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Biaxiality in 'isometric' and 'dimetric' crystals

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Abstract

In an attempt to explain the anomalous optical properties of certain cubic, tetragonal, and hexagonal (trigonal) mineral species, variations in $2V$, composition, and space-group symmetry have been determined for eight different minerals including garnet (And–Gross), rutile, jeremejevite [$Al_6B_5O_{15}(F,OH)_3$], apatite, kleinite [$Hg_2N(Cl,SO_4)\cdot xH_2O$], beryl, quartz, and elbaite. The space-group symmetries of the specimens, determined by single-crystal X-ray techniques, showed no deviations from previously-observed crystallographic symmetry, yet significant deviations from isometric and uniaxial optical character were observed. All specimens except rutile were found to be compositionally zoned, but no systematic correlation was found between elemental zoning and $2V$ measured along the same traverses. The anomalous optical properties are thought to be due to strain induced by chemical substitutions and/or defects occurring during crystal growth, by rapid temperature or pressure quenches, or by mechanical deformation.

Introduction

Numerous observations of anomalously biaxial cubic, tetragonal, and hexagonal (including trigonal) substances have been reported over the past half-century. Various hypotheses have been offered to explain the biaxiality of these materials, including internal stresses (Deer *et al.*, 1966), twinning (Winchell and Winchell, 1951; Turner, 1975a, b), and mechanical deformation (Johannsen, 1918; Turner, 1975a). These proposed causes of biaxiality need not affect the space-group symmetry as determined by X-ray diffraction. Thus, cubic, tetragonal, or hexagonal minerals displaying anomalous optics commonly display cubic, tetragonal, or hexagonal space-group symmetry.

From the many minerals exhibiting anomalous optical properties, the following have been chosen for further study: (1) garnet (cubic); (2) rutile (tetragonal); (3) jeremejevite, $Al_6B_5O_{15}(F,OH)_3$ (hexagonal); (4) apatite (hexagonal); (5) kleinite, $Hg_2N(Cl,SO_4)\cdot xH_2O$ (hexagonal); (6) beryl (hexagonal), including varieties goshenite, morganite, and emerald; (7) quartz (trigonal), variety amethyst; and (8) tourmaline (trigonal), variety schorl–elbaite. All but jeremejevite, quartz, and tourmaline have centrosymmetric structures. These eight minerals were chosen because of the range of crystallographic symmetry, crystal structure, and varying chemistry that they display.

The proposed causes of observed anomalous optical character can be considered conceptually as being primary or secondary in nature, depending on whether they originated during or after crystal growth. A primary cause for an anomalous optical axial angle, in an otherwise isotropic or uniaxial mineral, involves the generation of internal stresses produced by a range of chemical substitutions or by defects occurring during crystal growth. The compositionally-induced stresses could be especially large near contacts between zones of sharply contrasting composition, and may result in a $2V$ in these regions together with related changes in refractive indices. A possible secondary cause of anomalous biaxiality in compositionally-zoned crystals involves rapid pressure and temperature changes, subsequent to crystallization of the mineral considered, which produce internal stresses and anomalous optical properties. The effect of internal stresses produced by any of the above mechanisms on the magnitude of anomalous $2V$'s and refractive indices is at present unknown. The purpose of this study is to examine the range in

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anomalous optical properties of these eight minerals, most likely caused by chemical zonation, primary growth features, or secondary pressure–temperature effects.

Experimental details

All optical observations were made with a monocular Zeiss polarizing microscope utilizing a 3200°K (tungsten) light source, an 8× ocular, and a 40× objective (N.A. 0.85). A calibrated single-line micrometer ocular (6×) was used for measurement of isogyre separation. For all minerals examined optically, doubly-polished (3-micron polish) plates ranging from 0.03 to 1.00 mm thick were used. Single crystals were cut normal to the *c* axis (hexagonal or trigonal and tetragonal). The garnet (grossular-andradite) was examined in a doubly-polished petrographic thin section of 0.03 mm thickness. Measurements of $2V$ were made by Tobi's method (Tobi, 1956).

X-ray precession photographs were obtained for tourmaline, beryl, jeremejevite, quartz, and kleinite. For tourmaline, beryl, and quartz no deviations from previously-reported symmetry were observed. The space groups for jeremejevite and kleinite are currently being redetermined. No violations of hexagonal symmetry in either were observed.

An ARL-EMX-SM microprobe was used for quantitative element determinations. In all cases accelerating voltage was 15 kV, sample current was 0.04 to 0.06 microamperes, and the spot size was about 2 microns. Analyzed elements and standards for each mineral are listed in Table 1. Raw data were reduced using the MAGIC IV computer program (Colby, 1968). Microprobe scanning traverses were made at points separated by 0.01 to 0.5 mm with 10-second counting times. $2V$ determinations were made along the same traverses at intervals of 0.1 to 0.5 mm. All measurements were taken at 23° ± 2°C.

Data

Tourmaline

Of the eight minerals examined (Table 2), tourmaline received by far the most attention. "Pocket" tourmalines from the Mesa Grande, Pala, and Ramona districts in San Diego County, California; from the Newry and Paris districts, Oxford County, Maine; and from the state of Minas Gerais, Brazil, have been examined to evaluate the relationship between compositional zonation and optical character. Tourmaline from the Himalaya dike system (Mesa Grande) has been examined in most detail (Foord, 1976).

Table 1. Minerals analyzed by electron microprobe; elements and standards

Mineral	Analyzed elements (standards)
Tourmaline	Fe, Mn, Ca, Ti, Si, Al, Mg, F, Na (natural tourmalines) Zn (pure metal)
Beryl	
emerald	Cr (natural chromite)
goshenite-morganite	Na, Cs (natural beryls)
Utah red beryl	Fe (natural hematite)
	Mn, Zn, Sn (pure metals)
	Ti (synthetic TiO_2)
	Si, Al, K (natural orthoclase)
	Mg (synthetic MgO)
	Na, Cs (natural beryls)
Jeremejevite	Fe (natural hematite)
	Si (synthetic SiO_2)
	Al (synthetic Al_2O_3)
	F (synthetic LiF)
Kleinite	Cl (synthetic calomel)
	Hg, S (natural cinnabar)
Apatite	Ca, Si, P, Ce, Y, F (natural apatite)
	Mn, Fe (pure metals)
Garnet	
grossular-andradite	Ca, Si, Al, Fe, Mn, Ti, Mg (natural garnets)
Rutile Quartz	No quantitative work

"Pocket" tourmaline crystals show concentric growth zoning with or without additional sector zoning and twinning on $\{10\bar{1}1\}$. The basal portions (roots) of these crystals are usually very homogeneous over a large region (mm scale) and are perfectly uniaxial. Extinction positions are sharp, and basal sections show minimum birefringence at all positions of rotation of the microscope stage. In euhedral "pocket" crystals, chemical zonation becomes significant, as does varying degrees of biaxiality. This biaxiality is generally most pronounced at color boundaries (pink–green, pink–colorless, or others) where the steepest chemical gradients occur. Although there is an apparent correlation between $2V$ variation and elemental zonation within tourmaline, there is no consistent relationship between any one element and $2V$ variation (Figs. 1a and 2a). Secondary or later episodes of tourmaline growth (pencils) result in material which is also strongly compositionally zoned. These crystals, although flawless or nearly so, show large variations in $2V$ and optic-figure qual-

Table 2. Compositions, space groups, and anomalous optical properties of minerals examined

Mineral	Composition	Space group	Anomalous optical properties
Garnet			
grossular-	$Ca_3Fe_2Si_3O_{12}$	*Ia3d*	birefringence, 2*V*
andradite	$Ca_3Al_2Si_3O_{12}$		
Rutile	TiO_2	*P4/mnm*	birefringence ⊥ *c*, 2*V*
Jeremejevite	$Al_6B_5O_{15}(F,OH)_3$	?	"
Apatite	$Ca_5(PO_4)_3(F,OH)$	$P6_3/m$	"
Kleinite	$Hg_2N(Cl,SO_4)$-xH_2O	?	"
Beryl			
goshenite-	$Be_3Al_2Si_6O_{18}$	*P6/mmc*	"
morganite	"	"	"
emerald	"	"	"
Utah red beryl	"	"	"
Quartz			
amethyst	SiO_2	$P3_12$ or $P3_22$	"
Tourmaline			
schorl-	$Na(Fe,Mg)_3Al_6B_3Si_6O_{27}(OH,F)_4$	*R3m*	"
elbaite	$Na(Li,Al)_3Al_6B_3Si_6O_{27}(OH,F)_4$		

ity. However, strain shadows and patchy extinction are often noticeable, especially near small cracks. Occasionally, the extinction pattern resembles the grid twinning seen in microcline. Crystals in which domains of differing composition are in sharp contact with one another (*e.g.* dendritic growth) frequently show microcline-like grid twinning. In portions of crystals (tourmaline as well as others) where the lamellar pattern is present, 2*V* is clearly decreased. Source-image distortion techniques (Wagner *et al.*, 1971) showed the existence of domain structure in color-zoned tourmalines from Brazil. Mosaic textures are often noticeable in crystals examined from all districts. Those "pocket" crystals which are obviously deformed (*e.g.* bent) often show strain shadows and strain birefringence along with biaxial character. Most crystals are not visibly deformed but may still be biaxial.

Azimuth orientation of the optical axial plane within tourmaline has been observed to be generally very irregular. Figures 1b and 2b show orientation diagrams of the azimuths of the optical axial planes for two crystals cut normal to *c*. Other crystals examined in the same manner show essentially the same features. In some crystals (possibly strain-free or with minimum strain), the azimuth orientations of the optical axial planes often are nearly constant with relation to the crystallographic symmetry. Other crystals showing strain shadows and mosaic as well as lamellar textures show no observable relationship between the azimuth of the optical axial plane and crystallographic symmetry (Figs. 1b, 2b). The lack of correlation is probably related to the domain size being examined and the presence of irregularly distributed internal stresses. Primary development of internal stresses and consequent development of primary 2*V* may be due to growth imperfections and growth characteristics of the crystals, *e.g.*, screw dislocations and growth hillocks (spirals). These features are very commonly observed on the pinacoid and pedion terminations of pocket crystals of tourmaline and beryl. Differing elastic properties as a function of the composition in thermally shocked crystals at high pressures may produce internal stresses and consequently a secondary 2*V*. This is true for all other gem-pocket pegmatite minerals, and may be true for minerals formed in other lower temperature and pressure environments. A second mechanism involving rapid drop in pressure (pressure quench) may also produce a secondary 2*V* in a previously uniaxial crystal or even change the value of 2*V* in a biaxial crystal. It is most likely, however, in the case of tourmaline and probably other pocket minerals from pegmatites, that the 2*V* seen is primary in origin. Annealing of strain produced by thermal shock or pressure changes during crystallization

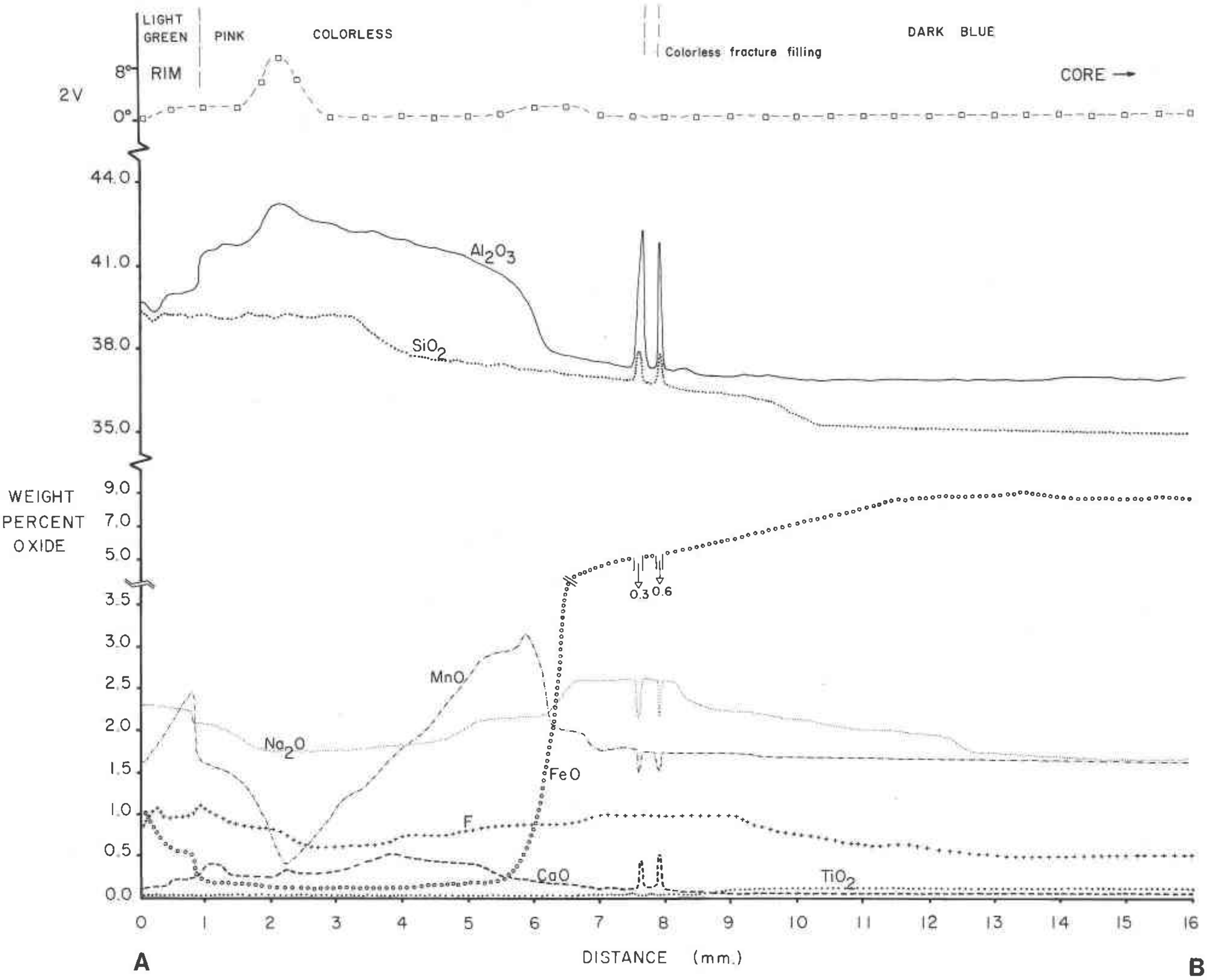

Fig. 1a. Weight percent oxide and 2*V* variation curves within a 'pocket' crystal of schorl–elbaite from the Tourmaline Queen Mine, Pala, California. MgO content decreases from about 0.04 weight percent in the core to less than 0.01 weight percent in the rim. Section cut normal to *c*.

would be expected in pegmatite pockets if slow cooling occurred subsequently; considerable evidence exists (Jahns and Burnham, 1969) to support this hypothesis. Cracking, also commonly observed in pocket minerals, may also reduce stress produced by external strain effects.

Beryl

Beryl, varieties goshenite and morganite from the Ocean View (Elizabeth R) mine at Pala and the Little Three mine at Ramona, shows strong compositional zoning of the alkalies and anomalous biaxial character. Figure 3a is a plot of 2*V* and Na + Cs content *vs.* distance for a beryl from the Ocean View mine. Figure 3b shows the azimuth orientations of the optical axial planes for the same crystal and the traverse along which probe data were obtained. No definite relationship between Na content or Cs content and 2*V* appears to exist. Viewed down *c*, goshenite and morganite from San Diego County and Brazil (total of 10 specimens) all show undulose, anisotropic rims with growth zones, whereas the cores are much more uniform and nearly perfectly isotropic. Loci of strain are defined by irregular areas of extinction which become evident upon rotation of the microscope stage. On the other hand, the unusual beryl described by Schaller *et al.* (1962) from Arizona contains the highest-known content of elements other than Be, Si, Al, and O (16.87 weight percent) but is *homogeneous* in composition and displays no biaxiality. From this

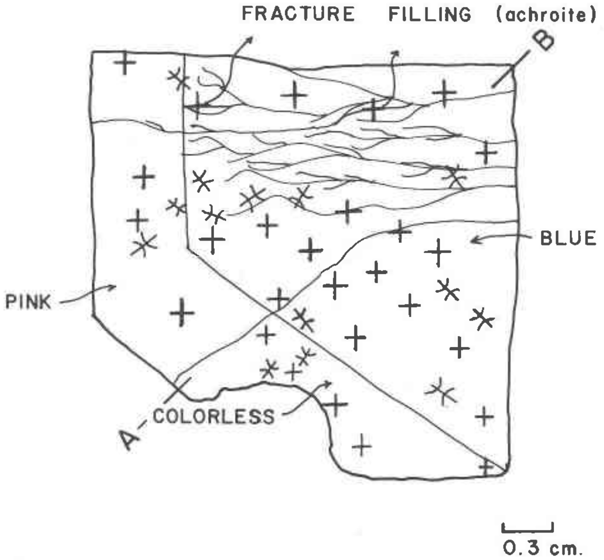

Fig. 1b. Azimuth orientations of optical axial plane measurements within the tourmaline shown in Fig. 1a. *A–B* indicates microprobe and 2*V* traverse line.

observation we infer that anomalous optics are not due to liberal substitution of elements alone. Zoned crystals of beryl from other than pegmatitic environments may or may not be anomalously biaxial (primary or secondary 2*V*).

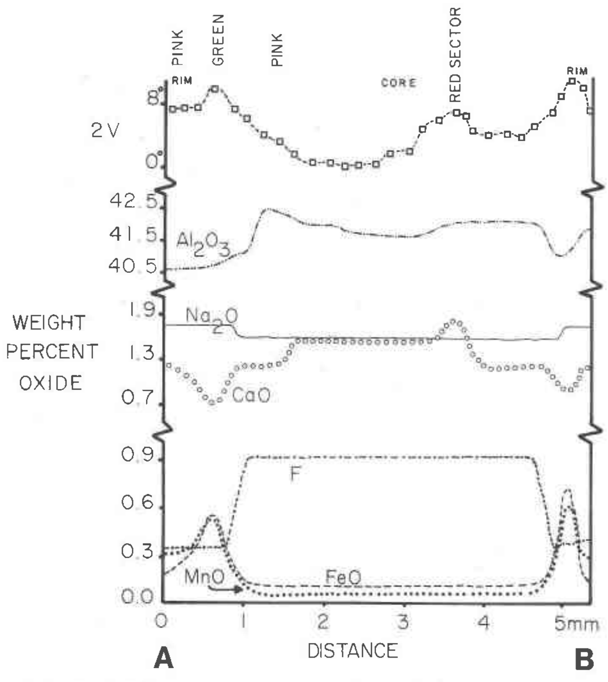

Fig. 2a. Weight percent oxide and 2*V* variation curves within a 'pencil' tourmaline crystal from the San Diego Mine, Mesa Grande, California. SiO_2 content is nearly constant at about 38.5 weight percent, while MgO and TiO_2 contents are always less than 0.02 weight percent. Section cut normal to *c*.

A specimen of the unusual red beryl from the Wah Wah Mountains, Utah, was examined in detail for compositional zoning and optical properties. There is no apparent correlation between 2*V* and compositional zonation. The core displays patchy areas showing strain centers and mosaic textures with high 2*V* values (as much as 15° ± 2°), while the rim displays fairly sharp extinction, and only portions are slightly biaxial. The core area may represent the combination of primary and secondary induced 2*V* while the rim may represent only primary 2*V* effects. Areas of lamellar twinning (within core and rim) are uniaxial or very slightly biaxial.

Synthetic emeralds with Cr_2O_3 contents ranging from 0.1 to 2.7 weight percent are both uniaxial and biaxial. Figure 4a is a plot of Cr_2O_3 content and 2*V* *vs.* distance in a crystal cut normal to *c*. The Cr_2O_3 content is clearly not responsible for the anomalous optical character. The emeralds examined were grown by flux-melt techniques at different times and in different batches. One crystal shows good uniaxial material in the core with biaxial material on the rim, while a second shows no uniaxial material at all. While the first crystal shows no strain birefringence in the core (most portions), the second contains numerous loci of strain shadows. Differing growth rates may possibly account for the difference in the strain birefringence and biaxiality observed. Where strain birefringence is at a minimum, the 2*V* is at a minimum regardless of the changes in chemistry. Thus, two different crystals with identical geometry and magnitude of chemical zonation may show completely different 2*V* traverse curves. Figure 4b shows the orientations of the optical axial planes within the crystal shown in Figure 4a.

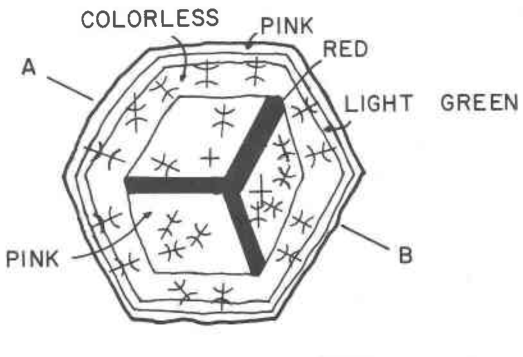

Fig. 2b. Azimuth orientations of optical axial plane measurements within the tourmaline shown in Fig. 2a. *A–B* indicates microprobe and 2*V* traverse line.

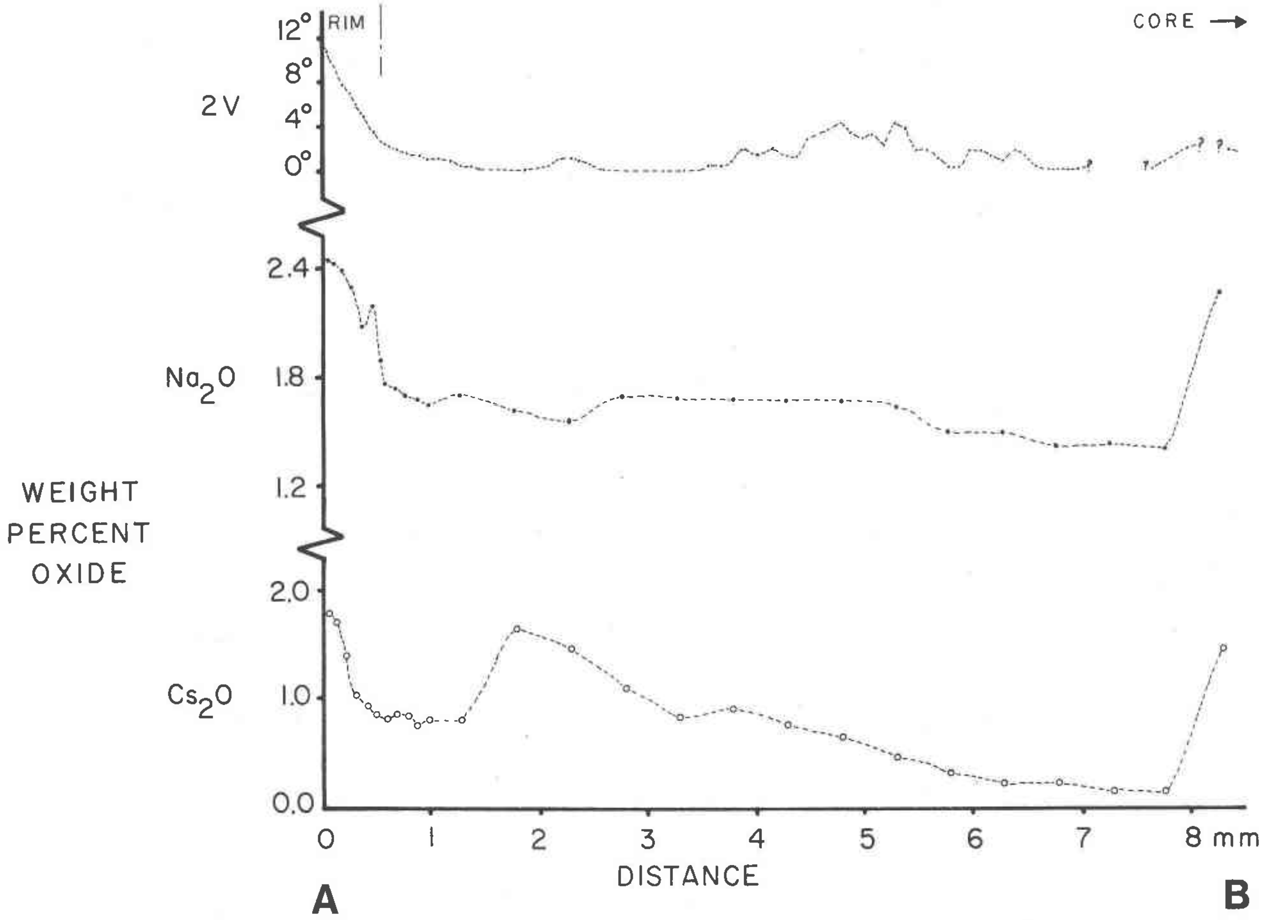

Fig. 3a. Weight percent Na_2O, Cs_2O, and $2V$ variation curves within a 'pocket' crystal of goshenite–morganite from the Ocean View Mine, Pala, California. Section cut normal to c.

Jeremejevite

Specimens of jeremejevite from the type locality in the USSR and from South Africa have been examined in detail. This study is part of a more comprehensive examination involving redetermination of the optical properties and composition as well as X-ray characterization (Erd and Foord, in preparation). Azimuth orientations of the optical axial planes in the various optical domains are extremely regular and related to the six-fold axis of the mineral (Strunz and Wilk, 1974). X-ray precession and Laue photographs show no deviations from hexagonal symmetry in different portions of material from both localities. A maximum $2V$ of 33° ± 1° has been determined for the Russian material. The material from both localities is of gem quality and has virtually no flaws or inclusions. Boundaries between the optical domains are very sharp. We note that in the Russian material a uniaxial core is surrounded by a zone of biaxial material with $2V$ ranging from 15° to 33° (± 1°), which in turn is mantled by a thin zone of lesser $2V$ (0° to 5°) and finally by a uniaxial rim. The South African material, on the other hand, has a uniaxial center with biaxial outer zones only, and the maximum $2V$ was 22° ± 1°. Sector extinction patterns are similar to those given by Strunz and Wilk (1974), and are consistent with hexagonal symmetry. Within each sector and outer growth zones extinction is undulatory, while the central core in both cases is generally perfectly isotropic (viewed down c). The Russian material has a portion of the core which is not uniaxial (is biaxial) and is homogeneous in chemical composition. There is no apparent correlation between $2V$ and chemical zonation (Fe, Si, F) in either sample. The apparent combination of first-order and second-order prisms may be due to differences in original growth velocities, or to recrystallization phenomena.

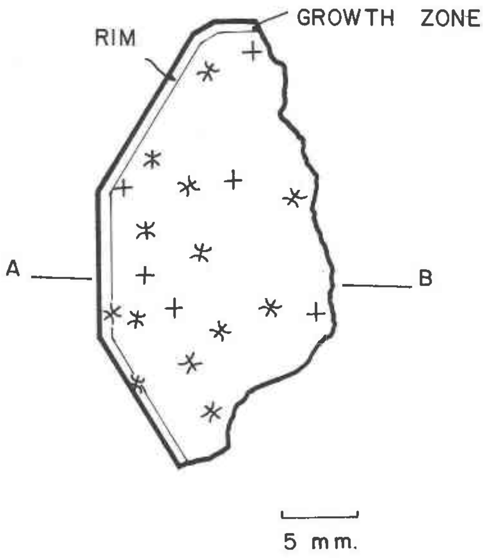

Fig. 3b. Azimuth orientations of optical axial plane measurements within the goshenite–morganite shown in Fig. 3a. *A–B* indicates microprobe and $2V$ traverse line.

Apatite

Compositionally-zoned apatite from the Himalaya dike system, showing a pink center in sharp contact with a light blue rim, is both uniaxial and biaxial. The weight percent MnO rises abruptly from about 0.08 to 0.65, while that of CaO decreases from 55.7 to 55.3, in traversing from the pink core to blue rim. There is no change in $2V$ across this contact ($2V$ = 0°). However, random areas within the apatite crystal have $2V$ values as high as 4° (± 1°). Mn-bearing carbonate–apatite from the Laacher See, with a uniaxial core (optically negative) and biaxial rim (optically positive) was described in Rosenbusch (1927, p. 242). Heating caused the disappearance of the biaxial optical character, most likely by the annealing out of internal stresses.

Quartz (amethyst)

Concentric and sector-zoned amethyst crystals are biaxial (Hurlbut and Walker, 1976). Vein-filling amethyst from Thunder Bay, Ontario, Canada, shows similar properties, with $2V$ values as high as 6° ± 1°. X-ray precession photographs show hexagonal symmetry. There is no apparent correlation between iron (FeO < 0.12) and aluminum (Al_2O_3 < 0.05) content, $2V$, or amethystine color. Schists and gneisses may contain strained quartz which often is anomalously biaxial.

Kleinite

Kleinite, $Hg_2N(Cl,SO_4)\cdot xH_2O$, from Terlingua, Texas, and McDermitt (Cordero), Nevada, shows biaxial character. Terlingua material containing both SO_4 and Cl is uniaxial or only slightly negative, whereas the McDermitt material, which is nearly the pure Cl end-member, has a high $2V$ (75–85°) and is optically positive. Two polymorphs of kleinite occur in the material from Terlingua (USNM 86641) with *a*

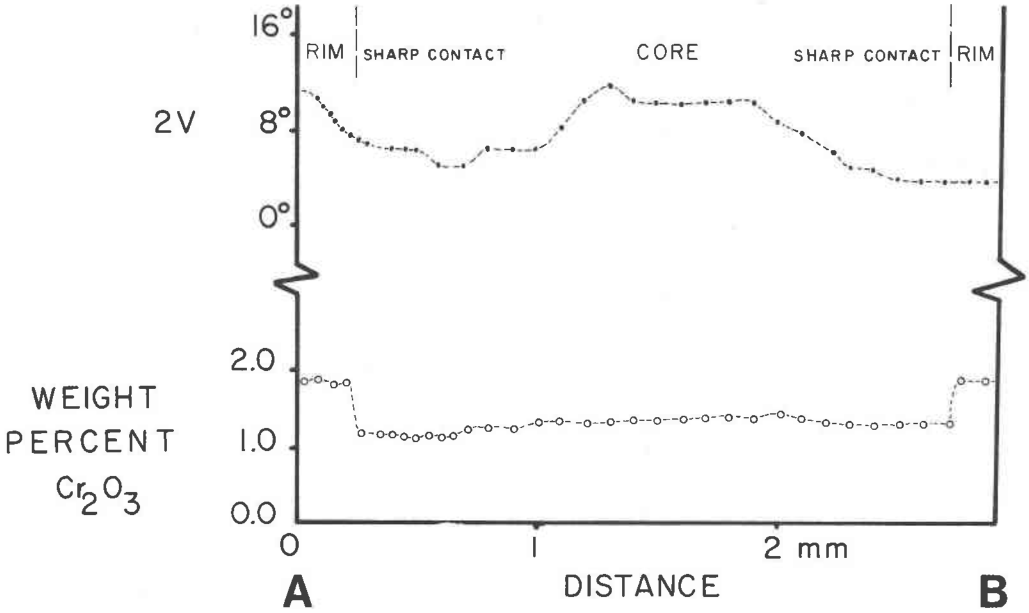

Fig. 4a. Weight percent Cr_2O_3 and $2V$ variation curves within a crystal of synthetic emerald cut normal to *c*.

= 13.5 A and a = 40.5 A, whereas all of the material from McDermitt has a = 13.5 A. Color-zoning is observed in the kleinite from McDermitt (clear yellow cores with reddish orange rims). It is not known if the material from Terlingua is growth-zoned as only crystal fragments were obtained for study purposes. In this near-surface hot-spring environment (about 1 atm and 150°C), external mechanical stresses can be considered negligible. However, internal stresses caused by cooling or crystal-growth irregularities may be present.

Rutile

Rutile often shows polysynthetic twinning on {011}. Such material examined in this study (locality unknown) shows $2V$ values at the twin boundaries [OAP = (110)] as high as 20° (+). Away from the twin boundaries, within chemically homogeneous material, no biaxiality is observed. Compositionally-zoned rutile has not been examined in this study. Winchell and Winchell (1951) ascribed the biaxiality to deformation and/or twinning.

Garnet

Minerals of the garnet group may show anomalous birefringence and optical character. Garnets showing strong anomalous optical character are either strained (mechanical stress) and/or noticeably compositionally zoned (internal stress). Mechanical strain can be ruled out in those crystals having alternating isotropic and biaxial zones, as for all other minerals previously discussed. Grossular–andradite from Darwin, California, shows excellent biaxial interference figures. Cores of homogeneous, isotropic andradite (And_{100}) are mantled by successive growth zones of grossular–andradite ranging in composition from $Gross_{50}And_{50}$ to $Gross_0And_{100}$ (H. S. Eastman, Stanford University, personal communication, 1976). Biaxial and isotropic zones are intermixed, with the isotropic zones being And_{90} or greater. $2V$ values from 30° (−) to 65° (+) have been measured, and the birefringence is about 0.01. Zones of extremely narrow lamellae (0.02 mm or less) yield lower-quality optic figures. Recently, Takeuchi and Haga (1976) have documented ordering of Fe and Al in grossular–andradite from Munam, Wanghedo, North Korea, which results in orthorhombic material with very high $2V$'s. Zoned uvarovite from Outokumpu, Finland, is birefringent (G. E. Brown, Stanford University, personal communication, 1976), but examination of symmetry-equivalent reflections on an automated diffractometer indicated no deviations from $Ia3d$ symmetry.

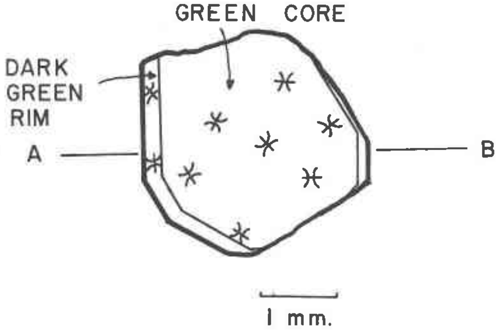

Fig. 4b. Azimuth orientations of optical axial plane measurements within the synthetic emerald shown in Fig. 4a. A–B indicates microprobe and $2V$ traverse line.

Discussion and conclusions

The optic angle is a function of the indices of refraction, which in turn are functions of the structure and composition of a mineral. Chemically-zoned crystals may also exhibit corresponding zones of differing thermal expansion coefficients and compressibility constants, which may be correlated with changes in optical properties. When pressure and temperature changes occur, secondary $2V$'s may be induced. At present, we are unable to differentiate between primary and secondary $2V$ or the combination thereof. If chemical zonation of sufficient magnitude is present over a small domain size (0.X mm), then the resultant changes in the indices of refraction cause biaxiality, whether or not secondary strain is developed during subsequent pressure and temperature changes.

Substitution of significant quantities of various elements into minerals results in changes of optical and X-ray properties. A single color-zoned tourmaline crystal having cell dimensions (black—a = 15.97 A, c = 7.19 A; pink—a = 15.85 A, c = 7.11 A) differing by one percent or more in the different colored zones may result in ω varying by as much as five percent (1.640–1.675). If the change in chemical composition and resulting changes in X-ray and optical parameters are distributed over a large domain, then the resulting internal stresses and the index of refraction differences will be minimal. However, where a sharp break in composition occurs, the cell dimensions differ over a smaller domain. The indices of refraction also differ, causing an apparent beta index and anomalous $2V$. A biaxial character can thereby be induced in a hexagonal substance.

Table 3. Proposed causes for anomalous biaxiality in some dimetric and isometric crystals

Mineral	Cause	Reference
Grossular-andradite	order-disorder	Takeuchi and Haga (1976)
Rutile	twinning	This paper
Jeremejevite	recrystallization ?	"
Calcite	phase transition	Boettcher and Wyllie (1967)
Calcite	mechanical deformation	Turner (1975a,b)
Tourmaline, beryl, apatite, kleinite, jeremejevite ?, amethyst ?, garnet ?	internal stress resulting from chemical zonation and/or included growth defects	(Primary 2*V*) This paper
Tourmaline, beryl, apatite, jeremejevite ?	internal stress resulting from pressure and/or temperature changes	(Secondary 2*V*) This paper
Uvarovite	?	G. E. Brown, personal communication, 1976

Many of the crystals examined (Table 3) show color zonation caused by compositional zonation (beryl, tourmaline, jeremejevite, apatite, and kleinite). Because the thermal expansion coefficients and compressibility constants are different for each of the zones, subsequent pressure and/or temperature changes will result in different internal stresses and secondary 2*V*'s in different zones. The release of these internal stresses may result in the fracturing of the interiors of many concentrically-zoned uniaxial pegmatite minerals, while the exteriors remain relatively fracture-free. In tourmaline, stress is further relieved by the development of microcline-like grid twinning. This type of stress-relief fracturing should not be confused with fracturing occurring from pressure quenching proposed by Jahns and Burnham (1969). Additionally, secondary 2*V* may be produced by phase transformations. Studies of calcite by Boettcher and Wyllie (1967) and Turner (1975a,b) have demonstrated that mechanical strain and phase transformation (aragonite–calcite) can induce an anomalous 2*V* in an otherwise uniaxial mineral.

In the observation of anomalous optics it is important to note the distinction between causes that are of crystallographic origin and those that are not. Numerous minerals of topologically higher symmetry have order–disorder relationships which result in a lowering of the space-group symmetry. Garnet (grossular–andradite) as described by Takeuchi and Haga (1976) is topologically cubic, but because of ordering in the octahedral M_1 sites (Fe–Al ordering), is topochemically orthorhombic with space group *Fddd*. Other common examples include potassium feldspar (Al–Si order) and cordierite (Al–Si order). For all of the cases discussed in this paper, except possibly the Darwin garnet, the anomalous optical character is believed to be due to non-topochemical causes.

Materials which are optically biaxial may be unquestionably hexagonal, tetragonal, or cubic on an X-ray scale. Optical methods sample far larger volumes of material than X-ray diffraction methods, and hence the symmetry as determined by both procedures may be the same or different. For example, if an entire cut plate from a biaxial tourmaline with no artificial strain release due to crushing were examined by X-ray diffraction, then the symmetry as determined by X-ray methods should be identical to that determined optically. In some cases, using the property of anomalous biaxiality, one can quickly determine the presence or absence of compositional homogeneity in materials not mechanically strained, even though chemical zonation may not be directly correlatable to the observed anomalous biaxiality. Very often color-zoning is absent, but anomalous biaxiality is observable (*e.g.* beryl). If a section is cut normal to *c* and shows variable 2*V*, one may suspect compositional zonation of varying magnitude with or without accompanying strain (internal or external). Chemically-homogeneous crystals containing primary growth defects may yield anomalous optical properties.

These factors may affect the optical properties of trimetric crystals as well. The observed 2*V* for a given trimetric crystal often will not agree with the 2*V* calculated from indices of refraction. Willard (1961) has succinctly stated the problems encountered between calculated and observed optical axial angles for biaxial minerals. As stated by him (p. 202) "within the limits of accuracy for measuring indices of refraction, the $2V$ cannot be definitely established as a specific value." The lower the birefringence of a mineral, the greater will be the possible variations in the calculated $2V$. Studies such as that by Rinne (1926) on topaz have shown the existence of strain-induced $2V$ changes which can be removed by heating. Isogami and Sunagawa (1975) have correlated growth defects with optical anomalies in topaz.

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