Appendix

Laboratory Sampling, Analysis and Instrumentation with the Berkeley Thermoscientific Quant’x EDXRF Spectrometer

The following is the analytical trajectory followed at the Berkeley XRF lab. It is substantially similar to the other lab protocols for all the reasons discussed in the volume (see also Lundblad et al. 2008).

All archaeological samples are analyzed whole. The results presented are quantitative in that they are derived from “filtered” intensity values rationed to the appropriate X-ray continuum regions through a least squares fitting formula rather than plotting the proportions of the net intensities in a ternary system (McCarthy and Schamber 1981; Schamber 1977). Or more essentially, these data through the analysis of international rock standards, allow for inter-instrument comparison with a predictable degree of certainty (Hampel 1984).

All analyses for this study were conducted on a ThermoScientific Quant’X EDXRF spectrometer, located in the Geoarchaeological XRF Laboratory, Department of Anthropology, University of California, Berkeley. It is equipped with a thermoelectrically Peltier cooled solid-state Si(Li) X-ray detector, with a 50 kV, 50 W, ultra-high-flux end window bremsstrahlung, Rh target X-ray tube and a 76 μm (3 mil) beryllium (Be) window (air cooled), that runs on a power supply operating 4–50 kV/0.02–1.0 mA at 0.02 increments. The spectrometer is equipped with a 200 l/min Edwards vacuum pump, allowing for the analysis of lower-atomic-weight elements between sodium (Na) and titanium (Ti). Data acquisition is accomplished with a pulse processor and an analog-to-digital converter. Elemental composition is identified with digital filter background removal, least squares empirical peak deconvolution, gross peak intensities and net peak intensities above background.

For the analysis of mid Zb condition elements Ti-Nb, Pb, Th, the X-ray tube is operated at 30 kV, using a 0.05 mm (medium) Pd primary beam filter in an air path at 200 s livetime to generate X-ray intensity Kα-line data for elements titanium (Ti), manganese (Mn), iron (as Fe2O3 T), cobalt (Co), nickel (Ni), copper, (Cu), zinc, (Zn), gallium (Ga), rubidium (Rb), strontium (Sr), yttrium (Y), zirconium (Zr), niobium (Nb), lead (Pb), and thorium (Th). Not all these elements are reported since their values in many volcanic rocks are very low. Trace element intensities were
converted to concentration estimates by employing a least-squares calibration line rationed to the Compton scatter established for each element from the analysis of international rock standards certified by the National Institute of Standards and Technology (NIST), the US. Geological Survey (USGS), Canadian Centre for Mineral and Energy Technology, and the Centre de Recherches Pétrographiques et Géochimiques in France (Govindaraju 1994). Line fitting is linear (XML) for all elements but Fe where a derivative fitting is used to improve the fit for iron and thus for all the other elements. When barium (Ba) is acquired in the High Zb condition, the Rh tube is operated at 50 kV and 1.0 mA, rationed to the bremsstrahlung region (see Davis et al. 1998). Further details concerning the petrological choice of these elements in Southwest obsidians is available in Shackley (1988, 1995, 2005; also Mahood and Stimac 1990; and Hughes and Smith 1993). Specific standards used for the best fit regression calibration for elements Ti-Nb, Pb, Th, and Ba, include G-2 (basalt), AGV-2 (andesite), GSP-1 (granodiorite), SY-2 (syenite), BHVO-2 (hawaiite), STM-1 (syenite), QLO-1 (quartz latite), RGM-1 (obsidian), W-2 - (diabase), BIR-1 (basalt), SDC-1 (mica schist), TLM-1 (tonalite), SCO-1 (shale), all US Geological Survey standards, BR-1 (basalt) from the Centre de Recherches Pétrographiques et Géochimiques in France, and JR-1 and JR-2 (obsidian) from the Geological Survey of Japan (Govindaraju 1994).

The data from the WinTrace software are translated directly into Excel for Windows software for manipulation and on into SPSS for Windows for statistical analyses when necessary. In order to evaluate these quantitative determinations, machine data were compared to measurements of known standards during each run. RGM-1 or an appropriate standard for the type of rock is analyzed during each sample run for obsidian artifacts to check machine calibration.

References


Glossary

The references in this volume are a good source for exploring the technical aspects of X-ray fluorescence spectrometry and archaeological stone. The glossary here is a small sample of what are the more critical terms useful in the field. There are a number of concepts in X-ray fluorescence spectrometry that are too complex for simple glossary definitions, and I refer the reader to the index and/or appropriate chapters. Six very useful references, from which the germ of most of these definitions are derived, are recommended for further reading, and Bates and Jackson (1984) or a similar geological dictionary should be on the shelves of all archaeologists (see also Goffer 1996; Jenkins 1999; Sigurdsson 2000; Thorpe and Brown 1985). For obsidian, the dominant material discussed in this volume, I refer you to the glossary in Shackley (2005). See also www.learnxrf.com.

**Absolute temperature**  The fundamental scale used for measuring temperatures in the physical sciences. Expressed in degrees Kelvin which are calculated by adding 273 to measurements in degrees centigrade.

**Absorption edge or absorption edge energy**  The highest or upper limit of the K and K or L and L line energies. For Rb \((Z = 37)\) it is 15.1999998 keV (see Fig. 2.2). This is crucial to understand when calculating the rationed region of interest, and peak overlaps in EDXRF.

**Absorption spectroscopy**  A technique of chemical analysis based on the measurement of electromagnetic radiation absorbed by substances. The wavelength or frequency of the radiation absorbed reveals information about the type of radiation absorbing substance of its constituent elements.

**Absorption spectrum**  The spectrum of radiant energy absorbed by any substance. The wavelengths of the absorbed radiation are identical to those of the radiation released.

**Abundance**  The mean concentration of an element in a geochemical reservoir; i.e., the abundance of rubidium in rhyolite glass. The order of abundance of elements in the earth’s crust is O, Si, Al.

**Accelerator mass spectrometric analysis**  A physical method based on the combination of a particle accelerator and a mass spectrometer. Useful in determining the nature and number of atoms in a given isotope, such as used in accelerator mass spectrometric radiocarbon \((^{14}\text{C})\) dating (AMS radiocarbon dating).
Accuracy  The degree that experimental measurements are free from errors, or the degree of error in those measurements – how closely a measurement value obtained conforms to the actual value of the sample. In XRF this is generally computed by the linear error in calibration (see also precision).

Acidic  A term applied to those igneous rocks, such as rhyolite and dacite, that contain more than 60% SiO₂, as contrasted with intermediate (andesite) or basic (basalt) rocks. Silicic is a more common modern term for these rocks.

Activation  The process of making a material radioactive, usually by bombarding the substance with nuclear particles such as neutrons in a reactor, as in activation analysis.

Activity  (1) The property of substances to react with other substances; (2) the number of atoms of a radioactive element decaying per unit time.

Adsorption  The attraction of one substance to the surface of another.

Alkalic igneous rocks  Those igneous rocks that contain more sodium than potassium than is average for that rock group.

Alkali feldspar  Sodium or potassium rich feldspar such as sanidine, common in rhyolite.

Alpha particle  A nuclear particle which is emitted during the decay of certain natural isotopes such as thorium; consisting of two protons and two neutrons with a double positive electrical charge.

Alumina  A refractory material composed of aluminum oxide (Al₂O₃). Aluminum oxides are relatively high in rhyolites, typically over 12 wt.%, and are one of the principal glass formers, along with SiO₂.

Analytical chemistry  The study, theory, and techniques (instrumentation) of determining the composition of matter, either qualitatively or quantitatively. Often known as analysis.

Andesite  A gray to black volcanic rock with between about 52 and 63 weight percent silica (SiO₂). Andesites contain crystals composed primarily of plagioclase feldspar and one or more of the minerals pyroxene (clinopyroxene and orthopyroxene) and lesser amounts of hornblende. At the lower end of the silica range, andesite lava may also contain olivine. Andesite magma commonly erupts from stratovolcanoes as thick lava flows, some reaching several kilometer in length, such as the San Francisco Peaks in northern Arizona. Andesite magma can also generate strong explosive eruptions to form pyroclastic flows and surges and enormous eruption columns. Andesites erupt at temperatures between 900 and 1,100°C. The extrusive equivalent of diorite. Andesite will grade into dacite exhibiting more alkali feldspar and quartz.

Angle of incidence  The angle made by a beam of radiation incident to a surface with a line perpendicular to that surface, as in the angle of incidence in wavelength X-ray fluorescence spectrometry.

Ångström unit  A unit of measure that is equal to one ten thousandth of a micron (0.00000001 cm; 10⁻⁸). Often Anglicized to Angstrom.

Anion  A negative ion – an atom or molecule that has gained one or more electrons and bears a negative charge.
Aphanitic  An igneous rock whose particles have a mean diameter of less than 1/16 mm; fine grained.
Aphyric  Fine-grained or glassy volcanic rocks with no observable minerals in hand sample.
Archaeometry  The study of the applications of the physical and natural sciences to archaeological problems, to include but not limited to: geophysical survey, materials analysis, dating methods, provenance studies – also archaeological science.
Atom  The smallest particle of an element that can take part in chemical reactions.
Atomic absorption spectroscopy  A spectroscopic technique based on the measurement of radiation absorbed by the atoms of the constituent elements of a material. Characteristic wavelength of the radiation is absorbed and the intensity of the absorption forms the basis for determining the relative proportion of each element in the substance.
Atomic number  The number of protons in the nucleus of an element – equal in value to the number of electrons in an atom of the element (see “Z”).
Background  Incidental signals obtained when measuring physical phenomena which may be confused with those required or desired for actual measurements. In EDXRF, any number of elements may emit characteristic radiation at various wavelengths that “interfere” with the element of interest. This background radiation is “stripped” from the element of interest radiation through a number of generally linear algorithms (see also bremsstrahlung radiation).
Banded  Said of a vein, sediment, or other deposit having alternating layers that differ in color or texture and that may or may not differ in mineral composition, e.g., banded Vulture obsidian from central Arizona.
Basalt  A hard, often black volcanic rock with less than about 52 weight percent silica (SiO₂). Because of basalt’s relatively low silica content, it has a low viscosity (resistance to flow). Therefore, basaltic lava can flow quickly and easily move >20 km from a vent. The low viscosity typically allows volcanic gases to escape without generating enormous eruption columns. Basaltic lava fountains and fissure eruptions, however, still form explosive fountains hundreds of meters tall. Common minerals in basalt include olivine, pyroxene, and plagioclase. Basalt is erupted at temperatures between 1,100 and 1,250°C. The most common volcanic rock on earth.
Basic  Igneous rocks that have relatively low silica content, ≈45–50%, such as gabbro and basalt. Basic rocks are relatively rich in iron, magnesium, and/or calcium and include most mafic rocks. Cf. silicic.
Batholith  A large, generally discordant plutonic mass that has more than 100 km² of surface exposure and no known floor; e.g., the Peninsular Range Batholith of northern Baja California and southern California.
Beam  The flow of radiation in only one direction.
Binary system  A system consisting of two components, such as the MgO–SiO₂ system.
**Bombardment**  The process of directing highly energy particles against a target element. It may either bounce off, or become absorbed by the nucleus and form an entirely new particle.

**Boulder**  A detached rock mass larger than a cobble with a diameter greater than 256 mm and generally rounded and indicating evidence of transport.

**Bragg’s law**  Derived by the English physicists Sir W.H. Bragg and his son Sir W.L. Bragg in 1913, stated that for every angle of incident radiation, the only wavelength reflected to the detector in wavelength X-ray fluorescence spectroscopy is the one that conforms to Bragg’s formula: \( n\lambda = 2d \sin \theta \), where \( n \) is a whole number \( 1-n \), \( \lambda \) is the wavelength of the X-ray radiation used; \( d \) is a constant characteristic of every crystalline substance (i.e., the X-ray crystal); and \( \theta \) is the angle on incidence of the x-radiation on the sample. So, by changing the angle of the crystal, you can select for specific elements of interest. In the Philips PW 2400 at Berkeley, this is all done automatically and any combination of elements can be analyzed. The system changes crystals for the various elements, calculates the overlap of elements within the spectrum and yields results in any form desired: qualitative, ratio, quantitative, graphic.

**Bremsstrahlung radiation**  Also called continuous or white radiation is produced as the impinging high energy electrons are decelerated by the atomic electrons of the elements making up the specimen and originating in the anode. In EDXRF, the bremsstrahlung scatter is used for ratioing in the higher energies, particularly for acquiring Ba in obsidian and other volcanic analyses (and Chap. 3).

**Calc-alkalic series**  Those igneous rocks in which the weight percent silica is between 56 and 61 when the weight percent of CaO and K2O + Na2O are equal; those igneous rocks containing plagioclase feldspar.

**Calcic series**  Igneous rocks in which weight percent Si is greater than 61 when the weight percent CaO and K2O + Na2O are equal.

**Caldera**  A large basin-shaped volcanic depression the diameter of which is many times greater than that of the forming vent or vents (e.g., Mule Creek and Valles Calderas in New Mexico).

**Calibration**  Data, obtained by measuring reference standards or employing fundamental parameters, used by the XRF instrument to create mathematical models for determining the composition of sample materials. Empirical calibration is based on the analysis of standards with known elemental compositions (see Chap. 2). Fundamental standardless calibration is based on mathematical algorithms that describe the physics of the detector’s response to pure elements. In this case, the typical composition of the sample must be known, while the calibration model may be verified and optimized by one single standard sample. Standardless fundamental calibrations are much less tedious than empirical calibrations, but often don’t yield the accuracy required for geoarchaeological problems.

**Cathode**  The negative terminal of an electrical source.

**Cation**  An ion with a positive electric charge.
**Centroid**  The weighted center of the peak, calculated as the energy in eV at which the side of the peak to the left has the same number of counts as the side of the peak to the right of this point.

**Chalcedony**  A mineral which consists of a porous mixture of microscopic crystals of quartz and amorphous hydrated silica in a fibrous structure. Often produced in intermediate and silicic eruptions by the removal of silica by water, as opposed to chert often precipitated from other sediments and having a granular crystalline structure.

**Charge**  A quantity of electricity due to an excess of electrons (negative charge) or a deficiency (positive charge).

**Chemical analysis**  The resolution of materials into their chemical components. The analysis can be classical (gravimetric or volumetric) or more recently instrumental (e.g., X-ray fluorescence spectrometry).

**Chert**  A hard, dense cryptocrystalline secondary sedimentary rock consisting chiefly of interlocking (granular fabric) quartz crystals less than 30 m in diameter. Chert can contain amorphous silica (opal) or chalcedony. Chert occurs principally as nodules or concretions often in marine environments where it is often precipitated through limestone, or less commonly as layered deposits. It occurs in nearly any color or combinations (agate), and in hand sample can look identical to chalcedony.

**Closed basin**  A region draining to a depression from which water escapes only through evaporation.

**Coarse grained**  A sedimentary rock in which the individual constituents are easily seen with the unaided eye.

**Cobble**  A rock fragment between 64 and 256 mm in diameter, between a pebble and boulder in size.

**Collimator**  A small aperture or optical focusing element used to shape and direct X-rays generated by the X-ray source.

**Compton scatter**  Crucial in the EDXRF and WXRF analysis of whole, nondestructive sample analysis, Compton scattering (C) occurs when the incident X-ray photon is deflected from its original path by an interaction with an electron. The electron gains energy and is ejected from its orbital position. The X-ray photon loses energy due to the interaction but continues to travel through the material along an altered path. Since the scattered X-ray photon has less energy, it, therefore, has a longer wavelength than the incident photon, and can be seen near the Rh peak in instruments with Rh targets. The event is also known as incoherent scattering because the photon energy change resulting from an interaction is not always orderly and consistent. The energy shift depends on the angle of scattering and not on the nature of the scattering medium. This rather simple linear relationship is at the core of the ability to analyze nondestructively by XRF (see calibration). In nondestructive EDXRF and WXRF, the elemental peak heights are rationed to the Compton scatter in order to eliminate matrix and size effects (see Chap. 2). First observed by Arthur Compton in 1923 and this discovery led to his award of the 1927 Nobel Prize in Physics.
Consanguinity  The genetic relationship between igneous rocks that are derived from common magmatic origin (e.g., the obsidian chemical groups within the Mule Creek Volcanic Field; Antelope Creek, Mule Mountains, and Mule Creek/North Sawmill Creek).

Continental crust  Crustal rocks that underlie the continents that range in thickness from about 35 km to as much as 60 km under mountain ranges.

Convection  In a magma chamber in which the central liquid rises while the marginal liquid descends due to the variability in heat.

Continuous radiation  See bremsstrahlung.

Cryptocrystalline  A rock fabric consisting of crystals too small to be discerned under a light microscope.

Count rate  The number of fluoresced X-rays per unit time counted from the sample under measurement.

Dacite  Dacite lava is most often light gray, but can be dark gray to black. Dacite lava consists of about 63–68% silica (SiO$_2$). Common minerals include plagioclase feldspar, pyroxene, and amphibole. Dacite generally erupts at temperatures between 800 and 1,000°C. It is one of the most common rock types associated with enormous Plinian-style eruptions. When relatively gas-poor dacite erupts onto a volcano’s surface, it typically forms thick rounded lava flow in the shape of a dome. It can form glass, but due to lower proportions of silica and aluminum oxides is generally vitrophyric (e.g., O’Leary Peak glass in the San Francisco Volcanic Field).

Deadtime  Amount of time required by the XRF instrument to detect a fluoresced X-ray and process the signal into a pulse. During this interval, other X-ray events cannot be detected or processed. In nondestructive EDXRF large samples have higher deadtime, while smaller samples have lower deadtimes. Optimally, 50% is best for modern detection in EDXRF.

Detector  XRF component that produces output charges (pulses) that are proportional to energy of X-ray photons entering the detector.

Devitrification  Conversion of a glass to crystalline material, as obsidian to perlite through hydration.

Diffraction  Diffraction occurs as waves interact with a regular structure whose repeat distance is about the same as the wavelength. The phenomenon is common in the natural world, and occurs across a broad range of scales. For example, light can be diffracted by a grating having scribed lines spaced on the order of a few thousand angstroms, about the wavelength of light. It happens that X-rays have wavelengths on the order of a few angstroms, the same as typical interatomic distances in crystalline solids. That means X-rays can be diffracted from minerals which, by definition, are crystalline and have regularly repeating atomic structures. When certain geometric requirements are met, X-rays scattered from a crystalline solid can constructively interfere, producing a diffracted beam. In 1912, W. L. Bragg recognized a predictable relationship among several factors (see Bragg’s Law).
EDX One of the acronym’s for energy dispersive X-ray fluorescence (XRF) spectrometry. See X-ray fluorescence analysis.

Electron An elementary particle which has a negative electric charge. One of the basic constituents of atoms.

Element A substance that cannot be decomposed into another substance except through radioactive decay (e.g., Rb, Sr, Zr, Nb, Ba).

Elemental analysis The determination of the elemental composition of a substance that can be either qualitative (determining the presence of) or quantitative (determining the relative amounts).

Empirical calibration See calibration.

Eruption The ejection of volcanic materials (lava, pyroclasts) onto the earth’s surface either through a vent or fissure.

Escape peak A false peak in the spectrum produced by the occasional loss of some photon energy absorbed by the detector due to fluorescence induced in the detector medium.

eV Electron volt; 1 kiloelectron volt (keV) = $1.60217646 \times 10^{-16}$ J. In EDXRF, the position of the peaks is measured in keV (Rb K1 = 13.375 keV (see peaks).

Excitation The process of a displacement of an electron from its normal or ground state.

Explosive Index The proportion of pyroclasts among the total products of a volcanic eruption.

Extrusive Igneous rocks that have been erupted onto the earth’s surface, including lava and ash flows.

Fabric The arrangement of the crystal constituents of a rock.

Felsite A generic term applied to any light-colored aphanitic igneous rock, often hypabyssal and intermediate or silicic in composition. In archaeology often applied to any light colored volcanic rock.

Filter A mechanical device (generally a foil) or mathematical technique used to distinguish X-rays fluoresced by materials with similar characteristic energy levels.

Fine-grained An igneous rock whose particles have a mean diameter of less than 1/16 mm. Synonym – aphanitic.

Fluorescence The process by which incident electromagnetic radiation induces atomic ionization. As a result of this ionization, electrons from higher energy orbitals drop (cascade) to lower energy orbitals. As a result of these transitions, characteristic energies are released by the atom in the form of X-ray photons.

Formation A mappable body of rock strata that consists of a certain lithologic type or combination of types. The fundamental lithostratigraphic unit.

Fractionation Crystallization from a magma in which the early formed crystals are prevented from equilibrating with the parent liquid resulting in a series of residual liquids that have a more extreme composition than would have resulted from a continuous reaction. In petrology, the residual liquids can be extruded and have a very different elemental composition from the parent magma.
**FWHM** “Full width half maximum” of the peak is an expression of the extent of a function, given by the difference between the two extreme values of the independent variable (this would be the elements of interest) at which the dependent variable is equal to half of its maximum value. In EDXRF this is also called resolution, calculated as the distance in eV between left and right sides of the peak at half of its maximum height.

**Gamma radiation** The form of electromagnetic radiation of very short wavelengths and high energy emitted by atoms undergoing radioactive disintegration. Since they penetrate matter, gamma rays are useful in radiography analyses.

**Geochemical facies** Any areal geological entity that is distinguished on the basis of trace element composition. (e.g., the Antelope Creek geochemical facies of the Mule Creek source).

**Geochemistry** The study of the distribution and amounts of chemical elements in minerals, ores, rocks, soils, and water on the basis of the properties of their atoms and ions through time and space.

**Geologic province** A large region characterized by similar geologic history and development (e.g., the Basin and Range Province of western North America).

**Gravel** An unconsolidated natural accumulation of mainly rounded rock fragments, mainly larger than sand (diameter greater than 2 mm) and may contain boulders, cobbles, pebbles or any combination; the unconsolidated equivalent of conglomerate.

**Glass** A solid material usually in the condition of a super-cooled liquid, formed when a molten mass of inorganic solids cools rapidly, without crystallizing. Natural glass is usually called obsidian, a rhyolite glass, but can also form from intermediate to mafic lavas under restricted conditions.

**Gravimetric analysis** Generic term for the classical methods of quantitative chemical analysis based on the measurement of weight.

**Half-life** For radioactive elements, the time required for one-half of the element to decay.

**Hand specimen** A piece of rock of a convenient size for megascopic study and for use in a reference collection.

**Hydration** A chemical reaction in which free water reacts with a solid to form hydrous materials, i.e., obsidian to perlite. In a glass, such as obsidian, a newly exposed surface hydration theoretically occurs at a regular and measurable rate, although environmental variables can intervene and cause the rate to fluctuate.

**Hypabyssal** A general term applied to minor intrusions such as dikes or sills and the rocks that compose them, such as felsite. These rocks often exhibit a finer grained fabric than the host lava due to more rapid cooling.

**Igneous** Said of a rock formed from the solidification of magma.

**Ignimbrite** Rock formed by the widespread deposition and consolidation of ash flows. The term includes welded tuffs and nonwelded, but recrystallized ash flows. In the western hemisphere ignimbrites tend to be defined as welded tuffs, while in European classification they tend to also include nonwelded tuffs.
**Incompatible elements**  An element (usually trace elements) that does not substitute for major elements in crystal lattices of minerals and is instead concentrated in the melt during evolution of the magma chamber.

**Infinite thickness**  The thickness, beyond which enough incident X-rays escape such that it is no longer possible to predict a calculated elemental quantity from a given. This is particularly an issue in XRF at high energies (i.e., 50 keV) with small samples such as obsidian debitage.

**Intensity**  The number of X-rays counted by the detector at a given energy level or range of energy levels.

**Interbedded**  Beds lying between or alternating with others of different character, especially contemporaneous lava flows *interbedded* between other sediments.

**Interior drainage basin**  See closed basin.

**Ion**  An atom or group of chemically bound atoms that have either a positive or negative charge.

**Intrusion**  The process of emplacement of magma in or below preexisting rock.

**Isomer**  One of two substances whose composition is identical except that the atoms in their molecules are arranged in different forms.

**Isotope**  One of two or more species of the same chemical element – having the same number of protons in the nucleus, but with a different number of neutrons. See radioisotope. Isotopes may be of natural or artificial origin, many useful in geoarchaeological studies.

**Isotropic**  Any medium whose properties are the same in all directions. In stone fracture mechanics, obsidian is isotropic in that force applied to any surface will travel at equal speed and force in all directions (i.e., Hertlian force).

**Jasper**  A variety of chert containing clay and iron oxide “impurities” within the quartz crystals that impart various colors particularly red and yellow. In the archaeological vernacular used to denote any chert or chalcedony colored red or yellow.

**Jet**  A dense relatively soft black lignite sometimes mistaken for opaque obsidian.

**K-feldspar**  Potassium feldspar.

**K spectra**  K spectra (i.e., K) arise following the transference of electrons to K shell vacancies. K spectra are relatively simple and consist of two doublets (K and K) with an extra line occurring for higher atomic numbers. In nondestructive EDXRF and WXRF analysis K spectra are most frequently analyzed in the mid-Z X-ray region due to very high energies, and L spectra (filling L level vacancies) for the higher energy elements such as Ba (see Chap. 2).

**Lamellar flow**  Flow of liquid in which the layers glide over each other.

**Lapilli**  Rock fragments between 2 and 64 mm (0.08–2.5 in.) in diameter that were ejected from a volcano during an explosive eruption are called lapilli. Lapilli (singular: lapillus) means “little stones” in Italian. Lapilli may consist of many different types of tephra, including scoria, pumice, marekanites, and reticulite.
Lattice  A regularly spaced, periodically repeated three-dimensional arrangement of points in space that specify the position of ions, atoms, or molecules in crystals.

Lava  Fluid molten rock that issues from a volcano or fissure; also the same material solidified by cooling.

Lava dome  Lava domes are rounded, steep-sided mounds built by very viscous magma, usually either dacite or rhyolite. Such magmas are typically too viscous (resistant to flow) to move far from the vent before cooling and crystallizing. Domes may consist of one or more individual lava flows. Classic domes that produced obsidian can be seen at Los Vidrios, Sonora, and Government Mountain in the San Francisco Volcanic Field in northern Arizona.

Lava flow  A lateral surficial outpouring of lava from a vent or fissure; also the same material solidified by cooling.

Law of superposition  In any sequence of sediments or igneous rocks that has not been overturned, the lowest strata will be older than the highest strata, and each bed is younger than the one beneath. First stated by Steno in 1669.

Layer  A bed or stratum of rock or sediment.

Lens  A body of rock that is thicker in the middle than at the ends; Adj. lenticular.

Liquidus  The locus of points in a temperature composition diagram representing the maximum saturation of a solid component or phase in the liquid phase.

Lithic  In geology a sediment or pyroclastic deposit containing abundant fragments of previously formed rocks. In geology and archaeology, pertaining to or produced from stone – lithic artifacts.

Lithostratigraphic unit  A body of rock that consists chiefly of a certain lithologic type or combination of types. It has a geographic name from the type area combined with a descriptive term, i.e., Coconino Sandstone.

L spectra  See K spectra and Chap. 2.

Magma  Naturally occurring molten rock material generated within the earth from which igneous rocks are derived, comprised of liquid silicate melt, suspended crystalline solids, and gas bubbles.

Magma chamber  A reservoir of magma in the shallow portion of the lithosphere (i.e., crust) from which volcanic material is derived.

Magma mixing  The mixing of two magmas to form a hybrid. Some rhyolite magmas that produced obsidian in the Southwest seem to be, in part, formed or derived from some magma mixing, such as Red Hill, New Mexico, and the San Francisco Peaks glass.

Magmatic differentiation  The process of developing more than one igneous rock type from a common in situ magma chamber, i.e., rhyolite to andesite.

Mantle  The zone of the earth below the crust divided into an upper and lower portion.

Marekanite or marekenite  Derived from eroded nodules of unhydrated obsidian that are part of the sediment load in the Marekanka River into the Okhotsk Sea of Eastern Russia. It applies specifically to nodules of obsidian, generally Tertiary in age in western North America, and called Apache Tears in the vernacular.
Mass absorption effects  Mass absorption effects result from fluorescence radiation being absorbed by coexisting elements (causing reduced intensity), or enhancement of fluorescence radiation due to secondary radiation from itself or coexisting elements (causing increased intensity).

Mass spectrometer  A instrument for separating atoms or ions of different mass and that can measure the exact mass of single atoms. Abbreviated as MS. Is often used in tandem with other instruments, i.e., accelerator mass spectrometer and ICP-MS.

Matrix  (1) The major constituents of a material in XRF analysis (see trace elements). (2) The groundmass of an igneous rock.

Matrix effect  The constituent parts and elements in a substance that serve to effect the photons in highly complex ways. The complexities are collectively known as matrix effects which can be subdivided into overlap effects and mass absorption effects. The matrix effects on element $i$ are the combination of mass absorption effects and overlap effects exerted on element $i$, by all coexisting elements $j$.

Medium grained  An igneous rock in which the crystals have an average diameter in the range of 1–5 mm.

Melt  A liquid, fused rock.

Mode  The actual mineral composition of a rock expressed in weight or volume percent.

Molecule  The smallest unit in which a substance can be divided and still retain it’s properties and composed of one or more atoms.

Multi-channel analyzer  Sorts detector output pulses according to energy level and counts the number of pulses accumulated at each level; from this information a spectrum (or pulse height analysis) is generated. From these data, the computer software can calculate elemental concentrations based on the instrument calibrations.

Neutron activation analysis  An instrumental method of chemical analysis based on nuclear activation reactions – the atoms or stable isotopes or elements in a sample are identified by activating the sample by neutron bombardment and then identifying and measuring the characteristic radiation each activated element emits in relation to the analysis of standards (see Chaps. 7 and 8 here).

Nodule  A small rounded lump or mass or a mineral or mineral aggregate, contrasting in composition to the surrounding rock matrix as in a nodule of obsidian in perlite.

Obsidian  Obsidian is a natural rhyolite glass, a super-cooled liquid that is liquid in all its properties except in its ability to flow easily. As a glass, its atomic structure, by definition, is entirely disordered. Because of this property it has no preferred direction of fracture and is entirely isotropic, at least when entirely aphyric. This property endows obsidian with its excellent flaking properties and extremely sharp edges when fractured. Compared with window glass, obsidian is rich in iron and magnesium; tiny ($<0.005$ mm) crystals of iron oxide within the
glass cause its dark color. Most sources of obsidian produce at least some red or mahogany colored nodules, some sources particularly in the southern Cascade Range of California and Oregon, are dominated by red obsidian. While it is certain that this coloring is produced by oxidation of the iron in the glass, it is not clear how the process transforms some portions of the flow and not others. There is no compositional difference between the red and black portions of a single nodule.

**Opaque** Said of a mineral that is impervious to transmitted light. Cf. translucent; transparent.

**Outcrop** That portion of a geologic formation that appears on the surface; v. To appear exposed on the surface.

**Oxidation** Once referred to a chemical reaction in which a substance combined with oxygen, but now refers to any reaction in which a substance loses electrons.

**Parental magma** The magma from which a particular igneous rock solidified.

**Parent element** The radioactive element from which a daughter element is produced by radioactive decay.

**Particle induced X-ray emission (PIXE)** A physical method of chemical analysis based on proton irradiation of a material. X-rays are re-emitted as a consequence of the irradiation and measured similar to EDXRF.

**Particle size** The average diameter or volume of the particles in a sediment or rock.

**Patina** A visible colored layer produced on the surface of a rock by weathering processes.

**Peak(s)** Channel in the spectrum containing the highest number of counts within a distribution of counts. The height and overall area of peaks within a spectrum yield quantitative information about the element(s) present within a sample.

**Peak count** The sum of all counts that fall inside the ROI. See ROI.

**Pebble** A rock fragment generally rounded by abrasion, larger than a granule and smaller than a cobble with a diameter in the range of 4–64 mm. The vast majority of marekanites derived from Tertiary sources in North American obsidian sources fall within this range.

**Peralkaline** A division of igneous rocks in which the molecular proportion of alumina (AlO₂) is less than that of sodium and potassium oxides combined. Peralkaline obsidians in the Southwest include many in the basin and range region of Chihuahua, including Antelope Wells on the New Mexico/Chihuahua border. These peralkaline obsidians are characterized by high iron and zirconium relative to rubidium and strontium, and are frequently dark green in color from the high iron content.

**Peraluminous** A division of igneous rocks in which the molecular proportion of alumina (AlO₂) exceeds that of sodium and potassium oxides combined. Many of the obsidian sources north of the US/Mexican border in the U.S. Southwest fall into this category (i.e., Antelope Wells/El Berrendo and Los Sitios del Agua).

**Perlite** A volcanic glass with a composition of rhyolite (obsidian) that has a higher water content than obsidian. Perlite is the eventual crystalline end for obsidian when it has completely hydrated.
**Perlitic structure**  A feature of volcanic rocks, particularly glassy rhyolites, that have cracked due to contraction during cooling forming small concentric pearl-like spheroidal structures. This occurs at megascopic and microscopic levels. Marekanites are often found as embedded remnants within perlite.

**Petrography**  The branch of geology, specifically petrology, dealing with the description and systematic classification of rocks by means of microscopic examination of thin sections.

**Petrology**  The study of rocks that form the earth’s crust.

**Phenocryst**  One of the relatively large megascopically visible crystals of the earliest generation in a porphyritic volcanic rock. In obsidian, the visible phenocrysts are most often sanidine feldspar.

**Pitchstone**  Obsidian with a higher proportion of water and as a result is generally vitrophyric and crystalline and a poor media for tool production. Geologists often map pitchstone as obsidian, but in the Southwest artifact quality obsidian rarely occurs in association with pitchstone. Tank Mountains, Vulture, and Saucedada Mountains source areas exhibit pitchstone, but no artifact quality marekanites have been found in direct association, while the Los Sitios del Agua source in northern Sonora exhibits aphyric marekanites in a perlitic matrix that resembles a pitchstone. The East Grants Ridge source in the Mount Taylor Volcanic Field appears to be a pitchstone in hand sample, but is still an adequate media for tool production.

**PIXE**  See particle induced X-ray emission.

**Plagioclase**  A group of triclinic feldspars of the general formula (Na, Ca)Al(Si, Al)Si$_2$O$_8$. Plagioclase is one of the most common rock forming minerals, particularly in intermediate and mafic volcanic rocks. It does occur in high silica rhyolites, but less commonly than sanidine.

**Plate boundary**  A zone of seismic and tectonic activity along the edges of lithospheric plates. The Tertiary activity along and underneath the plate boundary between the Pacific and North American plate was instrumental in creating the volcanism the produced most of the Tertiary obsidian sources in the Southwest.

**Pleistocene**  The epoch of the Quaternary Period after the Pliocene of the Tertiary and before the Holocene beginning about 2–3 million years ago and lasting until the Holocene about 8,000 years ago. The obsidian sources along the southern scarp of the Colorado Plateau and associated with the formation of the Valles Caldera in northern New Mexico were formed during the Pleistocene. Most of the secondary deposits of Tertiary sources are in Pleistocene formations, such as the 111 Ranch Formation in the Safford and San Simon Valleys of southeastern Arizona that contain pebbles of Cow Canyon and Mule Creek Tertiary obsidians.

**Plinian eruption**  An eruptive event in which a steady, turbulent stream of fragmented magma and magmatic gas is released at high velocity creating large volumes of pyroclastics and high eruption columns. Named for Pliny the Younger who was a surviving eye witness to the A.D. 79 eruption of the stratovolcano Vesuvius in southern Italy. Some of the obsidian in the Southwest was formed by smaller Plinian type eruptions where the pyroclasts quenched during the eruption.
and are preserved in the ash or ignimbrites; i.e., Los Vidrios, Mule Mountain (Mule Creek), some of Sand Tanks (Shackley 2005).

**Pliocene** The epoch of the late Tertiary after the Miocene and before the Pleistocene. The obsidian in the Mount Taylor Volcanic Field (Grants Ridge and Horace Mesa) were formed at the boundary of the Pliocene and Pleistocene, in part due to tectonic activity associated with the uplift of the Colorado Plateau (Shackley 2005).

**Plutonic rock** A rock formed at considerable depth by slowly cooling magma. It is characterized by medium to coarse grained texture – granitoid. Granite is the plutonic form of rhyolite.

**Porphyritic** A type of inequigranular texture in which there is a distinctly bimodal population of grain sizes. The large grains are phenocrysts surrounded by a finer grained matrix or groundmass. Porphyritic rocks occur in fairly small relatively shallow intrusive rock bodies (i.e., hypabyssal rocks) that have experienced extended period of relatively uniform crystallization. Many rhyolites are porphyritic due to this process even though they have been extruded. Obsidian that is porphyritic are called vitrophyric.

**Potassium feldspar** An alkali feldspar containing the molecule (KalSi$_3$O$_8$), such as orthoclase, and sanidine. K-feldspar in the vernacular and common in silicic rocks such as rhyolite.

**p.p.m** The abbreviation for parts per million a form expressing the concentration of substances (i.e., elements) highly diluted in a material. It is equivalent to 1 g per 1 metric ton. Often further abbreviated as “ppm.”

**Provenance** As used here, the geographical source of a material, either primary or secondary.

**Precision** The ability of an instrument to obtain consistent results when performing multiple measurements on the same sample (see also repeatability).

**Pulse** Analog output waveform produced by the XRF detector, electronics and amplifier. Each pulse is proportional in magnitude to the energy of a detected X-ray photon (see multi-channel analyzer).

**Pyroclastic flow** A pyroclastic flow is a ground-hugging avalanche of hot ash, pumice, rock fragments, and volcanic gas that rushes down the side of a volcano as fast as 100 km/h or more. The temperature within a pyroclastic flow may be greater than 500°C, sufficient to burn and carbonize wood. Once deposited, the ash, pumice, and rock fragments may deform (flatten) and weld together because of the intense heat and the weight of the overlying material. A number of pyroclastic flows produced obsidian in the Southwest including Los Vidrios, Sonora.

**Qualitative analysis** The study of the *identity* of the components of a substance; as opposed to quantitative analysis that serves to yield the proportions or absolute quantities of components.

**Quantitative analysis** The study of the exact relative amounts of each component of a substance. In obsidian analysis the elements and compounds are reported in parts per million or percent by weight.
Quarry  *Open* workings for the extraction of stone. As opposed to an adit or mine.

Quaternary  The second period of the Cenozoic Era, following the Tertiary that began about 2–3 million years ago and consisting of two unequal epochs; the Pleistocene followed by the Holocene that began about 8,000 years ago.

Quenching  Rapid or essentially instantaneous cooling of a material such that crystallization is hindered or eliminated. Obsidian is a quenched rhyolite such that it is completely disordered with no crystalline form.

Radioactive daughter  A nuclide produced by the radioactive decay of another nuclide known as the radioactive parent.

Repeatability  The ability of an instrument to obtain consistent results when performing multiple measurements on the same sample – the same as precision.

Reproducibility  The ability of an instrument to obtain consistent measurement results when measuring the same sample at different times and/or with different operators and/or using different instruments of the same type (see Chap. 2).

Region of interest (ROI)  The region of interest is used to calculate peak counts. The ROI depends on the element as well as the detector type used to conduct the test. For example, with a Cu sample on a Peltier cooled detector system like the ones in this volume, the ROI would be defined as ±5 channels or ±100 eV around the tallest channel in the very first spectrum analyzed during the test. To allow for advanced data acquisition, the ROI width can be modified manually prior to the start of the test.

Rhyolite  A group of silicic extrusive igneous rocks, often porphyritic and commonly exhibiting flow banding, with phenocrysts of quartz, and alkali feldspars (i.e., sanidine) in a glassy cryptocrystalline groundmass. Rhyolite is commonly light colored, but can be as dark as basalt, and is sometimes confused with basalt in archaeology. The Presley Wash rhyolites in the Mount Floyd Volcanic Field in northern Arizona are typical of dark glassy rhyolites. The extrusive equivalent of granite. Quenching of rhyolite lava can create obsidian.

Rhyolitic magma  Erupted at temperatures of 750–1,000°C, rhyolitic magma is comprised mainly of SiO₂ (75 wt.%), Al₂O₃ (13%), and the alkalis Na₂O and K₂O in about equal amounts (3–5%). Due, in part, to the extreme viscosity of rhyolite magma, little is actually erupted, but remains in the crust as plutons, and is eventually uplifted or otherwise exposed, such as the Sierra Nevada. Rhyolitic magma in what is now the Southwest is often produced by reprocessing (remelting) older crust. In western Arizona, Precambrian granites became the raw material, through reprocessing during the Tertiary, for rhyolite and when quenched, obsidian, such as Sand Tanks and Tank Mountains, both of which are surrounded by older Precambrian granite basements.

Rock  An aggregate of one or more minerals, e.g., quartz, granite, shale; or disordered mineral matter, e.g., obsidian, or solid organic matter, e.g., coal.

Röntgen, Wilhelm  Wilhelm Conrad Röntgen (1845–1923) who was a Professor at Würzburg University in Germany discovered X-rays in 1895.
Sanidine  A high temperature mineral of the alkali feldspar group, KalSi$_3$O$_8$. It is a disordered monoclinic feldspar occurring in clear, glassy crystals in unaltered silicic volcanic rocks such as obsidian, rhyolite, and dacite.

Scintillation counter  An instrument that measures ionizing radiation by counting the individual scintillation of a substance. The primary counting method in X-ray fluorescence spectrometry.

Sediment load  The solid material transported by a stream system, expressed as the dry weight of all sediment that passes a specified point in a given period of time.

Silicic  Silica rich igneous rock or magma. The amount of silica is generally said to constitute 65% or more or two thirds of the composition of the rock. These rocks generally contain free silica in the form of quartz; e.g., obsidian, rhyolite, granite, dacite. Formerly called acid igneous rocks.

Solidus  The temperature below which a magma is completely crystallized, or in the case of obsidian the point at which the glass quenches.

Spectroscopy  The study of the properties of electromagnetic radiation with a spectroscope; e.g., X-ray fluorescence spectroscopy (also spectrometry).

Spectrum  A frequency of occurrence histogram displaying the number of detected X-rays (counts) along a Y vertical axis and their respective energy levels (in keV) along its X horizontal axis; used to make qualitative and quantitative determinations about sample materials (see Figs. 2.2 and 2.7).

Spherulite  A rounded mass, usually feldspar, of acicular crystals radiating from a central point. Sometimes forming in obsidian, it is common in the Cerro Toledo Rhyolite glasses (spherulitic obsidian) at Valles Caldera in northern New Mexico, particularly those erupted from the Rabbit Mountain center, a dome on the southeastern rim of the caldera.

Standard  A sample material of known thickness and/or composition used to calibrate XRF units for specific applications (see calibration). Many standards are internationally recognized and used by the laboratories in this volume.

Stratigraphy  The arrangement of rock strata as to chronological sequence.

Stratovolcano  A volcano, usually intermediate lava, constructed of alternating strata of lava and pyroclastic deposits, usually with abundant dikes and sills. Also called a composite volcano or cone.

Stratum  A layer of sedimentary rock visually separable from layers above and below; a bed; plural strata.

Surface analysis  The general term for a number of chemical analytic methods that analyze the surface of a substance. Includes X-ray fluorescence spectrometry, both energy-dispersive and wavelength dispersive.

Tektite  A silicate glass of nonvolcanic origin, generally formed by extra-terrestrial impacts on terrestrial rocks. They often resemble marekanites and can have very similar composition with much less water (average 0.005%), but more often have a composition more similar to shale.

Tephra  Tephra is a general term for fragments of volcanic rock and lava regardless of size that are blasted into the air by explosions or carried upward by
hot gases in eruption columns or lava fountains. Tephra includes large dense blocks and bombs, and small light rock debris such as scoria, pumice, reticulite, and ash, and rhyolite lava fragments can be quenched into obsidian under the right conditions. As tephra falls to the ground with increasing distance from a volcano, the average size of the individual rock particles becomes smaller and thickness of the resulting deposit becomes thinner. Small tephra stays aloft in the eruption cloud for longer periods of time, which allows wind to blow tiny particles farther from an erupting volcano.

**Ternary system** A system of three components often displayed in an equilateral triangular graph. Early qualitative obsidian analyses used ternary graphs to display the relative proportions of elemental components, i.e., Rb, Sr, Zr.

**Tertiary** The first period of the Cenozoic Era after the Cretaceous of the Mesozoic Era and before the Quaternary. It is generally agreed that it covers the time span from 65 million to 2 million years ago, and is applied to the corresponding system of rocks. Divided into unequal epochs; Paleocene, Eocene, Oligocene, Miocene, and Pliocene. The earliest dated, still artifact quality, obsidian in the Southwest is Antelope Creek and Mule Mountains of the Mule Creek caldera that erupted during the Miocene at about 17 million years ago. Most of the Basin and Range obsidian in the Southwest dates to the middle to late Tertiary.

**Total counts** The sum of all counts in the spectrum between 400 and 41,960 eV, the effective range of acquisition for EDXRF ($Z = 11–92$).

**Trace element** A chemical element which while a component of a material is not essential to the composition of the material and occurs in very low concentrations usually below 0.01% (100 p.p.m.), but often up to 0.1% (1,000 p.p.m.) in the XRF vernacular. The concentration of trace elements are often unique signatures of a material, such as many of the incompatible elements in obsidian.

**Transition elements** The elements located between Group IIA and group IIIA in the periodic table.

**Tuff** A general term for all consolidated pyroclastic rocks. Not to be confused with the chemical sedimentary rock tufa.

**Tufflava** An extrusive rock containing pyroclastic and lava-flow characteristics and is considered to be an intermediate form between a lava flow and a welded tuff form of ignimbrite. The Mule Mountain/Mule Creek obsidian and some of the Los Vidrios obsidian were probably formed in tufflava eruptions.

**Type locality** The place from which a geologic feature, such as a specific igneous rock type, was first recognized and described; e.g., marekanite from the Marekanka River obsidian nodules in Eastern Siberia.

**Unconformity** A break or gap in the stratigraphic record such as an abnormal break in the sequence of sedimentary deposition; i.e., older strata found above younger strata.

**Unconsolidated material** Sedimentary material that is loosely associated in a stratum or on the surface, and whose particles are not cemented.
Valence  The property of atoms to combine chemically with only one definite number of other atoms.

Vesicular  Characterized by containing vesicles as in vesicular basalt.

Vitreous  Having the luster and appearance of glass.

Vitric tuff  An indurated deposit of volcanic ash composed mainly of fragments of glass ejected during eruption.

Vitrophyre  Any porphyritic volcanic rock having a glassy groundmass; generally restricted to rhyolite and dacite. Generally applied to non-aphyric obsidian.

Vitrophyric  Of or pertaining to vitrophyre. In the vernacular pertaining to perlitic and non-aphyric obsidian similar to pitchstone.

Volcanic ash  Fine pyroclastic ejecta under 2 mm in diameter. Usually refers to unconsolidated material but sometimes used to refer to tuff.

Volcanic breccia  Angular pyroclastic volcanic fragments that are larger than 64 mm in diameter.

Volcanic dome  A rounded protrusion of usually silicic lava that is squeezed out from a volcano forming a dome shape or bulbous mass above and around the vent.

Volcanic glass  Natural glass produced by the quenching of lava before crystallization can occur. Most common in silicic lavas where silicon and aluminum oxides are relatively high. Includes both obsidian and intermediate and mafic glasses.

Vug  A small cavity in a vein or rock usually lined with crystals of different chemical composition. Often chalcedony is deposited through precipitation in rhyolite and andesite lavas in the Southwest, in some cases offering artifact quality raw material for stone tool production.

Wavelength  The measured distance between successive wave crests, valleys, or other equivalent points in a wave of electromagnetic radiation or sound. The accepted symbol is “.”

Weathering  The mechanical or chemical destruction of a substance through interaction with the atmosphere with little or no transport of the substance.

Welded tuff  A glass rich pyroclastic rock that has been subjected to subsequent burial by other pyroclastic rock and through heat and compaction has welded the glass shards in the matrix. Often appears banded or streaked, and is extremely dense and hard; also called ignimbrite.

whole-rock analysis  A procedure whereby the entire rock is analyzed rather than a constituent. X-ray fluorescence spectrometry is a whole-rock analysis.

Xenocryst  A phenocryst in volcanic rock that resembles a native mineral, but is actually foreign to the environment in which it occurs.

Xenolith  A foreign intrusion into igneous rock larger than a mineral.

X-ray  Radiation of extremely short wavelength produced by the bombardment of a substance by a stream of electrons moving at high velocity.

X-ray diffraction analysis  A technique for identifying and analyzing the structure of crystalline materials by the three-dimensional periodic array of atoms
in a crystal that has periodic repeat distances (lattice dimensions) of the same order of magnitude as the wavelength of the X-rays. X-ray diffraction has been used in the analysis of minerals in ceramics with some success. Since there is really no mineral lattice dimensions in a glass, it is not useful in the analysis of obsidian.

**X-ray filters**  See filter(s).

**X-ray fluorescence analysis (see Chap. 2)** A potentially nondestructive method of chemical analysis (XRF) based on the use of high energy X-rays. An intensive beam of X-rays is used to irradiate a sample causing it to re-emit (fluoresce) radiation the wavelength (WXRF) or energy (EDXRF) of which is used to determine the elemental composition of the substance. XRF is a mass analysis method. All material that is subjected to irradiation is included in the analysis. Therefore, heterogeneous substances can issue spurious results if the area irradiated is too small to represent the modal character of the substance. Aphyric obsidian is an excellent media for EDXRF analysis since it is a homogeneous non-crystalline substance, and many of the incompatible elements that discriminate magma sources are well measured by EDXRF.

**X-ray tube** An evacuated enclosure containing an anode (or filament) and a quantity of target material. When high voltage is applied to the anode, electrons collide with the target material, inducing it to fluoresce X-ray photons.

**Z**  Equals atomic number (i.e., \( Z = 37 = \text{Rb} \)).

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