OBSERVATION ON ORDER-DISORDER RELATIONS OF NATURAL PLAGIOCLASE

I. A method of evaluating order-disorder

By

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Introduction

The mineralogical and petrographic work of Barth, Kano, Köhler, Muir, J. R. Smith, J. V. Smith, Tertsch, van der Kaaden and others have clearly demonstrated that there are optical differences between the structurally ordered types of plagioclase ("low-temperature", or plutonic and metamorphic), disordered types ("high-temperature", or volcanic and synthetic), and intermediate types (intermediate, "transitional", or hypabyssal). These optical differences include changes in optical orientation, which are well expressed for certain twin laws, and differences in the optic angle, $2V$. These relationships can be measured quickly and easily with the universal stage, a tool available to most petrographers and mineralogists. The chief disadvantage of these methods is the lack of sensitivity of the twin-axis method for bytownite and anorthite and for certain twin laws, and the lack of sensitivity of the optic angle, 2V, in plagioclases more calcic than An_{40}.

The structural studies of such crystallographers, mineralogists, and experimentalists as Davis, Donnay and Donnay, Gay, Laves, MacKenzie, J. R. Smith, J. V. Smith, Taylor, Tuttle, and Yoder have demonstrated that these optical variations are caused by basic structural differences related particularly to degree of ordering in the lattice structures. These structural differences can be demonstrated by X-ray single-crystal and powder methods. Such X-ray diffraction methods as those of Smith and Yoder (1956) are convenient and rapid for petrographic applications. The data of Smith and Yoder, summarized in Table 1, make it possible to determine the structural state by use of two pairs of reflection separations, $2\theta(131)-2\theta(1\bar{3}1)$, provided the composition of the plagioclase is known. The latter can be readily and accurately determined by a variety of universal stage or index of refraction methods.

Correlation between the optic angle measurements of J. R. Smith (1958) and the X-ray reflection measurements of Smith and Yoder (1956) indicate that there is an excellent agreement between the structural analysis based on optical data ($2V$) and that based on X-ray diffraction data. Moreover, the writer was kindly provided access to the specimens by Smith and Yoder, and his new twin axis measurements on some of the same specimens demonstrated that optical orientation also provides a structural picture that is consistent with that from the other three methods. The quality of such agreement, although seemingly good, is not easy to assess objectively without some quantitative measure which can be independently applied to all four methods, and which can yield numerical data that can be statistically analyzed.

The following method of measurement of order-disorder is proposed to give what is herein called the *ordering index*, O.I. or *intermediacy index*, I.I. For each method of evaluating order-disorder in plagioclase of a given composition, the most disordered form is assigned an index of 0, the most ordered form is assigned an index of 100, and all intermediate types are assigned intermediate indices according to their positions relative to the 0 and 100 values. The index is, therefore, a number, varying from 0 for extremely disordered types to 100 for thoroughly ordered types, which indicates the relative position of any given measurement of physical or structural property that is sensitive to order-disorder. The term "index" is used in preference to percentage, since it has not been established that these measures of ordering vary linearly with the amount of ordering in the lattice or even what the exact nature of ordering is for all varieties of plagioclase. Megaw (1959) has shown that it is possible to have several types of ordering, and the method here apllied do not recognize which ordering type, or combination of types are actually present in a plagioclase. Therefore, the descriptive term *intermediacy index* (I.I.) may be preferred to denote the relative position of plotted points rather than the genetic term "ordering index".

Measurement of the intermediacy index

X-ray diffraction methods

J. R. Smith and Yoder (1956) and J. R. Smith (1958) tabulated data on the 2θ reflection differences for two pairs of strong peaks that are sensitive to structural changes. The most disordered forms which can exist metastably at room temperature are probably those of Smith and Yoder's specimens which are synthesized in the dry way at temperatures near the melting point and which were then quenched quickly to room temperature. Therefore, the extreme disorder curves for the $2\theta(131)$–$2\theta(1\bar{3}1)$ and $2\theta(1\bar{3}1)$–$2\theta(220)$ of these samples (Figures 1 and 2) are assigned an index of 0.

Smith and Yoder also give the reflection differences for a larger number of natural and synthetic, analyzed plagioclases. Although there is no assurance that their samples include the most completely ordered plagioclases for all ranges of composition, it will be assumed that the most-ordered samples, at wide intervals of composition, are representative. Accordingly, the following samples were used to establish the $2\theta(131)$–$2\theta(1\bar{3}1)$ curve (Figure 1) for the most thoroughly ordered types, the O.I. 100 curve: $An_{0.2}$(D–761–1), $An_{15.9}$(4–156), $An_{28.7}$(KN11), $An_{51.9}$(KN6), $An_{88.7}$(HGIF–An–53). Nine curves were plotted at even spacing between the two extreme curves and each of these assumed to represent a change in index of 10 units.

The $2\theta(1\bar{3}1)$–$2\theta(220)$ curves for the most thoroughly ordered types (Figure 2) used $An_{15.9}$(4–156), $An_{51.9}$(KN 6), $An_{58.3}$(14–167), $An_{69.2}$(20–22), $An_{88.7}$(HGIF–An–53). Nine evenly spaced intermediate curves were plotted between the extreme curves and each of them assumed to represent a change in index of 10 units.

Al specimen data used for the curves in this report are tabulated in Table 1.

Optical Methods

The most satisfactory optical method for indicating the degree of ordering in the composition range An0–40 is the optic angle, $2V$. For higher anorthite percentages, the difference in $2V$ between ordered

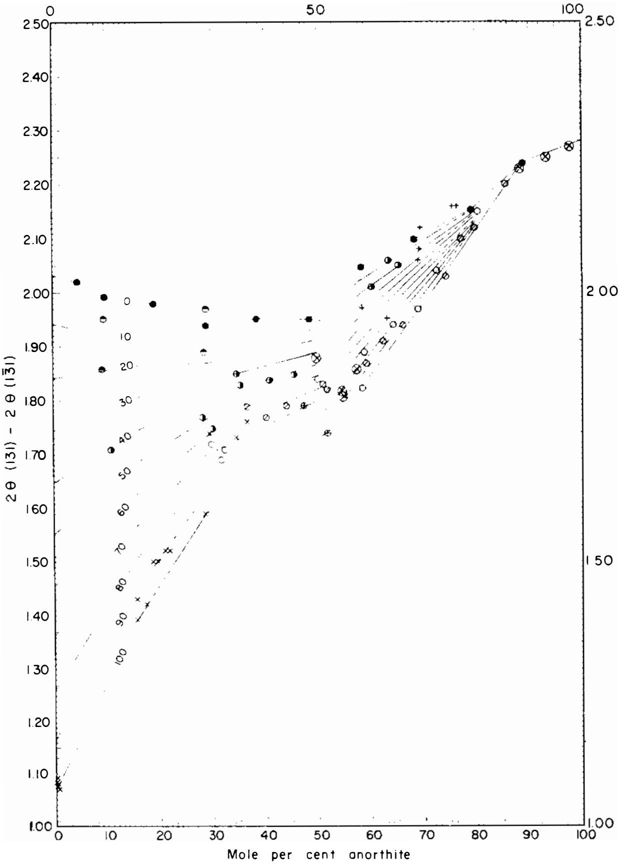

Figure 1. Intermediacy indices for $2\theta(131)$–$2\theta(1\bar{3}1)$ versus plagioclase composition in molecular percent anorthite. Plagioclases of J. R. Smith and H. S. Yoder, JR. (1956) are plotted with the following symbols:

× from pegmatites and granites
⊗ from metamorphic rocks
◐ from volcanic rocks
\+ from anorthositic masses near the tops of gabbroic sills, northern Minnesota
⊕ from Adirondack-type anorthosite massifs
○ from miscellaneous rocks, details of occurrence not known
● Synthesized the dry way
◒ synthesized hydrothermally from glass or crystalline material
⊘ from Bushveld-type rocks

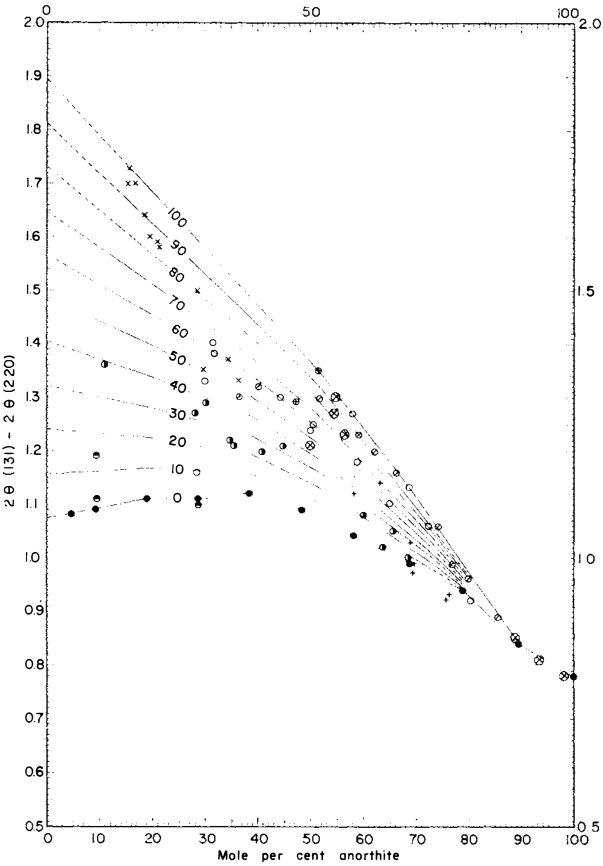

Figure 2. Intermediacy indices for $2\theta(131)$–$2\theta(220)$ versus plagioclase composition in molecular percent anorthite. Plagioclases of J. R. Smith and H. S. Yoder (1956) are plotted. Symbols are the same as in Figure 1.

and disordered types is small and the method less satisfactory. The carefully measured $2V$'s of Smith (1958) and Smith in the appendix to Hess (1960) were used with those of Emmons (1953) to establish the curves for the extreme disordered types and the ordered forms. J. R. Smith's "low temperature" curves were smoothed somewhat in the range An_{15-30} to be consistent with the X-ray data. The "high temperature" curves are based on measurements on heat-treated natural plagioclases, which are known from X-ray diffraction measurements to have extreme disordered structures (Smith (1958)). The $2V$ curve

Table 1. List of Samples, Data, and Intermediacy Indices (I.I.).

Sample no.	An %	Occurrence and locality of specimen	$2\theta(131)-2\theta(1\bar{3}1)$		$2\theta(1\bar{3}1)-2\theta(220)$		$2V_x$		Orient I.I.	Weighted Avg. I.I.
			Angle	I.I.	Angle	I.I.	Angle	I.I.		
		Plagioclases Synthesized in the Dry Way:								
05	4.7	Plagio. synthesized in the dry way	2.02*	0	1.08*	0	—	—	—	0
1	9.5	– – – – – –	1.99*	0	1.09*	0	—	—	—	0
2	19.0	– – – – – –	1.98*	0	1.11*	0	—	—	—	0
3	28.8	– – – – – –	1.94*	0	1.11*	0	—	—	—	0
4	38.6	– – – – – –	1.95*	0	1.12*	0	—	—	—	0
5	48.5	– – – – – –	1.95*	0	1.09*	0	—	—	—	0
6	58.6	– – – – – –	2.05*	0	1.04*	0	—	—	—	0
7	68.8	– – – – – –	2.10*	0	0.99*	0	—	—	—	0
8	79.0	– – – – – –	2.15*	0	0.94*	0	—	—	—	0
9	89.5	– – – – – –	2.24*	0	0.84*	0	—	—	—	0
10	100.0	– – – – – –	2.28*	0	0.78*	0	—	—	—	0
		Plagio. Synthesized Hydrothermally:								
S2–1	9.5	Plagio. Synthesized Hydrothermally (glass)	1.86	18	1.19	15	—	—	—	17 –
S2–2	9.5	Plagio. Synthesized Hydrothermally (dry synth. *X*ls)	1.95	6	1.11	3	—	—	—	5 –
S2–3	28.8	Plagio. Synthesized Hydrothermally (glass)	1.89	14	1.16	10	—	—	—	12
S2–4	28.8	Plagio. Synthesized Hydrothermally (dry synth. *X*ls)	1.97	0	1.10	0	—	—	—	0
		Plagioclase of the Bushveld Type:								
4145	36.5	Ferrogabbro Skaergaard, East Greenland	1.78	52	1.30	47	89.6	55	55	50
2580	40.2	Ferrogabbro Skaergaard, East Greenland	1.77	64	1.32	58	97.5	85	—	62

1963	44.2	Ferrogabbro Skaergaard, East Greenland	1.79	62	1.30	61	99.4	70	90	63
GD29	51.8	Dolerite, Great Dyke, S. Rhodesia	1.82	67	1.28	81	103.6	—	85	76
BV63	59.2	Gabbro, Bushveld, South Africa	1.87	84	1.23	92	100.5*	88	—	88
EB41	62.5	Gabbro, Stillwater, Montana	1.91	85	1.20	95	97.9*	90	—	90
EB42	66.2	– – –	1.94	81	1.16	100	95.5*	91	100	91
EB43	74.3	– – –	2.03	100	1.06	100	89.4*	91	100	100
26–109	77.0	Norite, Bushveld, South Africa	2.10	60	0.99	60	84.6	100+	—	70
EB38	80.0	Norite, Stillwater, Montana	2.12	(90)	0.96	(80)	85.0*	(90)	100	(90)
EB18	85.8	– – –	2.20	(80)	0.89	(85)	80.6	(90)	—	(85)
		Plagioclase from Pegmatites and Granites:								
1–87	0.1	Pegmatite, Peerless Mine, Keystone, S.D.	1.08	99	—	—	106	100	100	100–
D–761–1	0.2	Pegmatite, Ramona, California	1.08*	100	—	—	102.8*	100	100+	100
D–761–2	0.4	Pegmatite, Pala, California	1.08*	100	—	—	—	—	—	100
D–761–3	0.4	Pegmatite, Amelia, Virginia	1.09	98	—	—	—	—	—	98
KN–13	0.6	Pegmatite, Varutrask, Sweden	1.07	100	—	—	—	—	—	100
2–10	11.0	Granite, Peekskill, New York	—	—	—	—	94.8	100	—	100
3–73	15.4	Granite, Parishville, New York	1.43	93	1.70	95	90.0	94	—	94
4–156	15.9	Granite, Petrick Quarry, Llano Co., Texas	1.39*	100	1.73*	100	91.6*	100	—	100
KN8	16.8	Pegmatite, South Carolina	1.42	98	1.70	98	90.8	100	—	99–
5–94	18.7	Granite, Tigerton, Wisconsin	1.50	88	1.64	92	86.8	91	—	90
D–761–4	19.5	Pegmatite, Hawk Mine, Bakersville, North Carolina	1.50	90	1.60	86	—	—	—	88
KN 9	21.1	Pegmatite, Hawk Mine, Bakersville, North Carolina	1.52	90	1.59	87	—	—	—	89–
KN 10	21.6	Pegmatite, Hawk Mine, Bakersville, North Carolina	1.52	92	1.58	86	86.5*	(89)	—	89
KN 11	28.7	Pegmatite, Little Rock Creek, Mitchell Co., North Carolina	1.59*	100	1.50	82	89.7*	(91)	—	91

Table 1. (*Continued*).

Sample no.	An %	Occurrence and locality of specimen	$2\theta(131)-2\theta(1\bar{3}1)$		$2\theta(1\bar{3}1)-2\theta(220)$		$2V_x$		Orient. I.I.	Weighted Avg. I.I.
			Angle	I.I.	Angle	I.I.	Angle	I.I.		
		Plagioclase from Pegmatites and Granites continued:								
D–638	29.8	Pegmatite vein in dunite, Corundum Hill, Macon Co., North Carolina	1.74	58	1.35	51	86.4	73	—	55–
6–152	34.6	Gneissoid Granodiorite, Spanish Peak, California	1.73	68	1.37	61	92	82	—	64
8–144	36.6	Granodiorite, Crestmore, California	1.76	61	1.33	55	89	(45)	—	53
		Plagioclases from Metamorphic Rocks								
C 41	50	Metamorphosed gabbro, Salem District, India	1.88	34	1.21	44	101.8	—	—	39
12–97	54.5	Greenstone recrystallized to anorthositic rock, Eland, Wisconsin	1.82	81	1.27	85	101	(90)	(100+)	85–
13–92	54.9	Greenstone recrystallized to anorthositic rock, Tigerton, Wisconsin	1.81	86	1.30	96	102.1	90	(90+)	91
Howie 2941	56.7	Metamorphosed norite, Salem District, India	1.86	79	1.23	79	—	—	—	79
HGIF An–53	88.7	Vein-like masses in schist, Olricksfjord area, N.W. Greenland	2.23*	(100)	0.85*	(100)	76.3*	(100)	—	(100)
354	93.3	"Hornblende-olivine norite", San Luis Rey Quad., California	2.25	—	0.81	—	78.4	(70)	—	—
C 50	98.0	Metamorphosed anorthosite, Salem District, India	2.27	—	0.78	—	77.7	(0)	—	—
		Plagioclase from Volcanic Rocks:								
Larsen 9	11.1	Phenocrysts from obsidian, No Agua, New Mexico	1.71	41	1.36	39	—	—	—	40

Larsen 8	28.2	Phenocrysts from rhyolite, Uncompahgre Quad., New Mexico	1.77	47	1.27	33	—	—	—	40
Larsen 4	30.2	Phenocrysts from quartz latite, Uncompahgre, Quad., New Mexico	1.75	55	1.29	39	—	—	—	47
7–64	34.8	Dacite, San Luis Obispo Co., Calif.	1.85	30	1.22	28	82	5	—	24
Larsen 7	35.4	Phenocrysts from quartz latite, San Cristobal Quad., New Mexico	1.83	37	1.21	23	—	—	—	30
Larsen 5	41.0	Phenocrysts from latite, Conejos Quad., New Mexico	1.84	40	1.20	26	—	—	—	33
Larsen 3	45.8	Phenocrysts from andesite, Summitville Quad., New Mexico	1.85	41	1.21	35	—	—	—	38
Larsen 2	60.5	Groundmass of basalt, Servilleta Plaga, New Mexico	2.01	22	1.08	23	—	—	—	23 –
KN 7	63.8	Phenocrysts from basalt, Clear Lake, Utah	2.06	7	1.02	2	—	—	—	5 –
Larsen 1	65.5	Groundmass of basalt, Buffalo Butte, New Mexico	2.05	(20)	1.05	26	—	—	—	23
19–51	68.8	Basalt porphyry, Lake Co., Oregon	2.10	(0)	1.00	8	95+	(90)	(60)	22 –
		Plagioclases from Anorthositic Masses near Tops of Gabbroic Sills, Northern Minnesota:								
15–53	58.6	East of Duluth, Minn.	1.97	33	1.12	37	106.4	(0)	(45)	36
17–52	63.2	Grand Marais, Minn.	1.95	67	1.13	70	96.7	(15)	—	70 –
21–51	69.2	Crystal Bay, Minn.	2.06	32	1.03	30	93	(100)	(0)	32
22–54	69.5	Grand Marais, Minn.	2.08	18	0.99	4	93+	(100)	(0)	17
KN 5	69.7	Crystal Bay, Minn.	2.12	(0)	0.97	0	—	—	—	0
24–1B	75.7	Split Rock, Minn.	2.16	(0)	0.92	0	—	—	—	0
25–1A	76.2	Split Rock, Minn.	2.16	(0)	0.93	0	93.3	(20)	—	5
		Plagioclase from Adirondack-type Anorthosite Massifs:								
9–24	47.7	Anorthosite, Essex Co., New York	1.79	67	1.29	67	100.4	(—)	—	67
KN 6	51.9	Anorthosite, Isle of Paul, Labrador	1.74*	100	1.35*	100*	100.8*	100	—	100

Table 1. (*Continued*).

Sample no.	An %	Occurrence and locality of specimen	$2\theta(131)-2\theta(1\bar{3}1)$		$2\theta(1\bar{3}1)-2\theta(220)$		$2V_x$		Orient. I.I.	Weighted Avg. I.I.
			Angle	I.I.	Angle	I.I.	Angle	I.I.		
		Plagioclase from Plutonic and Hypabyssal Rocks, Details of Occurrence Not Known:								
Howie 9–347	30.0	Charnockitic rock, Mt. Wati, Uganda	1.72	65	1.33	47	—	—	—	56
Howie 22770	31.8	Charnockitic rock, Salem Dist., India	1.69	76	1.40	64	—	—	—	70
Howie 6436	32.1	Charnockitic rock, Meanambakam, Madras, India	1.71	71	1.38	60	—	—	—	66 –
10–132	50.2	Hornblende gabbro, Shelby, N.C.	1.84	52	1.24	56	103	(0)	—	49 –
11–151	50.8	Diorite, Fresno Co., Calif.	1.83	58	1.25	60	101.7	(55)	—	59 –
14–167	58.3	Gabbro, Merrill, Wisconsin	1.82	100	1.27*	100	101.5	(70)	—	97
16–132	59.0	Hornblende gabbro, Shelby, N.C.	1.89	72	1.18	68	—	—	—	70
18–132	65.0	Diabase, Chester Co., Penn.	2.01	(42)	1.10	56	96	(75)	—	49
20–22	69.2	Orthoclase quartz gabbro, Wichita Mts., Okla.	1.97	(100)	1.13*	100	—	—	—	100
23–165	72.7	Gabbro, Lincoln Co., Wisconsin	2.04	77	1.06	83	92.4	(70)	—	79
27–166	80.6	Troctolite, Merrill, Wisconsin	2.15	30	0.92	0	85.4	(80)	—	33

Note: The Intermediacy Index is shown in parentheses where it is approximate only. Asterisks denote reference measurements used to establish index curves for 0 and 100. All angles are in degrees.

for "low-temperature", or ordered plagioclases, is based on measurements on 24 chemically analyzed plagioclases. The "high-temperature" curve is assigned on the basis of the X-ray diffraction curves with Intermediacy Indices of 88 for $An_{59.2}$(BV63), 90 for $An_{62.5}$(EB41), 91 for $An_{66.2}$(EB42), 91 for $An_{74.3}$(EB43), 90 for $An_{80.0}$(EB38) and 100 at $An_{88.7}$(HGIF–An–53). Based on these points, curves were drawn for Indices of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 (Figure 3).

The second optical method of determining the ordering index is obtained from the optical orientation. For the purpose of this discussion, the albite twin law was chosen to represent the optical orientation since it is sensitive to structural type, and it is almost universally present in plagioclases. The method is moderately sensitive to structural type from An_0 to An_{35}; divergence between the "high-temperature" and "low-temperature" curves increases from An_{35} to An_{60} and this method is somewhat more useful for this range. For more calcic types than An_{60} the optical differences between ordered and disordered types are more difficult to establish.

The curves of Slemmons (1962) were used to establish the extreme ordered and disordered types (Figure 4). Although many of Smith and Yoder's specimens have been used, along with the usual reference feldspars used by other workers, the curves do not differ markedly

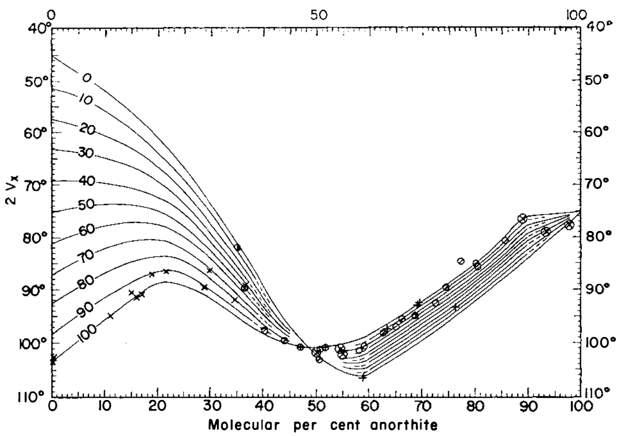

Figure 3. Intermediacy indices for the optic angle ($2V$) versus plagioclase composition in molecular percent anorthite. Plagioclases of Smith and Yoder (1956) are plotted. Symbols are the same as in Figure 1.

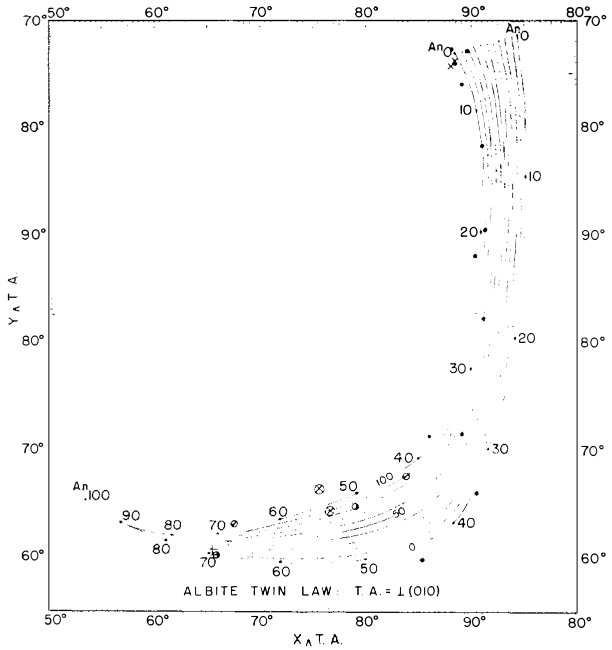

Figure 4. Intermediacy indices for the angles between the X and Y optical directions and the twinning axis as expressed by the albite twin law. Curves are based on Slemmons (1962). Data for the specimens plotted are given in Table 5. Small solid dots denote specimens not used by Smith and Yoder (1956); other symbols are the same as in Figure 1.

from those of Köhler (1942), van der Kaaden (1951), or Burri (1956). The closeness of these curves, relative to their usual accuracy of measurement, make this method less sensitive to structural change than either of the X-ray diffraction methods or the $2V$ method for the An_{0-40} range of composition. It is, however, more useful than the $2V$ method in the composition range AN_{40}–An_{70}. Since a relatively small number of Smith and Yoder's specimens were suited for accurate twin axis measurements, and since Emmons' data for many of these specimens is not published, this method could not be adequately tested with the specimens used to test the other three methods. Accordingly, a number of other reference feldspars have been tabulated with an intermediacy index assigned on the basis of both the $2V_x$ and the orientation.

Discussion of Results

Tables 2, 3, 4, 6, and 7 give the deviations in intermediacy index obtained by each method from the weighted average of the intermediacy indices of all methods. The weighted average of the inter-

Table 2. Deviations in Intermediacy Index for the $2\theta(131)-2\theta(1\bar{3}1)$ Method from the Mean Ordering Weighted Index for All Methods.

Intermediacy Index	Range in Composition (in Mole Percent Anorthite)								
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89
0-24	0* 0* +1 +1	0*	0* 0 +2	0* +6	0*	0*	0* 0 +1 −1 +2 −3 −22	0* 0 −5	(0*)
25-49		+1	+7	+7 +8	+3 +7	−3 +3 −5	0 −7		(−3)
50-74			+3	+2 +4 +5 +6 +8 +9	0 −1 +2	−1 +2	−3	−10	
75-100	0* 0* 0 0 −1	0* −1 −1 −2 +2	+1 +3 +9*			0* 0 +3 −4 −5 −9	0 −5 −10	0* −2	(0) (0*) (−5)
Sum/N	0	0	+3	+6	+2	−2	−4	−4	(−3)

Mean Deviation, $An_{0\text{-}79}$, exclusive of specimens used to define curves (shown by asterick) = ± 4.

Table 3. Deviations in Intermediacy Index for the $2\theta(1\bar{3}1) - 2\theta(220)$ Method from the Mean Weighted Index for All Methods.

Intermediacy Index	Range in Composition (in Mole Percent Anorthite)								
	0-0	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89
0-24	0*	0*	0*	0*	0*	0*	0*	0*	(0*)
	0*		0	+4			0	0	
	−2		−2				0	−5	
	−2						−3		
							+4		
							−13		
							−14		
25-49			−7	−8	−3	+1			(−33)
		−1		−7	−7	+5	−2		
						+7			
							+7		
50-74					0	+1	0		
			−4	+2				−10	
				−3					
				−3	−2	−2			
				−6	−4				
				−6					
				−9					
75-100		0*		+9		0	0*	0	(0)
			−2			0	+5		(0*)
		+1				0*			(−10)
		−1	−3			+3	+9	(+4)	
		−2				+4			
		+2	−9			+5			
						+5			
Sum/N	−2	0	−4	−3	−3	+3	−1	−2	(−14)

Mean Deviation, $An_{0\text{-}79}$, exclusive of specimens used to define curves (shown by asterick) $= \pm 4$.

mediacy index was obtained for each specimen by weighting each intermediacy index according to the relative accuracy of measurement of each method. In general, the weighting was accomplished for each 10 percent anorthite range of composition by making each 0.01° of

Table 4. Deviations in Intermediacy Index for the $2V_x$ Method from the Mean Weighted Index for All Methods.

Intermediacy Index	Range in Composition (in Mole Percent Anorthite)								
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89
0-24				−19			(+48) (+73)	(+15)	
25-49						(−4) (−36) (−49)	(+26) (−68)		(+47)
50-74			+18	+5 +18 −8	(+23) (+7)	(−4)	(−55)	(−30)	
75-100	0* 0	0* 0 0 +1 +1	0* 0*			(0) (−1) (−8) (+5) (−27)	(0*) (−1)	0* (−9)	(0) (0*) (+5)
Sum/N	0	+1	+18	−1	(+15)	(−14)	(+3)	(+11)	(+17)

Mean Deviation, $An_{0\text{-}39}$, exclusive of specimens used to define curves (shown asterick) $= \pm 6$.
Mean Deviation, $An_{40\text{-}79}$, exclusive of specimens used to define curves $= \pm 24$.
Mean Deviation, $An_{80\text{-}89}$, exclusive of specimens used to define curves $= 17$.

2θ equivalent to 1° of $2V$ and 1° in measurement of orientation. In general all methods are sensitive in the range of composition An_{0-40}. In the range, An_{40-79}, the 2θ differences, although still the most effective method, become decreasingly sensitive, the orientation method maintains its effectiveness to about An_{70}, and the $2V$ methods is relatively ineffective.

Table 7 summarizes the maximum deviation noted for each range of composition. The X-ray diffraction methods are most sensitive and accurate for the range An_{0-59}, where the sensitivity decreases from ± 2 at An_0 to about ± 10 at An_{59}. For An_{60-89}, the X-ray methods are less sensitive and the intermediacy indices can be estimated only to the nearest 10. The $2V_x$ method is most sensitive in the range An_{0-19}, where it is sensitive to about ± 1, for the range An_{20-59} the results are

Table 5. Data on Relationship between Intermediacy Index by Orientation of Optical Directions (for Albite Twin Axis) and the Intermediacy Index for Other Methods.

No.	An %	Spec. no. and source of data	Albite twin law			I.I. from orientation	I.I. from other methods	Deviation
			X/TA	Y/TA	$2V_x$			
1	0.15	1(87), Slemmons, unpublished	88.5	73.8	—	100	100	0
1 A	0.2	D–761–1 Slemmons, unpublished	88.3	74.2	—	100	100	0
2	0.4	Nikitin (1933)	89.9 –	73	102	80	100	– 20
3	0.5	Duparc and Reinhard (1924)	89.7	73	103	80	98	– 18
4	1.9	Zavaritsky (1953)	88 –	72.8	102	100	100	0
5	2.7	Zavaritsky (1953)	88.5	74	105	100	100	0
6	6.9	Zavaritsky (1953)	89	76	100.7	100	100	0
7	13	Duparc and Reinhard (1924)	– 89.2	81.8	95 –	100	100	0
8	20	Van der Kaaden (1951)	– 88.8	89.5	86	90	88	+ 2
9	22.2	Zavaritsky (1953)	– 89.8	88	96.5	100	86	+ 14
10	25	Duparc and Reinhard (1924)	– 89	82.2	82	85	65	+ 20
11	35	Duparc and Reinhard (1924)	89	71.5	87	60	45	+ 15
12	35.5	van der Kaaden (1951)	89.5	66	83	0	0	0
13	38.5	Zavaritsky (1953)	86	71.5	97	95	100	– 5
14	44.2	1963—Slemmons, unpublished	83.8 –	67.5	—	90	63	+ 27
15	45.5	van der Kaaden (1951)	85.2	59.8	99	0	(0)	0
16	51.8	GD 29, Slemmons, unpublished	79	64.75	103.6	80	74	+ 6
17	54.5	12(97), Slemmons, unpublished	76.3 –	66.4	—	100	85	+ 15
18	54.9	13(92), Slemmons, unpublished	76.5	64.5	—	95	91	+ 4
19	66.2	EB42, Slemmons, unpublished	67.8 –	63	—	100	91	+ 9
20	68.8	19(41), Slemmons, unpublished	67 –	61.5	—	60	22	+ 38
21	69.2	21(51), Slemmons, unpublished	65.8 –	60		0	22	– 22
22	69.5	22(54), Slemmons, unpublished	65.8 –	60	—	0	17	– 17
23	73	van der Kaaden (1951)	65.5	60.5	85.5	20	40	– 20
24	74.3	EB43, Slemmons, unpublished	63.5	61.8 –	—	100	100	0

Sum of deviation/$n = +2$.

Mean Deviation $\mathrm{An}_{0-79} = 10$.

Table 6. Deviations in Intermediacy Index of Orientation of Optical Direction (for Albite Twin Law) Method from the Weighted Average of the Intermediacy Indices for All Methods.

Intermediacy Index	Range in Composition (in Mole Percent Anorthite)							
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79
0-24				0	0		−17 −22 +38	
25-49				+15				−20
50-74			+17		−27	+6		
75-100	0 0 0 0 −18 −20	0	+2 +14	−5		+4 +15	+9	(0)
Sum/N	−6	0	+12	+3	−14	+8	+2	(−10)

Mean Deviation, $An_{0\text{-}79} = 10$.
Mean Deviation, $An_{20\text{-}79} = 12$.

Table 7. Maximum Deviations by Composition and Method.

Method	Range in Composition (in Mole Percent Anorthite)								
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89
$2\theta(131)$-$2\theta(1\bar{3}1)$	1	2	9	9	7	9	22	10	5
$2\theta(1\bar{3}1)$-$2\theta(\bar{2}20)$	2	2	9	9	7	7	14	10	33
$2V_x$	0	1	18	19	23	49	73	30	47
Orientation	20	0	17	15	27	15	38	20	

sensitive to about ± 30, and for the range An_{60-89}, the method has little value.

The orientation method is sensitive to approximately ± 10 for the range in composition An 0–69, for the more calcic types its value is limited. The sum/n for each method and range of composition is tabulated. It indicates that none of the methods have large, consistent deviations for any range of composition. The most consistent deviations appear in the X-ray diffraction methods for the composition range An_{20-49}, where the $2\theta(131)$–$2\theta(1\bar{3}1)$ method yields small positive deviations and the $2\theta(1\bar{3}1)$–$2\theta(220)$ method yields small negative deviations. The maximum deviations in intermediacy index for this range are about ± 5, which suggests that the two X-ray diffraction methods vary approximately linearly with respect to each other. For the optical methods, in the range of composition in which they are most sensitive, there is no pronounced tendency for the deviations to be consistent in sign when the methods are considered individually or together. Therefore, it is suggested that they too vary linearly with the X-ray diffraction methods.

Conclusions

The four methods of determining the intermediacy index vary with each other as an approximately linear function of order-disorder. For the composition range An_{0-19} the intermediacy index can be accurately established by either the very sensitive X-ray diffraction or $2V_x$ methods and the orientation method is of moderate sensitivity. For the composition range An_{20-39} the two X-ray diffraction methods are very sensitive, the $2V_x$ and the orientation method moderately sensitive. For the composition range An_{40-69} the X-ray diffraction method is moderately sensitive, the orientation methods is fairly sensitive, and the $2V_x$ method appears to be of questionable value. For the composition range An_{70-79} none of the methods are sensitive and the value of the X-ray diffraction methods is only slightly better than that of the $2V_x$ or orientation methods. For An_{80-100} the similarity of ordered and disordered types of plagioclase makes all of these methods relatively ineffective in distinguishing ordered from disordered types.

The close agreement in index assigned to such similar disordered types as dry synthetic plagioclases (I.I. $=0$), hydrothermal synthetic plagioclase (I.I. $=0$–17), volcanic plagioclases (I.I. 0–47) and typical plutonic igneous or metamorphic plagioclases (I.I. $=39$–100, including hypabyssal igneous types), all suggest that this method may be useful in correlating igneous rocks with similar cooling histories, and distinguishing between those of dissimilar petrologic occurrence.

The intermediacy indices assigned to specimens from the same or closely similar occurrences tend to be closely grouped. Thus the plagioclases of the Bushveld type from Skaergaard, East Greenland have indices of 50, 62, and 63; those from the Bushveld (70, 88) and the Stillwater area in Montana (85, 90, 90, 91, and 100) have distinctly higher values, and this in spite of a wide range in anorthite composition ($An_{62-85.8}$ for the Stillwater specimens, and $An_{59.2-77.0}$ for Bushveld specimens). Measurements on adjoining twin lamellae yield similar values, 0 and 5, for the Split Rock, Minn., specimens. The specimens from anorthositic masses near the tops of gabbroic sills in Northern Minnesota, with one exception, have similar values, 0, 0, 5, 17, 32, 36, and 70.

The wide range of intermediacy indices of the anorthosites, from extremely disordered to slightly ordered types as noted by van der Kaaden (1951), may have a bearing on the problem of the genesis of anorthosites.

A small number of specimens tend to fall beyond the "low-temperature" curves. This suggests that more thoroughly ordered types of plagioclase may be found, and eventually the data herein presented will need to be modificied. Many metamorphic rocks seem to have high intermediacy indices; for example specimen C41, a metamorphosed gabbro from Salem district, India, has an index of 39. This seems to be in accordance with the results by Smithson (1962) (page %) who has found metamorphic rocks with intermediate Δ value K-feldspars.

Intermediacy indices may prove especially useful in such applications as the following:

(1) It may be possible to distinguish between such different generations of intrusions as the hypabyssal intrusions associated with porphyry copper type of mineralization and older plutonic types of porphyry. Preliminary data by the writer indicate that the intermediacy indices from such porphyrys in southwesternUnited States have ranges from 40 to 75, which is a lower range than that of typical plutonic igneous types.

(2) Nevada plutons associated with contact metasomatic iron deposits contain plagioclase having low intermediacy indices; those associated with scheelite appear to contain highly ordered plagioclase.

(3) Hypabyssal granitic rocks have plagioclases with indices that

typically range from 40 to 75; plagioclase from plutonic igneous intrusions have higher indices. Studies should be made of the indices of plagioclases from granitized rocks, in order to determine whether their indices are higher than those from plutonic magmatic granites.
(4) Stony meteorites should be studied statistically for the frequency of occurrence and range of variation of indices. Such studies may lead to a more accurate appraisal of their cooling histories.
(5) The range of intermediacy indices, 60 to 100, in albitized rocks suggests that studies relating index to such functions as depth of albitization, type of structure in original plagioclases, water pressure and temperature of hydrothermal or pneumatolytic solutions may contribute to a better understanding of depth zones of mineralization, of the spilite-keratophyre problem, and of the nature of low-grade metamorphism. Such studies should evaluate the structural "memory" of replacement plagioclases.
(6) The search for proper specimens to represent the most extreme types of order-disorder of the recognition of structural discontinuities within the range of indices may be faciliated by using such a quantitative measure.

Limitation of Method

The reliability of this method appears to be limited mainly by the quality of the source material the accuracy of each of measurement and the present incomplete knowledge of plagioclase structures and their effect on X-ray diffraction and optical properties. Although general agreement is obtained between each of the four methods, some of the methods have limited supporting data. The optical orientation method is handicapped by the shortage of chemically analyzed specimens for which all types of data are available. Studies of the optical and diffraction character of some of the specimens from the Sudbury lopolith, Canada, suggest that the specimens used to define the 100/I.I. curve may not be most highly ordered types found in nature. A search is being made by Dr. A. Volborth and the author, both of the University of Nevada, for representative chemically analyzed specimens in order to perfect an instrumental method of chemical analysis using new X-ray fluorescence techniques. According to Dr. Volborth personal communication), this method should make it possible to prepare complete analyses for as many as four feldspars per day and it is planned to then re-evaluate the methods proposed in this paper with data from a larger number of specimens representing all types of geologic environment.

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