 4).

The primary advantage of the relational database approach is the efficient storage of data through the process of normalization. This is particularly true for complex databases relating 10's of tables (such as those for geochemical data). Allied with this storage advantage is the ability to rapidly retrieve data in an organized and flexible manner.

Modern relational database software is extremely optimized for storage and retrieval of large amounts of data. Combined with high-end computers, this gives very efficient operation. For example, a single instance or occurrence of a Oracle database can access more than 100 Terabytes of data across hundreds or thousands of individual tables.

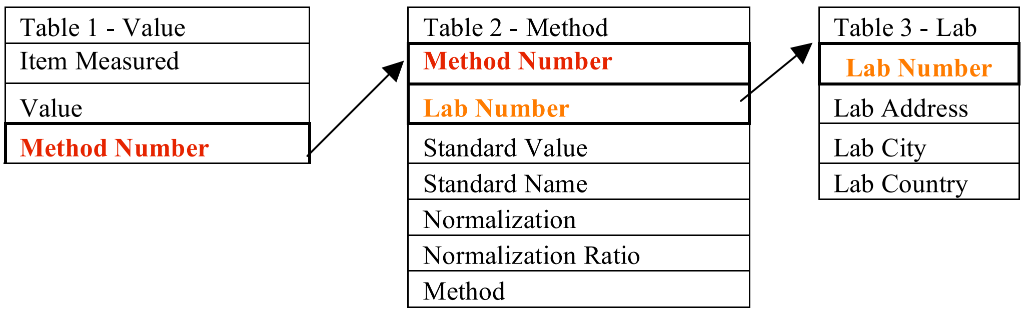

Figure 4. A simple schema showing the relation of 3 tables. Method Number is the primary key in Table 2 and relates to Table 1 information. Likewise, Lab Number is the primary key of Table 3 relating address information to the method describe in Table 2. No primary key is shown in Table 1, but one must be present.

Communicating and Aggregating Data and Databases

To be useful, a database must afford easy access and data retrieval. This is done using a web interface that exposes the database to exploration either by general, unsecured access or by registering users with associated access privileges (or a combination of both). There are a vast number of programming packages that work to serve data over the Internet, but well designed database interfaces are independent of which browser the client uses to access the host system (server).

Serving data from multiple databases or aggregating data presents many challenges. At the least, the schema and definitions used in each database must be known and put into a common usage. Although many approaches have been taken in the past, ranging from simply exporting the database to a flat file to opening a direct connection into the database from the outside, a common and powerful current method is to exchange data via a web service using an XML (extensive markup language) format and schema. This method is both scaleable and secure.

A web service is a simple way for a client or server to send a request to a server (machine to machine communication). Without getting into the coding of such a communication, a request would be something like "send major element data for all samples between 50 and 60 Ma that are located in South America." The contacted server then retrieves information from a database and sends it back to the client. There are many flavors of web services, but almost all rely on XML for sending requests and responses.

XML is a markup language permitting simple communication of complex data through a text file. The XML document is formatted so that each section relates some aspect of the information: the entire document contains information organized into parts equivalent to sections, chapters, paragraphs, and sentences of a normal text. The XML document can be organized using a schema functionally and logically equivalent to that described above for relational databases. In fact, many database programs (e.g., Oracle) can hold data in XML format natively with all the performance and database functionality of a more familiar table-based system. The value of the XML approach is that data providers can output (or publish) their source database to fit the XML schema to make the data accessible to anyone through transfer of a text document. This makes the aggregation of multiple databases a simple task; access to aggregated data is done with the same speed as any relational database. In addition, requests and responses require no additional security measures.

VISUALIZATION

Another aspect of communicating information from databases is visualizing the data in convenient ways using resources or representations that may not be readily available to the user. This might consist of maps, x-y or x-y-z diagrams, or possibly more interactive selection of data or manipulation of the plot or map. Online visualization packages mainly run in two modes: the first in on the server side where data is processed and then sent to the user usually as some sort of bitmap image; the second is on the client side where data and visualization methods are transferred processed using an application or plugin on the user's computer. Examples of the latter are the Flash, Java, and QuickTime plugins.

Both modes present advantages and disadvantages. The main issue in server-side visualization is speed of operation. For this mode, the user must interact directly with the server to change any aspects of the visualization. If the Internet connection is slow or the server busy, this can present aggravations to the user. Although client-side operations can be extremely fast and flexible, obtaining needed software/plugins as well as browser compatibility are the main issues with this mode. Visualizations are typically written for one version of the client software or plugin; this plugin likewise may have varying behavior from browser to browser. Different combinations of plugins and browsers can lead to incompatibilities that limit or block use. Visualizations that operate employing a combination of user programs with data streamed from a server can be extremely powerful (e.g., Google Earth), but potentially suffer the cumulative effects from issues related to both the server and client side problems.

REQUIRED METADATA

To be useful and to fully document information, databases must contain more than just a listing of values for different fields. Geochemical data especially requires much additional information on the sample and analysis methods in order to characterize a sample sufficiently. Listed below are a series of suggested background data to go with whatever chemical values are contained in a database.

1. A unique sample ID (or IGSN) obtained from SESAR (System for Solid Earth Sample Registration – http://www.geosamples.org)
2. A classification for the sample (e.g., Igneous, Volcanic, Mafic, Basalt)
3. All information relating to publications on the particular sample
4. Location as best known and pertinent information about sampling technique
5. The age of the sample and how it was determined
6. All measured chemical values for the sample and subsamples (e.g., minerals)
7. Detailed information about the nature of the analyses including:
    - Methods of analysis
    - Lab where the analyses were conducted
    - Values for standards and normalization applied to chemical values

Online Databases for Solid-Earth Geochemistry

Online geochemical databases, such as those at the EarthChem.org portal (Tables 1-4), present new opportunities and challenges for using data in the context of earth science instruction (Table 5). Besides allowing educators to rapidly produce customized datasets for a variety of teaching purposes, when used by the students themselves, the databases promote a wider understanding of the scale and diversity of natural materials and systems, allow for discovery-based learning, and require reasoned decisions regarding the quality, management, analysis, and interpretation of data.

Using databases in teaching also presents some challenges. In many contexts, a full disclosure of supporting data is not necessary to reach the required learning objectives. In addition, real earth science data is often messy and troublesome to work with and can be misunderstood or misused by untrained practitioners. Students require preliminary instruction and ongoing practice to know which data to use, how to ascertain data quality (e.g., error and precision), and how to use data to formulate and test hypotheses. Because databases are relatively new, few have well-developed educational support structures. Developing educational applications of these new information tools is just beginning.

Table 1. Features of the GEOROC online database.

GEOROC

URL
http://georoc.mpch-mainz.gwdg.de/georoc/

Focus
compositions of igneous materials from convergent margins, oceanic islands, and large igneous provinces

Geographic coverage
global (oceans and continents)

Tectonic settings

- oceanic islands
- seamounts
- oceanic plateaus
- submarine ridges
- ocean basin flood basalts
- continental flood basalts
- convergent margins (arcs)
- Archean cratons (including greenstone belts)
- intraplate volcanics
- rift volcanics

Earth materials

- volcanic igneous rocks
- plutonic igneous rocks
- mantle xenoliths
- volcanic glasses
- metamorphic rocks (not emphasized)
- sedimentary rocks (not emphasized)
- minerals (from rocks and veins)
- inclusions (glass, mineral, and fluid)

Analytical data

- major-elements
- trace-elements
- radiogenic isotopes

Strengths

- data are easily searchable by tectonic setting, geographic region, and in some cases igneous suite
- precompiled datasets include global rock data grouped by chemical element, and MORB data grouped by region

Limitations

- age data are only included if it is mentioned in the original reference, hence the number of samples with quantitative age information is limited

Downloading options

- Excel-compatible comma-separated text files (.csv format)
- HTML files

Table 2. Features of the NAVDAT online database.

NAVDAT

URL
http://navdat.kgs.ku.edu/

Focus
ages and compositions of igneous rocks from western North America

Geographic coverage
North America, but mostly from the western U.S., Mexico, and British Columbia

Earth materials
- volcanic igneous rocks
- plutonic igneous rocks (limited)
- mineral analyses (limited)

Analytical data
- major-elements
- trace-elements
- radiogenic isotopes
- stable isotopes
- U-series isotopes

Strengths
- Cenozoic volcanic rocks
- every sample is accompanied by quantitative age data. This makes it ideal for examining and plotting space-time-composition trends
- contains several automated features that generate interactive maps and diagrams
- at present, there is a limited capacity for searching by volcanic field

Limitations
- not easily searchable by tectonic setting, geographic regions smaller than states or provinces, or by igneous province or suite
- initial isotopic ratios are not available

Downloading options
- Excel-compatible tab-delimited text files
- HTML tables
- maps of sample locations
- major element variation ("Harker") diagrams
- total alkali vs. silica (TAS) diagrams (used for rock classification)
- geology, elevation, gravity, and magnetic GIS coverages for western states

Table 3. Features of the PETDB online database.

PETDB

URL
http://www.petdb.org

Focus
Compositions of igneous materials from the ocean floor

Geographic coverage
global (ocean floor)

Tectonic settings
- abyssal hills
- aseismic ridges
- back-arc basins
- failed rifts
- forearc basins
- fossil ridges
- fracture zones
- incipient rifts
- oceanic plateaus
- oceanic islands
- off-axis spreading centers
- old oceanic crust
- rift valleys
- seamounts
- spreading centers
- trenches
- triple junctions

Earth materials
- volcanic igneous rocks
- plutonic igneous rocks
- volcanic glasses
- mantle xenoliths
- metamorphic rocks (not emphasized)
- minerals (including ores)
- glass inclusions

Analytical data
- major-elements
- trace-elements
- radiogenic isotopes
- stable isotopes
- U-series
- noble gasses

Strengths
- data are easily searchable by tectonic setting, geographic region, rock type
- all available data for individual samples published in multiple sources are integrated into complete sample datasets to facilitate data processing and analysis

Limitations
- the database is limited to ocean floor basalts (mainly zero age) and abyssal peridotites
- map interface to data available only externally at www.geomapapp.org

Downloading options
- Excel-compatible comma-separated text files (.csv format)
- HTML files

Table4. Features of the EarthChem online database.

EarthChem

URL
http://www.earthchem.org

Focus
compositions of igneous materials

Geographic coverage
global (terrestrial and ocean floor) – includes all samples from the GEOROC, NAVDAT, and PETDB databases with some data on xenoliths; additional data entry planned as well as other databases

Tectonic settings
- same as those in GEOROC, NAVDAT, and PETDB, but the data are not searchable by tectonic setting

Earth materials
- volcanic igneous rocks
- plutonic igneous rocks
- altered igneous rocks
- metamorphic rocks (not emphasized)
- sedimentary rocks (not emphasized)
- minerals (including ores)
- veins (not emphasized)
- xenoliths

Analytical data
- major-elements
- trace-elements
- radiogenic isotopes
- stable isotopes
- U-series
- noble gasses

Strengths
- simultaneous searching of large amounts of data (>230,000 samples) from different databases
- data are easily searchable by reference information, geographic region (by coordinates, interactive map, or gazetteer), and rock type
- data from the different databases are integrated into a common output format

Limitations
- the EarthChem portal is a prototype system under development, so has some limitations at present as to functionality and content
- samples are not searchable by tectonic setting or igneous suite
- no age information is included in the downloaded data files

Downloading options
- "quick" and "advanced" HTML files
- tab-delimited text files (.txt)
- Excel files (.xls)
- interactive map

Table 5. Potential benefits and challenges for educational use of geochemical databases

Potential benefits	Potential challenges
➢ allows instructors to rapidly produce customized datasets	➢ databases may be somewhat overwhelming to beginning students
➢ highlights the considerable scale and diversity of natural materials and systems	➢ many databases are written for the primary benefit of professional researchers, and are not necessarily aimed at the needs and abilities of undergraduate-level students.
➢ provides a platform for discussing issues of data quality, data management, and other issues that scientists routinely face	➢ some databases do not have well-developed educational support structures
➢ promotes discovery-based learning (if accompanied by an appropriate level of structure and guidance)	➢ databases may not be as "clean" in terms of completeness and consistency as smaller datasets hand-selected by the instructor

Using the Databases

The purpose of this part of the workshop is to (1) discuss the benefits and challenges of using geochemical databases in the courses you teach, (2) demonstrate some example exercises and activities that make use of the GEOROC, PetDB, and NAVDAT databases at EarthChem.org, all of which are ready to download from a digital resource collection housed at the Science Education Resource Center (SERC), and (3) encourage you to create and share data-rich exercises and activities with your colleagues in the Geoscience community.

TEACHING WITH DATA

As geoscientists, we all know the importance of data in doing science. From our many years of training and research experience, we have first-hand knowledge of the considerable efforts that scientists take to acquire data and to ensure its integrity and proper use. Learning how to efficiently obtain and properly use information are fundamental skills that are required not only of future scientists, but ultimately of all citizens at some level.

Recent discussions within the scientific and educational communities make a strong case that the best way for students to learn science is to ***do science***! At its core, science is a way of knowing—a time-honored method of asking questions, constructing explanations, collecting evidence, engaging in dialogue, and applying knowledge to meaningful problems—but are these the skills our students are practicing in our classes? The answer is often sadly "no". Widespread educational methods often do not match our goals for students in science classes; while modern society wants citizens that can perform complex tasks, gather and synthesize information, and communicate with others, our current educational methods often emphasizes memorization of facts, passive reception of information (listening and reading), and practicing simple skills out of context[4]. The skills our students end up practicing in many college classes are not what they will be doing in the real world! Perhaps its time we tried some new methods that taught the skills we actually want to develop in our students!

Engaging students with data is an important component of this new approach of teaching science by doing science.[5][6][7][8] Listed below are several excellent online resources that explore a wide number of issues related to the use of data in Geoscience instruction.

Using Data in the Classroom
http://serc.carleton.edu/usingdata/index.html

This site, an outgrowth of a recent NSDL (National Science Digital Library) sponsored workshop, provides information and discussion for educators and resource developers interested in effective teaching methods and pedagogical approaches for using data in the classroom. The sites includes searchable lists of online resources (including datasheets, data sources, and tools), a searchable list of examples and activities that use data, pedagogic resources, a community discussion, a calendar of upcoming workshops and recent workshop reports, and recommendations for database developers.

Teaching Quantitative Skills in the Geosciences
http://serc.carleton.edu/quantskills/

From simple arithmetic or graphing to sophisticated use of equations and models, quantitative skills are an integral aspect of teaching Geoscience at the undergraduate level. This site provides resources, information, and discussion to support undergraduate students and faculty in the difficult task of mastering quantitative skills. The site includes a list of essential quantitative skills, a compendium of teaching techniques and tips, a searchable list of quantitative activities for classes and labs, a list of online student resources, a community discussion, and a calendar of upcoming workshops and conferences.

Using Data to Teach Earth Processes
http://serc.carleton.edu/NAGTWorkshops/usingdata/index.html

This NAGT/DLESE "On the Cutting Edge" site features a number of useful resources to help faculty teach with data more effectively and more easily, including links to program guides

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[4] Edelson, D.C., 2002, The value of teaching with data: insights from learning science: Keynote address, Using Global Data Sets in Teaching Earth Processes Workshop at the Annual Meeting of the American Geophysical Union, San Francisco, CA. http://serc.carleton.edu/NAGTWorkshops/globaldata02/guide.html (July 13, 2006).

[5] Manduca, C.A., and Mogk, D.W., 2003, Using data in undergraduate science classrooms, Northfield, MN, Science Education Resource Center, Carleton College, http://serc.carleton.edu/research_education/usingdata/report.html (July, 13 2006).

[6] On the Cutting Edge Professional Development Program, 2003, Using data to teach Earth processes, http://serc.carleton.edu/NAGTWorkshops/gsa03/index.html (July 13, 2006).

[7] On the Cutting Edge Professional Development Program, 2004, Using global data sets in teaching earth processes, http://serc.carleton.edu/NAGTWorkshops/globaldata02/ (July 13, 2006).

[8] On the Cutting Edge Professional Development Program, 2005, Using data to teach Earth processes, http://serc.carleton.edu/NAGTWorkshops/usingdata/index.html (July 13, 2006).

and PowerPoint presentations for the NAGT-sponsored "Using Global Data Sets to Teach Earth Processes" workshops at the 2002 AGU and the 2003 GSA meetings.

Example Exercises

The rest of this session will be a tour of some web-based example exercises and activities that use the EarthChem geochemical databases. These exercises are part of the "Teaching Geoscience in the New Cyberinfrastructure" digital resource collection at the Science Education Resource Center (SERC) at Carleton College. The exercises (Table 6) are written for a variety of solid-earth Geoscience disciplines and could complement or replace traditional class lectures. A "Teaching Notes" page accompanies each exercise and provides additional details about the target audience, required skills, goals and objectives, and evaluation. By working through the exercises, students emulate the scientific process by gathering data, manipulating complex datasets, formulating and testing hypotheses, and making reasoned conclusions. Sample topics and other information are listed in Table 6. The exercises vary in the amount of detail provided, from highly structured step-by-step instructions with hints and worked examples, to more open-ended study questions ideal for initiating and framing group discussion. All are ready for download and student use.

Visit the digital resource collection!
http://serc.carleton.edu/research_education/cyberinfrastructure/index.html

Table 6. Comparisons of the sample exercises at the SERC digital resource collection.

Exercises:
1. Global geochemistry of mid-ocean ridge basalts
2. Volcanic fields of North America
3. Volcanic landforms and magma composition
4. Cenozoic volcanic history of the western U.S.
5. Sr isotopic composition of mafic volcanic rocks, western U.S.
6. Igneous rock compositions and plate tectonics
7. Crystallization-differentiation of basaltic magma
8. Compositional diversity of volcanic suites

		1	2	3	4	5	6	7	8
student level	first-year non-major			✓					
	first-year Geoscience major			✓	✓				
	upper-level Geoscience major	✓	✓	✓	✓	✓	✓	✓	✓
	graduate student	✓	✓		✓	✓	✓	✓	
subject material	petrology	✓	✓	✓	✓	✓	✓	✓	✓
	volcanology	✓	✓	✓	✓	✓		✓	✓
	isotope geochemistry					✓			
	physical geology			✓					
	historical geology				✓				
	plate tectonics	✓			✓		✓		
tools used	GEOROC database						✓	✓	✓
	NAVDAT database		✓	✓	✓	✓			
	PETDB database	✓							
	Microsoft Word			✓					
	Microsoft Excel	✓				✓	✓	✓	✓
	QuickTime				✓				
	Google Earth			✓					
data used	major-element	✓	✓	✓	✓	✓	✓	✓	✓
	trace-element						✓	✓	✓
	isotopic					✓			
	spatial/topographic/geomorphologic	✓	✓	✓	✓	✓		✓	
	geochronologic		✓		✓	✓			
work load	minimal								
	moderate	✓	✓	✓	✓	✓	✓		
	considerable							✓	✓
student activities	perform database queries	✓	✓	✓	✓	✓	✓		✓
	quantitative reasoning and calculations	✓	✓			✓	✓	✓	
	make and interpret geochemical plots	✓	✓			✓	✓	✓	✓
	make and interpret maps		✓		✓	✓			
	make and test hypotheses	✓	✓	✓	✓	✓	✓	✓	✓
	check answers to selected questions							✓	✓
	prepare for class discussion	✓	✓	✓	✓	✓	✓	✓	✓

Global Geochemistry of Mid-Ocean Ridge Basalts

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Published Oct. 15, 2006.

Description

Geological processes at the mid-ocean ridges are responsible for the bulk of the Earth's heat loss and volcanic activity. The compositions of materials erupted at these locations, dominantly mid-ocean ridge basalts (MORB's), have profound implications for the inner workings of the Earth's mantle, the construction of oceanic crust, and global plate tectonics. In this exercise, students replicate a portion of a classic paper on MORB geochemistry [Klein and Langmuir, 1987] , but using a much larger global geochemical dataset downloaded from the PETDB database. Through a series of activities and questions, students are encouraged to think about the petrologic and geodynamic processes controlling the composition of Earth's most abundant volcanic rocks.

Five-year old basaltic pillow lavas, Juan de Fuca Ridge
Photo courtesty of the Submarine Ring of Fire 2002 Exploration, NOAA-OE

Context

Audience: undergraduate- or graduate-level petrology course

Skills and concepts that students must have mastered: divergent plate tectonics (mid-ocean ridges); major-element data and variation diagrams; fractionation; how to use Excel to manipulate data and make x-y plots; incompatible and compatible elements

How the activity is situated in the course: This activity can be used as a supplementary exercise to complement lectures on basalts and/or mid-ocean ridges. It may be completed in or out of class.

Goals

Content/concepts goals for this activity: Students who complete this exercise should be able to:

1. use the PETDB database to download a global dataset of glass analyses from mid-ocean ridge basalts
2. use Excel spreadsheets to plot major-element variation diagrams
3. recognize and interpret the significance of correlated data on major-element variation diagrams and plots of geochemical composition vs. axial ridge elevation

Higher order thinking skills for this activity: This exercise requires students to formulate hypotheses and to compare/contrast data.

Other skills/goals for this activity: Obtaining and using data from online databases like PETDB informs the students about the powerful resources that have recently become available to the scientific community via the creation of digital cyberinformatics and cyberinfrastructure. Carefully guiding students into these databases, through the various steps required to screen, download, import, and use their data, empowers the students to think and act like scientists in tangible and practical ways.

Evaluation

Students are presented with a series of questions to answer during this exercise. It is up to the instructor how the students' data might be evaluated. This exercise might to used to form the basis for an open-ended group discussion.

Notes

Volcanic Fields of North America

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Published Oct. 15, 2006

Description

In this activity, students gather gather data from selected North American volcanic fields which were active during the Cenozoic. Geographic, age, and geochemical data from each volcanic field are easily obtained from the North American Volcanic and Intrusive Rock Database (NAVDAT). Students are asked to compare and contrast the geochemical and age data, classify the field by geochemical criteria, and make hypotheses for the similarities and differences that they observe. This exercise provides a broad overview of the volcanic history of North America as well as opportunities to explore features of individual volcanic fields.

Sunset Crater, a prominent, young cinder cone in the San Francisco Volcanic Field of northern Arizona.
Photo by Dave Hoffman (University of Missouri-Rolla) and used by permission.

Context

Audience: undergraduate- or graduate-level petrology or volcanology course

Skills and concepts that students must have mastered:

1. the terms "mafic", "intermediate", and "silicic"
2. some knowledge of incompatible element behavior may be useful, but is not required

How the activity is situated in the course: This activity could be used early in an igneous petrology course to introduce the concept of petrologic diversity. This exercise does not require the students to interpret the geochemical data or to formulate detailed petrogenetic hypotheses; instead the main purpose of this exercise is to encourage the students to analyze, compare/contrast, and ask questions about volcanic rocks using geochemical data.

Goals

Content/concepts goals for this activity: Students who complete this exercise should be able to:

1. use the NAVDAT database to obtain geochemical and age data from ten volcanic fields in North America
2. note differences and similarities between geochemical and age data from various volcanic fields
3. answer simple questions concerning the datasets
4. ask new questions based on what they observe from the datasets

Higher order thinking skills for this activity: This exercise requires students to compare/contrast data and to ask novel questions based on their use of data.

Other skills/goals for this activity: Obtaining and using data from online databases like NAVDAT informs the students about the powerful resources that have recently become available to the scientific community via the creation of digital cyberinformatics and cyberinfrastructure. Carefully guiding students into these databases, through the various steps required to screen, download, import, and use their data, empowers the students to think and act like scientists in tangible and practical ways.

Evaluation

The exercise is written so that the students fill out a table with the data they obtain. It is up to the instructor how the students' data might be evaluated. The "wrap-up" questions at the end of the exercise could provide a basis for a class discussion.

Notes

Volcanic Landforms and Magma Composition

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Published July 12, 2006.

Description

Magma composition is an important control on the geomorphology of lava flows and volcanoes. In this exercise, students investigate this relationship by studying several classic examples of diverse volcano types in the western United States. Students use the interactive Google Earth software to determine the size and shape of the selected volcanoes, and then use the North American Volcanic and Intrusive Database (NAVDAT) to gather whole-rock geochemical data to test the nature of the relationship between magma composition and volcano geomorphology.

Wilson Butte in eastern California: an excellent example of a lava dome
Photo courtesy of the USGS.

Context

Audience: undergraduate-level petrology or volcanology course, and possibly honors-level introductory geology course

Skills and concepts that students must have mastered: The students should be familiar with the basic type of volcanoes as they are presented in an introductory physical geology course.

How the activity is situated in the course: This activity could be used as a supplementary exercise to complement lectures on the relationship between magma composition and volcano type/behavior. It could be used fairly early in an igneous petrology course as a review of material learned in previous classes.

Goals

Content/concepts goals for this activity: Students who complete this exercise should be able to:

1. use the free version of the Google Earth software program to measure sizes and shapes of volcanic landforms
2. identify types of volcanoes (shield, cinder cone, stratovolcano, lava dome, caldera) from digital topographic imagery
3. use the NAVDAT database to obtain data on the silica contents of volcanic rocks
4. recognize and test hypotheses relating volcano size/shape/type and silica content

Higher order thinking skills for this activity: This exercise requires students to formulate hypotheses and to compare/contrast data.

Other skills/goals for this activity: The act of obtaining and using data from online databases such as NAVDAT informs the students about the powerful resources that have recently become available to the scientific community via the creation of digital cyberinfrastructure. A carefully guided approach of guiding students into these databases, through the various steps required to screen, download, import, and use their data, empowers the students in a tangible, practical way to think and act like scientists.

Evaluation

The exercise is written so that the students fill out a table with the data they obtain. It is up to the instructor how the students' data might be evaluated. Of more importance to the evaluation of this exercise is the basis on which the students formulated their hypothesis that magma composition is (or isn't) related to volcano type (by morphology).

Notes

Cenozoic Volcanic History of the Western United States

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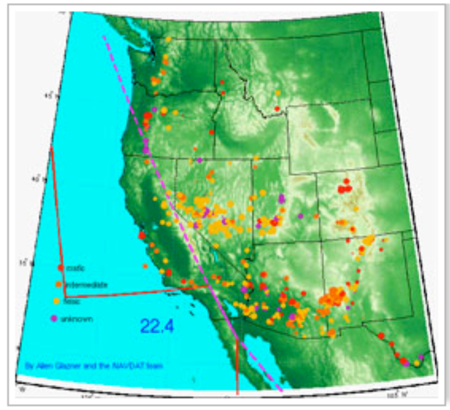
Published June 30, 2006

Description

In this activity, students view a Quicktime video animation based on data from the North American Volcanic and Intrusive Rock Database (NAVDAT) to learn about the history of volcanism in the western U.S. during the last 65 million years. Students are guided through the complex data-rich animation with a series of instructions and study questions which highlights time-space-composition relationships and links to plate tectonics.



Context

Audience: undergraduate- or graduate-level petrology, tectonics, or historical geology course.

Skills and concepts that students must have mastered: The students should be familiar with plate tectonic theory and how it relates to volcanism, particularly along continental-margins. Some familiarity with the geologic provinces of the western United States would also be helpful for this exercise.

How the activity is situated in the course: This activity could be used within a petrology or tectonics course to introduce links between plate tectonics and volcanism. Within a regional or historical geology course, the activity could be used as in introduction to the geological development of the North America Cordillera during the Cenozoic.

Goals

Content/concepts goals for this activity: Students who complete this exercise should be able to:

1. identify space-time-composition relationships in regional volcanic activity
2. make connections between plate tectonic processes and various aspects of volcanism along an active continental margin
3. interpret and speculate on the causes of volcanic activity
4. learn more about the geologic history of the western United States

Higher order thinking skills for this activity: This exercise requires students to formulate hypothesis based on space-time-composition data, and to compare/contrast data.

Other skills/goals for this activity: The act of obtaining and using data from online databases such as NAVDAT informs the students about the powerful resources that have recently become available to the scientific community via the creation of digital cyberinfrastructure. A carefully guided approach of guiding students into these databases, through the various steps required to screen, download, import, and use their data, empowers the students in a tangible, practical way to think and act like scientists.

Evaluation

The exercise is written as a series of questions that could be turned in for a grade or serve as a guide for initiating class discussion.

Notes

Sr Isotopic Compositions of Mafic Volcanic Rocks, Western United States

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Published June 30, 2006.

Description

In this exercise, students use whole-rock Sr isotopic compositions of volcanic rocks in the western United States to explore variability in mantle sources. The isotopic data are obtained from the North American Volcanic and Intrusive Database (NAVDAT) and analyzed using an interactive plotting and mapping tools at the NAVDAT website.

Basaltic cinder cone in the Mojave Desert.
Photo courtesy of the National Park Service.

Context

Audience: undergraduate- or graduate-level petrology or isotope geochemistry course.

Skills and concepts that students must have mastered: The students should be familiar with the theory and practice of whole-rock isotopic data, particularly the Rb-Sr system. They should also know how to copy and sort data in Excel spreadsheets. Some familiarity with the geologic provinces of the western United States would also be helpful for this exercise.

How the activity is situated in the course: This activity could be used fairly late in an igneous petrology course to introduce links between mafic magmatism and mantle sources. Within an isotope geochemistry course, the activity could be used as an exercise to complement lecture material on using Sr isotopes as tracers for magma sources.

Goals

Content/concepts goals for this activity: Students who complete this exercise should be able to:

1. use the radiogenic decay equation to solve quantitative problems related to the Rb-Sr system
2. use the NAVDAT database to obtain and plot Sr isotope data on a regional map of the western United States and on a scatterplot
3. interpret regional isotopic maps to infer information about the mantle sources of basaltic magmas

Higher order thinking skills for this activity: This exercise requires students to formulate hypothesis based on whole-rock isotopic data, and to compare/contrast data. Students are also required to apply the radiogenic decay equation for the Rb-Sr system to solve quantitative problems.

Other skills/goals for this activity: The act of obtaining and using data from online databases like NAVDAT informs the students about the powerful resources that have recently become available to the scientific community via the creation of digital cyberinfrastructure. A carefully guided approach of guiding students into these databases, through the various steps required to screen, download, import, and use their data, empowers the students in a tangible, practical way to think and act like scientists.

Evaluation

The exercise is written so that questions the students must answer are highlighted. It is up to the instructor how the students' answers are evaluated.

Notes

Igneous Rock Compositions and Plate Tectonics

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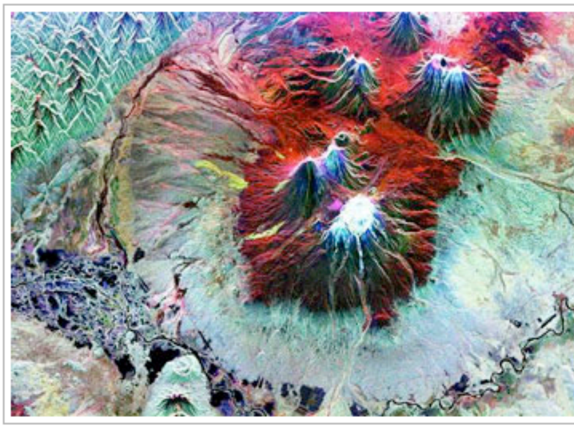
Department of Earth Sciences, Montana State University, Bozeman, MT

Published July 28, 2005.

Description

In this exercise, students use whole-rock major- and trace-element compositions of igneous rocks from a variety of tectonic settings and locations to explore the importance of plate setting in determining magma compositions. Students are split into groups and assigned different tectonic settings to examine and compare with other groups. Datasets are obtained from the GEOROC database, imported into Excel spreadsheets, and graphed to learn how igneous rock compositions are a function of plate tectonic setting.



Space radar image of stratovolcanoes in Kamchatka, Russia. Volcanic activity in this area is a result of subduction-related processes.
Photo courtesy of NASA. To learn more about this photo, see this link at Visible Earth.

Context

Audience: undergraduate- or graduate-level petrology course.

Skills and concepts that students must have mastered: Basic knowledge of plate tectonic settings and processes of igneous differentiation is assumed for this exercise. The students should be familiar with the theory and practice of variation diagrams and normalized REE plots, and should know how to manipulate and plot data in Excel spreadsheets.

How the activity is situated in the course: This activity could be used fairly early in an igneous petrology course to introduce the importance of plate tectonics in generating igneous rock diversity. It is recommended that this activity follow material on igneous processes, such as fractional crystallization and magma mixing.

Goals

Content/concepts goals for this activity: Students who complete this exercise should be able to:

1. use the GEOROC online geochemical database to extract useful whole-rock major- and trace-element data
2. make useful geochemical plots (variation and normalized REE diagrams)
3. interpret geochemical plots to suggest or rule out possible petrogenetic processes

Higher order thinking skills goals for this activity: This exercise requires students to formulate hypothesis based on geochemical data, and to compare/contrast datasets.

Other skills/goals for this activity: Students gain practice in using an Excel program to plot geochemical data, interpreting geochemical plots, working in groups, and making presentations in class. In addition, the act of obtaining and using data from online databases like GEOROC informs the students about the powerful resources that have recently become available to the scientific community via the creation of digital cyberinfrastructure. A carefully guided approach of guiding students into these databases, through the various steps required to screen, download, import, and use their data, empowers the students in a tangible, practical way to think and act like scientists.

Evaluation

This is up to the instructor.

Notes

Crystallization-Differentiation of Basaltic Magma

Kent Ratajeski, kratajeski@montana.edu
Department of Earth Sciences, Montana State University, Bozeman, MT
Published Oct. 26, 2004.

Description

In this exercise, students use major-element compositions of whole-rocks, volcanic glasses, and minerals in lavas and drill cores from the solidified Kilauea Iki lava lake. The data is presented in the form of a "precompiled" spreadsheet which contains selected analyses culled from the GEOROC database and a USGS Open File report. Students make graphs from the data to learn about the petrologic processes related to the eruption and *in situ* crystallization of basaltic magma.

Basaltic magma filling the crater of Kilauea Iki in 1959
Photo: Jerry Eaton, U.S. Geological Survey

Context

Audience: undergraduate- or graduate-level petrology course.

Skills and concepts that students must have mastered: This exercise assumes that the student is already familiar with plotting data in Excel. The student should have some basic knowledge of chemical variation diagrams, and how they work in situations of simple fractionation or binary magma mixing. No prior knowledge of the mineralogy and petrology of basalts is required.

How the activity is situated in the course: This activity could supplement class lectures on basalts or magmatic differentiation.

Goals

Content/concepts goals for this activity: Students who complete this exercise should be able to:

1. make useful geochemical plots (Harker diagrams) from geochemical data in an Excel spreadsheet
2. interpret geochemical plots to suggest or rule out possible petrogenetic processes

Higher order thinking skills goals for this activity: This exercise requires students to formulate hypothesis based on geochemical data.

Other skills/goals for this activity: Students gain practice in using an Excel program to plot geochemical data, interpreting geochemical plots, and writing answers to open-ended questions. In addition, the act of obtaining and using data from online databases like GEOROC informs the students about the powerful resources that have recently become available to the scientific community via the creation of digital cyberinfrastructure. A carefully guided approach of guiding students into these databases, through the various steps required to screen, download, import, and use their data, empowers the students in a tangible, practical way to think and act like scientists.

Evaluation

This activity is formatted as a self-paced exercise where students can check their own answers by clicking on "Show answer" tabs. The exercise could be reformatted as a normal homework assignment without the answers given, and graded by the instructor using his/her own evaluation scheme.

Notes

Compositional Diversity in Volcanic Suites

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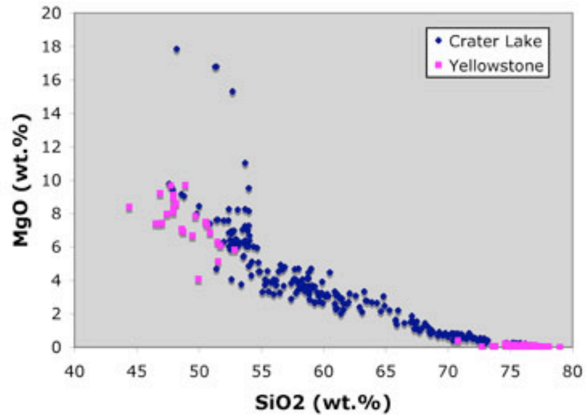
Published Oct. 26, 2004.

Description

In this exercise, students use whole-rock major- and trace-element compositions of volcanic rocks to explore the origins of compositional variation in igneous suites. Large datasets from the Yellowstone and Crater Lake calderas are downloaded from the GEOROC database, imported into Excel spreadsheets, and graphed to learn about the different petrogeneses of these two volcanic suites.



Context

Audience: undergraduate- or graduate-level petrology course.

Skills and concepts that students must have mastered: Some basic knowledge of plate tectonic settings (e.g., arcs and continental hotspots) is assumed for this exercise, but no advanced knowledge of the mineralogy and petrology of volcanic rocks beyond what is normally covered in introductory courses is required. No advanced knowledge of chemical variation diagrams is necessary, but it would probably be best if the instructor had covered the basics of whole-rock data and variation diagrams previously in lecture. This exercise does not assume that every student knows how to plot data in Excel spreadsheets, so I have included several pull-down text boxes (marked by 'Show me' tabs), as well as a separate page on plotting chemical variation diagrams in Excel, in order to help these students.

How the activity is situated in the course: This activity could supplement class lectures on compositional diversity or volcanic caldera complexes.

Goals

Content/concepts goals for this activity: Students who complete this exercise should be able to:

1. use the GEOROC online geochemical database to extract useful whole-rock major- and trace-element data from precompiled datasets
2. make useful geochemical plots (Harker diagrams)
3. interpret geochemical plots to suggest or rule out possible petrogenetic models

Higher order thinking skills goals for this activity: This exercise requires students to formulate hypothesis based on geochemical data, and to compare/contrast two different volcanic suites.

Other skills/goals for this activity: Students gain practice in using an Excel program to plot geochemical data, interpreting geochemical plots, and writing answers to open-ended questions. In addition, the act of obtaining and using data from online databases like GEOROC informs the students about the powerful resources that have recently become available to the scientific community via the creation of digital cyberinfrastructure. A carefully guided approach of guiding students into these databases, through the various steps required to screen, download, import, and use their data, empowers the students in a tangible, practical way to think and act like scientists.

Evaluation

This activity is formatted as a self-paced exercise where students can check their own answers by clicking on "Show answer" tabs. The exercise could be reformatted as a normal homework assignment without the answers given.

Notes

Create and contribute!

Now that you've seen some models for integrating online geochemical databases into the solid-earth Geoscience curriculum, think of **one** topic of interest in your own teaching that might benefit from a similar approach.

Your exercise or activity could take any number of forms—a series of linked web pages similar to those demonstrated in this workshop, or perhaps a simple handout. You may also wish to attach supporting files or documents along with your exercise:

- Excel spreadsheet of raw data
- bibliography of related resources
- image files
- .kmz file containing Google Earth placemarks

Now, go back to your office and write it!

Then consider sharing your favorite online database exercise or activity with the educational community in the form of a submission to the digital resource collection at SERC.

Share your favorite online database exercise/activity!
http://serc.carleton.edu/research_education/cyberinfrastructure/contribute.html

You retain all rights to your contributed work and are responsible for referencing other people's work and for obtaining permission to use any copyrighted material within your contribution. By contributing your work to the SERC web site, you give SERC a Creative Commons license for non-commercial distribution of the material, provided that we attribute the material to you.

Following submission, the SERC support staff must do some preparatory work to catalog and post these resources. Most submissions are made "live" within one to two weeks after they are submitted. Thank you in advance for your submission!

Acknowledgements

This course is presented as part of the EarthChem effort for establishing a Cyberinfrastructure for Solid Earth Geochemistry. Support for this was provided by the National Science Foundation Grants EAR-0522195 and OCE-0222752 to Lehnert, EAR-0312880 and EAR-0522222 to Walker, and Research Opportunity Award to Ratajeski.

Links

Some useful links to projects web site that provide data, tools, services, and information related to the EarthChem projects:

Geochemistry
- Earthchem [http://www.earthchem.org]
- EarthRef [http://www.earthref.org]
- Pangaea [http://www.pangaea.de]
- GeoReM [http://georem.mpch-mainz.gwdg.de/%5D
- GeoKem [http://www.geokem.com]

Tools
- CoreWall [http://www.evl.uic.edu/cavern/corewall]
- Chronos [http://www.chronos.org]
- GeoMapApp [http://www.marine-geo.org/geomapapp]

Samples
- SESAR [http://www.geosamples.org]
- NGDC [http://www.ngdc.noaa.gov/mgg/mggd.html]

Geoinformatics
- GEON [http://www.geongrid.org]
- Earth Science Cyberinfrastructure [http://www.geoinformatics.org]
- NSF Office of Cyberinfrastructure [http://www.nsf.gov/dir/index.jsp?org=OCI]

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