THE KNOOP MICROHARDNESS TESTER AS A MINERALOGICAL TOOL[1]

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ABSTRACT

The Tukon testing machine with a Knoop indenter has useful possibilities in the measurement of hardness of mineral specimens. Not only does the instrument afford numerical hardness values such as argentite=25, calcite=100, fluorite=150, magnetite=700, corundum=2000, SiC=3000, and diamond=about 8000, but it repeats these numbers with an accuracy of between 2 and 5 per cent when applied to a given crystal face under constant conditions. Surprisingly large variations of hardness have been found in many crystals, the variation being a function of the orientation of the surface tested and of the orientation of the long axis of the Knoop indenter in that surface. The results of 479 tests in 92 different orientations on 16 different minerals and mineral-like substances indicate the instrument is worthy of further study as a mineralogical tool.

INTRODUCTION

Metallurgists have long used various types of indenters for testing the hardness (defined as resistance to deformation) of metals. Attempts to apply to minerals the Rockwell, Vickers, and other types of machines which measure hardness in terms of deformation of the specimen by penetration of a standard-shaped point applied by a specified machine, have met with little success because of the tendency of minerals to fracture during the penetration of the indenter. Since the fracture represents displacement and deformation of other material than that immediately adjacent to the point of the indenter, greater penetration takes place than is proper for the indenter and its associated machine. Moreover, the displacement due to fracture cannot be measured readily, and therefore introduces an unknown factor into the measurement. Experiments conducted at the Research Laboratories of the Hamilton Watch Company have suggested that of all the various machines for measuring hardness by indentation, the Knoop microhardness tester may be the only tool that can give valid, or at least consistent, readings of the hardness of minerals.

THE KNOOP INDENTER

Knoop, Peters, and Emerson (1939) described an unusually sensitive pyramidal-diamond indenter which is known as the microhardness tester, or Knoop indenter. The Wilson Mechanical Instrument Company manufactures a machine, the Tukon tester (Fig. 1), which utilizes this indenter. In measuring the hardness of a specimen, a polished flat sur-

face is first prepared. The Knoop indenter is then brought into contact with this surface for 20 seconds (the minimum time found adequate to assure consistent results), with a known load. The indentation thus produced is measured with a microscope, and the hardness number I is proportional to the load divided by the area of the indentation. For relatively heavy loads—say 1 to 3 kilograms—the hardness number is essentially independent of the load. Tate (1944) showed, however, that this is not strictly true for loads of 100 grams or less; he concluded that the ap-

Fig. 1. Tukon testing machine, showing Knoop indenter and rising platform on which specimens are tested.

plied load should always be reported with the hardness number: that practice is followed here. The Tukon tester is provided with several weights corresponding to loads from 100 grams up. Our instrument is not provided with smaller loads, but slight changes could easily be made which would accomplish the purpose if necessary.

The latest model of the Tukon testing machine embodies an electro-

magnetic device for applying the load without overloading by impact between the specimen and the diamond indenter. The Hamilton instrument was rebuilt to afford that protection against shock after about half of the corundum tests reported here had been completed. The error due to impact before installation of the device is believed to be mostly the result of fractures in brittle specimens, although there must have been some decrease of the hardness number due to impact of the unguarded indenter in the old form of the instrument. The tests of a fluorite specimen (Table 2) before and after rebuilding show essentially no change in hardness number due to this modification to the instrument.
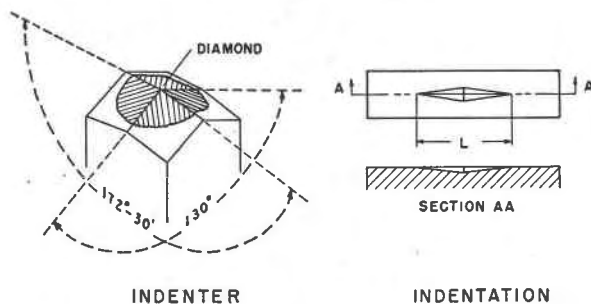

Fɪɢ. 2. Knoop indenter, showing angles between the edges of the flat pyramidal diamond point. Approximate ratios are: length:width = 7.1:1, and length:depth = 30:1.

The Knoop indenter possesses certain advantages over other similar hardness measuring tools, and these are exactly the advantages that make it suitable for testing minerals. Figure 2 shows the shape of the indenter. An extremely shallow penetration is sufficient to produce an indentation long enough to be measured with a relative accuracy of about 1%. Thus, for an indentation 100 microns (0.1 mm.) long, the penetration is only about 3 microns. The smallness of the penetrtaion was demonstrated by Peters and Knoop (1940) when they showed that a valid reading of the hardness of electrolytic chromium plate can be obtained, regardless of the nature of the base metal upon which the chromium was deposited, if the thickness of the plating is greater than 0.001 inch or 25 microns. The validity of extending this conclusion to cover small grains in a polished section of a mineral assemblage is not debated here, but does not seem unreasonable for roughly equant grains which appear about 100 microns in diameter in the plane of the section, especially if several such grains are tested and found to give consistent results. By reducing the load applied to the indenter, the length of the indentation can always be kept small.

Calculations

The conversion of the measured length of the indentation and the load on the indenter to the hardness number is made by means of the following formula, which may be expressed by a family of parallel straight lines on logarithmic graph paper:

$$I = W/L^2 c$$

I = Knoop hardness number.

W = Load applied to the indenter, in kilograms.

L = Length of the indentation, originally defined as in centimeters; but L may be measured in any length units desired and the conversion factor to centimeters may be included in c.

c = a constant depending upon the shape of the indenter. It may also include conversion factors depending upon the units actually used to measure W and L.

As stated above, the equation may be expressed by straight lines, one for each applicable load, on logarithmic graph paper. The scale of the graph may be made such that there will be no danger of introducing errors that are larger than probable errors inherent in the measurement of the indentation by optical methods.

The form of the above equation shows that to achieve a given relative or percentage accuracy in I, L must be measured with a maximum relative or percentage error one-half as great. For example, if L is measured with an error of 1 part in 100, the resulting error in I would be 2 parts in 100.

Reliability

To evaluate the accuracy or consistency of the Tukon tester in the laboratories of the Hamilton Watch Company, for mineral testing purposes, several specimens were tested many times each. The results will be found summarized and expressed as probable error[3] in Table 2. It was found that most hardness readings will be repeated within about 2 to 5 per cent of the average, when many indentations are made in the same orientation on the same crystal surface. The probable error of an observation or of the average of several observations is appreciably increased if any of the observations are made on indentations associated with cracks or other fractures. In accordance with logical arguments that the highest reading will be obtained with the least fracturing, it was concluded that the *maximum* of a series of readings should be selected if fractures appear with any of them; but the *average* should be considered the best value if no fractures occurred. According to that convention, the best value is indicated in Table 2 in **boldface.**

[3] If n observations of a quantity are represented by $x_1, x_2, \cdots, x_n$, and their mean by $\bar{x}$, and their respective deviations from $\bar{x}$ by d_i, then the probable error of any individual observation is $0.6745 \sqrt{\Sigma d_i^2/(n-1)}$ and the probable error of the mean is $0.6745 \sqrt{\Sigma d_i^2/n(n-1)}$.

A note of caution must be included here regarding these measures of accuracy. The "probable error" shown in Table 2 and defined above is really a measure of the self-consistency of the given set of observations. It takes no account of possible systematic errors such as the dependence of the hardness number upon the load on the indenter (Tate, 1944), or imperfectly shaped or polished indenters. "Probable errors" also do not include errors due to faulty specimen preparation (polishing, levelling, etc.) or improper adjustment of the Tukon testing machine. Our efforts were mainly to control such variables by holding them constant. We have made no attempt to determine the importance of such factors for this study. Another still undetermined source of possible error is the crystallographic orientation of the diamond indenter. So far as is known, the makers of the indenters do not attempt to hold this constant. This factor would undoubtedly be negligible for soft and medium specimens but in testing materials of great hardness, the elastic properties and hardness of the diamond itself would be of the same order of magnitude as those of the specimen, and should therefore be considered. It is our impression that such properties would vary appreciably with the orientation of the diamond.

For all these reasons, then, the reader is cautioned not to accept uncritically the fourth, nor even the third significant figures of the hardness numbers quoted in Table 2. The probable error alone (2% to 5%) would generally indicate that the fourth digit can have little significance. Nevertheless, until full information on validity of results is available from all sources, it seems best not to round off the numbers farther than to the nearest 5 units in the fourth significant figure. This consideration probably would not affect results for soft materials, but might noticeably affect those reported for materials of greater hardness than 1000.

Specification of Orientation

To correlate hardness numbers with orientation of the test surface and of the long axis of the indenter in that surface, three independent coordinate angles are necessary. These angles may be compared with longitude, colatitude, and azimuth or bearing on the surface of the earth. The two-circle goniometer studies of Goldschmidt, Palache, and others (Dana-Palache et al. 1944, pp. 3–37) form the basis for the definition of the orientation coordinates of the surface tested:

> "longitude" = phi (ϕ)
> "colatitude" or polar distance = rho (ρ).

The azimuth or bearing, designated theta (θ), is measured clockwise from the north or meridian direction to the long axis of the indenter. Figure 3 shows these angles in stereographic projection. Phi (ϕ) is measured
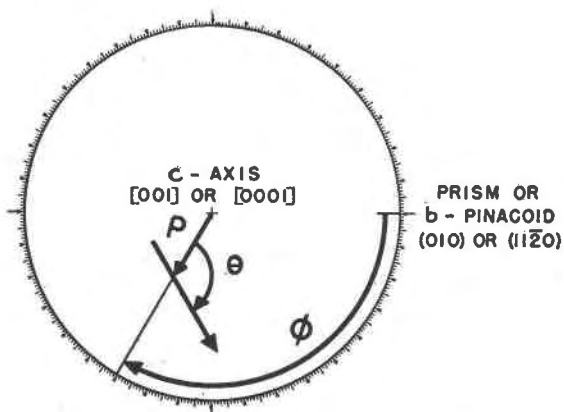
FIG. 3. Stereographic projection illustrating the definitions of ϕ, ρ, θ, the angular co-ordinates of the test surface and of the long axis of the indentation therein, taken with respect to conventional crystal axes of any system. For the orientation $\rho = 0°$, ϕ is indeterminate and θ is specially defined as the direction-angle, measured around the fundamental circle normally used for ϕ.

clockwise about the fundamental circle of the projection from the point representing the plane (010) or (11$\bar{2}$0). Rho (ρ) is the polar angle, measured radially outward from the center of the projection (the point representing the axis of the prism zone). And theta (θ) is measured clockwise about the point representing the test plane. These definitions serve for all points except the pole of the sphere ($\rho = 0°$). At this point, θ must be defined specially, as the direction-angle measured like ϕ around the fundamental circle.

It will be evident that these definitions permit choosing the following ranges for the three coordinate angles:

$$-180° < \phi \leqq 180°$$
$$0° \leqq \rho \leqq 180°$$
$$0° \leqq \theta < 360°$$

However, ϕ and ρ may be limited to smaller values by taking into consideration the symmetry of the applicable crystal class, as shown in Table 1. Also θ may be limited to smaller values by the twofold symmetry axis of the indenter itself, and also to special values if the test plane is normal to certain symmetry planes or to an axis of higher symmetry in the crystal. In general, $0° \leqq \theta < 180°$, because of the symmetry of the indenter only.

Graphical calculations leading to the expression of the coordinates are not difficult for most crystals. They are most easily carried out by means of gnomonic or stereographic projections based upon Laue back-reflection

TABLE 1. LIMITS OF VARIATION OF ϕ AND ρ RESULTING FROM CRYSTAL SYMMETRY

Symmetry Class				ϕ		ρ	
Symbol			Name	From	To	From	To
Isometric System							
4/m	$\bar{3}$	2/m	Normal	0	45	0	55
4	3	2	Plagiohedral	0	90	0	55
$\bar{4}$	3	m	Tetrahedral	0	45	0	55
2/m	$\bar{3}$		Pyritohedral	0	90	0	55
2	3		Tetartohedral	-90	90	0	55
Hexagonal System							
6/m	2/m	2/m	Normal	0	30	0	90
6	2	2	Trapezohedral	0	60	0	90
6	m	m	Hemimorphic	0	30	0	180
$\bar{6}$	m	2	Trigonal	-30	30	0	90
6/m			Tripyramidal	0	60	0	90
6			Pyramidal-Hemimorphic	0	60	0	180
$\bar{6}$			Trigonal-Tetartohedral	-60	60	0	90
$\bar{3}$	2/m		Rhombohedral	-30	30	0	90
3	2		Trapezohedral	0	60	0	90
3	m		Rhombohedral-Hemimorphic	-30	30	0	180
$\bar{3}$			Tri-Rhombohedral	-60	60	0	90
3			Trigonal-Tetartohedral-Hemimorphic	-60	60	0	180
Tetragonal System							
4/m	2/m	2/m	Normal	0	45	0	90
4	2	2	Trapezohedral	-45	45	0	90
4	m	m	Hemimorphic	0	45	0	180
$\bar{4}$	2	m	Sphenoidal	-45	45	0	90
4/m			Tripyramidal	0	90	0	90
$\bar{4}$			Tetartohedral	-90	90	0	90
4			Pyramidal-Hemimorphic	0	90	0	180
Orthorhombic System							
2/m	2/m	2/m	Normal	0	90	0	90
2	2	2	Sphenoidal	-90	90	0	90
2	m	m	Hemimorphic	0	90	0	180
Monoclinic System							
2/m			Normal	-90	90	0	90
2			Hemimorphic	-180	180	0	90
m			Clinohedral	-90	90	0	180
Triclinic System							
$\bar{1}$			Normal	-180	180	0	90
1			Asymmetric	-180	180	0	180

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TABLE 2. KNOOP HARDNESS AS A FUNCTION OF ORIENTATION IN CERTAIN MINERALS

Substance Tested (Tests conducted on polished artificial surfaces unless otherwise noted.)	Orientation: Angular Coordinates (1)			Surface (hkl) or (hkil)	Direction [hkl] or [hkil]	No. Observations	Load (Kilograms)	Hardness			Probable Error (2)	Fractures (2)
	ϕ	ρ	θ					Minimum	Maximum (2)	Average (2)		
Beta Alumina,												
crystal surface	22	2		0001		3	.1	1025	1090	1055	26	x
Argentite						4	.1	24	26	25	1	
Calcite,												
cleavage surface	30	45	0	$10\bar{1}1$	$\bar{1}012$	5	.1	111	122	116		x
same surface			38	$10\bar{1}1$	$01\bar{1}1$	5	.1	84	118	99		x
same surface			90	$10\bar{1}1$	$\bar{1}2\bar{1}0$	5	.1	64	85	75		x
Corundum, synthetic												
Colorless block	27	89	0	$10\bar{1}0$	0001	3	.1	2065	2135	2110	16	
same surface			47	$10\bar{1}0$		3	.1	2135	2210	2185	17	
same surface			90	$10\bar{1}0$	$\bar{1}2\bar{1}0$	3	.1	2100	2175	2135	25	x
same surface			130	$10\bar{1}0$		3	.1	1900	1960	1940	14	
Colorless block	8	89	47	$11\bar{2}0$		3	.1	2065	2135	2100	25	x
same surface			90	$11\bar{2}0$	$\bar{1}100$	3	.1	1995	2065	2030	23	x
same surface			133	$11\bar{2}0$		3	.1	2175	2335	2240	23	
same surface			179	$11\bar{2}0$	0001	2	.1	1900	2030	1965	44	
Colorless block	—	2	0	0001	$11\bar{2}0$	3	.1	1960	1995	1985	13	x
same surface			30	0001	$10\bar{1}0$	3	.1	1725	1930	1850	75	x
same surface (3)			var	0001	var	31	.1	1865	2210	2050	49	x
selected indentations (4)			var	0001	var	18	.1	1960	2210	2075	11	
selected indentations (5)			var	0001	var	13	.1	1865	2100	2015	53	x
Light ruby block	27	88	0	$10\bar{1}0$	0001	3	.1	2065	2135	2085	16	
same surface			47	$10\bar{1}0$		3	.1	2135	2210	2175	15	
same surface			90	$10\bar{1}0$	$\bar{1}2\bar{1}0$	3	.1	1960	2100	2040	28	
same surface			130	$10\bar{1}0$		3	.1	2250	2420	2310	36	
Light ruby block	−1	88	0	$11\bar{2}0$	0001	3	.1	2065	2250	2175	39	
same surface			36	$11\bar{2}0$		3	.1	1900	2065	1985	32	
same surface			92	$11\bar{2}0$	$\bar{1}100$	3	.1	1670	1900	1765	76	x
same surface			144	$11\bar{2}0$		3	.1	1750	1900	1840	30	
Light ruby block	8	5	26	0001	$10\bar{1}0$	3	.1	1835	2065	1935	45	
same surface			112	0001	$\bar{1}2\bar{1}0$	3	.1	1810	1960	1900	31	
Light ruby slab	14	4	35	0001		5	.3	1510	1630	1560		x
same surface			80	0001	$1\bar{1}00$	5	.3	1355	1535	1435		x
same surface			128	0001		5	.3	1365	1535	1420		x
same surface			171	0001	$\bar{1}\bar{1}20$	5	.3	1265	1425	1350		x
Light ruby slab	−20	46	42			5	.3	1645	1720	1690		x
same surface			83			5	.3	1525	1720	1640		x
same surface			133			5	.3	1815	1870	1850		
same surface			179			5	.3	1765	1800	1785		
Light ruby slab	14	53	43			5	.3	1645	1815	1770		x
same surface			88			5	.3	1600	1705	1650		x
same surface			142			5	.3	1765	1850	1800		
same surface			175			5	.3	1785	1850	1830		
Light ruby slab (6)	−28	58	var			81	.3	1160	1905	1725	79	x
same surface			2			28	.3	1615	1785	1705	5	
same surface			40			23	.3	1765	1905	1850	28	x
same surface			95			12	.3	1470	1765	1660	77	x
same surface			129			9	.3	1160	1720	1570	115	x
Light ruby rod	28	63	63			4	.1	1780	1835	1815		x
same surface			154			4	.1	2100	2210	2145		

Table 2. Knoop Hardness as a Function of Orientation in Certain Minerals—*Cont.*

Substance Tested (Tests conducted on polished artificial surfaces unless otherwise noted.)	Orientation					No. Observations	Load (kilograms)	Hardness			Probable Error (2)	Fractures (2)
	Angular Coordinates (1)			Surface (hkl) or (hkil)	Direction [hkl] or [hkil]			Minimum	Maximum (2)	Average (2)		
	φ	ρ	θ									
Light ruby rod	28	75	69			4	.1	1900	1960	1930		x
same surface			159			4	.1	1995	2065	2030		
Light ruby rod	−24	53	42			4	.1	1995	2100	2045		
same surface			129			4	.1	2030	2100	2055		x
Dark ruby slab	0	66	45			5	.3	1675	1850	1755		x
same surface			86			5	.3	1660	1750	1725		x
same surface			130			5	.3	1940	1975	1955		
same surface			178			5	.3	1735	1815	1780		
Fluorite	42	53	0	111	1̄1̄2	3	.1	137	141	139	1	
repeat run (10)						8	.1	142	155	148	1	
same surface			30	111	1̄01	3	.1	143	157	152	4	
repeat run (10)						8	.1	144	158	155	1	
Galena (7)		1	0	001	010	4	.1	66	79	71	4	?
same surface			45	001	110	4	.1	62	74	67	4	?
Galena (7)	45	53	0	111	1̄1̄2	5	.1	53	69	60	4	?
same surface			30	111	1̄01	5	.1	55	65	59	3	?
Glass												
Micro slide						7	.1	438	507	478		
Cover glass						5	.1	482	494	489		
High-alumina glass for jewel bearings												
Fire polished							.5	542	553	548		
Mechanically polished							.5	546	557	551		
Gypsum,												
cleavage surface	0	90	0	010	001		.1		(8)			x
same surface			81	010	100	3	.1	43	46	44	2	x
same surface			115	010	1̄01̄	3	.1	33	54	40	10	x
Kyanite	40	5	36	001	100	5	.1	1175	1255	1205		x
same surface			126	001	010	6	.1	165	205	184		x
Kyanite	12	91	0	010	001	6	.1	1035	1420	1260		x
same surface			90	010	100	6	.1	1645	1695	1665		x
Kyanite	70	90	0	100	001	5	.1	933	1325	1120		x
same surface			90	100	010	5	.1	360	520	462		x
Magnetite	10	25	(?)			4	.1	735	782	761	8	
Magnetite	45	35	(?)			4	.1	611	623	618	2	
Quartz, crystal face	30	52	0	101̄1	1̄012	3	.1	640	685	666	11	
same surface			48	101̄1	01̄11	3	.1	728	766	748	9	
same surface			90	101̄1	1̄21̄0	3	.1	628	653	640	8	x
Quartz, crystal face	−30	52	0	011̄1	01̄12	3	.1	679	720	699	14	x
same surface			43	011̄1	1̄011	3	.1	728	766	748	9	
same surface			90	011̄1	21̄1̄0	3	.1	665	685	674	5	
Quartz, crystal face	30	90	2	101̄0	0001	3	.1	872	922	902	10	
same surface			50	101̄0	2̄423	3	.1	808	816	811	2	
same surface			87	101̄0	1̄21̄0	3	.1	774	834	797	22	x
Silicon carbide (9)												
Black, crystal face (9)		0	0	0001	112̄0	10	.1	2760	3220	3010	60	
same surface			15	0001		10	.1	2620	3000	2855	60	
same surface			30	0001	101̄0	10	.1	2800	3225	3010	60	
same surface, average		0		0001	var	30	.1	2620	3225	2960		

TABLE 2. KNOOP HARDNESS AS A FUNCTION OF ORIENTATION IN CERTAIN MINERALS—*Cont.*

Substance Tested (Tests conducted on polished artificial surfaces unless otherwise noted.)	Orientation					No. Observations	Load (Kilograms)	Hardness			Probable Error (2)	Fractures (2)
	Angular Coordinates (1)			Surface (hkil) or (hkil)	Direction [hkl] or [hkil]			Minimum	Maximum (2)	Average (2)		
	ϕ	ρ	θ									
Green, crystal face (9)		0	0	0001	11$\bar{2}$0	10	.1	2650	2800	**2740**	60	
same surface			15	0001		10	.1	2430	2920	**2675**	60	
same surface			30	0001	10$\bar{1}$0	10	.1	2690	3000	**2830**	60	
same surface, average		0		0001	var	30	.1	2430	3000	2740		
Sphalerite	6	42	(?)			3	.1	175	180	177	2	
Spinel, synthetic blue	40	30	63			3	.3	1200	1235	1225	15	x
same surface			123			3	.3	1105	1165	1135	20	x
same surface			177			3	.3	1080	1115	1100	11	x
Topaz, cleavage surface		0	0	001	010	5	.1	846	1040	960		x
same surface			45	001		5	.1	889	1160	1060		x
same surface			90	001	100	5	.1	769	985	894		x
same surface			−45	001		5	.1	1160	1230	1215		x

NOTES TO TABLE 2

(1) Angular coordinates are as defined in Fig. 3 and as measured by means of *x*-ray diffraction patterns.
(2) In the column headed *Fractures* is indicated the presence of small fractures observed about the marks of the indenter. If fractures were present, the *maximum* hardness reading of a series is considered the best, and is so indicated by **boldface** numerals, but if no fractures were observed, the *average* is considered the best value obtainable from the series, and is so indicated by the same means. The *probable errors* were calculated for the maximum or for the average, whichever is considered best value.
(3) Indentations in 31 different directions.
(4) Selected indentations with no fractures.
(5) Selected indentations with minor fractures.
(6) Combined results from the following four items.
(7) No fractures visible, but fractures probable on account of the excellent cleavage.
(8) Large fractures; measurements impossible at lightest available loads (.1 Kg).
(9) Probable errors for silicon carbide observations are approximate.
(10) Original measurements August, 1942. Repeated January, 1945, because of question raised by comparison with published results (Table 3), and to observe effect of addition of magnetic device for preventing indenter-overload due to impact.

x-ray patterns made with the test plane parallel with the *x*-ray film and normal to the *x*-ray beam. The position of the long axis of the indentation must be noted with respect to the top or other mark on the *x*-ray film at the time of setting up for the diffraction pattern; otherwise θ may be lost. In hexagonal and tetragonal crystals, the extinction angle may be measured by polarized light to determine θ, provided the specimen is transparent and in a suitable mounting.

RESULTS OF TESTS

Table 2 contains the collected results of mineral hardness determinations made at the Hamilton Watch Company laboratories over a period of approximately 3 years. Bearing in mind the rather academic importance of most of these results, the reader will understand why more ex-

tensive tests cannot easily be made here. This list does include a wide enough variety of minerals and mineral-like materials to indicate very promising possibilities for application of the Knoop indenter to determinative mineralogy and to crystallography. Several type-minerals in Mohs' scale, and some in the scale of hardness of Talmage (1925), are included in Table 2. It should be emphasized that determinations from fractured indentations marked "x" were of a reduced order of accuracy because of the fractures. Such determinations should not be considered final nor necessarily even approximately accurate; they are the best we have available, however, and it will be noted that even in spite of the uncertainty introduced by the presence of fractures, the fractures themselves appear to have been fairly consistent for any given orientation, and the readings therefore were fairly constant. Analysis of the table will show that the largest probable error for a good determination is less than 5% of the hardness number.

It is especially to be noted that most of the substances tested in several orientations showed *considerable variations of hardness with orientation*. The well-known variation of scratch-hardness with scratch direction on the macropinacoid of kyanite is reflected by variations obtained by indenting that surface with the indenter either parallel to, or at right angles to the direction of the c-axis. If we consider the direction of scratching and the azimuth of the indenter for the highest hardness value observed on the surface tested, we note a discrepancy as follows:

Azimuth (θ) for maximum hardness in kyanite

Test Surface	Method of Test	
	Indenter	Scratch
(001)	about 36°	same
(100)	0°	90°

No explanation of this apparent anomaly can be offered here. It may be due to the excellent cleavage of the mineral, and it may be due in part to the fractures that were produced in the material by the indenter.

COMPARISON WITH RESULTS OF OTHERS

So far, only a few investigators have reported any findings regarding the applicability of the Knoop microhardness tester to mineral specimens. Knoop, Peters, and Emerson (1939), and Peters and Knoop (1940) published a few mineral hardness tests in their early descriptions of the instrument. Table 3 shows the mineral hardness values quoted by them,

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TABLE 3. COMPARISON OF KNOOP MICROHARDNESS NUMBERS

Mineral	Knoop et al. (1939)	Peters et al. (1940)	Winchell (1945)
Gypsum	32	32	46–54*
Calcite	135	135	75–120*
Fluorite	163		139–152*
Apatite	360–493*		
Albite	490		
Orthoclase	560		
Quartz	710–790*	710–790*	666–902*
Topaz	1250		1040†
Alundum	1635	1620–1635	
Synthetic corundum			1700–2200*
Black SiC		2050–2150	2850–3000
Green SiC		2130–2140	2675–2825
Diamond	8000–8500	8000–8500	

* Variation due at least in part to orientation of different test surfaces and/or different positions of indenter therein.

† Topaz determinations at Hamilton probably low on account of fractures.

together with results obtained here. Our results (Table 2) suggest that the ranges indicated are real, and may be due to the variations of hardness with crystallographic orientation: since they do not represent a complete exploration of all orientations, it is likely that they should be even wider than indicated. Differences between our results and those of the Bureau of Standards appear to be real, possibly instrumental differences, but they are probably due in part to orientation differences. Some differences may be due also to the use of indentations with small fractures.

otherwise could easily have been misunderstood. Statements of fact or opinion, however, are the writer's, and do not necessarily reflect Dr. Thibault's views.

Conclusion

The Knoop microhardness tester, embodied in the Tukon testing machine, is a new mineralogical tool which appears to deserve further investigation. This tool is apparently capable of detecting and measuring variations in hardness on different crystal faces of corundum, magnetite, calcite, and other materials. It shows some unexplained anomalies when applied to kyanite, which is a mineral noted for its hardness variations. Kyanite shows hardnesses ranging from 205 to 1700, depending upon the orientation of the test surface, and of the long axis of the Knoop indenter in that surface. The Knoop hardness of gypsum is approximately 32 to 45 or more, depending upon orientation; that of calcite is 75 to 135; that of fluorite, 140 to 150; of orthoclase, 560; of quartz, 666 to 900; of topaz, 1250; of corundum, 1700 to 2200; and of diamond, about 8000. The instrument reproduces its own results within an accuracy of 2% to 5%, depending upon the hardness and brittleness of the specimen, and such accuracy can be achieved in testing grains only 100 microns in diameter in polished sections.

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