The Universal Stage: The Past, Present, and Future of a Mineralogical Research Instrument

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Introduction

The optical behavior in crystals (with the exception of those crystallizing in the cubic system) varies with the direction of light travel within the crystal, and measurement of optical properties has to be carried out in specific orientations. Therefore a great variety of rotating devices have been designed to align crystals into a proper orientation. The universal stage is certainly the most important of such devices, and for more than half a century it was considered essential for petrographic work.

One of the most elegant of all accessories for the petrographic microscope, the universal stage could be regarded as an elaborate crystallographic goniometer, the only difference from traditional goniometers being that *optical*, in addition to geometric features, can be measured. Named for its capability for angular measurements in both horizontal and vertical planes, it is an intricate device that consists of concentric, graduated rings that can be tilted (via gimbals) and rotated, which, in addition to folding, graduated Wright arcs, permit quantification of the angular movement of multiple axes. This device was designed to be used primarily with thin sections (i.e., rock sections that are mounted on a glass slide and cut to a thickness of 0.03 mm), whereby a sample is positioned on the stage between glass hemispheres (also known as segments) using glycerin as a mounting fluid; this arrangement allows light to pass unobstructed through the mineral grain without deviation by reflection when the stage is tilted to high angles. Thus, planar features such as twin planes, cleavage, and principal optical directions can be located, giving details of the relation between optical and crystallographic orientation on a sample that cannot be obtained in any other way. Unfortunately, because of increasing reliance on computer-driven microbeam instruments, use of the universal stage has decreased in past years, despite its irreplaceable utility.

Construction of the 4-Axis Universal Stage

Universal stages have been developed with two, three, four, or five axes; these axes have been described by a variety of nomenclatures, but one of the most convenient is that proposed by Berek (1924), whereby the axes are numbered sequentially from innermost to outermost, i.e., from A_1 to A_5 for a five-axis stage (the stage of the microscope itself would constitute a sixth axis). Of the above options, it is the 4-axis stage that has proven to be the most commonly manufactured and used, despite that the third, A_3 axis (the outer rotating graduated circle, vertical axis), is seldom required for routine measurement. Thus, in practice, only three axes are essential: two inner axes, designated as A_1 (the inner rotating graduated circle, vertical axis) and A_2 (the inner horizontal tilting axis), and one outer tilting horizontal axis, the A_4 (see FIGURE 1), which is controlled by a large graduated vertical drum on the right side of the stage. Two hinged Wright arcs, used to measure the tilt of the A_2 axis, are provided in most versions of the universal stage, although some manufacturers substituted a graduated protractor in place of the Wright arcs; the arcs are normally folded down when not needed. The angular movement of each axis can be quantified: rotation of the A_1 and A_3 axes are read from the 360° scales on their rings, the tilt of the A_2 axis is read from graduations on one of the folding Wright arcs, and the tilt of the A_4 axis is measured from a vernier scale on the vertical drum. Each axis also has its own locking device to fix it in place as needed during manipulation. Most stages have a center glass plate that is set into a threaded ring, which is used to adjust the height of a slide. The entire stage is attached, via solid uprights, to a base plate with a large central aperture; the plate is drilled to fit the microscope stage using two threaded screws; more modern universal stages feature an x-y centerable base plate that is attached to the microscope stage, which facilitates adjustment. Variations to this general design are described in more detail below.

Historical Development and Design

E.S. Fedorov developed a four-axis universal stage in 1892 (Fedorov, 1892, 1894) in response to a need to characterize feldspar-group minerals (FIGURE 2). By the late 1800s, classification and petrological interpretation of rocks had become increasingly important, and this required the identification of the feldspars, which constitute a major group of the rock-forming minerals. Identification of the plagioclase feldspars was based on the relation between the principal optical vibration directions (*X, Y, Z*) and crystal twin planes (albite, pericline, Carlsbad, and Carlsbad-albite) of a mineral grain, from which its chemical composition could be determined. Fedorov's universal stage, with independently tilting and rotating axes, facilitated these measurements by allowing complete freedom to orient crystallographic and optical planes of the sample to vertical, north-south positions, which can then be plotted (as east-west horizontal poles) on a Wulff stereonet to assess angular relations between the planes.

One drawback of the early Fedorov stage, however, was its small size (the outer ring is only about 7 cm in diameter), which rendered it difficult to manipulate. These stages required use of circular, 2-cm diameter thin sections that were prepared without a coverslip; such preparations were oriented on the stage with the rock section facing down (Medenbach, 2008) in order to ensure its proper height within the glass segments. Moreover, the earliest form of the Fedorov stage provided no means of measuring the tilt of the inner horizontal axis, but by 1911, F.E. Wright had introduced graduated, folding arcs (which now bear his name) that permitted quantitative angular measurement from the innermost tilting graduated circle.

A larger-format stage was introduced in 1912, as an integral part of a large theodolite microscope, by the firm of R. Fuess, Berlin-Steglitz (Leiss, 1912; Fuess, 1919); this instrument was later manufactured also by C. Leiss, Berlin-Steglitz (FIGURE 3; see also Leiss, 1925). This stage was an important improvement in that, rather than being constrained by the small and unwieldy circular slides required by the Fedorov stage, it allowed use of a standard size (ca. 25 x 45 mm) thin section. In addition to its universal stage, the theodolite microscope features a slotted Wright universal eyepiece and synchronous rotation of analyzer and polarizer; it is thus one of the most complex mineralogical microscopes ever made. Accordingly, a significant drawback to this instrument was its high cost - which was on the order of the annual salary of the company's chief mechanic.

The issue of cost was mitigated by Max Berek, who designed a large-format detachable 4-axis universal stage in the early 1920s (FIGURE 4), which was introduced by the firm of E. Leitz (Berek, 1924); this stage could easily be attached to most of the petrographic microscopes of the era. Although there are numerous variations of this pattern by different makers, Berek's design (described in the preceding section) is the general form, essentially unchanged to the present day (FIGURE 5), which was manufactured by numerous instrument makers through the 1980s. Nonetheless, some modifications are evident among the various firms; for example, each company fabricated their hemispheres with a differing size and configuration of the metal frame. Most makers, including Leitz and Bausch & Lomb, incorporated a removable center glass plate, but others, such as Zeiss, used a drop-in lower hemisphere that eliminated the necessity for this center glass.
Though the 4-axis stage is by far the most common, alternative ideas appeared early. A 5-axis universal stage was developed in 1929 by R.C. Emmons at the University of Wisconsin (Emmons, 1929a). This design (FIGURE 6) featured an additional ring between the A_1 and A_3 graduated circles, and a second set of Wright arcs; it had some advantages in that it simplified stereonet plotting, but has otherwise fallen

into disuse because of its greater complexity, reduced stability, and higher cost. By the early 1950s, a 3-axis stage was introduced by the English firm of Cooke, Troughton & Simms in recognition of the fact that fewer axes equate to greater stability and simplified operation, and that only three axes are necessary for almost all required measurements; Rathenow Optical Works in Germany manufactured their own version of a 3-axis stage in the 1960s. However, this innovative design, like the 5-axis, never attained a high level of popularity. A further variant is the 2-axis stage, manufactured by E. Leitz; designated the UT-2, this stage has only the A_1 and A_4 axes; Wright arcs, unnecessary in the absence of a tilting A_2 axis, are absent. This seldom-seen stage was intended primarily for classroom instruction or for use with a universal stage ¬refractometer.

Principles of Universal Stage Measurement

The optical data of any mineral are in general very sensitive to changes in chemical and physical conditions during their formation, and thus may be excellent petrogenetic indicators. As many as five different optical values can be measured in birefringent crystals, which are subdivided into uniaxial (one optic axis) and biaxial (two optic axes) groups (e.g., see Nesse, 2004; Dyar et al., 2008). These are the principal indices of refraction (which correspond to a principal vibration direction; there are two for uniaxial minerals in the tetragonal and hexagonal systems, and three for biaxial minerals in the orthorhombic, monoclinic, and triclinic systems), the optic axial angle (2V), and in monoclinic and triclinic crystals, the orientation of the principal indices of refraction with respect to the crystallographic axes. The universal stage, with its capability for multi-axis orientation of a crystal grain, is well suited for the determination of the axial angle (2V) and the assessment of crystal optics (i.e., principal vibration directions, designated *X, Y, Z*) relative to crystallographic axes (designated a, b, c). The principal indices of refraction can also be measured with good accuracy using specialized equipment (see following section).

Minerals in the tetragonal and orthorhombic crystal systems have three crystallographic axes that are mutually perpendicular, and hexagonal minerals have four axes, three of which are at 60° to each other and perpendicular to the c-axis. Optical directions (i.e., principal vibration directions) must always be mutually perpendicular. Thus, for tetragonal and hexagonal minerals, one optical direction is parallel to the c axis and the other lies in a plane perpendicular to it. For orthorhombic minerals, all three optical directions coincide with crystallographic axes. However, for lower symmetries, crystallographic axes are not all mutually perpendicular. For example, in the case of monoclinic minerals (the most common symmetry in naturally occurring species), the angle between the crystallographic a- and c- axes is different from 90°. Thus, for these symmetries, only the b-axis coincides with an optical direction, and the other two axes are related to optical directions by an angle other than 90°. In the case of triclinic minerals, none of the crystallographic axes correspond to any optical direction.

Knowledge of the angular relation between crystallographic and optical axes is important because this relation changes with compositional substitution throughout a solid-solution series of minerals, for example, such as seen with the plagioclase feldspars (FIGURE 7). When optical and crystallographic orientation data for the plagioclase feldspars are compared to well-established diagrams showing the relation of these data to composition (e.g., see Tröger et al., 1979, or Burri et al., 1967), an accuracy to ± 2% or better can be quickly and easily attained.

Further information on the use of the universal stage is given in Berek, 1924; Reinhard, 1931; Nikitin, 1936; Haff, 1940, 1942; Emmons, 1943; Naidu, 1958; Slemmons, 1970; Phillips, 1971; and Muir, 1981.

Utility of the Universal Stage, Past and Present

The universal stage was originally designed for work with the plagioclase feldspars, and indeed it is still effective for that task, but in recent decades it has been supplanted by microprobe analysis (e.g., see Kile, 2006). In contrast to microbeam instruments, however, the universal stage remains much more affordable, permits a much quicker analysis, and provides accuracy at least as high as that of the microprobe. The major drawback to using the universal stage is that using it requires a specialized knowledge, which is becoming increasingly difficult to acquire as those proficient in its operation are rapidly dwindling in number.

Some earlier as well as more contemporary applications for the universal stage include:

1. Assessment of the fabric and deformation-recrystallization history of metamorphic rocks by determining the orientation of the c-axis in quartz grains in thin section (e.g., see Fairbairn, 1949).
2. Identification of plagioclase feldspar crystals based on the relation between crystallographic planes (i.e., twin planes) and optic orientation (i.e., principal vibration directions), which in turn provides chemistry (e.g., Reinhard, 1931; Tröger et al., 1979). Additionally, an analysis of Si/Al order/disorder of sanidine-orthoclase crystals, based on an assessment of the optic orientation relative to the Carlsbad twin plane and measurement of the optic angle, can provide information on the cooling history of the crystals (e.g., see Su, 1984).
3. Identification of minerals in thin section (especially for thin sections with cover slips that cannot be analyzed with a microprobe) by determining relations between crystallographic directions (i.e., cleavage planes and zone axes) and optic vibration directions, quantitative measurement of optic angle, characterization of extinction angles (i.e., Z-to-c), and determination of birefringence using a Berek compensator. For example, measurement of the optic angle (2V) for minerals in the olivine group can distinguish among species in a solid-solution series from Mg-rich forsterite to Fe-rich fayalite (e.g., see Nesse, 2004 and references therein).
4. Evaluation of twinning in mineral fragments and identification of twin laws (e.g., normal, parallel, or complex twins; see Phillips, 1971). Minerals often studied include those in the plagioclase, pyroxene, and amphibole groups.
5. Measurement of refractive index in grains. With specialized equipment (such as proposed by Wilcox, 1959), including an Emmons cell for temperature control, refractive indices can be rapidly determined with a 'double variation' method, whereby both temperature and wavelength can be varied such that a match in the index of a mineral grain and an index liquid can be attained with a minimal changing of index liquids (Emmons, 1928, 1929b). This procedure has not seen much use since the early 1960s with the universal stage, but has been used in recent years with the spindle stage (e.g., Medenbach, 1985).
6. Assessment of meteorite impact sites by determining the relation between crystallographic orientation (i.e., c-axis orientation) and shock-induced planar deformation features in quartz (e.g., see Stöffler and Langenhorst, 1994; Grieve et al., 1996; and Ellwood et al., 2003).
7. Measurement of extinction angles (e.g., Z-to-c) in pyroxene- and amphibole-group minerals (Haff, 1941; Turner, 1942) can aid in the identification the species within a group (e.g., Winchell, 1951).
8. Measurement of dihedral angles of crystal grain boundaries in thin sections to evaluate crystallization and other magmatic processes in igneous rocks (e.g., Holness, 2005; Holness et al., 2005, 2007).

It is of note that many of the measurements described above cannot be done by any other method.

Abbreviated Procedure for Universal Stage Manipulation

Although a complete understanding of the function of the universal stage, in context with the fundamentals of mineral optics, requires considerable practice, the basic elements of its manipulation are straightforward. The universal stage is used with two hemispheres whose refractive indices are selected to approximately match the mineral being examined (usually in thin section, but grain mounts can also be used in special preparations). The sample is mounted between glass hemispheres (glycerin is often used because it is water-soluble, greatly simplifying instrument cleanup), which, in conjunction with a center glass and the thin section, constitute a sphere, allowing an axis to be tilted without exceeding the critical angle for reflection at an air interface. The basics of operation entail orienting either a crystallographic plane (cleavage or twin) or a principal optical plane (*X-Y*, *X-Z*, or *Y-Z*) to a vertical and north-south position, whereby its pole will be horizontal and east-west.

Before work can begin, the stage must be properly aligned. A detailed description of this procedure is beyond the scope of this paper, but in brief, a series of steps are carried out to ensure that the grain being examined is in the exact center of the sphere (formed by the hemispheres, slide, and center plate), that the vertical axes are coaxial with the optical axis of the microscope (i.e., centered to the microscope stage), and that both horizontal axes are exactly parallel to an eyepiece cross hair, such that when an axis is tilted, a particle in the field of view travels exactly north-south or east-west.

Orientation of cleavage planes is a relatively simple operation: the inner vertical (A_1) axis, is rotated, and the inner horizontal (A_2) axis is tilted in an alternating manner such that the plane is vertical and north-south, evidenced by a sharp line in plane polarized light. Its pole, now oriented horizontal and east-west, is then plotted on a stereonet based on the angular readings taken from the A_1 and A_2 axes. The Wulff stereographic net, introduced in 1902, is used for plotting (e.g., Haff, 1940); it is a circular grid from which angular relations of objects plotted in two dimensions can be determined in three dimensions (FIGURE 8).

Orientation of optic planes is somewhat more difficult. The mineral is oriented by sequentially rotating the inner vertical (A_1) axis, and tilting the inner horizontal (A_2) axis, in an alternating fashion such that the mineral is brought to extinction, and remains at extinction when the outer horizontal axis (A_4) is turned (thus tilting the entire stage on an east-west axis). The plane is now vertical and north-south. If one of the planes thus oriented (north-south) contains an optic axis, it can readily be located by rotating the microscope stage (designated A_5) counterclockwise 45° and tilting the horizontal A_4 axis to a point where the grain is dark (this is a point of optic axis zero retardation, seen when the optic axis is vertical to the microscope stage); an optic axis position (vs. an extinction position) is confirmed if the grain remains dark with complete rotation of the microscope stage (A_5). Two principal vibration directions can always be directly located from these measurements, and the position of the third is established geometrically on the stereonet plot, which is unambiguous since all poles must be mutually 90° apart.

The above protocol allows for a very complete evaluation of the mineral. Cleavage angles, zone axes, optic axes, and their relation to the principal vibration directions are now known, giving a detailed knowledge of the relation between the crystallographic axes and principal optic directions (see accompanying diagram). No other method exists to completely characterize the optical and crystallographic properties of a mineral in thin section!

Equipment for the Universal Stage

Leitz equipment will be mostly described in this section, inasmuch as these stages and accessories are most often available on the surplus science instrument market; they are also readily adaptable to a wider range of microscope.

Two kinds of observation are possible with the universal stage. The universal stage is generally used orthoscopically, with special long-working-distance objectives of relatively low magnification. However, it can also be used conoscopically (i.e., for observation of interference figures), using objectives of higher magnification in conjunction with smaller-diameter hemispheres (which accommodate shorter objective working distances) and either a special dedicated high-numerical-aperture conoscopic condenser, or a normal polarizing condenser to which a conoscopic top element is attached. Additional details are provided below in this section.

Hemispheres

Universal stage hemisphere glass is typically provided (as by E. Leitz) in three refractive indices: 1.516, 1.554, and 1.649. These indices are intended to approximately match those of minerals from one of three major groups (K-feldspar, quartz-plagioclase, or pyroxene-amphibole, respectively), which minimizes deviation in the light path between the glass and the mineral. In addition to the large-diameter orthoscopic segments, conoscopic hemispheres of the same refractive indices with smaller diameters were manufactured to accommodate the shorter working distance of the higher numerical aperture conoscopic objectives used with them. Additionally, specially modified metal frames for the upper hemispheres were offered with a trackway that permitted use of a graduated Schmidt guide; this arrangement provided a calibrated parallel displacement of a slide, used for petrofabric and structural analyses of thin sections. Considering that the firm of E. Leitz manufactured both orthoscopic and conoscopic upper hemispheres in three refractive indices, in addition to the modification for the Schmidt guide, a total of 12 distinct upper hemispheres were marketed by Leitz for use with their universal stage. High-index hemispheres (e.g., n_D = 1.71) were also available by special order.

Objectives

Because of the thickness of the glass hemispheres, special long-working-distance objectives are required in order to focus on the slide. These objectives also must have an internal iris diaphragm that provides parallel (i.e., orthoscopic) illumination, which is essential for the accurate setting of a mineral to extinction; alternatively, Zeiss provided fixed-diaphragm inserts that were placed inside the objectives. It should be noted that the resolution (i.e., numerical aperture) of long- working-distance objectives is greatly diminished compared to that of a normal objective; this becomes even more readily apparent when the internal diaphragm is partially stopped down. Manufacturers provided several magnifications for work in orthoscopic illumination, e.g., 5, 10, 20, and 32x. Objectives for conoscopic examination were provided by Leitz in magnifications of 32 and 50x.

Condensers and condenser top elements

Orthoscopic observation requires only the normal polarizing condenser, although special condenser top elements were available for this purpose. Work at higher magnifications or conoscopic observation necessitates the use of converging light, provided by either an auxiliary condenser top lens element, or a dedicated high-numerical-aperture condenser (Zeiss also provided a high-numerical-aperture 'UD' condenser for this purpose). The firm of E. Leitz provided a bewildering variety of such top elements to fit different generations of condenser design, each with different optics and thread sizes.

In summary, altogether the firm of E. Leitz in the 1970s manufactured six long-working-distance objectives (three orthoscopic and two conoscopic, not counting a special low-magnification centering objective), a variety of condensers and top elements to fit different condenser types, three lower hemispheres (n_D = 1.515, 1.554, and 1.649), and 12 different upper hemispheres. The above totals do not include hemispheres that could be special ordered, such as high-index hemispheres, typically manufactured in indices around n_D = 1.72. Needless to say, the use of the universal stage in an earlier era warranted manufacture of all manner of accessories to accommodate them.

Accessories for the Universal Stage

A variety of accessories were developed for the universal stage, which extend its capability throughout a wide range of observation; a few are briefly described below. Further details are given in Kile (2003) and references therein.

Waldmann hollow sphere

The Waldmann hollow sphere, manufactured by E. Leitz (FIGURE 9), allows examination of mineral fragments or small gemstones that are immersed in an index liquid within the sphere. The specimen is mounted on a fitted holder, which then is inserted into a hollow glass sphere (25-mm diameter) which is filled with an index liquid; it is then placed in a special holder in the center of a universal stage. This arrangement permits almost unlimited rotation and orientation of a mineral grain or faceted gemstone for optical study.

Emmons cell
An Emmons cell consists of a circular hollow metal frame that holds a central glass plate and an integral lower hemisphere; it is temperature-controlled with circulating water, and used in the double variation method of refractive index determination for mineral grains, in which wavelength and temperature are both varied. Because the index of refraction for a liquid is inversely proportional to both temperature and wavelength, changing these variables (in conjunction with the ability to orient the mineral on the universal stage) greatly expedites the refractive index determination of a mineral by minimizing the necessity of changing calibrated liquids to achieve a match in index (i.e., no relief) with the mineral.

Berek compensator
Use of a Berek compensator in conjunction with a universal stage affords a powerful and expedient means of quantitatively measuring the retardation, from which birefringence (i.e., the mathematical difference in the high and low indices of refraction) of a mineral can be calculated. The compensator, which is inserted into the accessory slot above the nosepiece of the microscope, consists of a calcite plate approximately 0.1-mm thick, or, in more recently manufactured instruments, a magnesium fluoride plate. These plates, cut perpendicular to the c-axis, are mounted in a tilting frame that is connected to a geared drive mechanism and a graduated drum and vernier scale for measurement of rotation. This compensator was developed by Max Berek in 1913 (Berek, 1913), and its design had not appreciably changed for more than 60 years.

Tilting the compensator plate, when superimposed over an appropriately oriented mineral grain, will vary the degree of compensation until a point is reached when the compensator brings the grain to a point of zero retardation. A suitable grain is one whose optic axis (or optic plane) is parallel to the microscope stage in a 'subtractive' position relative to the compensator plate, i.e., the grain is oriented with its slow ray parallel to the fast ray of the plate. Attaining this orientation is greatly facilitated with the universal stage because of its multi-axis construction. Once compensation is achieved, a reading is taken from the drum of the compensator, and retardation is calculated. Birefringence is then calculated based on the measured retardation and a known grain thickness (the latter of which is dependent on the degree of tilt of the universal stage, and which can be determined from a simple trigonometric calculation).

Wright eyepiece
The Wright universal eyepiece, described by F. E. Wright in 1911, is used primarily for quantifying birefringence using a graduated quartz wedge, or to accurately set extinction positions, such as would be necessary to measure extinction angles. This instrument consists of a slotted eyepiece and cap analyzer that replace the regular cross hair eyepiece; the slot, located below the analyzer, is designed to accept a variety of specialized compensators. Two plates can be used to set extinction; these are the half-shade plate after Nakamura and the half-shade wedge after Macé de Lépinay. Both plates are composed of two parallel quartz sections, right- and left-handed, oriented in opposite directions. When one of these plates is superimposed over a grain, the precise setting of extinction is evidenced when the light intensity is perfectly balanced between both halves of the plate.

The Present and Future of the Universal Stage

With Zeiss having recently (1999) discontinued production of their universal stage (Leitz and Nikon had discontinued manufacture of their universal stages in the mid-1990s), there is currently no worldwide production of them. Used instruments are sometimes available, some of which may be in as new condition, but others of which can be in an unusable condition.

Moreover, petrographic microscopes capable of accommodating a universal stage, i.e., those with adequate stage clearance and a removable center stage plate to allow for freedom of tilting the outer A_4 axis, are no longer manufactured. Despite the fact that no modern manufacturer provides a microscope that will directly accommodate the universal stage, it is possible to adapt at least the Olympus BX-51P polarized light microscope, and perhaps other recently manufactured microscopes as well, to accommodate the universal stage (FIGURE 10). In the case of the Olympus microscope, a removable stage center plate is present, but a riser block needed to be fitted to achieve adequate stage clearance, and a stage intermediate adapter had to be fabricated that fit the universal stage mounting screws and allowed the assembly to be attached to the microscope stage (Delly, 2007).

Despite the fact that the last list price, in the mid-1990s, for a Leitz 4-axis stage with three sets of hemispheres was quite high, about $12,500, the cost of a modern microbeam instrument greatly exceeds that figure by more than an order of magnitude, with annual maintenance expenses being equally high. Thus given the comparative expense of a universal stage (including the cost of a polarized light microscope), the polarized light equipment is far more cost effective. Furthermore, most professionals in the working world will find that there is not a microprobe down the corridor, and contracting analytical work for x-ray diffraction and microbeam analysis can be both expensive and time consuming. However, the principal drawback to the petrographic microscope and universal stage, as mentioned earlier, is the effort required to learn the underlying principles and become proficient; well-grounded training in optical mineralogy takes a substantial investment of time and considerable practice that may take some years. In contrast, for the case of an x-ray diffractometer, a technician can be trained to prepare samples, operate the instrument, and generate a list of mineral phases present in about an hour (taking note that there is a strong possibility that the phases so identified - the result of a computer database search - may be incorrect).

Although some consider the universal stage to be obsolete, suggesting that it (along with polarized light microscopy in general) has been replaced by modern microbeam or x-ray diffraction instrumentation, the bottom line is that this equipment is a valuable adjunct to modern instrumental methods of analysis, as *nothing* can replace a trained human eye to interpret and evaluate the physical features of the sample and assess the veracity of computer-generated data (see Kile, 2006, for a further discussion of some of these issues). Thus, while there is no question that these modern computer-driven devices are extremely effective, they do *not* replace the light microscope. In the case of the universal stage, a declining number of professionals having a specialized knowledge (such methods are no longer taught at universities in the U.S.), and an increasing scarcity of equipment, will likely mandate its extinction, if for no other reason than no one will realize its capabilities; unfortunately, the outcome will be the loss of the irreplaceable utility of this instrument.

References

Berek, M. (1913) Zur Messung der Doppelbrechung hauptsächlich mit Hilfe des Polarisationsmikroskops. *Centralblatt für Mineralogie, Geologie und Paläontologie*, pp. 388-396, 427-435, 464-470.

Berek, M. (1924) *Mikroskopische Mineralbestimmung mit Hilfe der Universaldrehtischmethoden*. Gebrüder Borntraeger, Berlin, 168 p.

Burri, C., Parker, R.L., and Wenk, E. (1967) *Die optische Orientierung der Plagioklase*. Birkhäuser Verlag, Basel, Stuttgart, 334 p.

Delly, J.G. (2007) Universal stage use on the Olympus BX-51-pol microscope.
http://www.modernmicroscopy.com

Dyar, M.D., Gunter, M.E., and Tasa, D. (2008) *Mineralogy and Optical Mineralogy*. Mineralogical Society of America, Chantilly, Virginia, 708 p.

Ellwood, B.B., Benoist, S.L., El Hassani, A., Wheeler, C., and Crick, R.E. (2003) Impact ejecta layer from the Mid-Devonian: Possible connection to global mass extinctions. *Science*, 300, 1734-1737.

Emmons, R.C. (1928) The double dispersion method of mineral determination. *The American Mineralogist*, **13**, 504-515.

Emmons, R.C. (1929a) A modified universal stage. *The American Mineralogist*, **14**, 441-461.

Emmons, R.C. (1929b) The double variation method of refractive index determination (second paper). *The American Mineralogist*, **14**, 414-426.

Emmons, R.C. (1943) The Universal Stage, with Five Axes of Rotation. *Geological Society of America Memoir* **8**, 205 p.

Fairbairn, H.W. (1949) *Structural Petrology of Deformed Rocks*. Addison-Wesley Publishing Co., Cambridge, 344 p.

Fedorov, E.S. (1892) Eine neue Methode der optischen Untersuchung von Krystallplatten in parallelem Lichte. *Tschermak's Mineralogische und Petrographische Mittheilungen* (for the year 1891), **12**, 505-509.

Fedorov, E.S. (1894) Universal- (Theodolith-) Methode in der Mineralogie und Petrographie. *Zeitschrift für Kristallographie und Mineralogie*, **22**, 229-268.

Fuess, R. (1919) Mineralogische und krystallographische In¬stru¬mente und Hilfs-Apparate; Katalog 180. E. Mikroskope für Mineralogie und physikalische Studien. R. Fuess mechanisch-optische Werkstätten, Berlin-Steglitz, p. 57-107.

Grieve, R.A.F., Langenhorst, F., and Stöffler, D. (1996) Shock metamorphism of quartz in nature and experiment: II. Significance in geoscience. *Meteoritics & Planetary Science*, **31**, 6-35.
Haff, J.C. (1940) Use of the Wulff net in mineral determination with the universal stage. *American Mineralogist*, **24**, 689-707.

Haff, J.C. (1941) Determination of extinction angles in augite and hornblende with the universal stage according to the method of Conrad Burri. *American Journal of Science*, **239**, 489-492.

Haff, J.C. (1942) Fedorow method (universal-stage) of indicatrix orientation. *Colorado School of Mines Quarterly*, **37**, 3-28.

Holness, M. (2005) Petrographic clues to overturn and eruption of open-system magma chambers: Santorini, Greece. In Abstracts of the 15th Annual V.M. Goldschmidt Conference, Moscow, Idaho, May 2005. *Geochimica et Cosmochimica Acta*, **69**, A-147.

Holness, M.B., Cheadle, M.J., and McKenzie, D. (2005) On the use of changes in dihedral angle to decode late-stage textural evolution in cumulates. *Journal of Petrology*, **46**, 1565-1583.

Holness, M.B., Nielson, T.F.D., and Tegner, C. (2007) Textural maturity of cumulates: A record of chamber filling, liquidus assemblage, cooling rate and large-scale convection in mafic layered intrusions. *Journal of Petrology*, **48**, 141-157.

Kile, D.E. (2003) *The Petrographic Microscope: Evolution of a Mineralogical Research Instrument*. Special Publication No. 1, Mineralogical Record Inc., Tucson, Arizona, 96 p.

Kile, D.E. (2006) Polarized light microscopy in geoscience education: Relevant or obsolete? *Elements* **2**, August 2006, 197-198.

Leiss, C. (1912) Neues petrographisches Mikroskop für die Theodolite-Methode. *Centralblatt für Mineralogie, Geologie und Paläontologie*, 733-736.

Leiss, C. (1925) *Die modernen optischen Messinstrumente des Kristallographen und Petrographen: ihre Beschreibung und Justierung*. Verlag von Gustav Fischer, Jena, 91 p.
Medenbach, O. (1985) A new microrefractometer spindle-stage and its application. *Fortschritte der Mineralogie*, **63**, 111-133.

Medenbach, O. (2008) On antique crystal rotating apparatus and requirements regarding samples and their preparation. *Journal of the Microscope Historical Society*, **16**, 76-83.

Muir, I.D. (1981) *The 4-Axis Universal Stage*. Microscope Publications, Ltd., Chicago, 145 p.

Naidu, P.R.J. (1958) *4-Axes Universal Stage*. Commercial Printing & Publishing House, Madras, 106 p.

Nesse, W.D. (2004) *Introduction to Optical Mineralogy*, 3rd ed. Oxford University Press, New York, 348 p.

Nikitin, W. (1936) *Die Fedorow-Methode*. Verlag Gebrüder Borntraeger, Berlin, 109 p.

Phillips, W.R. (1971) *Mineral Optics: Principles and Techniques*. W.H. Freeman and Company, San Francisco, 249 p.

Reinhard, M. (1931) *Universal Drehtischmethoden. Einführung in die kristalloptischen Grundbegriffe und die Plagioklasbestimmung*. B. Wepf & Cie, Basel, 119 p.

Slemmons, D.B. (1970) *Universal Stage Procedures*. Department of Geology, MacKay School of Mines, University of Nevada, Reno, 14 p.

Stöffler, D., and Langenhorst, F. (1994) Shock metamorphism of quartz in nature and experiment: I. Basic observation and theory. *Meteoritics*, **29**, 155-181.

Su, S.-C., Bloss, F.D., Ribbe, P.H. (1984) Optic axial angle, a precise measure of Al,Si ordering in T1 tetrahedral sites of K-rich alkali feldspars. *American Mineralogist*, **69**, 440-448.

Tröger, W.E., Bambauer, H. U., Taborsky, F., and Trochim, H.D. (1979) *Optical Determination of Rock-Forming Minerals* [English edition]. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 188 p.

Wilcox, R.E. (1959) Universal stage accessory for direct determination of the three principal indices of refraction. *The American Mineralogist*, **44**, 1064-1067.

Winchell, A.N., and Winchell, H. (1951) *Elements of Optical Mineralogy, Part II: Descriptions of Minerals*, 4th ed. John Wiley and Sons, Inc., New York, 551 p.

Wright, F.E. (1911) *The Methods of Petrographic-Microscopic Research: Their Relative Accuracy and Range of Application*. Carnegie Institution of Washington, Publication no.158, 204 p.

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Any use of trade, firm, or product names is for instructive purposes only and does not imply endorsement by the U.S. Government.

Figures and Captions

FIGURE 1
Diagram of a 4-axis universal stage, showing inner (A_1) and outer (A_3) graduated circles, both of which rotate on a vertical axis. The A_2 and A_4 axes tilt, via gimbals, on horizontal axes, with A_2 north-south, and A_4 east-west. Wright arcs, used to measure the tilt of A_2, are shown in a folded position, resting on top of A_3.

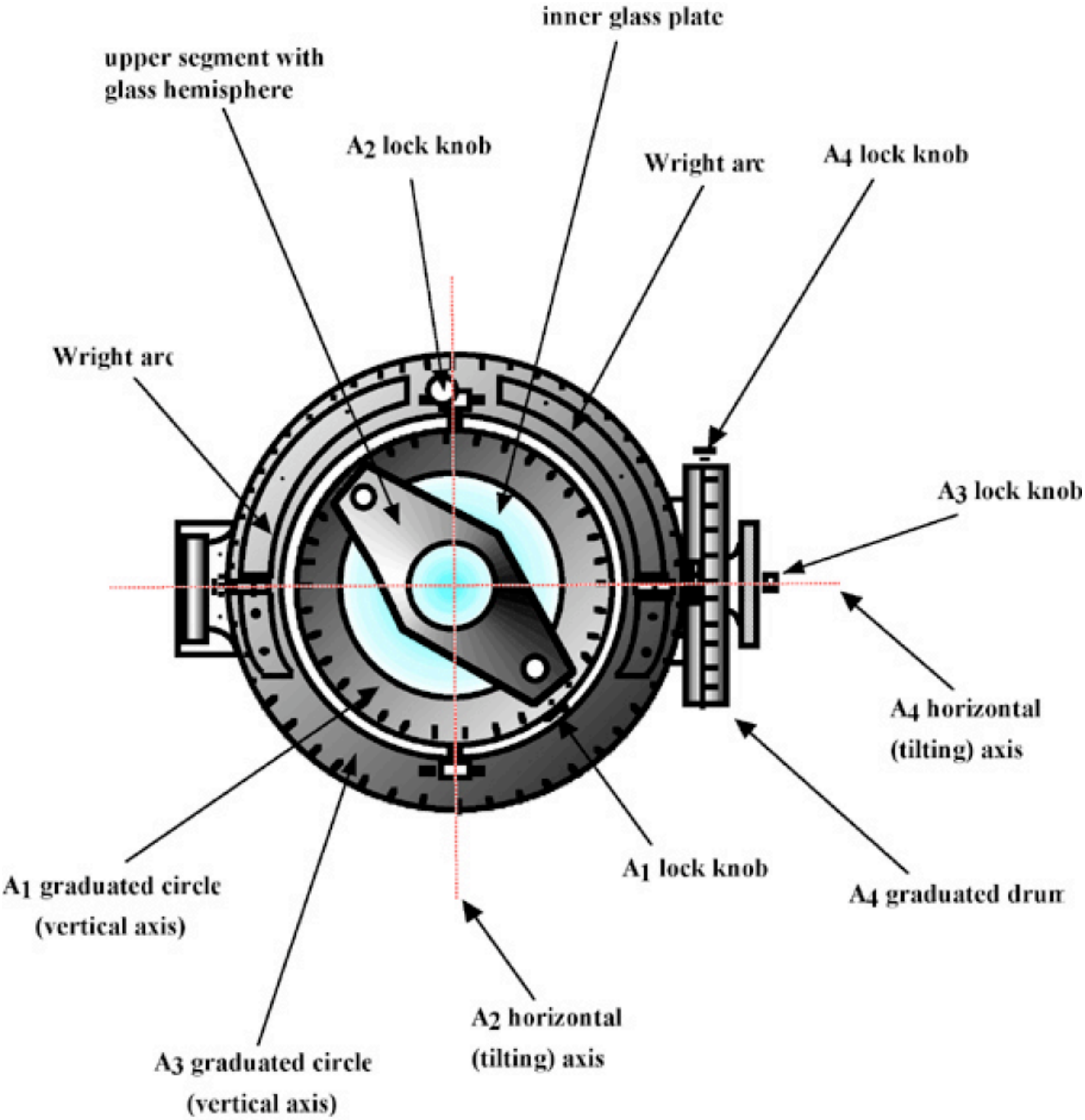

FIGURE 2
An early Fedorov universal stage, manufactured by the firm of R. Fuess, Berlin-Steglitz, Germany, ca. 1900; stage ca. 11 cm across.

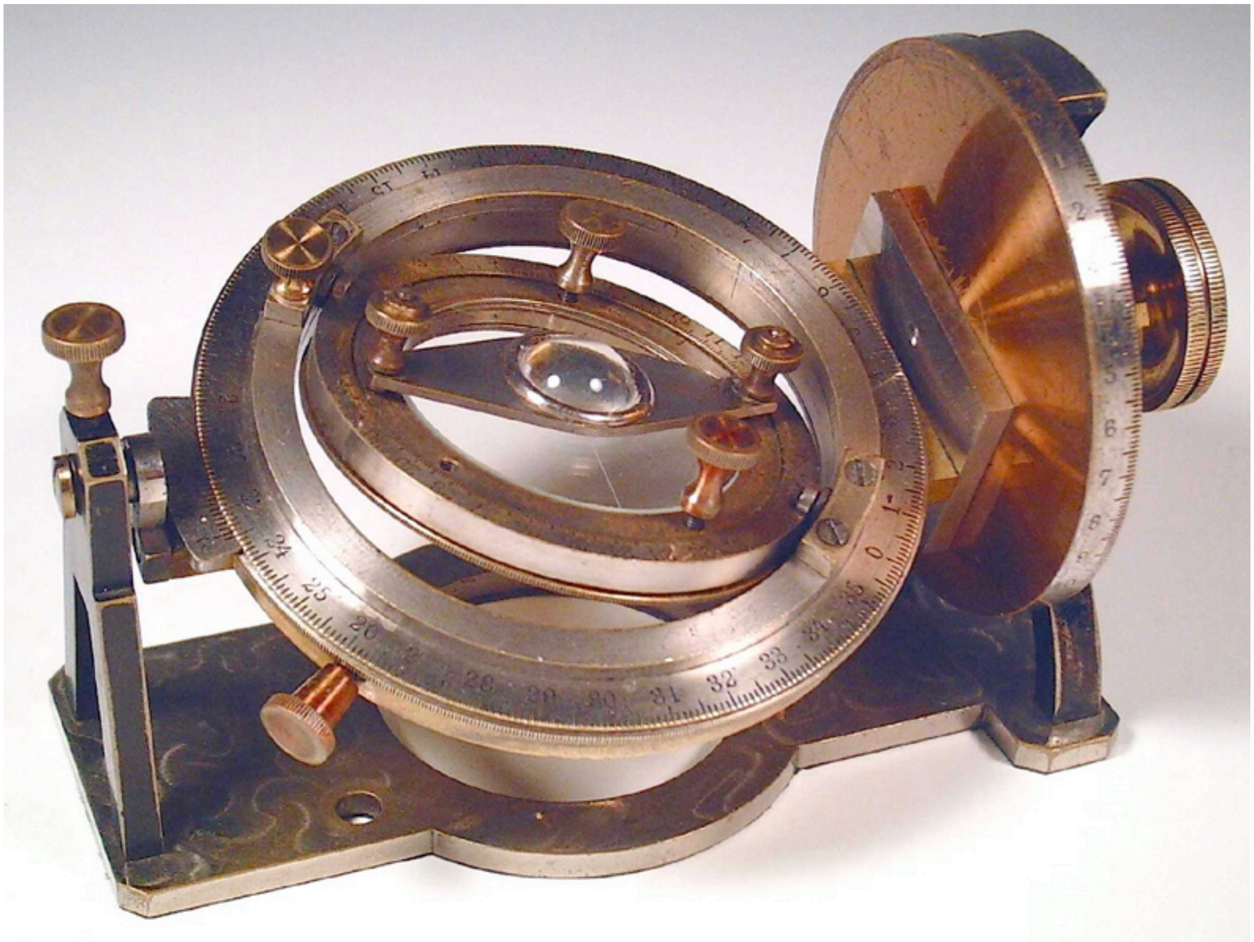

FIGURE 3
Theodolite microscope, manufactured by C. Leiss, Berlin-Steglitz, Germany, ca. 1920, illustrating the first large-format universal stage that was an integral part of this complex instrument.

FIGURE 4
A classic petrographic microscope, model GM, ca. 1925, manufactured by the E. Leitz firm; shown with an early version of their 4-axis universal stage that was designed by Max Berek in the 1920s.

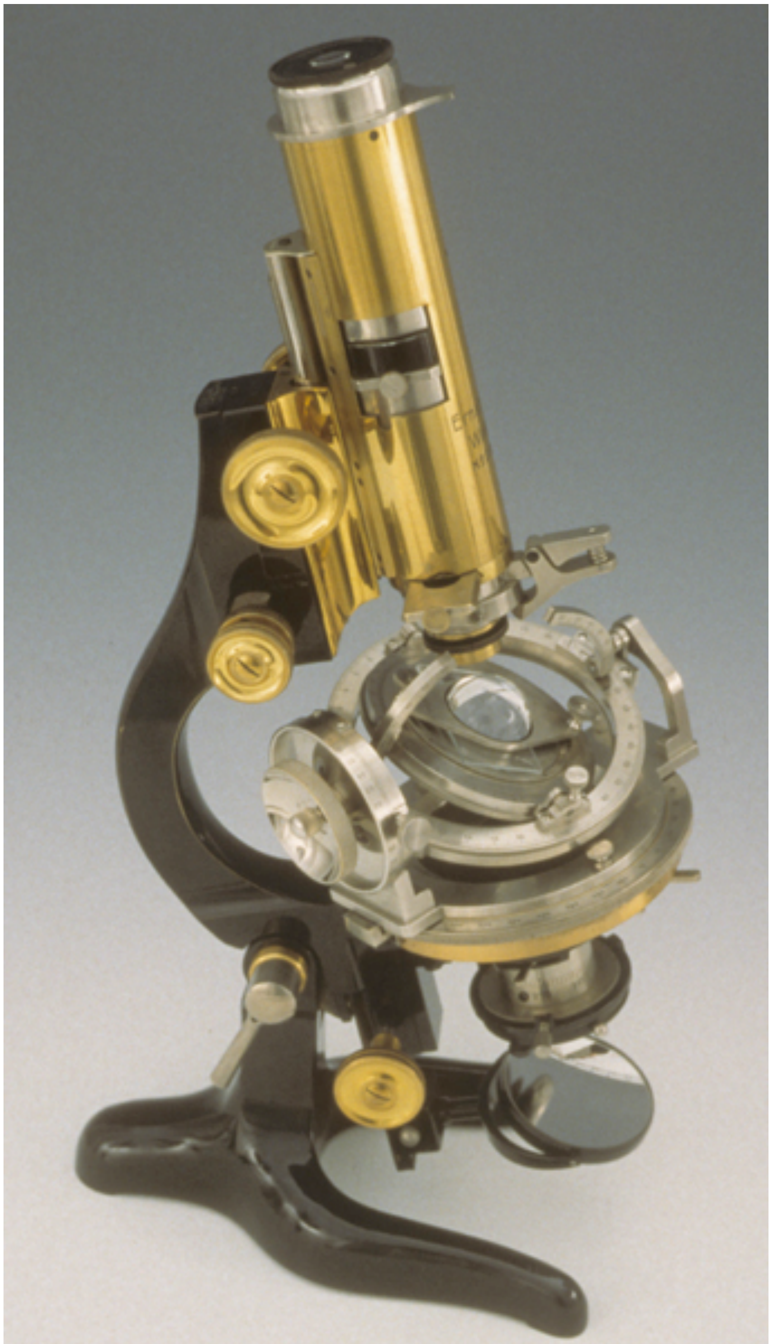

FIGURE 5
A modern version of the detachable 4-axis universal stage. This example, with Wright arcs shown in a raised position, features a centering base, and was manufactured by E. Leitz, Wetzlar, Germany, ca. 1970s.

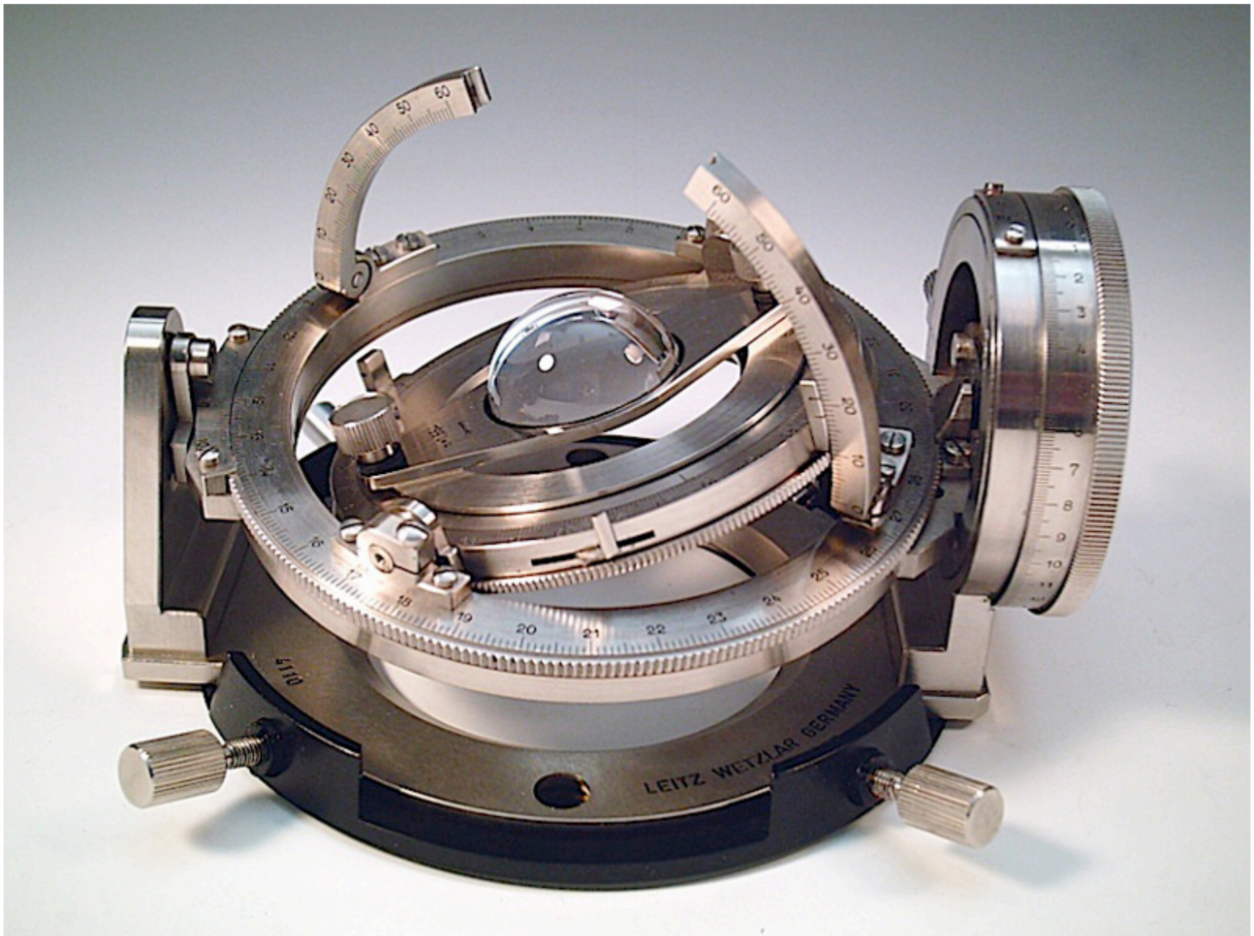

FIGURE 6
A 5-axis universal stage designed by R.C. Emmons in 1929, manufactured by the Bausch & Lomb Company, Rochester, New York. Note the presence of a third (ungraduated) ring and a second pair of Wright arcs.

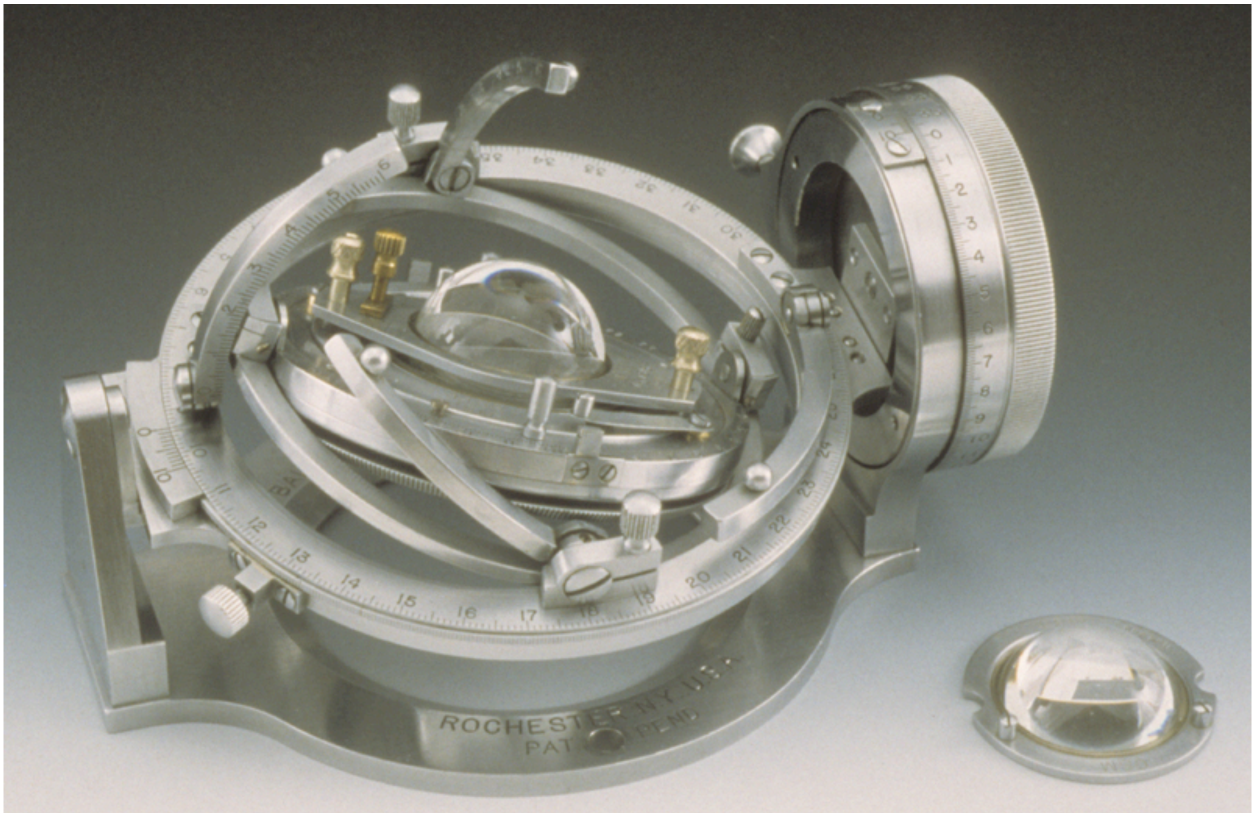

FIGURE 7
Diagram showing the change in orientation of the principal optic vibration directions (heavy black line represents the optic X-Z plane) with changing composition for plagioclase. From left to right: albite (sodic), andesine, labradorite, and anorthite (calcic). Illustration courtesy Olaf Medenbach.

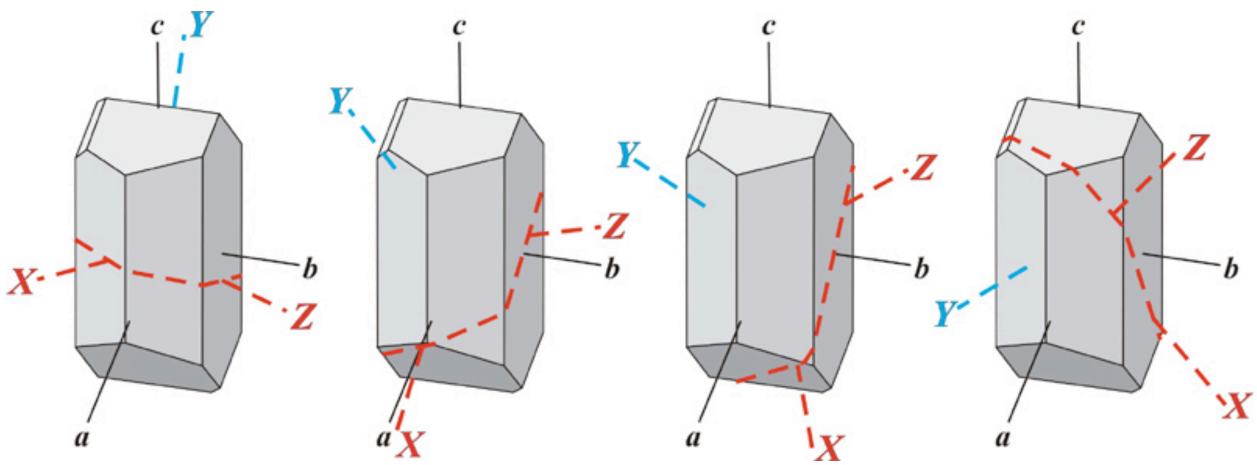

FIGURE 8
Wulff stereonet plot from universal stage data, showing an augite crystal showing the three principal vibration directions (X, Y, and Z), two 110 cleavage directions (# = poles, dashed lines = planes, with their intersection representing the c-axis), and the optic axes. From this plot, drawn on a tracing paper overlay that can be rotated on the stereonet, cleavage and optic angles can be accurately determined, as well as the angle between the c-axis and the slow (Z) vibration direction. Presence of a 'Z-to-c' angle signifies a crystal symmetry that is lower than orthorhombic.

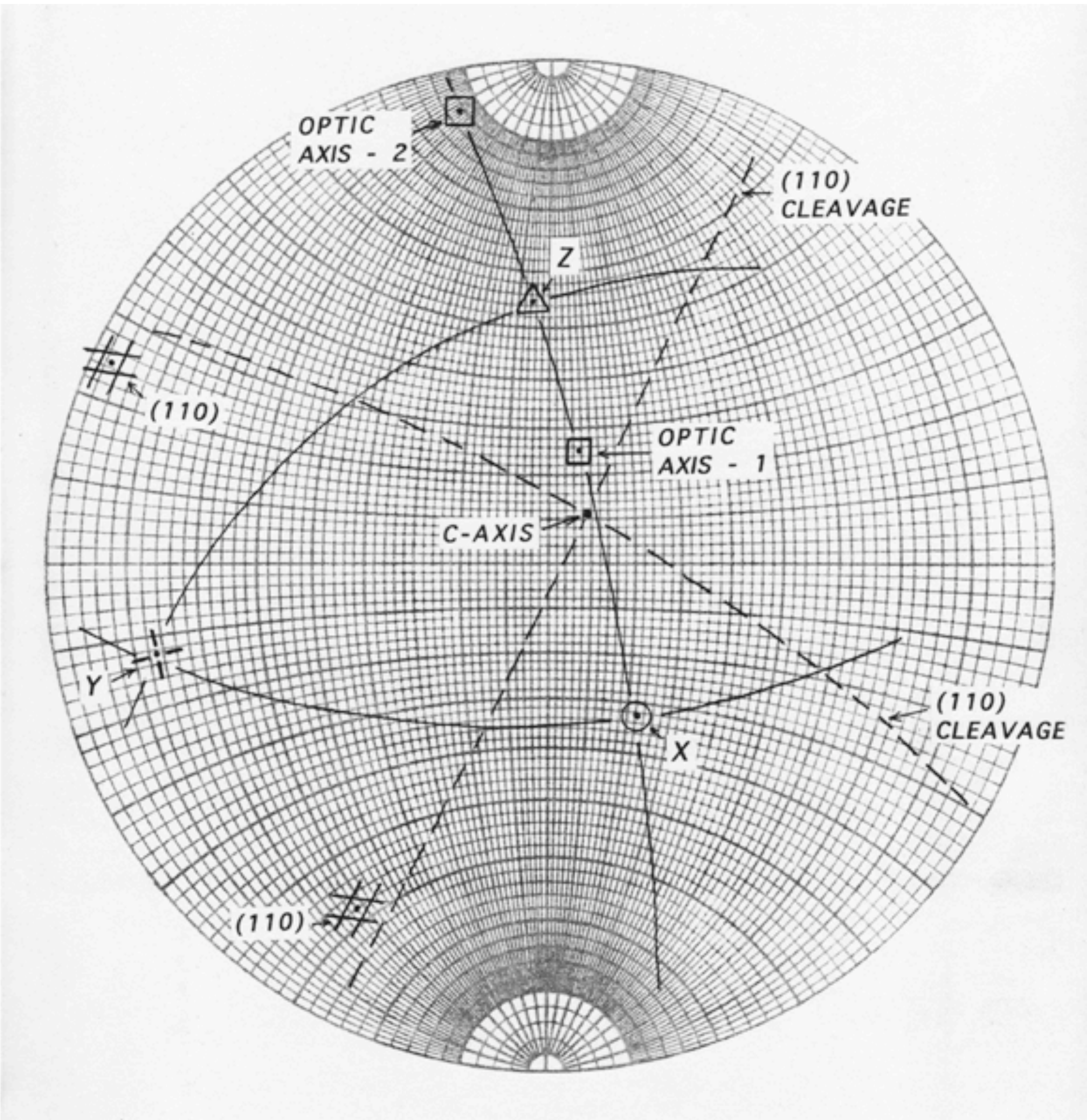

FIGURE 9
Waldmann hollow sphere set, manufactured ca. 1960 by E. Leitz, Wetzlar, Germany. The 25-mm diameter sphere, with fitted caps and holders, is placed in the center of a universal stage, permitting almost unlimited rotation and orientation of a mineral grain or faceted gemstone for optical study. The set includes two wood rings for holding the glass sphere, three caps (with a variety of specimen holders) that fit the sphere, tools to manipulate the end caps, and components necessary to adapt the sphere to the universal stage.

FIGURE 10
An Olympus BX-51P microscope used for classroom instruction, shown as adapted to accommodate a Leitz 4-axis universal stage. Photo courtesy College of Microscopy, Westmont, Illinois.