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STATISTICAL METHOD IN OPTICAL CRYSTALLOGRAPHY:
TECHNIQUE AND APPLICATION TO ROCK FORMING MINERALS.

University of Hawaii, Ph.D., 1972
Geology

STATISTICAL METHOD IN OPTICAL CRYSTALLOGRAPHY: TECHNIQUE AND APPLICATION TO ROCK FORMING MINERALS

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By

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ABSTRACT

This work provides a new rapid way to determine mean principal refractive indices of minerals. Crushed mineral grains yield immersion data which are treated in a way new to optical crystallography.

The mineral families so treated yield mean refractive indices and the standard deviation of the refractive index probability function for each sample. Raw data are provided by the percent of randomly encountered mineral grains which display indices less than, equal to, and greater than each of several different immersion medium refractive indices. The mean refractive indices from randomly encountered grains are plotted against the mean indices for grains of the same sample population oriented in chosen principal optical directions.

Statistics are treated graphically with probability paper or with electronic computer programmed to simulate normal probability paper.

Plagioclase feldspars, olivines, augitic clinopyroxenes, and orthopyroxenes are treated. A third degree equation is fit to 26 data points for plagioclases. The other mineral families yield straight line equations. However the data for olivines and pyroxenes are considered preliminary, being based on fewer data points than were obtained for plagioclases, and only linear fits were completed.

A temperature-controlled modified Jelley refractometer capable of measuring oil refractive indices to accuracies of 0.001 and precisions of 0.0002 is coupled to and calibrated with a temperature-controlled microscope stage.

The costs in time and money of this method are less than for conventional optical methods. The portability of the system make it applicable to use in the field or aboard ships.

The precision and flexibility of the system permit the empirical drafting of density functions for specimens which do not display a Gaussian distribution of indices.

A feasibility study is made of the applicability of the technique to derivation of rock modes.

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PURPOSE

The first purpose of this work is to create a new optical mineral identification technique which is applicable to both oriented and randomly encountered mineral grains. The second purpose is to create for various minerals determinative curves relating randomly encountered to known principle optic direction (POD; see Bloss, 1961) indices.

Few previous workers have emphasized the range of indices encountered in immersed grains of a solid solution displaying a phase region, whether the phase region be natural or artificial, isotropic or anisotropic, oriented or unoriented.[1]

This work was prompted by examination of coarse-grained rocks from several Maui, Hawaii, bosses. The plagioclase feldspars of these rocks range from about An25 to about An75. When crushed grains of these feldspars are randomly scattered on a slide and are randomly encountered in oils chosen somewhere near the apparent mean index of the sample population viewed as a whole, there is a noticeable difference

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[1] I know of no previous statistical petrographic approach aimed specifically at making quantitative statements about the compositional density function of a mineral phase region in any rock. Nobody seems to have attempted empirical definition of the density function of composition through definition of refractive indices.

in the number of grains above or below various oil indices so chosen. The germ of originality here arose in the quantification of grains less than (L), equal to (E), and greater than (G), each of several chosen oil indices with the aim of seeking the mean index of the phase region.[2] Application and development of descriptive statistics followed successful quantification of L, E, and G.

The phase region may include more than one mineral species, and the nomenclature is complicated. (See Berry and Mason, 1959, p. 271-5.) A phase region is here considered to be encompassed by the concept of a mineral name in the more general sense. Thus, for present purposes, plagioclase, olivine, augitic clinopyroxene, and orthopyroxene are four different phase regions.

A refractive index encountered at a random stage setting in a grain scattered at random and immersed in oil on the stage is here defined as beta-prime (BP). The mean (DMEAN) of some number of beta-primes for the same mineral phase region in a specimen is called here DMEANBP. DMEANBP is here related to the mean beta (DMEANB) for plagioclase, olivine, and augitic clinopyroxene; to the mean gamma-prime (DMEANGP) for orthopyroxenes.

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[2] The present work incorporates the useful distinction of Darken and Gurry (1953, p. 290) between "phase" and "phase region."

The present work explores the relationship between DMEANBP and means of indices measured in known POD's.

Rocks are usually composed of only a few principal phase regions, each of which varies compositionally. In specimens containing a mineral species confined to a narrow phase region, data from one or a few grains reasonably represent the entire phase region. However, if the mineral ranges over a rather broad phase region, single-grain methods (e.g. Wilcox, 1959) may well fail to define the mean composition of the phase region. Other grains from the same phase region of the same rock chip may be quite different.

The problem of gaining insight with respect to the total rock body under study is compounded by the variability commonly evident even megascopically in the field within the same outcrop.[3]

The present method seeks to ignore weathering and to isolate fresh minerals with the hope that they are sufficiently representative of the original unweathered rock.

This method is aimed at the elimination of tedium and at the generation of a more complete quantitative description of the rock body as a whole than is now available by other inexpensive methods. Broad compositional variations are

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[3] Koch and Link (1970, p. 255-335) discuss the problems involved in sampling a rock body to obtain statistically significant information on the entire body.

emphasized. Rapid mineral determinations by this technique should enable workers to make a highly accurate statistical treatment of large rock bodies.

This method provides a way to estimate quickly the probability density function (Baird, 1962) of refractive indices for any phase region in a rock. DMEANBP of a phase region and the standard deviation of the refractive index density function for many rock specimens may be compared graphically or mathematically. By extension of this principle, comparisons of parameters are possible among specimens from different bosses, batholiths, aureoles, or whatever seems appropriate to the investigator.

The results are presented as mathematical formulas and as graphs to be of use to workers with or without computers.

Plagioclase feldspars receive emphasis. Olivines, orthopyroxenes, and augitic clinopyroxenes receive preliminary treatment.

A feasibility study of obtaining rock modes from this method is undertaken.

BACKGROUND OF OPTICAL MINERALOGY

RELATION OF REFRACTIVE INDICES TO COMPOSITION.

The important relation of refractive index to composition among many minerals is well known. A great advantage of optical work is the ability to extract the mineral from a mixture of minerals by visual inspection. No single technique can extract all possible information from a rock. But refractive indices provide inexpensive results when compared to other methods yielding compositional estimates. Appendix A contains a discussion of immersion medium refractive index controls and a discussion of related methods of identification of plagioclases.

Most routine work does not warrant the expense of chemical analysis, X-ray, microprobe, or atomic absorption methods. Also, chemical analyses are to be viewed with caution in light of the conclusions drawn by Fairbairn _et al_. (1951), Flanagan (1969), and Stevens _et al_. (1960).

There are other workers who agree that optical methods have not been outdated by the more expensive modern analytical techniques: " ...microprobe and/or optic data are considered to be a better measure of the plagioclase composition [than chemical analyses]" (Borg and Heard, 1970, p. 378). Morse (1968, p. 106) says: "For comparative studies of plagioclases from a single environment or genetic history, it is even probable that compositional variation can be determined with greater precision by the dispersion method than by any analytical means, possibly excepting the electron microprobe, which gives comparable results and statistics." Since the statistics of this work are comparable to Morse's, his statement is germane.

Friedman (1960, p. 74) finds that "for rocks in which the composition of the individual minerals can be obtained by optical measurements, the major constituents can be determined with the petrographic microscope and the results can be considered reliable for most purposes. Petrologists should therefore make more chemical analyses with the aid of the microscope."

Careful determination of refractive indices seems the most expedient and perhaps the most accurate way to estimate composition for most of the major, common rock forming minerals. Successful establishment of the relationship of DMEANBP to the mean index of a known POD for the same sample population forms the logical link between mean random indices and known compositions when composition is reasonably estimated by index.

PREVIOUS OIL IMMERSION WORK.

The traditional, and currently the usual, approach to optical mineralogy is well presented by Bloss (1961). Some of his notation is adopted here.

Becke line and oblique illumination methods.

The relationships of principal refractive indices to indices of immersion media are established by the use of the Becke line or the oblique illumination method (Bloss, 1961).

Use of transmitted, white, plane-polarized light with reduced diaphragm under low and medium powers produces colored Becke lines for grains displaying indices close to that of the immersion medium (Bloss, 1961; Emmons and Gates, 1948). Use of a monochromatic light source eliminates the colored Becke lines and narrows the zone of apparent match.

EFFECTS OF PHASE REGION ON INDICES AND BIREFRINGENCE.

When grains in a sample are comprised of a single phase and do not range appreciably over a phase region of a solid solution, comparisons from grain to grain of a given POD's index yield essentially identical results, and there is no need for the present method. Quartz provides the best natural example of such an occurrence (though even quartz displays slight variability of omega in the perfectly clear sample used in this work to calibrate the refractive index scale). However, most minerals commonly display solid solutions over some range of composition and therefore of indices.

Larsen and Berman (1964, p. 20) say: "To test the lowest and highest indices of refraction of... minerals against the embedding media a grain should be chosen that appears to show strong birefringence, both the thickness of the grain and the interference color being taken into account. The grain should be turned to extinction (or the lower nicol should be revolved 90°) and tested again. This procedure should be repeated on a number of grains, and with a little practice, unless the birefringence is extreme, many of them will show the lowest index of refraction, equal to [alpha], or the highest index equal to [gamma], within the limits of error of the immersion method." I consider this advice faulty.

Birefringence is usually about the same from grain to grain for grains of the same phase region in the same hand specimen. But it is my experience that refractive indices vary from grain to grain in powders from a single hand specimen. So the smallest alpha found subtracted from the greatest gamma found is not the birefringence for a grain, but might be called the birefringence of the phase region, a distinctly different concept.

Tsuboi's dispersion method.

Tsuboi (1926) fell into the trap of regional birefringence when he treated indices of crystals "in powders of random orientation."[4]

It is interesting that even though he states that of all the pyrogenic minerals, only quartz is not a member of a solid solution series, when he compares refractive indices he derived for a sample of danburite from Obira, Bungo, Japan with indices determined by M. Kawamura for the same mineral from the same locality, he obtains a gamma index .00168 higher than that obtained by Kawamura (which he calls a "close approximation"). Tsuboi concludes (p. 146): "If a larger number of grains had been used, better results would have been obtained."

However, the value for gamma could never be reduced by applying his method to more grains; his method selects not the

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[4] But he derandomized his approach by bringing each crystal to a position of extinction.

birefringence of a grain but the maximum and minimum index values to be obtained from the phase region. Therefore, had a larger number of grains been used, the measured range of the phase region probably would have been increased and the tails of the refractive index density distribution probably would have been better determined, increasing the value of the regional birefringence which he mistook for the phase birefringence. This opinion is supported by the fact that Tröger (1959) lists danburite birefringences from .0057 to .0059. That Tsuboi found a danburite birefringence of .007 confirms the belief that he ignored the presence of solid solution effects on indices to the disadvantage of his method. Workers currently using methods directly or indirectly involving the method of Tsuboi should take note of this warning.

STATISTICS IN OPTICAL PETROGRAPHY

Only if data are available in enough abundance and in short enough time per specimen are statistical studies involving a large number of specimens practical.

The statistical quantification of rocks has been delayed by many factors. Among them are:

1. The difficulty of obtaining statistically meaningful amounts of data on extinction angles, optic figures, oriented indices and 2V within a reasonable amount of time,
2. Seriate size relationships among grains of the same phase in a single specimen,
3. Time required to orient grains for measurements of principal or significant (Bloss, 1961, pp. 75, 151, 293) indices,
4. Contradictory indices indicated by different optical methods for the same grain,
5. The inordinate amount of time required by universal stage methods or such tedious and complex uniaxial stage methods as those of Nieuwenkamp (1966) to produce enough compositional data for statistical significance,
6. Lack of a quantitative method capable of dealing rapidly and inexpensively with data relating to composition,

7. The difficulty of obtaining optic figures from small grains, whether in thin sections or immersion media.

The above problems are largely solved by: 1. Use of on line computers which make measurements of 2V's less tedious than otherwise; though no work has been done here with extinction angles , the same statement must hold for them. 2. Crushing a specimen to a size smaller than the general rock grain size and addressing the question of that phase region's density function rather than the composition of a single grain. 3. The great rapidity of counting indices of grains scattered and encountered randomly. 4. The advantage of averaging many grains' indices to produce a mean index for that phase region in the rock, thereby establishing enough knowledge of the index distribution for the effects of conflicting results on a few grains to become insignificant. 5. The rapidity of this method. 6. This method. 7. The advantage of being able to work quantitatively with grains too small to yield optic figures.

It is time to join the powerful, available immersion techniques (Emmons, 1928, 1929, 1943; El-Hinnawi, 1966; van der Plas, 1966) to the recently developed powerful statistical and electronic computer techniques. This work indicates that the resulting marriage can be exciting and elucidating.

MATERIALS AND METHODS

MATERIALS

A description of the petrographic laboratory appears in Appendix B, which is intended for readers wanting to construct a laboratory similar to the one used in this work.

CHOICE OF MINERAL AND ROCK TYPES APPROPRIATE TO THIS STUDY.

MINERALS.

This work treats plagioclase feldspars, olivines, augitic clinopyroxenes, and orthorhombic pyroxenes. These common minerals represent the triclinic, monoclinic, and orthorhombic crystal systems.[5] They range in birefringence from low (plagioclase) to high (olivine); in refractive index, from low (plagioclase) to medium and high (pyroxenes and olivines). Demonstration of the applicability of the present method to these minerals, while in no way providing an exhaustive overview of all crystal systems, birefringences, or ranges of refractive indices, does provide a significant first step in a continuing investigation.

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[5] Readers wanting a general and concise review of the literature relevant to the mineral groups treated here are referred to volumes 1, 2, and 4 of Deer _et al_. (1967a, 1965, 1967b).

Plagioclases.

"Feldspars are the most important of all rock-forming substances... There is no mineral group which has been studied more thoroughly in the past, and yet there is no mineral group which has presented, and still presents to the mineralogist so many puzzling problems" (Barth, 1969, p. xi). The importance of the feldspars in the total context of mineralogy and their importance in rock classification makes their emphasis here most apt. Part of the emphasis they receive here is simply due to the fact that it was study of them which prompted development of the present method.

Special conditions imposed by plagioclase feldspars on the present method are: 1. Low birefringence and 2. Two prominent directions of cleavage. Successful establishment of a relationship between DMEANBP and DMEANB for feldspars prompted the preliminary work on the other mineral phase regions treated here.

Olivines.

Olivines are orthorhombic. They have high birefringence. They are said to have virtually perfect conchoidal fracture when crushed (Deer *et al.*, 1967a).[6]

"The approximate composition of an (Mg,Fe)-olivine may be determined optically most expeditiously by measurement of the optic axial angle. More precise results can be obtained from the refractive indices. These, however, are not readily determined in grains, for although the optic axial plane is perpendicular to the two cleavages, these usually are not developed sufficiently well to give cleavage fragments on crushing" (Deer *et al.*, 1967a, p. 24). Thus, olivines are different from plagioclase feldspars in crystal system, birefringence, and manner of break. Furthermore, a successful demonstration of a relationship between beta and beta-prime for olivines would reduce the difficulties involved in obtaining for them precise compositional determinations from refractive indices which were noted by Deer *et al.*

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[6] However, the dominant frequency of Bxax figures over Bxox figures noted in Table 15 here suggests that the fracture is not perfectly conchoidal. The question deserves further work.

Augitic clinopyroxenes.

"Pyroxenes are the most important group of rock-forming ferromagnesian silicates, and occur as stable phases in almost every type of igneous rock" (Deer et al., 1965, p. 1).

The complexities of ionic substitution in the augitic pyroxenes results in the need to determine both the beta refractive index and 2V in order to use determinative charts such as those presented by Deer et al. (1965, p. 132). Even then "compositions estimated from the optic axial angle and beta indices may differ by as much as 5 per cent. of the Ca, Mg or Fe content from their true values" (Deer et al., 1965, p. 132).

The augitic pyroxenes differ from plagioclase feldspars, olivines, and orthorhombic pyroxenes in that they have monoclinic rather than triclinic or orthorhombic structure. Their birefringence is greater than that of orthopyroxenes, less than that of olivines. Just as orthopyroxenes possess a dominant cleavage, so do the augitic pyroxenes: "crushed fragments of the pyroxenes include tablets lying parallel to the prismatic cleavage $\{110\}$ and a smaller number of tablets parallel to the $\{100\}$ parting. The latter are easy to recognize by their low birefringence since an optic axis emerges from them at about 20^0 from the vertical, and if bounded by the prismatic cleavage or $\{010\}$ parting planes such fragments exhibit straight extinction. The orientation of these tablets can be checked by observing the interference figure which, if the fragment is parallel to the (100) plane, will show an off-center optic axis figure. If on rotating the stage until the isogyre is east-west the brush divides the field exactly, then the optic axial plane is normal to the section and the [beta] vibration direction north-south" (Deer et al., 1965, p. 133). Thus, DMEANBP is graphed against DMEANB for all but the orthopyroxenes in the present work.

Orthorhombic pyroxenes.

Orthopyroxenes form a continuous series of mineral species increasing in refractive index in the order: enstatite, bronzite, hypersthene, ferrohypersthene, eulite, and orthoferrosilite. Deer *et al.* (1965, p. 28) fit straight lines through the alpha and gamma (-prime) indices but do not plot the beta index. Therefore, no *a priori* assumption of a straight line relationship between composition of the orthopyroxenes and the beta indices is made here.

Gamma-prime taken as POD.

Although most references advise determination of the "gamma" index for orthopyroxenes, they generally do not mention use of an optic figure to check orientation. "Since most orthopyroxene cleavage fragments in a crush lie on a (110) face, the [gamma] index can generally be determined with the greatest ease and accuracy" (Poldervaart, 1950, p. 1075). The implication is that one need only align the cleavage with the polarizer and check that extinction is parallel to measure gamma. However, a check of the frequency of useful optic figures for gamma and beta in several orthopyroxene samples showed that optic figures yielding gamma are more difficult to find than those yielding beta. This is because in general the alignment of the cleavage and extinction of an orthopyroxene with the polarizer does not assure that the c crystallographic axis (and therefore gamma proper) is really in the plane of the stage. More often the crystal breaks unevenly and gamma-prime, not gamma proper, is found. Exhaustive, quantitative work to see which POD, gamma proper or beta, is most useful over the entire orthopyroxene range is beyond the scope of the present work but is a problem worthy of further attention.

Birefringence of the series ranges from low to moderate, intermediate to the birefringences of plagioclase feldspars and olivines. "Because most crushed fragments of the mineral lie on a {210} cleavage plane, the [gamma-prime] refractive index can be measured with the greatest ease and accuracy and this is the most accurate optical method of determining the En:Fs ratio of an orthopyroxene" (Deer _et al_., 1965, p. 29).

Use of gamma-prime here shows that the difference in precision between gamma and gamma-prime measurements is likely to be quite small, for the gamma-prime statistics are comparable in precision to those of beta for plagioclases, augitic clinopyroxenes, and olivines. Certainly it is quicker to use gamma-prime than to use gamma for orthopyroxenes. It has therefore been decided to relate DMEANBP to DMEANGP indices for orthopyroxenes treated here.

ROCKS.

Of the Maui rocks that gave rise to this study, eight of the fresher ones were chemically analyzed at the Japan Analytical Chemistry Research Institute. Later work will give more complete field descriptions for the locations of the sites at which the Maui rocks were collected. These, with a single rock provided by Lindsley and Smith (1971), were chosen to test the applicability of the present method to total rock counts and to concentrates known to range over a considerable phase region. It was hoped that statistics for total rock crushed grains similar to those to be presented for mineral phase regions might provide a way to determine modal percentages. Also, it was hoped that index counts from concentrated felsic grains from a rock known to have extreme variation of feldspars might provide an empirically derived density function useful in determining relative amounts of different plagioclases in the sample.

MINERAL AND ROCK SAMPLES STUDIED

MINERALS.

The majority of samples treated here were kindly donated by other workers. As a result, most have been previously discussed in the literature.

Many of the following tables are self explanatory and are presented without comment.

Plagioclases.

Specimens P1 through P5 and P8 were selected at random from drawers labeled with general names like 'bytownite'; they are from unknown localities, which choice was purposely made during initial work to maximize the randomness of that aspect of the approach.[7] Specimens 6 and 7 are respectively University of Hawaii specimens No. 10.3.14 and 10.3.12 from the Stillwater complex. Following the success of initial work, other samples were obtained from other workers as summarized in Table 1.

All tables list samples in increasing DMEANB or DMEANGP determined by this work.

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[7] The initial purpose was to see whether a relationship might be found among plagioclases regardless of structural state or rock suite. This is why no initial effort was made to do anything but obtain a few samples which ranged over the plagioclase indices at intervals as even as possible.

Table 1. Published plagioclase data of other work.

SAMPLE NUMBER	SAMPLE SOURCE	STRUCT. STATE	CHEM. ANAL.	MICROPROBE AVG.	MICROPROBE RANGE	XRAY	OPTICS (PERCENT AN)
P-25	BORG AND HEARD (1970)	LOW	AN01.0 OR0.7				2
U111	"	PERIS-TERITE	AN11.2 OR1.35	AN06.2 OR0.7	AN06- AN8		8
2693	"	PERIS-TERITE	AN13.8 OR3.8	AN12.9 OR2.2	AN10- AN14		13
U112	"	LOW	AN20.3 OR3.9	AN18.9 OR1.5	AN15- AN20		18
P-5[1]	"	LOW	AN31.9 OR2.1				30
P-8[1]	"	LOW	AN38.6 OR1.7	AN37.4 OR0.6	AN37- AN38		39
A-175	"	LOW	AN51.9 OR3.7	AN44.4 OR1.5	AN41- AN50		50
U116	"	LOW	AN53.2 OR4.1	AN54.6 OR3.0	AN51- AN56		55
531N-2	JACKSON (1961)					59.9	

Table 1. (Continued) Published plagioclase data of other work.

363-69	LINDSLEY&SMITH[2] (1971)						
52BE-35	JACKSON (1961)					70.3	
EK1955 AP	ANDERSON *et al.* (1971)			AN63 OR1.0	AN62- AN72		
HML1950 SE	"			AN68 OR0.7	AN60- AN72		
HK1868 G2	"			AN76 OR0.5	AN76- AN78		
55MV-32	"					73.0	
P-24	BORG AND HEARD (1970)	LOW[3]	AN76.2 OR0.4	AN76.9 OR0.4			77
52BE-29	JACKSON (1961)					76.6	
55BE-1	"					83.3	
P-18	BORG AND HEARD (1970)	PRIMI-TIVE AN		AN95.0 OR0.2			96

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[1] Do not confuse P5 and P8 with P-5 and P-8 throughout this work.

[2] "The bulk of the plagioclase compositions will be those of the phenocryst cores (around An80) and ground mass (around An60) [Lindsley, personal communication]." See much more below under "ROCKS".

[3] Transitional anorthite.

Olivines.

Table 2. Olivine sample sources and source forsterite estimates from microprobe data.

	SOURCE	PERCENT FORSTERITE COMPOSITION	
		AVG.	RANGE
DTS-1	Flanagan (1969)		
JJG-352	Kushiro (unpub.)		
PCC-1	Flanagan (1969)		
HML1950SE	Anderson *et al.* (1971)	84	84-86
HK1868G2	"	79	77-81
4526 #3	Burns & Huggins (1972)	78.9	
5111 #5	"	60.0	
5107 #4	"	59.3	
54087 #7	"		
5181 #9	"		

Twenty-six separate bulk analyses of total rock for both PCC-1 and DTS-1 are collated by Flanagan(1969, p. 87-8) and are not repeated here.

Table 3. Olivine chemical data of other work.

	JJG-352[1]	4526 #3[2]	5111 #5[2]	5107 #4[2]	54087 #7[2]	5181 #9[2]
SiO_2	042.1	039.66	036.80	036.26	035.35	032.63
Al_2O_3	000.00	000.06	000.06	000.06	000.02	000.09
Fe_2O_3		n.d.	n.d.	n.d.	n.d.	n.d.
FeO	007.73[3]	019.60	034.38	034.37	041.15	055.50
MgO	050.8	040.85	028.80	028.05	023.50	011.90
CaO	000.0	000.07	000.08	000.10	000.03	000.11
Na_2O	000.00					
TiO_2	000.00	000.01	000.03	000.02	000.00	000.05
MnO	000.06	000.27	000.47	000.48	000.54	000.39
Cr_2O_3	000.00					
NiO		000.27	000.10	000.10	000.15	000.00
Total	100.8	100.88	100.72	099.44	100.74	100.67
Fe_2SiO_4[4]		021.02	039.76	040.33	049.09	071.78
Mg_2SiO_4		078.30	059.46	058.82	050.04	027.51
Mn_2SiO_4		000.30	000.54	000.58	000.65	000.51
Ca_2SiO_4		000.10	000.11	000.16	000.04	000.19
Ni_2SiO_4		000.28	000.13	000.11	000.18	000.00

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[1] Microprobe analysis.

[2] Bulk chemical analysis assumed.

[3] Total iron as FeO.

[4] The rest of the table consists of partial olivine formulas listed by Burns and Huggins (1972).

Augitic clinopyroxenes.

A sample I collected at the locality of free-augite crystals at the 8500-foot level of Haleakala, Maui, is probably reasonably close in composition to the sample analyzed by Washington and Merwin (1922, p. 119, analysis 1). Though the locality is a fair distance downhill from the Red Hill location mentioned by those authors, the collection sites are probably the same. This is inferred from the reasoning of Washington and Merwin (1922, p. 117). An abundant supply of free augite crystals remains there yet.

Eight of the augite crystals from this site, ranging in size from about 3 mm to 15 mm across, were pounded together and passed through a 0.061 mm sieve. They should provide a reasonable sample of the locality. The powder is called 1972cpx (1972 for short). Part of the sample was purified for chemical analysis. Before purification it consisted of a mixture of cpx and red glass. Initial separations on the Frantz magnetic separator failed to purify the sample.

Heavy liquid separation with bromoform also failed, for the glass remained admixed with all densities of the cpx. About one third of the sample was enclosed in a glass tube and heated in a bunsen flame to convert the glass' hematite to magnetite. Optical work was done on the unseparated portion of the sample to avoid any change of optical properties as a result of the heat treatment. Passes of the heat-treated sample through the Frantz magnetic separator resulted in purification at the 99 percent level. This purified sample is being analyzed by atomic absorption spectro-photometry by Patricia Fryer at the Hawaii Institute of Geophysics. The results are not yet available.

Table 4. Augitic clinopyroxene sample sources and sources' reported indices.

	SOURCE	ALPHA	BETA	GAMMA
Px-1	Boettcher (1967)[1]	1.6739	1.6791	1.7015
209	Butler (1969)			
215	"			
128	Best and Mercy (1967)	1.684	1.689	1.710
269	Butler (1969)			
277	"			
259	"			
189	"			
227	"			
205	"			
153	Best and Mercy (1967)	1.696 to 98	1.700 to 20	1.720 to 30
254	Butler (1969)			
248	"			
1972cpx	present work			
187	Butler (1969)			
250	"			
249	"			

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[1] Also treated by Goldich et al. (1967); indices measured by Boettcher on spindle stage with sodium light (personal communication).

Table 5. Augitic clinopyroxene chemistries (weight percents).

	Px-1[1]	209[2-3]	215[3]	128[4]	269[3]	277[3]	259[3]	189[3]	227[3]
SiO_2	053.94	054.48	054.06	052.51	053.26	053.06	052.79	052.27	052.19
Al_2O_3	000.66			002.11					
Fe_2O_3	001.13			001.09					
FeO	001.91	004.62	006.26	007.97	010.62	011.36	012.62	012.39	014.97
MgO	016.93	016.77	015.50	014.23	013.74	013.18	012.65	012.00	010.90
CaO	024.55	023.05	023.34	021.58	022.00	022.02	021.38	018.97	021.57
Na_2O	000.24			000.28					
K_2O	<0.01			000.04					
TiO_2	000.26			000.37					
P_2O_5	000.00								
MnO	000.07	001.08	000.84	000.20	000.38	000.38	000.57	004.37	000.36
F	000.00								
Cr_2O_3	000.21								
BaO	000.006								
SrO	000.035								
RbO	000.00								
BeO	000.00								
H_2O+	000.00								
H_2O-	000.03								
Total	099.97	100.00	100.00	100.38	100.00	100.00	100.00	100.00	100.00

Table 5. (Continued) Augitic clinopyroxene chemistries (weight percents).

	205^3	153^4	254^{2-3}	248^3	187^3	250^{2-3}	249^{2-3}
SiO_2	051.82	051.20	052.46	051.65	051.23	051.02	050.66
Al_2O_3		000.80					
Fe_2O_3		001.58					
FeO	015.77	014.81	014.29	017.74	019.10	019.81	020.64
MgO	010.12	010.27	012.22	009.73	008.53	007.99	007.07
CaO	020.80	020.37	019.92	020.60	020.65	020.54	020.23
Na_2O		000.32					
K_2O		000.06					
TiO_2		000.27					
MnO	001.49	000.36	001.11	000.27	000.50	000.64	001.41
Total	100.00	100.04	100.00	100.00	100.00	100.00	100.00

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[1] Bulk analyses reported in Goldich *et al.* preferable to that of Boettcher (1967) (Boettcher, personal communication); Cr_2O_3 and SrO by emission spectrometer; BaO by mass spectrometer.

[2] Average of four analyses.

[3] FeO, MnO, and CaO by X-ray emission spectrochemical analysis; other values from differences based on ideal structure formulas, so total is 100 percent.

[4] Bulk chemical analysis assumed.

Orthopyroxenes.

Table 6. Orthopyroxene sample sources and sources' reported refractive indices.

	SOURCE	ALPHA	BETA	GAMMA
JJG-352	Kushiro (unpublished)			
128	Best and Mercy (1967)	1.694	1.704	1.707
277	Butler (1968)			
189	"			
259	"			
227	"			
254	"			
153	Best and Mercy (1967)	1.719	1.732	1.737
205	Butler (1969)			
248	"			
187	"			
250	"			
249	"			
171	"			

Table 7. Orthopyroxene chemistries (weight percents).

	JJG-352	128	277[3]	189[3]	259[3]	277[3]	254[3]
SiO_2	058.5	052.77	052.40	050.82	051.03	050.62	050.54
Al_2O_3	000.66	001.12					
Fe_2O_3		003.37					
FeO	004.56[1]	019.92	026.92	025.46	031.64	033.86	032.20
MgO	035.6	021.06	018.05	014.31	015.13	014.03	013.80
CaO	000.40	001.15	000.50	001.03	000.63	000.58	000.45
Na_2O	000.04	000.04					
K_2O		000.02					
TiO_2	000.00	000.33					
MnO	000.06	000.52	001.13	008.37	001.57	000.81	003.01
Cr_2O_3	000.20						
Total	100.0	100.30	100.00	100.00	100.00	100.00	100.00

	153	205[3]	248[3]	187[3]	250[2-3]	249[3]	171[3]
SiO_2	049.27	049.75	049.70	049.14	048.74	048.46	048.09
Al_2O_3	000.94						
Fe_2O_3	003.53						
FeO	031.43	034.02	037.51	039.17	040.19	039.49	041.85
MgO	012.34	011.48	011.39	009.81	008.67	007.74	007.01
CaO	001.38	000.73	000.75	000.76	000.80	001.09	000.23
Na_2O	000.04						
K_2O	000.04						
TiO_2	000.43						
MnO	000.87	004.02	000.65	001.13	001.60	003.23	002.81
Total	100.36	100.00	100.00	100.00	100.00	100.00	100.00

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[1] Total iron as FeO.

[2] Average of four analyses.

[3] FeO, MnO, and CaO by Xray emission spectrochemical analysis; other values from differences based on ideal structure formulas, so total is 100 percent.

ROCKS.

Sample 363-69.

Sample 363-69 is part of a core studied by Lindsley and Smith (1971). Lindsley says the sample "was collected close to the host rock sample on which the chemical analyses were done... The more alkalic portions make up but a small volume of the total feldspar" (personal communication). A sketch included with his remarks shows 363-69 about 1 to 2 eters above 351-96 which was analyzed and called "host rock" in their Figure 73b (1971, p. 274).

Other pertinent remarks based on U-stage work are made by Lindsley and Smith (1971): " ...most [plagioclase] from host rock and other zones of the flows are in the 'high' structural state. Of the remainder, most are 'intermediate' and only a very few are in the 'low' state. All parts of the flows except [emphasis theirs] the pegmatoids contain phenocrysts with optically distinct cores of calcic plagioclase and with rims identical in composition with that of the groundmass laths. There is a compositional gap between phenocryst cores and rims extending from approximately An65 to An75 as determined optically. Pegmatoid feldspars range from An48 to An53 in the cores and are progressively zoned toward albite and alkali feldspar. Most plagioclase twinning in the pegmatoids is according to the simple albite law, whereas that from the host rock is dominantly by the simple Carlsbad or combined albite-Carlsbad laws...

"Because of nearly ubiquitous compositional zoning, most feldspar analyses presented here are of a single point only; averaging values for several points would be meaningless... [See also the remarks of Anderson below, following Table 22.]

"The optically detected compositional gap between phenocryst cores on the one hand and phenocryst rims and ground mass plagioclase on the other is confirmed (Fig. 73), although the microprobe data show a narrower gap (An70-74). The width of the gap is probably more accurately determined by optical methods, for whereas the break between phenocryst cores and rims is sharp (<1 [millimicron] in width), the 8-12 [millimicron] spot size used to minimize Na loss undoubtedly resulted in hybrid values when the beam overlapped core and rim during step-scan traverses of the phenocrysts. [Work reported here later shows that optical work closes the noted gap very nicely.] The compositional trends in Fig. 73 are similar to those reported for feldspars from a Hawaiian lake lava (Evans and Moore, 1968), although the Hawaiian alkali feldspars tend to contain more calcium.

"Large numbers of analyses were made of feldspars from the host rock, dark pegmatoid, and light pegmatoid in an attempt to detect sympathetic or antipathetic relations among them.

Although the distribution of analyzed points is not [emphasis theirs] rigorously proportional to the volume of feldspar having a given composition (the sampling was biased toward sodic and potassic feldspars), the dominance of points from step-scan traverses gives meaning to variations in point density for adjacent compositions [emphasis theirs]. Thus if traverses across eight or ten crystals in a given sample all show a gap in the same compositional range, it is likely that feldspar of that composition crystallized sparsely, if at all, in that sample. A concentration of points, on the other hand, may indicate an abundance of feldspar of that composition, but may also represent the results of a traverse across a grain sectioned parallel to a growth surface rather than through its center. Thus, concentrations of points indicate relative abundance only if they appear on two or more traverses" (pp. 275-6).

Maui rocks.

Maui rock samples 27, 31F, 32D, 33C, and 52 are from Ukumehame Valley; sample 45 is from Kahakuloa Valley; sample 55 is from Iao Valley; and sample 62 is from Kahoma Valley. All are phanerites of the gabbroic facies. More detailed field descriptions will be given later but are available on a personal basis for now.

Chemistries are reported here to make them available to other workers and to provide background data against which to view future results of optical work on their minerals.

Table 8. Maui phanerite chemistries.
(Weight percents; Shiro Imai, analyst.)

	27	31F	32D	33C	45	52	55	62
SiO_2	49.30	49.96	50.19	50.74	46.82	50.35	50.77	50.74
TiO_2	2.70	3.50	3.08	2.87	2.42	2.33	2.83	2.71
Al_2O_3	14.72	13.86	13.48	14.56	12.21	14.55	9.86	10.09
Fe_2O_3	4.30	3.18	2.57	2.49	2.26	2.04	3.81	3.91
FeO	6.27	10.00	10.18	9.47	10.79	8.85	10.50	10.52
CaO	10.22	10.29	10.92	10.62	9.98	11.84	10.36	10.32
MgO	6.99	5.86	6.42	5.74	12.23	6.98	7.91	7.74
MnO	0.12	0.16	0.16	0.14	0.15	0.15	0.18	0.18
Na_2O	2.19	2.28	2.27	2.41	2.04	2.23	1.87	1.90
K_2O	0.24	0.34	0.30	0.33	0.36	0.23	0.26	0.27
$H_2O(+)$	0.70	0.32	0.43	0.48	0.62	0.53	0.54	0.43
$H_2O(-)$	1.61	0.35	0.37	0.46	0.39	0.35	0.88	1.01
P_2O_5	0.23	0.29	0.27	0.29	0.28	0.17	0.28	0.29
Total	99.59	100.39	100.65	100.60	100.55	100.60	100.05	100.11

METHODS

Instability of immersion media results in the well known need to calibrate immersion media rather often in careful work.[8]

SEARCH FOR ACCURACY AND PRECISION.

Although 3-place accuracies are sufficient for most purposes of mineral identification, this work seeks four-place accuracy and precision to ensure the validity of the results.

The limiting factor of precise and accurate knowledge of immersion media indices has been the major impediment to the production of trustworthy data. Temperature-controlled laboratory, stage, and refractometer are necessary to achieve the desired accuracy and precision in this work. The system constructed to meet these needs employs a common monocular uniaxial petrographic microscope and a Jelley refractometer (Jelley, 1934). See "DESCRIPTION OF PETROGRAPHIC LABORATORY," Appendix B, for details. Appendix C is included primarily for the use of students at the University of Hawaii who are currently making use of the laboratory. It may also be

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[8] Evaporation, contamination, precipitation, oxidation, and chemical changes during the aging process of an immersion medium as well as changes of refractive index due to temperature fluctuations, all necessitate immersion medium calibrations when accuracy is important. The problems of instability are especially critical for immersion oils of indices greater than 1.65 due to their volatility.

instructive to readers wanting a more detailed listing of steps performed during analytical operations than is given in the body of this text.

ELEMENTS OF THIS METHOD.

Currently, workers are trained to rely only on indices determined from grains previously brought to extinction positions. The present work departs from the traditional approach by comparing indices of grains scattered randomly and immersed in oil. The stage is not rotated to bring each grain to extinction. Instead, grain indices are examined at whatever orientations they have when encountered during a traverse of the mount at a fixed stage position.

Orientations of the grains are not entirely random, because they may lie on cleavage, fracture, parting, or remnant crystal faces. This may partially derandomize the orientation of the indicatrix.

If an immersion oil is held at constant temperature, its refractive index zone may be considered to be a line so thin that any mineral grain by comparison must be of either higher or lower index. Given the theoretically perfect situation, there should be no grains which display indices matching that of the immersion medium. However physiological limitations coupled perhaps with inability to control temperature perfectly have resulted in the traditional, practical, and routine "matching" of minerals to oils. Saylor (1935) treats sensitivity of the criterion of match under various methods of illumination using monochromatic light. He finds the upper limit of precision available to extremely careful optical microscopists determining mineral refractive indices to be about .0001.

Data description.

Mineral grains viewed under plane polarized sodium light in immersion media selected somewhere near the mean index established by preliminary work may or may not display Becke lines. Of those that do, some display refractive indices higher than, while others display refractive indices lower than, that of each immersion medium. Grains which are in the field but are seen only under crossed nicols are said to be equal in index to the immersion medium.

The data consist of percentages of grains whose indices of refraction are determined to fall in the categories less than, equal to, and greater than each of several immersion medium indices. The data are generated either from grains oriented at random with respect to the rotation of the microscope stage, or from grains oriented conoscopically to display a refractive index associated with a known axis of the indicatrix.

The statistics.

Gaussian distributions.

The most common distribution found in nature is normal (Gaussian). The most powerful statistics are based on assumptions of normal probability density functions (Figure 1). Therefore, the assumption that the frequency distribution of refractive indices in such natural solid solution series as the plagioclase feldspars is normal is the most convenient one on which to base a first statistical treatment of the data. The statistics developed for the present application (Johnson and Langford, in preparation) are therefore based on the assumption of a normal distribution.

Graphics and numerical statistics generated by electronic computer data analysis are described below; these may display radical departures of the data from the best normal curve fit to the data, thus providing a convenient check on the appropriateness of the assumed refractive index Gaussian distribution.

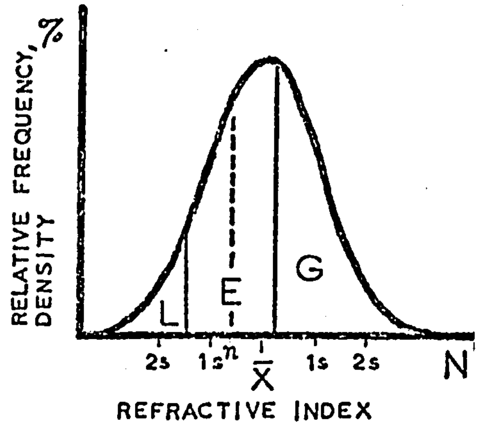

Figure 1. Normal probability density function.

Probability density function of refractive index (N) of a solid solution (abcissa) versus density, relative frequency in percent (ordinate). L, E, G, and n are explained in the text. (After Baird, 1962.)

Figure 1 shows the best fit normal (Gaussian) distribution probability density function of phase region indices. The total area under the curve is 1. The areas labeled L, E, and G represent the fraction of total area under the curve occupied by grains which appear respectively to be less than, equal to, and greater than each particular oil index (n) chosen. Since the oil index theoretically cannot precisely match that of the grain, addition of E/2 to L yields (Johnson and Langford, in preparation) an adjusted fraction of the total area less than n which is called Y (not drawn).[9]

Xbar is the mean refractive index sought for the sample population; s is the standard deviation of refractive index. These are here called DMEAN and DSD when determined by electronic computer.

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[9] Recall the work of Saylor (1935).

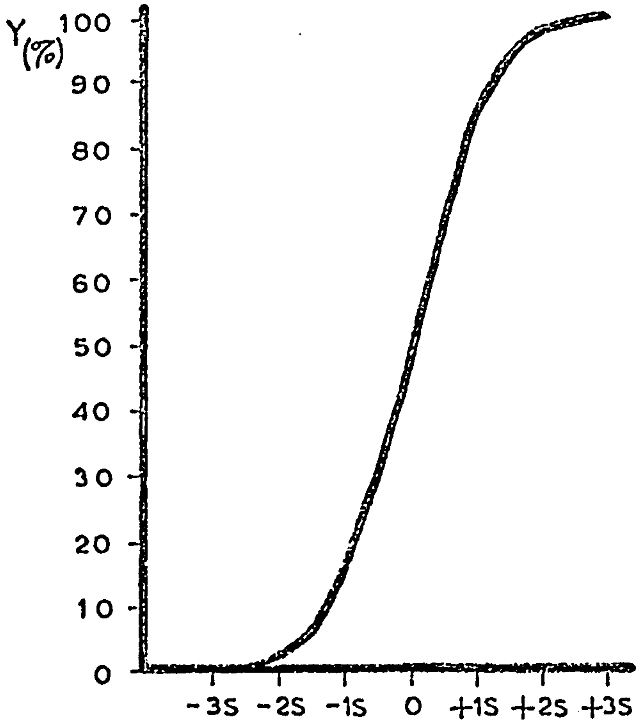

Figure 2. Cumulative normal distribution function. (After King, 1971.)

Figure 2 shows the same normal distribution as shown in Figure 1, but in figure 2 the relations to indices are omitted and the curve is the cumulative normal probability distribution function rather than the density function.

Gaussian probability paper graphics.

Normal probability paper (Spiegel, 1961, p. 136; King, 1971) would convert the curve of Figure 2 to a straight line. Plotting data on normal probability paper therefore provides a test of the normal distribution of indices assumed in the sample. Departures from a straight line indicate a violation of the normal probability function assumption.

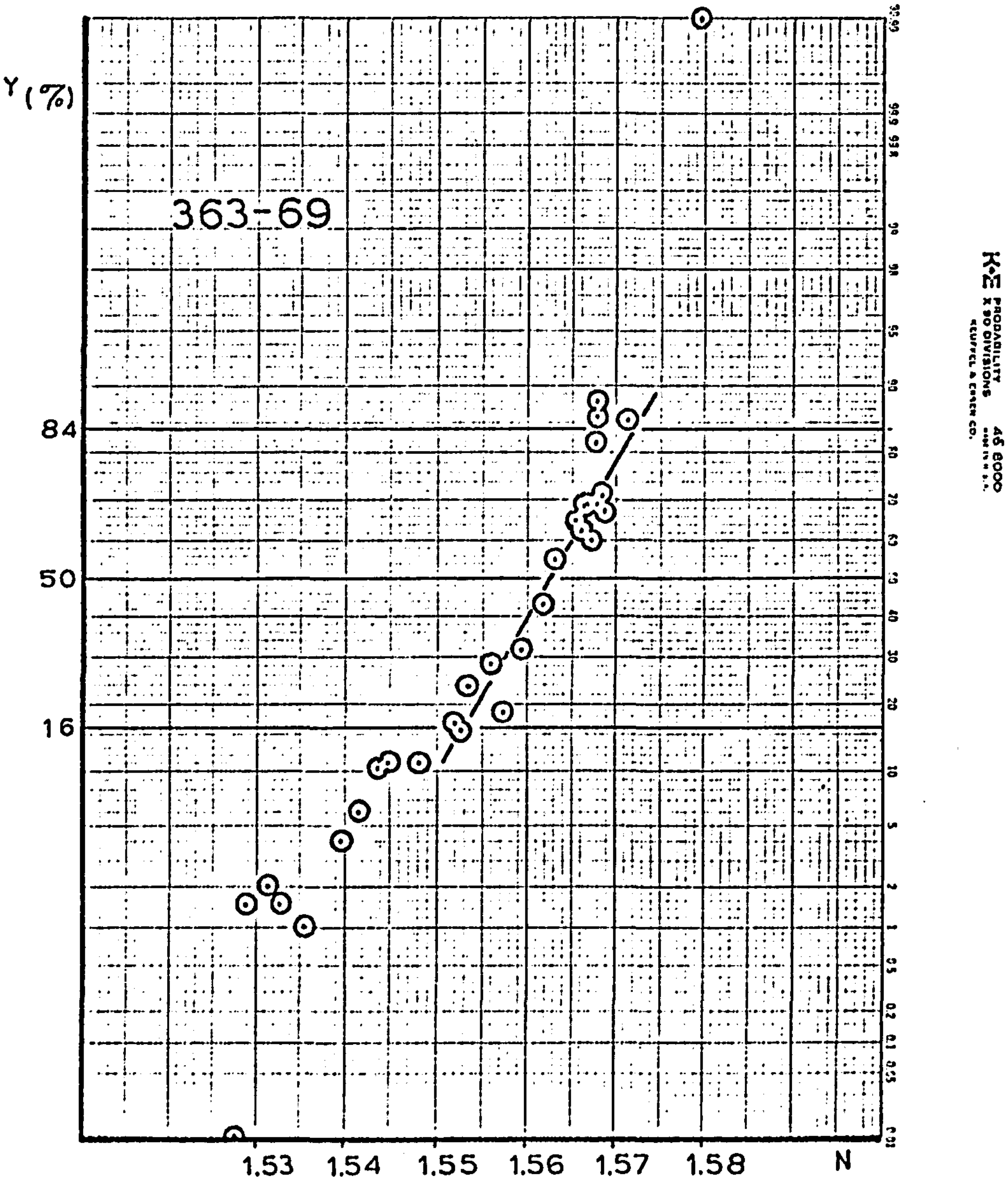

Figure 3. Gaussian probability paper plot.

Straight line fit by eye to immersion data plotted on normal probability paper. Refractive index N (abcissa) versus cumulative relative frequency Y (ordinate). The sample is 363-69 (Lindsley and Smith, 1971). Thirty-one points from 22-26 July 1972 work are shown. Indices are measured as randomly encountered. See also Figures 7, 8, 9A, 9B, and Table 21.

A straight line is fit by eye to the data within the limits of one standard deviation (1 s) on either side of the mean. The straight line fits the data sufficiently well within 1 s of the mean.[10] The graphically determined mean refractive index of the randomly encountered grains is about 1.5625.

The standard deviation of the best Gaussian curve fit to the data is the absolute difference between the value of the mean and the value on the abcissa of either of two lines parallel to the density axis, drawn equally far from the mean, and enclosing between themselves 68 percent of the area under the curve (Baird, 1962). Therefore, the refractive index values, one standard deviation on each side of the mean refractive index, are found by reading the indices corresponding to values on the cumulative relative frequency axis at 16 or 84 percent against the best straight line fit to the data on probability paper. The absolute difference between one of these index values and the value of the mean index defines the value of one standard deviation of the refractive index curve.

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[10] The mean refractive index is found in Figure 3 by fitting the best straight line to the data by eye and then reading the value on the abcissa that corresponds to the 50 percent level on the ordinate. A mathematical best fit is quite a tedious chore without a computer. Use of a computer obviates the need for a probability paper solution.

The Gaussian assumption of index distribution is apparently violated beyond 1 s in both increasing and decreasing index directions. There are fewer high index and more low index members of the sample population than would be expected in a Gaussian distribution. This apparent violation of the normal distribution assumption prompted the work shown in Figure 8.

USE OF COMPUTERS IN THIS WORK.

When a large number of data points in a set or a large number of data sets require treatment, the more elegant numerical solutions available through electronic computer become attractive especially with regard to time savings. A teletype is connected remotely to an IBM 360 or a Nova 1200 computer.

Use of IBM 360.

The mean (DMEAN), the standard deviation (DSD), half the width of the zone of apparent match (DX), the standard error of DMEAN (SDM), the standard error of DSD (SDS), the standard error of DX (SDX), and the standard deviation of the residuals of the data about the best fit Gaussian curve to the data (SD) are computed by program CUM which is available on request. Data input to CUM are a minimum of 3 counts of L and E at 3 different indices n for each phase region investigated in a sample. The program handles any number of successive such calculations.

Consistently repeatable departures of data from the best fit straight line through the data plotted on normal probability paper and large values of SD returned from program CUM are both indicators of departures of the data from the assumption of a Gaussian distribution.

Detailed empirical definition of density functions may be desired, especially if the values of SD or DSD are high.

The importance of use of computers in the present work cannot be overemphasized, for a principle aim has been to construct reliable determinative curves. Computers yield results to precisions unavailable by graphics. But workers without computers should realize that the reason for producing graphical representations of the mathematical relations defined is precisely to make the results available to all petrographers, whether or not they have computers.

It is here emphasized that the work treated in the present dissertation considers only the parameters DMEAN and DSD in detail, their analogs being available also from the graphical approach. The parameters not treated here in detail will be more fully explained in the aforementioned work of Johnson and Langford.

The IBM time sharing option which makes remote terminals interactive with the IBM 360 computer is called TSO. It is now possible to do all work at the microscope even to the extent of entering data for CUM and having returned to the terminal the statistics fit by computer to the data just submitted. It is also possible to submit all or any part of the data sets stored on disk as card images and receive the return either at the terminal, as standard IBM printout, or both. However, TSO is not always available at this installation, the costs are rather high, the system is rather inefficient and time consuming, and the procedure is not recommended as a standard operation. In particular, the excessive connect time required while work is done at the microscope and the resultant cost of typing in card images tend to make the procedure prohibitively expensive unless connect time costs are reduced. Storage of such data on a disk available to several remote terminals would make possible an interlaboratory data bank which could be of great importance in such works as the present. A program which lists the data in any data set on disk and at the same time punches out cards is available.

Use of Nova 1200.

The language used with the Nova 1200 is Multiuser BASIC. An adaptable program of about 6000 words of core storage is used for oil calibrations and generation of data for program

CUM. The program is interactive and requests data input in a repeating logical pattern which frees the operator's mind from most calculations. It stores calibration equations for each calibrated oil. The program is stored on paper tape and is available on request.

It is now possible to enter program CUM to the Nova and have it work from disk on data entered from the terminal near the microscope. This should in the future avoid IBM connect time costs for workers wanting quick numerical returns on data as generated. It should also make possible computerized data processing at laboratories without IBM computers but with mini computers. For instance, such computerized data processing aboard ships now seems feasible.

SAMPLE PREPARATION.

Mineral samples.

Mineral samples were crushed by pounding and were sieved into various size fractions. Some samples were already so processed when received from donors. There is no obvious reason to select any particular size fraction other than convenience unless grains very often display distinctly different indices within the same grain. This is due to zoning. In such cases, finer pounding is indicated. The largest size used here is .124 mm; the smallest, .032 mm.

Low concentration of the subject mineral in a crushed rock specimen at times (*e.g.* 55MV-32) necessitates magnetic separation, but heavy liquid and magnetic separations are generally not needed unless coexisting phase regions generate confused results or concentration of an unweathered portion of a mineral phase region seems indicated. More often, counting is possible by visible separation of the mineral desired in a mount of mixed minerals. The present results confirm the *a priori* assumption that these guidelines would suffice.

<u>Rock samples</u>.

When working with rock samples, pounding should reduce the grains to a fraction smaller than the predominant rock grain size.

Each chip of rock is pounded in an iron mortar with an iron pestle. Although it is not known what proportion of the opaque grains seen are iron from these tools, the malleability of the iron seems sufficiently greater than that of the opaque minerals, and such contamination is believed to be negligible.

Pounding is done gently at first, sifting often to obtain a 0.032-0.061 mm fraction. As the specimen is reduced to smaller sizes, first the weathering products, then the fresher non-opaque minerals, and finally the tenaceous opaques are passed through the 0.061 mm sieve until no sample remains greater than that size.

After the first few pounding and sieving cycles, the sample tends to form clods from pounding. These are broken up by gentle rubbing between mortar and pestle. This is not grinding.

The -0.32 mm part is set aside and not treated here. It probably contains a greater proportion of weathering products than the part used for immersion work. Thus, comparison of a chemical analysis to modes produced by the present method may show some discrepancies; for chemical analyses refer to total rock, in most cases somewhat weathered.

Possibility of modes from immersion data.

Plots of Y derived from counting in crushed rock containing several minerals are made to pinpoint index ranges of particular interest. A range of indices between the maximum of one and the minimum of another mineral is at times so defined. Optical separation of one mineral from the other is then trivial. A best fitted horizontal straight line to data points taken at various indices yielding an approximately constant value of Y theoretically should provide an estimate of such a phase region's modal percent, assuming a lower or upper bound to the phase region is found in the same way. The method is explored and discussion is continued below, but sufficient data have not yet been generated to allow best fitting of a horizontal straight line between two such mineral index ranges for any rock sample.

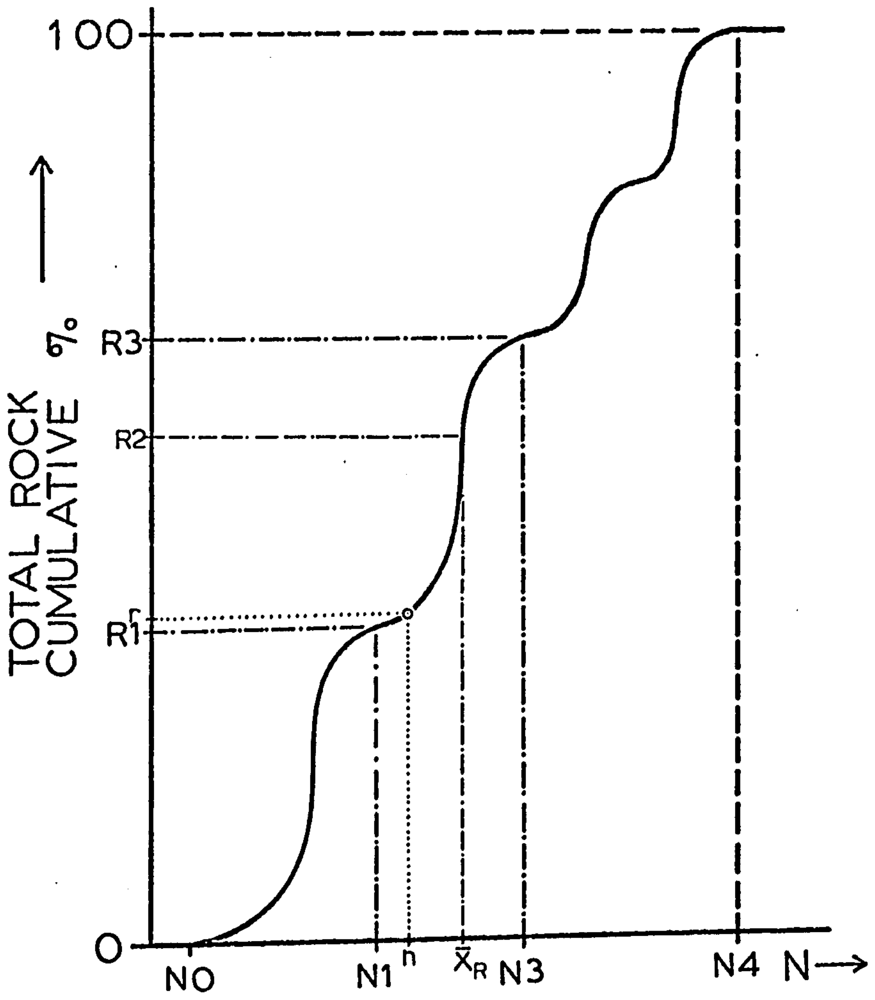

Figure 4. Theoretical model relating total rock cumulative frequency distribution to modal percents.

Figure 4 provides the theoretical background, the working hypothesis, for the work shown in Figure 7.

Grains of a total rock are crushed and not separated. Immersed in a series of oils, there is some index N0 below which no grain in any orientation matches the oil; and there is an index N4 above which no grains in whatever orientations match the oil. Opaques, when present, are assigned to the highest step, in which case the value of N4 is not defined.

For purposes of initial simplicity, each phase region is assumed to range over a distinct and limited range of indices; and phase region indices are assumed not to overlap. So, no matter whether or not the phase region of interest has a Gaussian distribution of indices, tails of phase regions are defined by slopes approaching the horizontal.

If there is no index overlap between two contiguous phase regions, as for plagioclases and apatite, a truly horizontal slope is expected over some range of N. But more generally, phase regions overlap to some extent. N1 and N3 of Figure 4 are the lower and upper limit of a phase region whose mean index is at Xbar(R). R1, R3, and R2 are the corresponding counts of cumulative frequency (Y = L + E/2). Any index chosen is labelled *n*; for each *n* there exists an *r*.

Preliminary work shown in Figure 7 was done on the assumption that a wide gap of indices in the total rock probably exists between the upper limit of plagioclases and the next higher mineral, say, apatite, for all rocks considered. Definition of the total rock cumulative percent at which the curve becomes horizontal for such a case would provide a new way to estimate the modal percent of minerals in rocks--the modal percent would simply be the difference between R1 and R3 for each phase region.[11] R1 could be 0; R3 could be 100.

Treatment of broad phase regions in crushed rock.

Separation by magnetic and heavy liquid methods of the various rock phase regions in a sample may yield broad or narrow standard deviations of the refractive index distribution function for each. If DSD or SD values are high and the specimen is of particular interest, it may be necessary to get lots of data at closely spaced index intervals in an attempt to define the actual density function of indices in the sample. Such is the case here below with sample 363-69.

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[11] Of course, rocks generally have overlapping indices from contiguous phase regions. But the theory is young and must first work for simple cases before development to fit more complicated situations makes sense.

Part of sample 363-69 was separated by Frantz magnetic separator to allow precise empirical definition of the felsic portion alone. The data are analyzed graphically and the unweighted data are analyzed by program CUM and are reported in Table 10 for DMEANBP only. Table 21 summarizes the raw data and shows a run of CUM.

CHOICE OF IMMERSION MEDIA.

All indices treated here are measured with monochromatic sodium light.

Preliminary work establishes the range of indices to be encountered in a phase, and an oil is chosen of an index somewhat higher than what appears to be the mean index of the subject mineral. Different stage temperatures are used to obtain immersion indices at several different values over the range of indices of the subject mineral phase region so that counts may be made.

Graphs are useful during data collection even if a computer is to be used. Plots of Y[12] on normal probability paper can guide the choice of the next oil index n. Also, graphs may be used during data collection to spot outliers so that counts may be repeated immediately as a check.

Having plotted a point on the normal probability paper,

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[12] Recall, $Y = L + E/2$.

assume a slope similar to slopes already plotted for other samples nearby. Choose next an oil index which is determined by the intersection of the projected line and the 50 percent value of the probability paper ordinate. Plot the point resulting from a count at this index and connect the two plotted points. Project the resulting line to intersect the ordinate of 16 or 84 percent to choose an index about one standard deviation from the mean. Count at the indicated index and plot the result. Count at other indices as necessary to give confidence that the best straight line fit by eye to the data is sufficiently good for your purposes. Submit the data to computer fitting if possible.

When determining a mineral already determined by another worker who has supplied a compositional estimate, relate the reported composition to an expected index for the POD related by the present work to DMEANBP. If the mineral is not treated here, a need for new work along the present lines exists for the mineral. Use the best formula available, if one exists, to estimate the expected DMEANBP for the sample. Select an appropriate oil. Determine graphically or by on line computer the temperature desired at the stage thermistor. Translate the temperature desired to ohms balancing the Wheatstone bridge; set the stepped resistor accordingly. Adjust the substage heater and the superstage infrared heater to bring the thermistor to the desired temperature under the optical conditions to be used while counting.

COUNTING INDICES IN SEGREGATED MINERAL GRAINS.

Two methods of counting have been used: the first applies to randomly-oriented grains; the second, to grains oriented by optic figure to display the desired principal index when lit by plane-polarized light from below.

Either high (40X, NA=0.85) or medium (10X, NA=0.22) power objectives are used in conjunction with a 10X ocular to establish by Becke line or van der Kolk illumination techniques whether each grain is less than, equal to, or greater than the index of the immersion medium. Care is taken that no operator bias in any way affects the orientation of the grain prior to assignment of the grain to the most appropriate index category.

For both unoriented and oriented grains, each grain is assigned to the most predominating category it displays unless, as happens often enough to be remarkable, the grain is large enough to display quite clearly that half of it belongs to one category, half to another. If the half-volume of the grain is comparable to the volumes of other grains commonly in the field, one count is assigned to each of the appropriate categories. Otherwise, the grain is assigned to the category of the most prominently displayed index. Following such a count, the sample is pounded to a finer size to eliminate this zoning problem. See more in Appendix C under "DETAILED SUGGESTIONS FOR COUNTING INDICES."

COUNTING INDICES IN UNSEGREGATED GRAINS OF CRUSHED ROCK.

Counts of L, E, and G for the Maui, Hawaii, rocks as well as for a sample of the Lindsley and Smith sample 363-69 were made without separating one mineral phase region from another. The attempt was made to keep each mount of grains in oils representative of the total rock with respect to proportions of minerals. Sampling of the vial containing the powder was done by tilting the vial over the slide on the stage and tapping until enough grains fell out.

NUMEROUS INDEX COUNTS OVER A BROAD PHASE REGION.

An empirically drawn density function of sample 363-69 segregated felsics is constructed by plotting E (percent equal) from beta-prime counts at 31 different indices. During these counts, though 100 grains were counted at most chosen indices, some counts were made of as few as 50 grains.

RESULTS, DISCUSSION AND CONCLUSION

RESULTS

STATEMENT OF PRECISION AND ACCURACY.

Temperature precision.

A typical oil rounds to the same thousandths of refractive index over a temperature range of about 2° Celsius. So temperatures should be controlled to +/- 1°C for work rounding to thousandths. Temperature control in this work is precise to at least one and possibly two orders of magnitude better than required.

Repeatability of immersion medium calibrations.

Using the enlarged version of the Jelley refractometer (Appendix B) increases precision from about 0.0008 for the unmodified model to about 0.0002.

Eighteen readings of index (N) vs. temperature (T) were taken on 4 March 1972 for an oil labeled 1.536 (at 25°C in sodium light) by the manufacturer. The resulting equation chosen was of second degree, and it indicated a refractive index of 1.5361 at 25.0°C. The same oil was again calibrated with 7 readings of N vs. T on 7 March 1972. A second degree equation was again chosen. It indicated a refractive index of

1.5355 at 25°C. A combination of the data from the two days resulted in 25 data points and a second degree equation which was virtually a straight line. The indicated refractive index at 25°C was 1.5359. The significance of this work is that repeatability of immersion medium calibrations to 3-place accuracies seems to hold for as few as 7 datum points.

Mineral index measurement precision and accuracy.

All refractive indices measured by the present study are subject to inaccuracies which may be present in the numbers assigned to the indices of the Corning calibration glass and the quartz omega used in calibrating the system. Independent corroboration of these values would be ideal, but lack of such corroboration here does not reduce the usefulness of the derived relationships between DMEANBP's and indices of known POD's.

Indices obtained by varying the temperature in a single medium rather than by changing the medium itself are relatively more precise, probably being on the same order of precision as is the ability to reproduce readings on the big refractometer scale, i.e. 0.0002.

Since use of more than one oil produces a systematic change, if more than one oil is used, use of as many oils as possible results in averaging the systematic errors of each and tends to improve accuracy.

Although the double variation method has not been used in this work, use of that method would reduce the number of immersion media required for most mineral work and would thereby allow increased precision and accuracy.[13]

Grains of the Corning glass were found to disappear over a zone of up to about .0004, in accordance with the results of Saylor (1935).

The conclusions of Gillberg (1960, p. 509) are pertinent: "For a refractive index, accuracy of 0.001, orientation error is of little importance compared with the other errors in routine determinations by the immersion method, at least for minerals with weak to strong birefringence. Only for minerals with very strong birefringence, e.g. many carbonates, need the orientation be perfect.

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[13] Emmons (1928, p. 506) used only 13 liquids to cover the range of indices "from 1.40 to 1.78 without a single interruption, and usually with considerable overlap."

"When an accuracy of 0.0005 is desired, the orientation must be almost perfect for minerals of strong and very strong birefringence. In the case of an accuracy of 0.0001, the orientation must be perfect except for minerals with very weak birefringence."

Examination of outlying data points and addition of new data to test the truth of outliers or reduce the residual in all cases resulted in discovering errors. These were most often linked to a series of data taken with an almost dead 12 volt battery driving the Wheatstone bridge. It was at the time the dead battery was producing sporadic readings that an accident with too much heat from a soldering iron produced such strains in the stage slide glass that a new stage slide and thermistor had to be built and the entire system recalibrated.

The six weeks' of resulting down time in operations was used in part to make the Nova program more efficient and the electronics more precise.

Whereas the conclusions of Gillberg are based on pure theory, the results reported here are empirical, and it is important to realize that the present results encompass inaccuracies of calibration equations, operator errors both at the refractometer and at the stage, and fluctuations due to temperature variations.

The standard error of the mean (SDM) is never more than 0.00125, is usually less than 0.0005, and is at times below 0.0001 (see Tables 10, 14, 17, and 19).

MINERAL RESULTS.

Plagioclase results.

Plagioclase weight percents were determined by microprobe (analyst, Fodor, R. V.) for samples original to this work and not previously reported in the literature. These were done at the courtesy of Dr. Klaus Keil, Director, Institute of Meteoritics, University of New Mexico. They are reported in Table 9. Estimates of An and Or in Table 9 are mine. They are based on ideal formulas and molecular weights as given by Johannsen (1969). The program which calculates these estimates is available on request.

Table 9. Plagioclase microprobe analyses.

	CaO	Na_2O	K_2O	An	Or	Xbar An	s An	Xbar Or	s Or
	00.112	11.689	.012	00.56	0.07				
	00.069	11.251	.029	00.36	0.18				
P1	00.068	10.980	.130	00.36	0.82	00.54	0.22	0.32	0.26
	00.155	10.796	.054	00.83	0.35				
	00.069	10.901	.039	00.37	0.25				
	00.151	11.204	.036	00.78	0.22				
	02.446	09.636	.386	12.67	2.38				
	02.474	09.428	.340	13.07	2.14				
P2	02.269	09.453	.446	12.01	2.81	12.54	0.59	2.54	0.32
	02.379	10.044	.389	11.93	2.32				
	02.357	09.645	.485	12.18	2.99				
	02.442	09.023	.403	13.36	2.63				
	08.886	06.188	.150	45.34	0.92				
	08.943	06.300	.165	45.02	0.99				
	09.275	06.108	.148	46.73	0.89				
P3	09.375	06.308	.140	46.23	0.82	45.69	0.60	0.81	0.15
	09.085	06.364	.092	45.36	0.55				
	09.103	06.500	.130	45.79	0.76				
	09.416	06.572	.126	45.37	0.72				
	10.177	04.986	.229	53.14	1.44				
	10.307	04.787	.258	54.93	1.64				
P4	10.816	05.370	.299	53.24	1.75	53.61	0.65	1.44	0.25
	10.577	05.490	.193	52.48	1.14				
	10.235	05.107	.183	53.45	1.14				
	10.570	05.155	.251	53.80	1.52				

Table 9. (Continued) Plagioclase microprobe analyses.

	CaO	Na_2O	K_2O	An	Or	Xbar An	s An	Xbar Or	s Or
	14.172	03.243	.208	71.07	1.24				
	13.765	03.490	.216	69.95	1.29				
	13.877	03.714	.126	68.19	0.74				
	15.816	02.621	.153	77.30	0.89				
P5	14.440	02.885	.170	73.85	1.04	71.24	2.88	1.03	0.23
	14.064	03.132	.165	71.78	1.00				
	14.142	03.300	.106	71.11	0.64				
	13.873	03.659	.198	68.21	1.17				
	14.443	03.531	.215	69.74	1.24				
	16.016	02.561	.087	78.20	0.51				
	16.684	02.114	.132	81.62	0.77				
P6	16.646	02.305	.156	80.20	0.90	79.97	1.26	0.83	0.20
	15.945	02.393	.188	78.77	1.11				
	16.480	02.218	.149	80.65	0.87				
	16.439	02.258	.138	80.39	0.81				
	17.220	01.650	.125	85.34	0.74				
	17.450	01.658	.108	85.53	0.63				
P7	16.702	01.874	.133	83.30	0.79	86.35	2.25	0.50	0.24
	17.494	01.634	.048	86.04	0.28				
	17.694	01.355	.043	88.24	0.26				
	18.524	01.219	.056	89.63	0.32				
	19.158	00.508	.000	95.68	0.00				
	19.126	00.691	.027	94.06	0.16				
	18.984	00.795	.037	93.14	0.22				
P8	19.545	00.723	.064	93.73	0.37	94.12	1.19	0.17	0.13
	19.767	00.444	.010	96.26	0.06				
	19.494	00.787	.024	93.44	0.14				
	18.918	00.803	.012	93.19	0.07				
	18.923	00.739	.056	93.46	0.33				

In the following tables of indices, suffixed to the returns from program CUM[14] are letters indicating the principal optic direction to which the data apply unless the indices were measured as randomly encountered, in which case the suffix is BP. Thus, suffix B is for beta; GP is for gamma-prime.

Prefix N stands for the number of indices at which counts were made. The confused N notation is unfortunate, but context makes the meaning clear.

An estimate of the number of grains counted is obtained by the product of N and 20 for counts in known POD's; of N and 100 for beta-prime counts.

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[14] DMEAN, DSD, DX, SDM, SDS, SDX, AND SD.

Table 10. Plagioclase indices from this work.

	P1	P-25	U111	P2	2693	U112	P-5	P-8	P3
NB	13	11	15	6	13	5	5	8	13
DMEANB	1.53402	1.53453	1.53751	1.53997	1.54112	1.54394	1.54836	1.55266	1.55604
DSDB	0.00212	0.00114	0.00140	0.00156	0.00113	0.00105	0.00083	0.00113	0.00127
DXB	0.00142	0.00058	0.00093	0.00116	0.00077	0.00101	0.00079	0.00090	0.00067
SDMB	0.00030	0.00010	0.00018	0.00017	0.00013	0.00006	0.00007	0.00010	0.00017
SDSB	0.00044	0.00016	0.00030	0.00023	0.00020	0.00010	0.00012	0.00017	0.00026
SDXB	0.00030	0.00010	0.00019	0.00017	0.00013	0.00006	0.00007	0.00011	0.00017
SDB	1.68	10.66	19.16	8.22	15.73	4.13	6.52	8.91	13.30
NBP	15	13	7	5	14	6	6	7	8
DMEANBP	1.53477	1.53509	1.53723	1.53952	1.54016	1.54318	1.54673	1.55186	1.55491
DSDBP	0.00311	0.00366	0.00285	0.00313	0.00302	0.00281	0.00304	0.00162	0.00346
DXBP	0.00085	0.00075	0.00089	0.00154	0.00062	0.00095	0.00093	0.00068	0.00131
SDMBP	0.00015	0.00013	0.00015	0.00012	0.00014	0.00016	0.00009	0.00013	0.00026
SDSBP	0.00026	0.00026	0.00027	0.00023	0.00038	0.00042	0.00017	0.00025	0.00044
SDXBP	0.00015	0.00012	0.00013	0.00013	0.00015	0.00019	0.00009	0.00014	0.00026
SDBP	7.76	5.33	4.91	3.57	9.04	6.95	3.17	9.83	8.34

Table 10. (Continued) Plagioclase indices from this work.

	P4	A-175	U116	53IN-2	363-69	52BE-35	HK1955 AP	P5	HML1950 SE
NB	6	8	6	5	no data	11	4	5	6
DMEANB	1.55853	1.56067	1.56311	1.56403		1.56761	1.56852	1.56902	1.57034
DSDB	0.00091	0.00185	0.00171	0.00154		0.00164	0.00129	0.00159	0.00288
DXB	0.00087	0.00100	0.00077	0.00044		0.00074	0.00051	0.00110	0.00095
SDMB	0.00008	0.00019	0.00020	0.00017		0.00013	0.00016	0.00014	0.00020
SDSB	0.00014	0.00029	0.00027	0.00029		0.00022	0.00028	0.00018	0.00038
SDXB	0.00011	0.00019	0.00020	0.00017		0.00013	0.00016	0.00014	0.00021
SDB	5.73	11.08	9.28	10.88		10.33	10.44	4.98	7.33
NBP	7	19	4	9	31	13	5	9	11
DMEANBP	1.55760	1.56020	1.56177	1.56391	1.56411	1.56757	1.56810	1.56805	1.57015
DSDBP	0.00202	0.00195	0.00172	0.00198	0.01029	0.00336	0.00158	0.00238	0.00308
DXBP	0.00079	0.00038	0.00034	0.00034	0.00228	0.00073	0.00037	0.00089	0.00084
SDMBP	0.00019	0.00004	0.00003	0.00012	0.00028	0.00026	0.00009	0.00020	0.00013
SDSBP	0.00038	0.00010	0.00008	0.00024	0.00056	0.00047	0.00013	0.00027	0.00020
SDXBP	0.00020	0.00004	0.00003	0.00011	0.00029	0.00023	0.00009	0.00020	0.00012
SDBP	9.83	4.16	1.92	7.29	6.03	11.24	5.02	8.24	5.32

Table 10. (Continued) Plagioclase indices from this work.

	HK1868 G2	55MV-32	P-24	52BE-29	P6	55BE-1	P7	P-18	P8
NB	5	5	4	5	12	4	13	4	8
DMEANB	1.57087	1.57092	1.57210	1.57236	1.57492	1.57861	1.57997	1.58282	1.58412
DSDB	0.00116	0.00251	0.00102	0.00133	0.00130	0.00172	0.00252	0.00074	0.00170
DXB	0.00062	0.00092	0.00065	0.00012	0.00099	0.00088	0.00133	0.00038	0.00130
SDMB	0.00008	0.00024	0.00014	0.00016	0.00011	0.00017	0.00022	0.00030	0.00013
SDSB	0.00012	0.00042	0.00026	0.00030	0.00016	0.00026	0.00035	0.00060	0.00021
SDXB	0.00008	0.00024	0.00016	0.00017	0.00011	0.00017	0.00022	0.00028	0.00013
SDB	5.35	9.49	11.32	11.47	8.74	6.52	11.46	15.79	6.77
NBP	11	9	8	6	19	10	10	7	7
DMEANBP	1.57102	1.57047	1.57197	1.57225	1.57410	1.57898	1.57770	1.58103	1.58287
DSDBP	0.00254	0.00427	0.00192	0.00312	0.00288	0.00288	0.00341	0.00282	0.00553
DXBP	0.00054	0.00096	0.00045	0.00059	0.00085	0.00092	0.00075	0.00058	0.00153
SDMBP	0.00018	0.00019	0.00012	0.00009	0.00011	0.00021	0.00015	0.00007	0.00030
SDSBP	0.00028	0.00069	0.00027	0.00024	0.00017	0.00034	0.00024	0.00020	0.00053
SDXBP	0.00017	0.00023	0.00011	0.00010	0.00011	0.00021	0.00015	0.00008	0.00030
SDBP	8.11	7.09	7.63	3.68	6.31	9.93	5.49	3.35	5.89

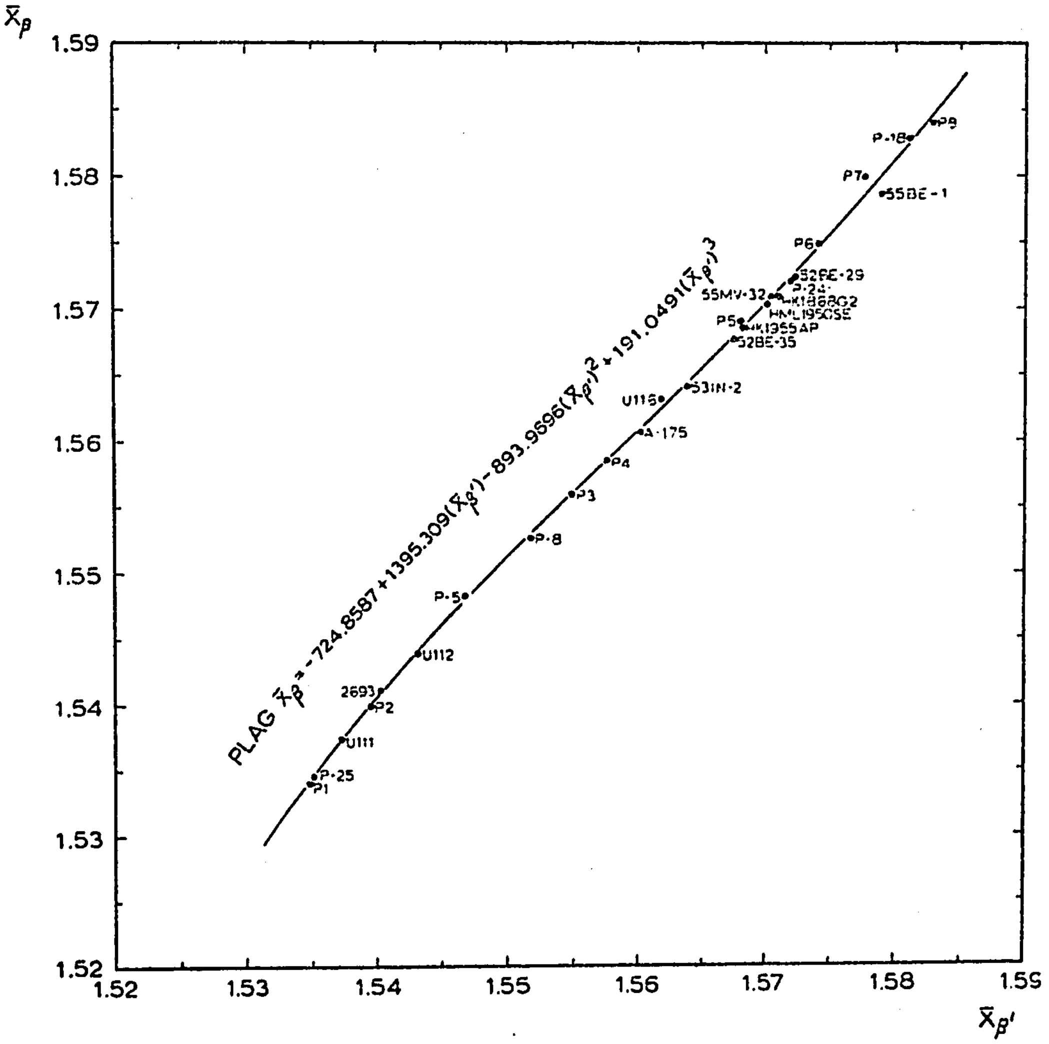

Figure 5. *DMEANB* as a function of *DMEANBP* in plagioclases.

Statistics for the third degree equation relating DMEANBP to DMEANB in plagioclases (Figure 5) are returned by the BMD05R program and are given in Table 11.

Table 11. Analysis of variance for 3 degree polynomial fit to plagioclase index data.

SOURCE OF VARIATION	DEG. OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F VALUE
LINEAR TERM	1	.0059407	.0059407	6485.7
QUADRATIC TERM	1	.0000001	.0000001	
CUBIC TERM	1	.0000053	.0000053	
DEV. ABOUT REG.	22	.0000067	.0000003	
TOTAL	25	.0059529		

The Fisher statistic (F value) indicates that the data are good to better than the 1 percent level of significance (Neville and Kennedy, 1964, p. 313; Dr. Harold G. Loomis, personal communication).

These statistics generated such small numbers as to induce a zero divide, so it was necessary to convert the BMD05R packaged program to double precision throughout (including all called subroutines). The double precision version was checked against the unmodified version of BMD05R as kept on disk by the University of Hawaii Computing Center. The returns were identical for data which did not produce such extremely small values.

Table 12. Plagioclase 2VZ's measured in this work.

	2VZ's	Xbar2Vz	s2Vz
P1	85.6,82,77.2,76,87.0,85.74,82.4,76.4,77.2	80.28	4.65
P-25	87.4,82,90.4,85.8,75.0,83.4,77.8	79.33	4.37
U111	80.4,88.0,78.4,82.8,76.0,86.0,84.2	86.30	4.75
2693	83.4,82.0,83.0,88.4,90,85.8,82.2,83.4	85.40	3.09
U112	87.6,89.4,86.8,88.4,84.4,88.6,81.8	86.71	2.71
P-5	82.4,85.8,86.4,81.6,90.8,79.0,91.6,92.4,84.6	86.07	4.73
P-8	92.0,96.0	94.00	2.83
P3	91.8,85.4,84.0,78.6,78.2,88.2,80.4	83.80	5.10
P4	81.6,86.0	83.80	3.11
A-175	89.4		
U116	77.0,78.5,79.8,81.6,74.6,87.8	79.88	4.56
53IN-2	101.0,101.0,100.4	100.80	0.35
363-69	n.d.		
52BE-35	93.0,89.5,83.4,86.4,80.0,83.8,81.2	85.33	4.63
HK1955AP	77.6,73.4,82.2,90.0,77.6,71.6	78.73	6.65
P5	87.0		
HML1950SB	92.2,75.6,84.6,68.0,89.0,75.0,92.2,90.8	83.42	9.34
HK1868G2	80.5,85.4,79.0,79.2,85.0,80.0	81.52	2.91
55MV-32	85.4,97.4,87.0,91.4,82.4,78.6,84.2,89.4	86.98	5.80
P-24	80.8,91.6,88.6,88.6	87.40	4.62
52BE-29	92.0,96.0,91.6,98.6,88.2	93.28	4.06
P6	94.2,91.4,94.4,96.4,85.0,93.4,89.6,97.6	92.70	4.01
55BE-1	88.6,95.8,96.4,96.0,90.4	93.44	3.66
P7	90.8,95.2,87.8,99.5,91.6,100.6,102.6	95.44	5.61
P-18	99.2,108.2,86.0,95.6,93.0;77.2(*sic*)	93.20	10.72
P-8	92.4,102.6,94.4,107.4,95.6	98.48	6.29

Table 13. Plagioclase anorthite percents estimated from sample's mean beta index.

	An	S&C[1]		An	S&C		An	S&C
P1	04.05	0.78	P4	52.26	1.35	55MV-32	75.70	1.50
P-25	04.98	0.81	A-175	56.57	1.64	P-24	78.27	1.35
U111	10.43	0.97	U116	60.85	1.33	52BE-29	78.19	1.28
P2	14.93	1.09	53IN-2	62.71	1.35	P6	83.21	1.50
2693	17.03	1.15	52BE-35	69.34	1.36	55BE-1	90.27	1.62
U112	22.70	0.78	HK1955AP	71.66	1.97	P7	92.73	1.51
P-5	31.86	0.07	P5	71.98	1.35	P-18	97.85	1.28
P-8	46.31	0.43	HML1950SE	74.84	1.73	P8	99.51	0.50
P3	47.21	0.99	HK1868G2					

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[1] DMEANB is entered in the formula of Chayes (1952) and is also entered with the sample's Xbar2VZ to formulas based on the graphs of Smith (1956,1957) for a separate estimate of An content. The mean of the two values returned is here tabulated as An; S&C represents half the absolute value of the sum of the An contents returned by the Chayes formula and the formulas based on Smith's graphs.

Olivine results.

Table 14. Olivine indices from this work.

	DTS-1	JJG-352	PCC-1	HML1950 SE	HK1868 G2
NB	6	5	10	8	7
DMEANB	1.66935	1.67013	1.67162	1.68852	1.68935
DSDB	0.00187	0.00100	0.00273	0.00814	0.00293
DXB	0.00108	0.00046	0.00090	0.00082	0.00084
SDMB	0.00018	0.00018	0.00020	0.00082	0.00034
SDSB	0.00027	0.00028	0.00033	0.00148	0.00050
SDXB	0.00018	0.00018	0.00020	0.00082	0.00034
SDB	7.76	13.48	7.60	12.36	10.98
NBP	9	9	15	5	7
DMEANBP	1.67266	1.67238	1.67046	1.69219	1.69924
DSDBP	0.00862	0.00856	0.01130	0.01160	0.01034
DXBP	0.00104	0.00177	0.00084	0.00052	0.00091
SDMBP	0.00025	0.00042	0.00027	0.00054	0.00058
SDSBP	0.00042	0.00070	0.00037	0.00084	0.00078
SDXBP	0.00024	0.00041	0.00026	0.00054	0.00058
SDBP	3.73	5.49	3.46	4.54	5.43

	4526 #3	5111 #5	5107 #4	54087 #7	5181 #9
NB	4	7	3	3	6
DMEANB	1.69667	1.73563	1.73822	1.75593	1.80421
DSDB	0.00301	0.00141	0.00261	0.00379	0.00301
DXB	0.00167	0.00038	0.00528	0.00120	0.00190
SDMB	0.00059	0.00018	0.00024	0.00049	0.00045
SDSB	0.00119	0.00026	0.00045	0.00105	0.00069
SDXB	0.00068	0.00017	0.00024	0.00052	0.00046
SDB	17.10	11.27	7.32	10.56	13.14
NBP	8	13	5	4	13
DMEANBP	1.69640	1.73684	1.73936	1.75725	1.79853
DSDBP	0.00992	0.12798	0.01147	0.01267	0.01404
DXBP	0.00169	0.00062	0.00138	0.00163	0.00094
SDMBP	0.00040	0.00082	0.00125	0.00062	0.00040
SDSBP	0.00073	0.00125	0.00284	0.00091	0.00055
SDXBP	0.00039	0.00078	0.00121	0.00061	0.00040
SDBP	4.53	7.03	11.21	3.87	3.99

Table 15. Olivine 2VZ's measured in this work.

	MEASURED 2VZ's (Kamb method)	Xbar	s
DTS-1	84.2,84.6,85.0,86.4, 88.6,89.6,92.0,92.2, 92.6,93.4	88.86	3.61
JJG-352	84.4,86.2,87.0,88.2[1], 90.4,90.6,91.4,91.6, 91.6,92.6,92.6	89.69	2.79
PCC-1	87.0,87.4,89.5,89.6, 90.2,90.2,91.2,93.4, 93.4,95.2	90.71	2.64
HML1950SE	89.4,90.2,90.2,93.6, 94.0,94.0,94.4,94.6, 100.4,103.6	94.44	4.50
HK1868G2	64.2,65.4,66.2,69.2, 71.0	67.20	2.81
4526 #3	94.0,94.8,95.6,96.8, 97.4,97.4	96.00	1.43
5111 #5	96.8,98.8,99.6, 100.8,101.0,101.6, 101.6,101.8,104.0	100.67	2.06
5107 #4	100.4,103,0,103.2, 103.6	102.55	1.45
54087 #7	100.4,103.6,105.8, 107.6	104.35	3.10
5181 #9	96.6[1],98.6[1],112.0, 113.2,114.0,114.0, 114.6,116.6,119.4	111.00	7.90

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[1] Measured on Bxaz; all others measured on Bxax.

Table 16. Forsterite estimates from mean beta indices of this work.

Estimated from data of Bowen and Shairer (1935) as presented by Deer <u>et al</u>. (1967, v. 1, p. 22).

	DTS-1	JJG-352	PCC-1	HML 1950SE	HK1868 G2
Fo	91.05	90.70	89.85	82.25	81.70

	4526 #3	5111 #5	5107 #4	54087 #7	5181 #9
Fo	78.00	59.80	58.65	50.30	27.70

Augitic clinopyroxene results.

Table 17. Augitic clinopyroxene refractive indices from this work.

	Px-1	209	215	128	269	277	259	189	227
NB	7	4	3	3	4	4	5	4	4
DMEANB	1.68277	1.68578	1.68941	1.68950	1.69397	1.69450	1.69728	1.70192	1.70280
DSDB	0.00477	0.00334	0.00212	0.00306	0.00268	0.00216	0.00272	0.00278	0.00239
DXB	0.00104	0.00136	0.00043	0.00122	0.00109	0.00120	0.00088	0.00117	0.00109
SDNB	0.00055	0.00040	0.00015	0.00016	0.00020	0.00021	0.00013	0.00032	0.00018
SDSB	0.00149	0.00068	0.00025	0.00043	0.00033	0.00032	0.00032	0.00057	0.00030
SDXB	0.00058	0.00040	0.00015	0.00020	0.00019	0.00020	0.00014	0.00033	0.00018
SDB	14.73	10.31	5.44	4.52	5.77	5.97	5.19	10.12	6.04
NBP	9	6	6	7	6	4	4	6	4
DMEANBP	1.69003	1.69236	1.69768	1.69733	1.70090	1.70303	1.70336	1.70722	1.70933
DSDBP	0.00831	0.01074	0.00753	0.00930	0.00741	0.00834	0.00911	0.00976	0.00756
DXBP	0.00074	0.00126	0.00086	0.00116	0.00098	0.00133	0.00167	0.00137	0.00086
SDNBP	0.00034	0.00092	0.00027	0.00052	0.00041	0.00025	0.00089	0.00067	0.00066
SDSBP	0.00075	0.00142	0.00049	0.00078	0.00069	0.00030	0.00113	0.00091	0.00101
SDXBP	0.00034	0.00092	0.00027	0.00052	0.00039	0.00025	0.00089	0.00067	0.00061
SDBP	5.38	9.10	3.87	6.33	4.98	2.13	7.50	6.56	6.24

Table 17. (Continued) Augitic clinopyroxene refractive indices from this work.

	205	153	254	248	1972	187	250	249
NB	4	4	3	3	3	3	4	5
DMEANB	1.70427	1.70465	1.70635	1.70713	1.70792	1.71261	1.71394	1.71670
DSDB	0.00326	0.00372	0.00286	0.00232	0.00288	0.00217	0.00296	0.00354
DXB	0.00126	0.00111	0.00075	0.00088	0.00076	0.00089	0.00177	0.00104
SDMB	0.00016	0.00041	0.00014	0.00029	0.00026	0.00023	0.00023	0.00035
SDSB	0.00026	0.00116	0.00027	0.00060	0.00051	0.00040	0.00043	0.00065
SDXB	0.00015	0.00045	0.00014	0.00031	0.00027	0.00024	0.00025	0.00034
SDB	3.40	9.24	4.00	10.28	7.48	7.77	6.51	8.60
NBP	5	6	5	4	5	4	6	6
DMEANBP	1.71170	1.70979	1.71111	1.71381	1.71552	1.71638	1.71967	1.72334
DSDBP	0.00854	0.00818	0.00659	0.00786	0.00930	0.00306	0.00826	0.00740
DXBP	0.00123	0.00039	0.00072	0.00133	0.00173	0.00318	0.00117	0.00057
SDMBP	0.00045	0.00056	0.00036	0 00072	0.00044	0.00108	0.00050	0.00030
SDSBP	0.00075	0.00081	0.00060	0.00119	0.00065	0.00234	0.00085	0.00041
SDXBP	0.00045	0.00055	0.00035	0.00071	0.00044	0.00125	0.00049	0.00029
SDBP	5.28	6.50	4.90	7.67	4.32	14.36	6.48	3.74

Table 18. Augitic clinopyroxene 2VZ's measured in this work.

	2VZ's	Xbar	s
Px-1	62.6,72.8	67.70	07.21
128	70.8		
269	68.0		
259	78.6		
189	63.6,69.4,61.0	64.67	04.30
153	85.4		
254	80.0,79.8,79.4	79.73	00.31
1972cpx	62.0		
250	63.6,88.4	76.00	17.54
249	60.0		

The reason for the augitic pyroxene 2V's being greater than those measured by other workers for the same samples and greater than augitic pyroxenes should display according to the literature is not known. It may be a function of these present 2V's having been measured quantitatively by the Kamb method, whereas the methods of other workers, generally not stated, may have been qualitative estimates based on the curves of Wright (e.g. Bloss, 1961). Comparison (not shown) of the 2V's measured by Borg and Heard (1970) to those reported here in Table 12 discloses reasonable agreement, on the other hand.

Orthopyroxene results.

Table 19. Orthopyroxene indices from this work.

	JJG-352	128	277	189	259	227	254
NGP	8	4	4	3	4	4	5
DMEANGP	1.67396	1.71500	1.72311	1.73335	1.73498	1.73658	1.74031
DSDGP	0.00154	0.00201	0.00136	0.00095	0.00093	0.00144	0.00121
DXGP	0.00104	0.00118	0.00054	0.00088	0.00078	0.00070	0.00115
SDMGP	0.00023	0.00024	0.00018	0.00067	0.00007	0.00007	0.00014
SDSGP	0.00036	0.00041	0.00038	0.00010	0.00012	0.00014	0.00019
SDXGP	0.00023	0.00023	0.00020	0.00007	0.00007	0.00008	0.00014
SDGP	15.47	9.27	11.96	4.37	5.80	4.28	7.97
NBP	5	3	6	3	5	4	4
DMEANBP	1.66835	1.70675	1.71626	1.72891	1.72932	1.73075	1.73296
DSDBP	0.00228	0.00692	0.00808	0.00376	0.00576	0.00505	0.00581
DXBP	0.00073	0.00151	0.00117	0.00043	0.00081	0.00080	0.00152
SDMBP	0.00017	0.00018	0.00069	0.00014	0.00043	0.00015	0.00018
SDSBP	0.00025	0.00026	0.00109	0.00030	0.00066	0.00023	0.00023
SDXBP	0.00016	0.00018	0.00069	0.00014	0.00043	0.00015	0.00018
SDBP	4.98	1.77	7.39	3.27	7.20	2.56	2.27

Table 19. (Continued) Orthopyroxene indices from this work.

	153	205	248	187	250	249	171
NGP	4	3	4	3	4	3	4
DMEANGP	1.74130	1.74343	1.74867	1.75472	1.75761	1.75962	1.76461
DSDGP	0.00118	0.00067	0.00056	0.00174	0.00119	0.00114	0.00286
DXGP	0.00090	0.00093	0.00033	0.00077	0.00061	0.00062	0.00143
SDMGP	0.00006	0.00093	0.00008	0.00010	0.00013	0.00011	0.00031
SDSGP	0.00008	0.00026	0.00013	0.00014	0.00018	0.00017	0.00069
SDXGP	0.00006	0.00094	0.00008	0.00010	0.00013	0.00011	0.00039
SDGP	3.04	23.80	7.53	3.79	6.77	6.43	9.68
NBP	3	4	3	4	5	5	5
DMEANBP	1.73466	1.74014	1.74163	1.74798	1.75083	1.75273	1.75793
DSDBP	0.00656	0.00285	0.00749	0.00623	0.00497	0.00559	0.00787
DXBP	0.00106	0.00057	0.00117	0.00115	0.00097	0.00096	0.00116
SDMBP	0.00033	0.00073	0.00064	0.00074	0.00036	0.00020	0.00061
SDSBP	0.00054	0.00128	0.00105	0.00099	0.00069	0.00034	0.00106
SDXBP	0.00033	0.00073	0.00062	0.00071	0.00037	0.00020	0.00058
SDBP	3.87	17.28	6.01	8.27	6.00	3.55	7.35

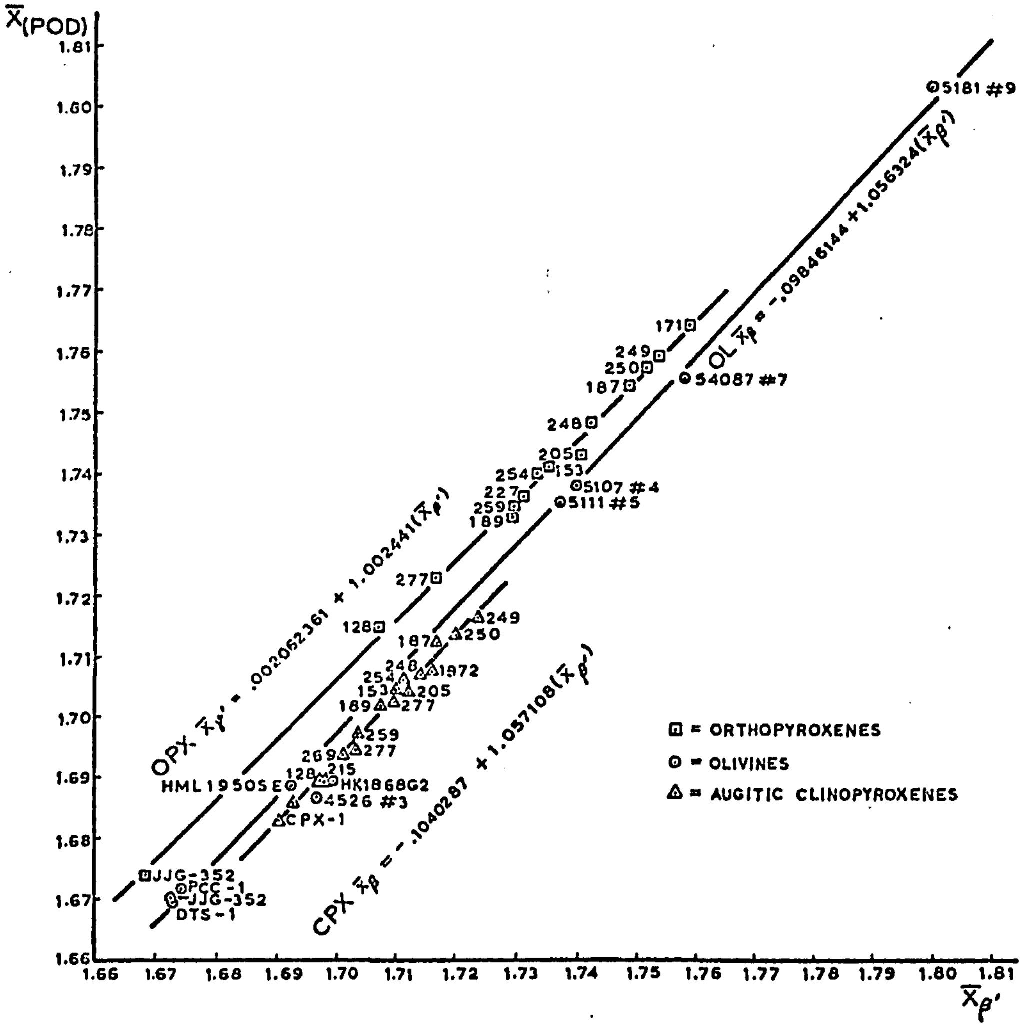

Figure 6. POD indices as a function of DMEANBP in olivines, augites, and orthopyroxenes.

Table 20. Statistics of straight line equations fit to olivine, cpx, and opx data.

	OLIVINES	AUGITES	ORTHOPYROXENES
STD. ERROR OF REG. COEF.	0.2505604	0.3179683	0.1576731
CORRELATION COEF.	0.9877570	0.9932827	0.9985189

ANALYSIS OF VARIANCE FOR SIMPLE LINEAR REGRESSION TO OLIVINE DATA

SOURCE OF VARIATION	DEG. OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F VALUE
DUE TO REG.	1	.0180989	.0180989	1777.34
DEV. ABOUT REG.	8	.0000815	.0000102	
TOTAL	9	.0181804		

ANALYSIS OF VARIANCE FOR SIMPLE LINEAR REGRESSION TO AUGITE DATA

SOURCE OF VARIATION	DEG. OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F VALUE
DUE TO REG.	1	.0016034	.0016034	1105.28
DEV. ABOUT REG.	15	.0000218	.0000015	
TOTAL	16	.0016252		

ANALYSIS OF VARIANCE FOR SIMPLE LINEAR REGRESSION TO OPX DATA

SOURCE OF VARIATION	DEG. OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F VALUE
DUE TO REG.	1	.0068618	.0068618	4042.06
DEV. ABOUT REG.	12	.0000202	.0000017	
TOTAL	13	.0068822		

Statistics returned by BMD05R for olivine, augitic clinopyroxene, and orthopyroxene straight line equations are given in Table 20. The temptation to extrapolate beyond the data should be avoided. Initial work on the plagioclases also indicated a straight line relationship. More data revealed a third degree relationship. More data may indicate higher order equations for these other minerals too.

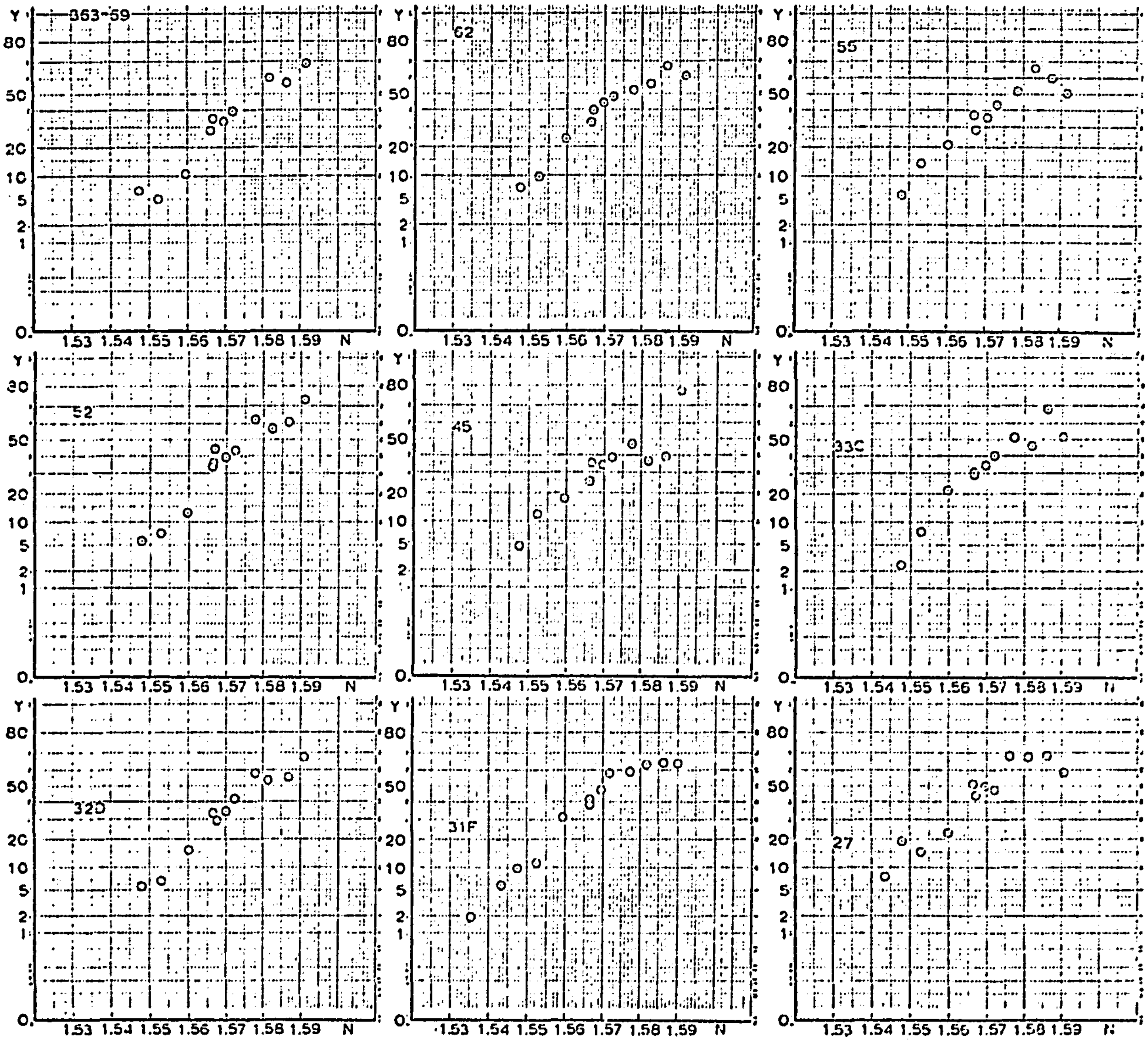

Figure 7. Cumulative frequency distribution of minerals in the refractive index range of feldspars for 9 rocks.

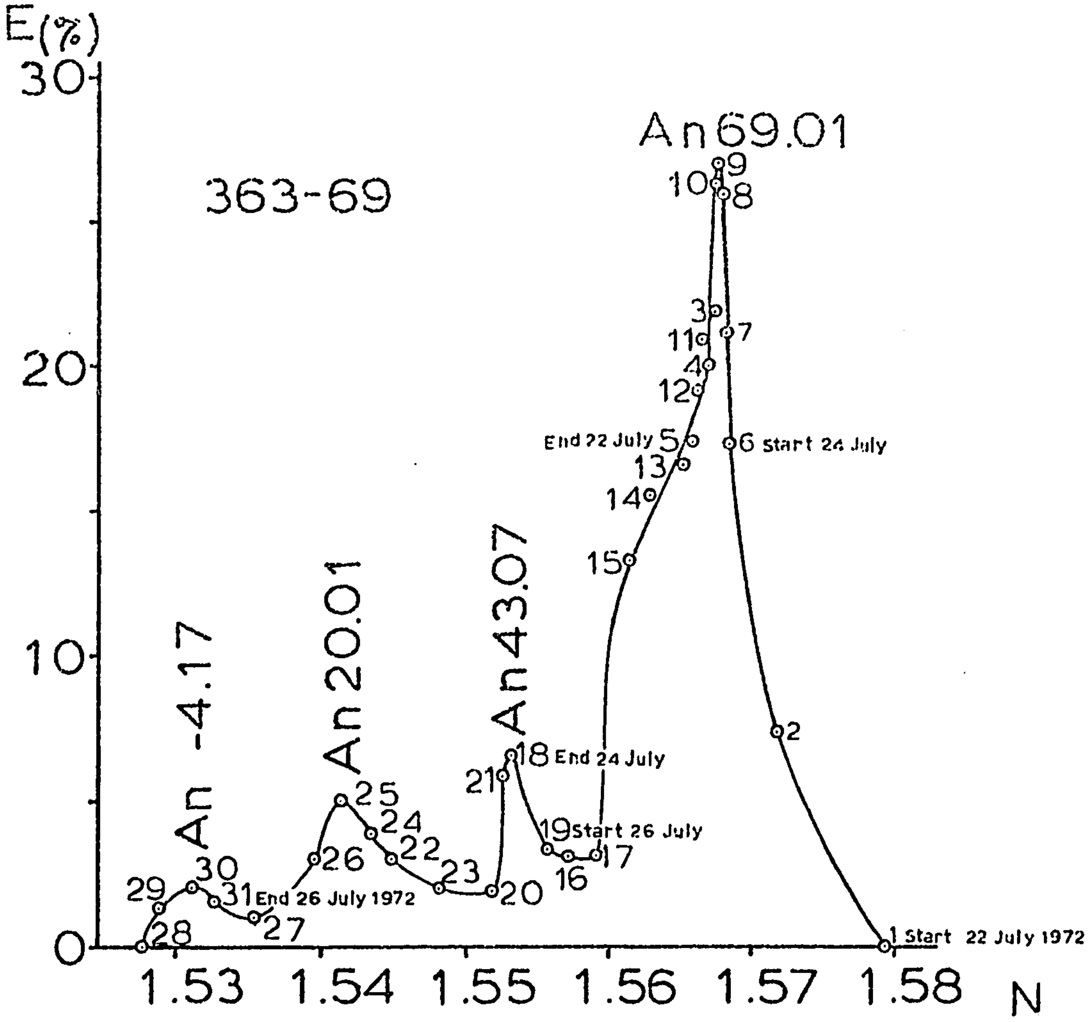

Figure 8. Empirically drawn density function.

Sample 363-69 nonmagnetic fraction: E (percent of beta-prime counts found equal the chosen n) is plotted on the ordinate against chosen refractive indices N on the abcissa of orthogonal graph paper. See also Figures 3, 7, 9, and Table 21.

The E peaks of the curve drawn in Figure 8 are interpreted by the formula of Figure 4 into DMEANB; DMEANB is then entered in the formula of Chayes (1952, p. 96, formula (2)) which returns an estimate of An. Anorthite estimates are written above each E peak in Figure 8.

```
                 LINDSLEY AND SMITH (1971), 363-69, BETA-PRIME, 22-26 JULY 1972

  I.R.    PCLT    PCEQ        IDENTIFICATION
1.527783   0.0    0.0         363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.528459   0.0    1.50        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.531070   0.0    2.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.532709   0.0    1.50        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.535483   1.00   1.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.539519   1.00   3.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.541289   1.00   5.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.543593   6.40   3.80        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.544930   8.00   3.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.548019   9.00   2.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.552010  14.90   1.90        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.552500   9.80   5.90        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.553190  17.40   6.50        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.555929  25.40   3.40        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.557249  15.40   3.10        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.559330  28.60   3.20        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.561563  30.00  13.30        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.563003  37.40  15.50        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.565209  48.60  16.70        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.566003  44.90  17.40        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.566270  49.30  19.20        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.566589  47.60  21.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.567030  40.00  20.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.567593  47.30  21.80        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.567613  57.40  26.20        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.567769  61.00  27.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.567929  60.20  25.00        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.568270  50.00  21.70        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.568589  50.00  17.30        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.571753  77.80   7.40        363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC
1.574650100.00    0.0         363-69, BETA-PRIME, ALL 7207 WORK; NO CAL ADJ NEC

  DMEAN       DSD        DX
  1.564126  0.010382  0.002314
  1.564081  0.010349  0.002288
  1.564109  0.010300  0.002285
  1.564111  0.010288  0.002285
  1.564112  0.010287  0.002285

SDM=0.00028 SDS=0.00056 SDX=0.00029

SD= 6.03PERCENT

 0.8001E-07 -0.1038E-07 -0.2652E-08
-0.1038E-07  0.3078E-06  0.3415E-07
-0.2652E-08  0.3415E-07  0.8342E-07

RESIDUALS
      -0.000087 -0.000468     0.000555
      -0.000132  0.014323     0.014455
      -0.000298  0.018602     0.018900
      -0.000530  0.012673     0.013203
       0.008672  0.014778     0.023450
       0.005503  0.024925     0.030428
       0.002062  0.037037     0.039098
       0.053678  0.060843     0.114521
       0.061531  0.059732     0.121263
       0.052960  0.020190     0.073150
       0.065986 -0.003017     0.069003
       0.008025 -0.027934     0.035959
       0.074525  0.038648     0.113173
       0.099498  0.004721     0.104219
      -0.032994 -0.143218     0.176213
       0.039886 -0.086165     0.126051
      -0.019159 -0.056684     0.075844
       0.023332  0.003577     0.026909
       0.031901  0.024124     0.056025
      -0.035658 -0.034527     0.070185
      -0.002119  0.017888     0.020007
      -0.035398  0.004199     0.039597
      -0.124576 -0.093513     0.218088
      -0.073562 -0.021659     0.095221
       0.027034  0.122993     0.150027
       0.056907  0.161744     0.218651
       0.042757  0.136510     0.179266
      -0.072265 -0.022452     0.094717
      -0.084414 -0.071533     0.155947
       0.072650  0.014548     0.087198
       0.102257  0.043358     0.145615
```

Table 21. Raw data used in Figures 3, 7, 8, and 9A.

Oil refractive index (n) and percent of grain indices matching n (E) are listed for data collected 22-26 July, 1972, on sample 363-69.

Table 21 (CUM output) lists the 31 indices *n* (here labeled "I.R." at which counts were made. L is here called "PCLT"; E, "PCEQ." The identification field follows for each case.

DMEANBP is determined in a series of iterations to be 1.5641 while DSD and DX respectively iterate to values of 0.0103 and 0.0023. The values for SDM, SDS, SDX, and SD are printed out in turn. SD is followed by a correlation matrix and table of residuals, two generated for each oil (Johnson and Langford, in preparation). The right hand column of the table of residuals is the sum of the absolute values of the two residuals generated for each oil. Since the residuals are mathematically independent entities, a large value for their absolutes summed may be a reasonable indicator of systematic errors for some *n*'s.

Raw data of this nature is available on request for all minerals treated here, but not for the Maui rocks.

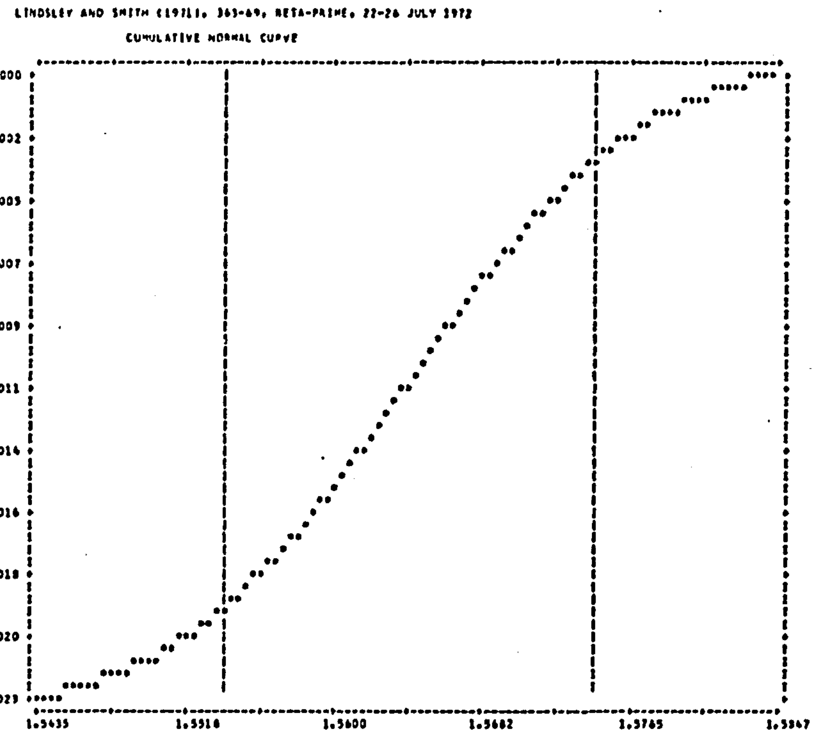

Figure 9A. Cumulative normal curve for 363-69.

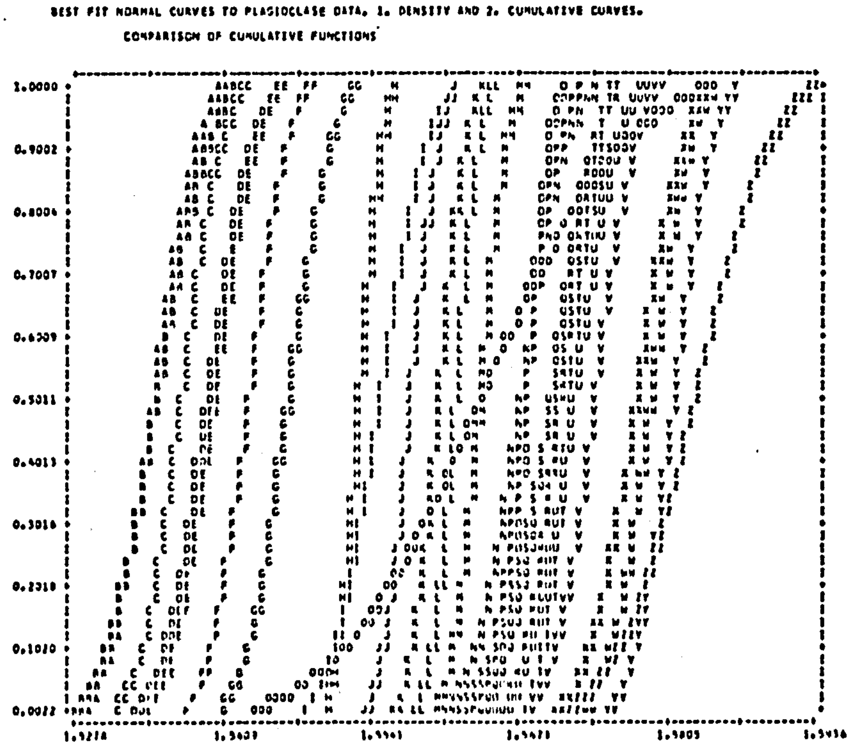

Figure 9B. Accumulated cumulative curves for all DMEANBP indices treated in Table 10.

Each set of CUM data processed generates a graph like that of Figure 9A. The program also accumulates all such plots and prints them all out at once, adjusting the scale on the abscissa to cover the range reported among all specimens (Figure 9B). This pictures nicely the remaining gaps that could be filled with new plagioclase samples.

In addition to all of the plagioclase minerals used in obtaining the equation given in Figure 5, the graph of 363-69 is shown as zeroes (do not confuse with the letter O's) in Figure 9B. The samples are ordered by increasing beta indices as listed in Table 10. The occasional reversal of the alphabet read at the 0.5011 level on the ordinate is due to slight scatter in the data. Omission of a letter is due to the space being overlaid with a later, congruent DMEANBP.

DISCUSSION

COMPARISON OF PRESENT RESULTS TO THOSE OF OTHERS.

The following tables collate refractive index or compositional estimates of this work and comparable available data stated by or inferred from works of others.

Plagioclases

Table 22. Estimates of anorthite contents in plagioclases (percents).

	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
FROM TABLE:	13	1	1	1	1	9		
AN% from:	DMEANB	CHEM. ANAL.	PROBE AVG.	X RAY	OP-TICS	PROBE AVG.	DIFF[1]	ADJ. AN EST.[2]
P1	04.05					00.54	3.51	00.80
P-25	04.98	01.0			02		3.48	01.72
U111	10.43	11.2	06.2		08		1.96	07.18
P2	14.93					12.54	2.39	11.68
2693	17.03	13.8	12.9		13		3.80	13.78
U112	22.70	20.3	18.9		18		3.63	19.44
P-5	31.86	31.9			30		0.91	28.60
P-8	40.31	38.6	37.4		39		1.98	37.06
P3	47.21					45.69	1.52	43.96
P4	52.26					53.61	-1.35	49.00
A-175	56.57	51.9	44.4		50		7.80	53.32
U116	60.85	53.2	54.6		55		6.58	57.60
53IN-2	62.71			59.9			2.81	59.46
52BE-35	68.34			70.3			-0.96	66.08
HK1955AP	71.66		63				8.66	68.40
P5	71.98					71.24	0.74	68.72
HML1950SE	74.84		68				6.84	71.58
HK1868G2	76.04		76				0.04	72.78
55MV-32	75.70			73.0			2.70	72.44
P-24	78.27	76.2			77		1.67	75.02
52BE-29	78.19			76.6			1.59	74.94
P6	83.21					79.97	3.24	79.96
55BE-1	90.27			83.3			6.97	87.02
P7	92.73					86.35	6.38	89.48
P-18	97.85		95.0		96		2.35	94.60
P8	99.51					94.12	5.39	96.26
						XBAR =	3.255	
						s =	2.663	

[1] DIFF for each sample is the difference in An percent between the estimate from Table 13 and the average of other estimates shown in this table.

[2] An adjusted estimate in terms of An percent is derived by subtracting the mean DIFF of column (8) from each value in column (2).

Discussion of Table 22.

Indices of refraction are generally not stated in the literature for the plagioclase samples treated here. Therefore, the compositional estimates given in Table 13 are repeated in Table 22 and are compared to compositional estimates shown also in Tables 1 and 9. Column (8) of Table 22 lists the difference (DIFF) obtained by subtracting values from Tables 1 and 9, or the average of such values, from the respective values from Table 13. The average difference is +3.255 percent An, and the standard deviation of DIFF is 2.663 percent An.

The mean DIFF of 3.255 indicates that a systematic error in refractive index of +0.00173 exists in the present work if the average An contents reported by others is taken as a standard.

Corrections to the An values reported in Table 13 are made in Table 22 by adding the mean DIFF to each; the resulting "adjusted An estimate" is given in column (9) of Table 22.

In response to my questioning the value Anderson reported for HK1955AP, Anderson replied (personal communication) with a list of original data and the six, separate microprobe estimates of An: 63, 64, 64, 64, 67, and 73. He says: "You will note there is little significance to my average value." Recall the similar statement quoted above from Lindsley and Smith (1971).

Compositional estimates of Borg and Heard (1970) given in

Tables 1 and 22 display wide ranges, making direct comparison of the present results to theirs somewhat tenuous. The 7.5 percent difference between An values estimated by chemical analysis versus microprobe analysis for sample A-175 is particularly noteworthy. The standard deviation of beta indices (DSDB) reported here in Table 10 is 0.00185, the largest such figure among all measured for samples from Borg and Heard. Furthermore, the microprobe ranges of An content reported in Table 1 also yield the largest value for sample A-175 among samples from Borg and Heard.

It is instructive to tabulate the available reported An ranges determined by microprobe (Table 1) against the values of DSDB given in Table 10. This is done in Table 23.

Table 23. Comparison of An range from microprobe to DSDB of this work.

	PROBE	DSDB
P-8	01	0.00113
U111	02	0.00140
HK1868G2	02	0.00116
2693	04	0.00113
U112	05	0.00105
U116	05	0.00171
A-175	09	0.00185
HK1955AP	10	0.00129
HML1950SE	12	0.00288

Discussion of Table 23.

A plot (not shown) of the data in Table 23 reveals a poor correlation between the absolute range observed by microprobe and the standard deviation defined by this method. Correlation would probably be improved if the standard deviation of microprobe compositional estimates were available rather than the absolute observed range.

In any case, when the worker is primarily interested in differentiation or other phenomena for which definition of compositional density function tails is particularly important, work like that shown in Figure 8 is indicated .

Olivines.

The most interesting olivine studied is HK1868G2 which has an anomalous 2V and the largest residual with respect to the best fit straight line of Figure 6. A direct relation between anomalous 2V's and distance from a line best fit to points of DMEANBP vs. a known POD index may be indicated.

Only five of the ten olivines treated here have compositional estimates given directly for them (Table 2), though chemical compositions are available for the others (Table 3).

Table 24 compares the estimates of forsterite based on the present work (from Table 16) with forsterite estimates made by other workers (Table 2).

Table 24. Comparison of forsterite estimates in olivines.

	(2) TABLE 16	(3) TABLE 2	(2)-(3)
HML1950SE	82.25	84	-1.75
HK1868G2	81.70	79	2.70
4526 #3	78.00	78.9	-0.90
5111 #5	59.8	60.0	-0.20
5107 #4	58.65	59.3	-0.65
		Xbar =	-0.16
		s =	1.70

Discussion of Table 24.

The -0.16 mean difference in forsterite estimates derived in Table 24 indicates a systematic error of refractive index in the present work of about 0.00034 too high. The differences are small enough to be ignored.

Augitic clinopyroxenes.

Refractive index data of the present work are compared in Table 25 to refractive indices reported in the literature (128 and 153), reported in personal communication (Px-1), or inferred from the X-ray emission spectrochemical analyses of Butler (1969) (all the other samples):

Table 25. Comparison of DMEANB indices to reported or estimated indices of other workers for augitic clinopyroxenes.

	(2) DMEANB[1]	(3) BETA[2]	(4) (2)-(3)
Px-1	1.68277	1.6791	.0037
209	1.68578	1.6826	.0032
215	1.68941	1.6855	.0039
128	1.68950	1.689	.0005
269	1.69397	1.6932	.0008
277	1.69450	1.6945	.0000
259	1.69728	1.6967	.0006
189	1.70192	1.7019	.0000
227	1.7028	1.7023	.0005
205	1.70427	1.7068	-.0025
153	1.70465	1.710+/-.01	-.0054
254	1.70635	1.7000	.0064
248	1.70713	1.7073	-.0002
1972	1.70792	----	---
187	1.71261	1.7122	.0004
250	1.71394	1.7140	-.001
249	1.71670	1.7177	-.0010
		Xbar =	.0007
		s =	.0027

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[1] Data from Table 17.

[2] Indices for Butler (1969) samples (Table 4) estimated from plots of Butler analyses on quadrilateral of Deer *et al.* (1965, p. 132).

Discussion of Table 25.

Table 25 shows that the systematic error detected in the present work with respect to refractive indices of plagioclases and olivines is corroborated. It also shows that the standard deviation of refractive indices measured in this work compared to indices from other work is 0.0027 for augites. However, the large majority of data in column (3) are inferred from graphical interpretation of X-ray emission spectrochemical analyses. They are subject to errors of drafting as well as to errors of inference. Nonetheless, the errors seem to be quite small.

Orthopyroxenes.

Whereas the relationship of indices to composition in augitic clinopyroxenes is complex, it is quite straightforward between the gamma index and composition for orthopyroxenes. This permits translation of orthopyroxene analyses directly into inferred gamma indices via an equation. Such is the approach taken in Table 26 for the samples of Butler (1969):

Table 26. Comparison of DMEANGP and reported or estimated indices from work of others for orthopyroxenes.

	(2) DMEANGP[1]	(3) GAMMA[2]	(4) (2)-(3)
JJG-352	1.67396	-----	---
128	1.71500	1.707	.0080
277	1.72311	1.72017	.0029
189	1.73335	1.73472	-.0014
259	1.73498	1.73240	.0026
227	1.73658	1.73606	.0005
254	1.74031	1.73696	.0034
153	1.74130	1.737	.0043
205	1.74343	1.74456	-.0011
248	1.74867	1.74479	.0039
187	1.75472	1.75028	.0044
250	1.75761	1.75431	.0033
249	1.75962	1.75749	.0021
171	1.76461	1.76061	.0040
		Xbar =	.0028
		s =	.0025

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[1] From Table 18.

[2] 128 and 153 from literature. Other samples those of Butler (1969).

Discussion of Table 26.

The systematic error of refractive indices measured in the present work is again apparent. The standard deviation of refractive indices inferred from or stated by other work relative to those measured in this work is 0.0025. This is on the same order as was found for augitic clinopyroxenes. The orthopyroxene refractive indices measured seem to be about 0.0028 higher than might be expected from the work of others.

FEASIBILITY OF MODES FROM IMMERSION DATA.

Referring to Figure 7, data for samples 62, 55, 31F, and 27 indicate approximate modal percentages of feldspar respectively of 60%, 60%, 64%, and 68%. These percentages are derived by assuming all of the data below the break in the straight lines fit to the data for each to be due only to plagioclase. Also, it is not always clear just where to draw a horizontal line. The presumption is made, but work has not been done to demonstrate that it is so, that there are no other minerals in the samples having indices near those of high-index plagioclases. Lack of a distinct break in the trend of data points for samples 363-69, 52, 45, 33C, and 32D may be due to minerals other than plagioclase with indices in the 1.59 region, but is more likely due to some other cause. No minerals obviously not plagioclase were noted in this region.

Lack of complete success in this first attempt to determine modal percent from total rock counts of L, E, and G may be due to the sampling technique used between vial and stage slide. The sample in the vial was twirled and shaken before and after each removal of material. But the material was removed by tipping the vial and tapping the mouth above the stage thermistor until a sufficient number of grains were on the slide. This may have permitted lighter grains to slip differentially over heavier grains during some but not all counts. Perhaps the use of a small sampling spoon (such as a flattened end of a paper clip) might reduce the suspected effect. Further work on the problem is needed to find out whether modal estimates can be done practicably in crushed grain work without resorting to tedious separation and weighing methods. Also the theory deserves further attention. For instance, what are the effects of counting percent of mica by this method vs. the Chayes method? If the effects are sufficiently strong, can a correction factor be applied?

Also, lack of success in the initial work may be due to not having taken enough counts between the upper limit of plagioclase indices and the lower limit of the mineral of next higher indices. Perhaps the next step should be to mix some known proportions of feldspar, apatite, and some ferromagnesian mineral of high index, say, olivine. Count results could be meaningfully compared to the known proportions to provide quickly the answer as to whether the method is worth further pursuit.

DENSITY FUNCTION OF CONCENTRATED FELSICS.

With respect to the results of the empirically drawn density function for the felsic portion of 363-69, it appears that graphs of probability density functions for mineral phase regions which do not adhere to the assumption of normal refractive index distribution provide useful comparisons of kindred rock specimens. The data of Figure 8 display a high degree of reproducibility. Notice the fact that DMEANBP returned by program CUM for 363-69 (Table 10) falls centrally in the region of the widest peak of Figure 8. If workers require rapid knowledge of the approximate distribution of indices for a mineral phase region, either the graphical methods or the computer method should be useful. The difference between the graphically drawn solution for DMEANBP and that returned by CUM for 363-69 is only 0.0016, indicating that the graphical solution is quite good even for a sample with so large a DSD value.

Figure 8 shows a strong peak at An69.01. This is in direct conflict with results expected from the description of Lindsley and Smith who define a compositional gap between An65 and An75 (1971, p. 275). However, they refer to phenocryst cores and rims in general for the area studied, while the present results refer to total rock felsics in a specific sample. So this notable exception to the general agreement of the present results to results of other workers may be resolved.

The negative An percent displayed by the lower index end of Figure 8 is interpreted as being caused by potassium feldspar. This suggests the possibility that a negative An percent may ultimately be translatable by equations into an Or percent; or that a single equation may be found to cover all feldspars. Lack of a significant mode between 1.544 and 1.553 suggests that 363-69 contains no amount of quartz detectable by this method.

REVIEW OF ACCURACY OF THIS WORK.

The results of all four mineral groups treated show a systematic error in the present work which has resulted in index measurements slightly higher than expected in view of the work of others. For plagioclases, olivines, augites, and orthopyroxenes respectively, the indices seem to be too high by : 0.00173, 0.00034, 0.0007, and 0.0028.

The source of the systematic error is not known, and the pattern of error is not consistent.

Part of the error for plagioclases may be due to the use of 2V in estimating compositions here. Other workers, who generally do not state their optic methods or their methods of estimating compositions from indices in detail, may not have taken such data into account. Discrepancies as large as

0.0017 exist between beta indices measured on high and low state plagioclases (Smith, 1957). Since 2V's measured in the present work have at times been outside the range defined by Smith (1956), more work seems to be needed to refine Smith's 1956 graph with data from a much larger number of samples. Work of this nature for other common minerals seems to be indicated as well; recall the anomalous 2V of olivine sample HK1868G2 and the concomitant departure from the best fit straight line to the olivine data of Figure 6.

It is possible that the choice of an arbitrary value for the omega index of the quartz used for calibration rather than the index stated by the manufacturer for the prism glass was an unfortunate one. That the error in the plagioclase index neighborhood seems to be about 0.00173 too high while the manufacturer's stated index for the prism glass was judged to be 0.00131 too low (see above: "*Integration and calibration of stage-refractometer system*) seems suspicious. However, if this were the only problem, higher indices closer to the Corning calibration glass index should become progressively more accurate. This does not seem to be so. Therefore, the stated index of the Corning glass must also remain in doubt. It is possible that enough variation between the glass actually measured and that provided for calibration of the refractometer existed to account for the problem in the higher index range.

These results emphasize the need for even more careful calibrations in future related work. The indices of minerals or glasses used for calibration should perhaps be determined by several independent, dependable laboratories and the results averaged.

It is also possible that the lack of pattern to the apparent inaccuracies over the range of indices treated is largely a function of how well previous workers have related indices to compositions for each of the four mineral groups.

However, this work has been aimed at: 1. Development of a new identification technique, and 2. Derivation of curves relating DMEANBP to mean indices of minerals whose privileged directions are known to be aligned with the polarizer. While inaccuracies noted on the order of 0.003 and less indicate some lack of success in the present work's effort to identify mineral compositions by indices, these inaccuracies have no effect at all on aim 1, and negligibly affect the equations (Figures 5 and 6) derived to satisfy aim 2.

SOURCES OF ERROR.

Discrepancies between refractive index values reported here and those reported previously by others may best be explained by either poor oil calibration, poor temperature control, or choice of a grain for single-grain study which was not representative of the mean sample populace composition. Errors in the present work may have several sources.

Not determining the mean beta-prime and POD indices at about the same time when generating data to define determinative curves relating randomly-encountered to oriented indices subjects results to inaccuracies which might result from known or unknown changes in system calibration. During the present work with plagioclases, the system was recalibrated and difficulties were encountered in attempts to mesh older with newer data. The problem was probably due to some of the older data having been generated while the Wheatstone bridge's 12 V. battery charge was near zero. But had both beta and beta-prime mean indices been determined at the same time under similar conditions, the relative precisions would have been about the same even if both were inaccurate by the same amount; a useful point for the determinative curve relating beta to beta-prime would probably have been obtained.

Fatigue may produce errors in coordination which produce sloppy counts.

The wrong equation may have been chosen from among several degrees of equations returned by the BMD05R program. The choice to use only second degree equations was somewhat arbitrary, and perhaps the first degree equations at times more closely approximate the true behavior of some oils.

Samples which have not been concentrated by magnetic or heavy liquid methods may produce standard deviations different from that of the mineral phase under consideration. Acceptance of a value for the mean refractive index of a sample population whose extreme indices are not included may produce an increase in the value of the standard error of the mean.

Counts of too few grains at each index chosen may yield so much scatter that too many counts must be made. This means a greater number of changes of temperature. It is better to count enough grains per count so that the number of counts needed is on the order of 3 to 6. Twelve counts of oriented grains and 50 of randomly encountered grains proved inefficient. Standard counts of 20 and 100 were adopted respectively. Inadvertence while entering data to the on-line computer or while keypunching data either on line from a remote terminal or on cards may produce errors. Errors of equations used in a program may appear unnoticed due to a copying or keypunching error. Each equation used has been checked initially and repeatedly during use to be sure it is the same one returned by BMD05R.

Contamination of a new oil by an old one results if the slide holding the stage thermistor is not thoroughly cleansed between oils. Sometimes, cleaning is done with acetone and then with the oil to be introduced; more often the oils are similar enough that a drop of the new oil used to dilute the film of oil left after wiping with a tissue is sufficient. The dilution effect is important here.

Some oils in use are sufficiently volatile to change index at cool temperatures and all oils are subject to driving off volatiles at the elevated temperatures used here. Evaporation of oils is accelerated if cooling of the stage is done with a fan, so dry ice was used in later work.

Indices of coatings on grains may be mistaken for those of the grain itself. Check of a Becke line by van der Kolk's oblique illumination method is done in case of doubt.

If a crystal is zoned, the index observed from the Becke line can be different from the index to be ascribed to the larger volume of the grain as indicated by the method of oblique illumination. If various grains in the crushed sample commonly show more than one index category (L, E, or G), the sample should be sized at a finer range.

The oil may be poorly calibrated.

A random optic figure may be misread.

Dirty or slightly-ajar stepped-resistor contacts may cause a wrong reading of ohms in use to balance the bridge.

Unknown uncertainties exist due to effects of heat on optics, especially during use of a high-power objective at high stage temperatures.

The thermistor can get too close to the metal of the stage which can conduct heat to or from the thermistor and cause it to give a reading different from that of the grains being counted under the objective. To keep the thermistor close to the center of the field and close to the grains being counted, cover slips are taped together in bundles and then cut by diamond saw to one centimeter squares. Reduction of the cover slip size encourages minimum waste of both mineral and oil.

Air bubbles introduced over the thermistor during installation of grains and oil may produce a pocket of insulation which would produce a reading different from one taken with the thermistor immersed in the oil.

During a period of one month, a residual potential from the thermistor was noted when the power was taken off the circuit for a null reading. The charge was initially about 70 mv. This may contribute to the noted systematic errors.

LIMITATIONS OF THIS TECHNIQUE.

Some samples may prove to be too difficult to work with; such difficulties encountered in the present work on two olivines of high index may be due to attempts to work with very old arsenic dibromide oils. Conflicting results derived from Becke line vs. van der Kolk method of oblique illumination were noted in this work at indices above 1.80 and the reason for the difficulty is not yet clear.

When two phase regions have overlapping refractive index ranges (to the limit, one may be completely contained in the other, as for quartz in the midst of the plagioclases), other methods may be necessary to determine proportions. Such work might include determinations of habit, birefringence, and even 2V if necessary.

A further limitation on this method is the large number of oils required for its use by workers unwilling or unable to use either temperature or light wavelength in order to vary the apparent index of the immersion medium.

Application of the method in the field is limited by the worker's ability to control temperatures. However, work at ambient temperatures with well calibrated oils and a thermometer should produce useful preliminary results.

REVIEW OF GRAPHICAL METHODS.

Construction of curves relating DMEANBP to POD indices.

Because of the large number of samples treated here, computers have here been a virtual necessity. But workers without computers available, whether in the field or in the laboratory, can confidently use the graphical methods of normal probability paper.

The limitation on results is probably most strongly controlled by how well calibrated the immersion media are and how well temperature is known, whether or not wavelengths of light are varied in conjunction with this technique. But with little temperature control, results good to +/- 0.002 should prove to be easily obtainable even in field camps.

To resketch the process briefly, one counts a number of grains which may be randomly encountered or oriented in known POD's in an immersion medium of known refractive index. The percentage of grains less than the medium's index is L. To this is added half of the percentage of the count which seems to match the chosen index. Call L + E/2 the graphable quantity Y (see Figure 3). On normal probability paper, graph Y against the index chosen for the count. Repeat these steps at different indices until enough points are assembled that a straight line through them may be drawn with reasonable confidence. The mean refractive index for the beta-prime or known optic directions is simply read on the refractive index axis against the intersection of the 50 percent value of cumulative relative frequency Y and the line drawn through the data points.

Following the methods outlined here, other workers can add data to the data presented here for plagioclases, olivines, augites, and orthopyroxenes. Other mineral groups deserve attention as well. I will appreciate receipt of samples from other workers who have used this method. Limited amounts of some of the samples treated here are available on request.

CONCLUSION

The results of this work on plagioclases are generally compatible with the results of other workers on the same specimens.

DMEANBP displays a distinct, useful, and important relationship to DMEANB among plagioclases. This close relationship indicates that it is no longer necessary to orient plagioclases to estimate compositions from optical immersion data.

Similarly close relationships seem to exist among olivines, augitic clinopyroxenes, and orthopyroxenes. No large refractive index discrepancies exist between work of others and this work. Compositional estimates made here agree reasonably with those of others. This suggests that the concept of relating data of randomly encountered indices to indices of known privileged directions is universally applicable to transparent solids.

EASE AND SPEED OF METHOD.

Counts of beta-prime mineral indices for minerals having a defined relationship of beta-prime to a known POD index have the great advantage of freeing the worker's mind from considerations of the indicatrix during determinative work.

Although the counting of indices as randomly encountered is only one of the novel aspects of the present method, this latter consideration makes it an important one. However, the technique is rapid even for grains in known orientations.

All of the laboratory work directly related to this dissertation has been done in a 14 month time period. This has included development of refractometer theory and construction as well as all work related to the development of the technique under discussion. The speed of this method can be judged by the fact that all data presented here for the olivines, augitic pyroxenes, and orthopyroxenes; as well as the data presented in Figures 7 and 8 were collected in less than one month's time.

Division of the number of hours at the microscope by the number of points generated for Table 21 yields about 17 minutes per point in Figure 8. This time includes the time needed to keep a running plot of data as shown in Figure 8.

Comparison of the value obtained in Figure 3 for 363-69's mean beta-prime index (1.5625) to that shown for its DMEANBP in Table 10 (1.5641) suggests that workers seeking the mean refractive index to 3 decimal places will in most cases find the graphical solution sufficient. The argument is strengthened since the sample in question was purposefully chosen because of its known wide variation of feldspars.[15]

It is conceivable that shipboard operations could at times hinge on such rapid petrologic determinations. Interesting work with rapid mineral determinations on the R. V. PITSIULAK have been reported by S. A. Morse (1971).

SUGGESTIONS FOR FUTURE WORK.

Corroborative work is needed before the data given here for olivines, orthopyroxenes, and augitic pyroxenes are to be trusted by other workers. The successful results for the plagioclase feldspars and the apparently encouraging results for the olivines, orthopyroxenes, and augitic pyroxenes, encourage completion of the work for the minerals treated here and initiation of similar investigations among other natural and artificial solid solution phase regions.

The avenues for other future work are almost too multitudinous to contemplate.

Theoretical explanations for the empirical results presented here are needed.

Genetic interpretations of well-defined refractive index density functions in terms of the Bowen reaction series and

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[15] These variations are such that both Lindsley and Smith in personal communications expressed strong doubt as to the applicability of their specimens to a study seeking definition of determinative curves!

more recent phase diagrams may yield interesting results for igneous rocks. However, other rock types may also be found to yield interesting results when compared in this way. The concept of comparing precisely defined density functions among various rock specimens is not restricted to any single rock type.

The refractive index effects produced by changes of indicatrix and cleavage through ranges of composition are not treated here but deserve attention. The consistency with which any given phase breaks in a given way is a related topic of interest.

Adaptation of the extinction method of Michel-Levy to a modern statistical viewpoint might produce a useful method for working on zoned plagioclase feldspars in thin section on the uniaxial petrographic stage where twins and zones coexist.

Numerical methods of comparison such as factor or cluster analysis might in some cases prove more powerful than the graphically oriented methods discussed here.

Future work should relate random indices obtained by the present method to other useful parameters not treated here, for example the Tsuboi alpha-prime indices of the plagioclases.

Recommended changes in procedure.

Thermistors should be calibrated over even wider temperature ranges, using dry ice and hotplates over, say, −30 to +75 degrees Celsius. Thermistors and thermometer bulbs should be calibrated in the same chamber of a one liter aluminum cube.

Thermistors should be calibrated after epoxy has cured. This will reduce a battery effect noted in the present work.

As large as possible a volume of each oil calibrated should be used to reduce the number of interruptions of petrographic work in order to calibrate an oil similar to one exhausted during use. Fresh Cargille Laboratory H Series immersion oils should be used for indices above 1.80. The double variation method should be used.

Percent counts should in the future be weighted by the total number of grains counted at each chosen oil index.

SUMMARY OF CONCLUSIONS.

1. Temperature can be controlled sufficiently well for precise control of immersion medium indices. Double variation methods are preferable.

2. The birefringence of a mineral grain should not be confused with the range of indices exhibited by a mineral phase region. The method of Tsuboi (1926) suffers from this confusion.

3. The method of Michel-Levy generally fails for albite-twinned crystals if they are zoned. The present method provides a viable alternative.

4. Whereas optical identification methods available prior to this work have generally failed to achieve the rapidity necessary for amassing enough data for statistical definition of density functions, this method makes such data accumulation feasible.

5. Plagioclase feldspar compositions can be precisely estimated from indices measured on randomly encountered grains in oils. A third degree equation relating the means of randomly encountered refractive indices to the means of beta indices for the same plagioclase sample populations is provided. The equation covers the entire plagioclase range.

6. For olivines, augites, and orthopyroxenes, straight line equations are fit to data relating means of

randomly encountered indices to means of indices in chosen principal optic directions. The equations are preliminary. Additional data may yield equations of higher order for these three mineral groups.

7. Successful application of this method to four mineral groups strongly suggests that similar relationships remain to be defined for many and maybe for all natural and artificial transparent solids.

8. This method provides a successful way to view the compositional distribution of a mineral in context of total rock rather than single grain.

9. Modal estimates from crushed but unseparated rock samples appear to be possible from immersion data.

10. Empirically drawn compositional density functions are available from this method.

11. This method achieves a high degree of internal consistency. The results generally agree well with results of other workers treating the same samples. An apparent exception seems resolvable.

12. The portability and flexibility of the system make it applicable to use in field camps or aboard ships. Thermometers can replace electronic temperature control devices during such preliminary work.

13. The method evolved and described in this study offers a quick and relatively cheap way to determine average composi-

tions of different minerals in a rock with accuracy comparable to that obtained by more expensive and more time-consuming methods.

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METHODS OF REFRACTIVE INDEX CONTROL

DOUBLE VARIATION DEPENDENCY OF INDICES.

Refractive indices are generally strongly dependent on both the wavelength of impinging light and the temperature of the subject material. The present work controls oil indices by temperature changes. Temperature variations change indices of oils appreciably and affect mineral indices insignificantly.

Variations of both wavelength and temperature are treated by Emmons (1928) who produces by them respectively chromatic and thermal dispersions in what he later (Emmons; 1929, 1943) calls the double variation method. He points (Emmons, 1928) to the advantages of often being able to work with a single, small grain without needing to transfer it to other immersion media (a tedious and sometimes impossible task).

Poldervaart (1950, p. 1071) divides refractive index methods into "(1) the ordinary immersion method using sodium light, (2) the single variation method, and (3) the double variation method; the three methods being of increasing accuracy in the order stated.

The double variation method, perfected by Emmons (1929), is undoubtedly the most accurate, but it requires elaborate and expensive apparatus and consumes more time than the other two methods."

Differential thermocouples capable of measuring temperatures to plus or minus 1° C[16] are reported as early as 1928 (Ashton and Taylor).

Ashton and Taylor show that mercury thermometers are probably satisfactory for work where temperature control of plus or minus 2° (Celsius again inferred) is sufficient. But they state that even the plus or minus 1° (C) accuracies obtained with a thermocouple are "not reliable when precise data are desired" (p. 417).

In his above-mentioned study of the zone over which mineral indices seem to match those of immersion media under varying conditions, Saylor (1935, p. 285) used "a 5-junction, copper-constantan thermocouple, with its warm end placed between the slide and cover glass so that it was just at the edge of the field when the 45X objective was used."

Although variation of wavelength methods in single or double variation have been used for years, workers generally translate results to the common denominator of the index of

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[16] The temperature scale in use is inferred to be Celsius, though the authors neglect to say so; the inference rests on the fact that readings are in the 25 degree range common to microscope work in Celsius degrees.

refraction in monochromatic sodium light at 25° C. So the observed mineral dispersion is lost as an independently reported quantity in most of the literature. This is unfortunate. It would be interesting to see whether different samples from different places of the same kind of mineral showing the same index at 25° C in sodium light might not have markedly different dispersions which could be used quite independently of refractive index information to help in identification and a further refinement of knowledge.

Van der Plas (1966) says that variable monochromators are now inexpensive, though he does not quote prices. Holgate (1963) and Harrison and Day (1963) treat respectively the use of an inexpensive graded interference filter and a precision mount for use with a graded interference filter. Specific costs are mentioned in neither of these works. But Leitz now sells a substage variable filter (12.5 millimicron, <u>veril</u> S 200, 400-700 millimicron range) with graduated mount and diaphragm housing for $453.00. This compares with the cost of $363.00 for a complete sodium vapor lamp system from the same company. Though the cost of a light system to project through the variable filter is not included in the latter's cost it should be possible to adapt the filter to existing white light sources, so its cost is competitive with that of a monochromatic light source. The reduced cost of immersion liquids needed to cover the complete range of mineral indices, the advantages of the double variation method, and the evident educational opportunities, all suggest that the variable monochromator should be in more common use than it seems to be.

REVIEW OF LITERATURE PERTINENT TO FELDSPAR INDICES

Poldervaart (1950, p. 1068-70) says: "A large number of methods have been devised to correlate physical properties with chemical composition. Since plagioclase occurs in nearly every igneous rock and in many metamorphic and sedimentary rocks, the determination of the An content of the feldspar is one of the most essential and common parts of petrological procedure. Yet many problems remain in determining compositions of members of the series by optical means. It is seldom realized how difficult is the correct determination of the average plagioclase composition in a rock in which the feldspar is strongly zoned (Wenk, 1945). Merely taking the mean of extreme values determined in one or more crystals rarely provides the correct result, unless a large number of crystals is examined. Determination of the mean index of refraction by comparison of a large number of grains oriented at random is less time-robbing, but likewise not very accurate." The present work effectively refutes the phrase "but likewise not very accurate."

A comprehensive overview of the state of the art of feldspar identification is given by van der Plas (1966). In spite of its restrictive title, this work is valuable to all workers concerned with feldspars, because so much of the work deals with properties of feldspars which are not restricted to detrital occurrences.

A myriad of feldspar identification techniques exists.[17] It seems strange that in summarizing the methods for determination of plagioclase feldspar chemical compositions on the basis of indicatrix orientations, van der Plas (1966, p. 137) ignores oil immersion work: "These methods may be divided into two groups. For the first group a universal stage is needed; the second group tries to make the best of the information that can be drawn from inspecting a thin section with a uniaxial petrographic microscope. This seemingly reversed order has been chosen because it is necessary to have a clear understanding of the possible behavior of sections of plagioclase fragments in order to make the proper guesses, simply by looking at a thin section with an ordinary microscope. It must be admitted that the study of the plagioclases in thin sections ...without a universal stage, engaging as it may be, is a rather difficult job."

Surely the careful determination of principal indices in oils involves orientation of the indicatrix! Van der Plas is

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[17] Van der Plas (p. 100-5) points to recent work relating Euler angles to feldspar identification with an eye to computer techniques, though the computer techniques are not treated. The approach looks promising, but it is not treated here.

not ignorant of immersion methods, however, and the above quotation follows a chapter entitled "The indices of refraction and the axial angle of feldspars." In closing his section on feldspar refractive indices, van der Plas (p. 90) writes: "In summary, the determination of the chemical composition of plagioclases with immersion liquids is a reliable and efficient method. This is especially true for the workers [sedimentologists] for whom this review is intended. The inaccuracies that may result from not recognizing the presence of high-temperature phases are small, and do not constitute an annoying disturbance of the reliability of a set of measurements."[18]

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[18] See also the work of Chayes (1952).

Method of Michel-Levy.

The method of Michel-Levy is "perhaps the single most useful method in thin section [work on plagioclases]" (Heinrich, 1965, p. 360). That the method may also be of use in immersion media makes it germane to this work. However, the absence of twins in plagioclases at times makes the Michel-Levy method impossible.

Although it seems sufficiently obvious that the Michel-Levy method fails for twinned crystals which are zoned, no previous statement has been found in the literature to that effect. Though being fundamentally statistical (Kerr, 1959, p. 257) like the present method, the method of Michel-Levy fails for zoned twins because it selects only the most calcic composition available in a particular section. It works for compositionally zoned crystals only if one takes the trouble to use it for individual compositional zones in a section known certainly to be cut normal to the (010) face and to be rotated about the [010] zone so as to give the maximum extinction possible for each zone. The method also does not take into account the variations in zoning which seem to be caused by twinning (Emmons _et al._, 1953). Since application of the method generally necessitates universal stage work, the original definition of the method is somewhat stretched. The method also becomes impractical for amassing data for statistical treatment.

Poldervaart (1950, p. 1070) mentions the discrepancies to be expected between work on the same sample done with U-stage vs. refractive index methods: "In zoned crystals refractive index methods tend to emphasize lower An values, since the edges of cleavage fragments are employed [is the assumption that the rock cleaves around rather than through most grains?], while universal stage methods emphasize higher An values, as crystal cores are most conveniently used (Wenk, 1945)."[19] Crushing grains to size fractions small enough to break grains through the cores makes the results of the present method more representative of the true compositional distribution in the total rock and does not bias toward either lower or higher An contents. The observations of Emmons et al. (1953, p. 41-54) point to the apparent incompatibility of zoned and twinned crystals and therefore the failure of the method of Michel-Levy for a large number of plagioclase crystals: "since polysynthetic twinning develops so consistently at the time zoning disappears, the two must be related. This does not negate the reaction principle; in fact, the

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[19] The implication that U-stage methods deal only with thin sections is unfortunate and ignores the cited work of Emmons. See also the undated publication of Leitz in my list of references.

development of twinning may help to implement reaction, or to trigger its operation (p. 41)." And again: "one conclusion is that, in a crystal which lost its zoning as it was twinned, the compositional differences which pre-existed in the zones, in part at least are now found in the difference in composition of the contiguous twin lamellae. Such a difference in composition between lamellae is no more permanent than is a difference in composition between zones, but may be removed with the advancing history of the crystal.... Especially interesting and apparently significant is the observation that the difference in composition between lamellae is not constant throughout the crystal.... Our overall conclusion is that twinning, which forms late in the history of the crystal and postdates zoning, is one of the factors and often the dominant factor in the elimination of zoning. The difference in composition of contiguous twin lamellae, in part at least, substitutes for the difference in composition between zones. Tentatively we conclude that the difference in composition between contiguous twin lamellae is less for twins according to the albite law than for twins according to the other polysynthetic laws. This is an observation and is offered without explanation (Emmons et al., 1953, p. 42-3)."

To summarize, the Michel-Levy method ignores the phase region's range completely, not only in each single grain treated, but also in the total rock specimen. It should be possible to adapt the technique to a more modern statistical viewpoint, but such an adaptation is beyond the scope of the present work.

Other feldspar work.

The rhombic section method, the method of Schuster, and the method of Tsuboi are all applicable to cleavage fragments of plagioclase feldspar (Heinrich, 1965, p. 359ff); all are ignored in the remainder of this work.

Van der Plas (1966, p. 83) mentions work by Marfunin (1962). Van der Plas says: "MARFUNIN ... lists 59 samples whose refractive indices are measured and mentions a number of data not published in the compilation of CHAYES (1952b).[20] He also lists the mean index of refraction. [The meaning of "mean" in this context is crucial, and bears on the originality of the present work.] It is shown graphically that this mean index of refraction exhibits a rather perfect linear relationship with the Ca-content." The quotation suggests that the same relationship used here to demonstrate the present method may already have been found by totally independent work, for the third degree equation relating mean beta to mean beta-prime indices (Figure 5) was at first believed to be a straight line relationship.

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[20] The reference is to Chayes (1952).

Marfunin (1962, p. 172) says: "The composition of all the specimens of Ernst and Nieland was determined, therefore, by means of the average refractive index as calculated from the presented values [gamma, beta, and alpha] according to the empirical formula:

$$\%\text{An} = 1{,}960.78 \cdot \underline{n}\,[\text{avg.}] - 3{,}004.31.\text{"}$$

The work of Marfunin clearly does not impair the claim of the present work to originality. He is not concerned with creating a new mineral identification technique, and his definition of "mean refractive index" is quite different from the meaning given DMEAN in the present work.

INDICES OF OTHER MINERALS.

Even for minerals whose compositions must be estimated from additional optical parameters, the value of refractive indices remains essential to the determination.

Deer *et al.* (1967a, p. 22) relate refractive indices of olivines to compositions via straight lines for all 3 principal indices. The same authors (Deer *et al.*, 1965, p. 28) fit straight lines to the alpha and gamma indices (they deal with gamma-prime but call it gamma) of orthopyroxenes as a function of composition. They do not plot or show the line for the beta index as a function of composition. The more complex relationship of optical properties displayed by augitic pyroxenes necessitates the plotting of 2V together with refractive indices (Deer *et al.*, 1965, p. 132) to determine the best estimate of composition based on optical parameters alone. But the failure of the relationship between refractive indices and composition *per se* is no impediment to the present work; for the investigation over compositional phase regions of the relationship between DMEANBP and known principal refractive indices is a primary present purpose. Successful establishment of a relationship between DMEANBP and DMEANB for augitic pyroxenes must be supplemented by 2V data in order to determine composition.

OTHER RELATED WORK.

The strongest parallel to the present work is that of Morse (1968). He produced a new dispersion chart based on the 1923 and following work of Tsuboi and others who have identified plagioclases on the basis of alpha-prime curves. Morse says: For comparative studies of plagioclases from a single environment or genetic history, it is even probable that compositional variation can be determined with greater precision by the dispersion method than by any analytical means, possibly excepting the electron microprobe, which gives comparable results and statistics" (Morse, 1968, p. 106). The similarities of the present work to Morse's will become apparent: Morse says "composition range and statistical parameters can be read off" (1968, p. 113). Morse reports precisions on the order of .00026 (Morse, 1868, p. 114). He does not estimate the accuracy of his method, however, saying "it must be stressed that we speak here of precision, which is a necessary but not sufficient requirement for the accurate knowledge of a natural plagioclase composition" (Morse, 1698, p. 114). His data suggest to him the possibility that errors in assigning values to the immersion media are comparable to the order of precision of mineral index determinations by his method. Similar inferences are drawn from the present work. Though concern for accurate results is important in any case, it is precision, not accuracy, which weighs most heavily on the outcome of the present work. This is because the relation of DMEANBP to a known privileged direction's index is the subject of the study.

Morse (1968) used only sodium and mercury vapor lamp light sources in his work, holding temperature steady. The present work uses only sodium light and varies temperature. Both methods fall short of the sophistication of the double variation method (Emmons, 1943).

The present work shows that single variation of temperature is rapid. Morse's work shows that single variation of wave length is rapid. Both are precise. Reversion by optical mineralogists to the double variation method in combination with the identification techniques presented here should result in more rapid determinations than Poldervaart could get by double variation as outlined by Emmons. The cost of apparatus is little compared to costs of modern microprobes, X-ray machines, and wet chemical analyses. Of course, these other techniques provide other kinds of information and are not going to be replaced by the present method.

APPENDIX B

DESCRIPTION OF PETROGRAPHIC LABORATORY

ELECTRONICS.

A stepped decade resistor is set to balance the resistance of the thermistor on the stage, the thermistors at the prism trough, or the standard resistor used to check the circuitry (switch to activate prism thermistors or standard resistor, prism thermistors, and standard resistor are not shown) in a Wheatstone bridge driven by a 12 V. dry battery (Figure B1). Readings in ohms of the stepped variable resistor are converted by calibration equations to temperature in Celsius degrees.

The upper legs of the bridge contain matched 24,000 ohm resistors. Balance in the bridge is indicated by a digital volt meter with a minus indicator which activates a heat control relay to turn on an above-stage infrared heat source as needed to hold the temperature desired. Variable transformers are used to permit different amounts of heat to be generated by four 300 ohm resistors fastened beneath the stage and by the 100 Watt lamp set in a housing with variable focus, a diaphragm, and an infrared camera filter between the lamp and the stage.

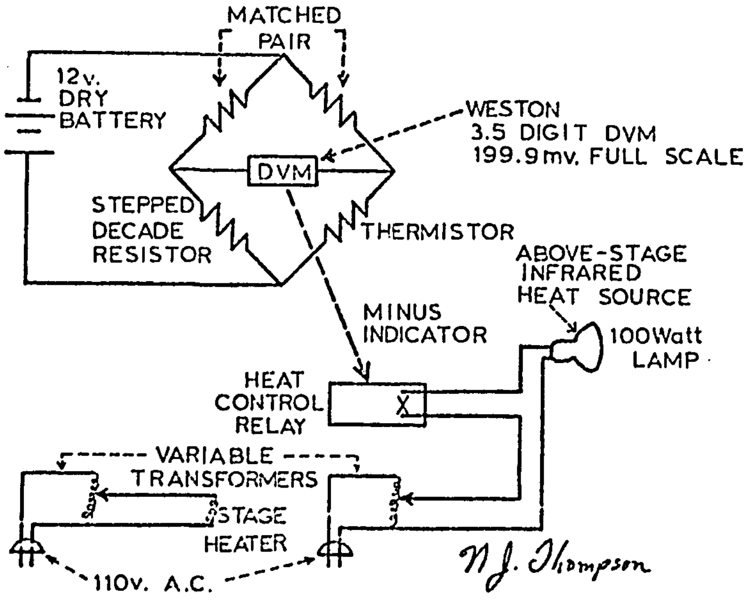

Figure B1. Temperature control circuitry.

(Schematic by Noel J. Thompson.)

The thermistors used are manufactured by Fenwal Electronics, Inc. They are Model GB32 MM172, described by Fenwal Data Sheet #D-7. The beads each have .060" diameters and come as glass-encapsulated pairs. Thus, the pair is .120" wide; the glass covers the 1 3/8" leads for a distance of 1/2". Glass protecting the leads is removed as necessary.

<u>Stage temperature controls</u>.

A thermistor set in a standard petrographic slide senses temperature.

A Zeiss Model KFT student polarizing microscope is used. Changes in stage temperature are made by adjusting the voltage to resistors in series affixed to the stationary horizontal plate beneath the rotating stage. The microscope is grounded.

Refractometer prism temperature controls.

Resistors mounted to the steel frame of the Jelley refractometer and placed close to the steel plate against which the prism slide is held provide heat to the prism by conduction. The temperature is varied by variable transformer. The above stage infrared heat source is moved to interact with the refractometer thermistors during oil calibrations.

Refractometer temperatures are monitored by two thermistor beads.

Room temperature.

Room temperature is controlled by air conditioning.

An improved larger Jelley refractometer.

Although more precise and more expensive refractometers are currently manufactured, the instrument described here yields significantly increased precision in spite of budget restrictions.[21]

Refractometer components and costs.

The prototype uses Leitz Jelley refractometer Model II, serial #2673 and Leitz microprism R7 640005, 1/333 ($212.00 manufacturer's list price). A General Electric 7 NA-1 sodium vapor lamp provides the monochromatic light source. A precisely machined adjustable tripod designed to support gravity meters is used to support the Jelley refractometer. An

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[21] Readers interested in methods yielding 7 place precision are referred to the work of Werner (1968).

Alteneder and Sons steel meter stick serves as the big scale.

Refractometer optics.

Figure B2 shows a family of rays generated by a sodium light and projected to the left as drawn.

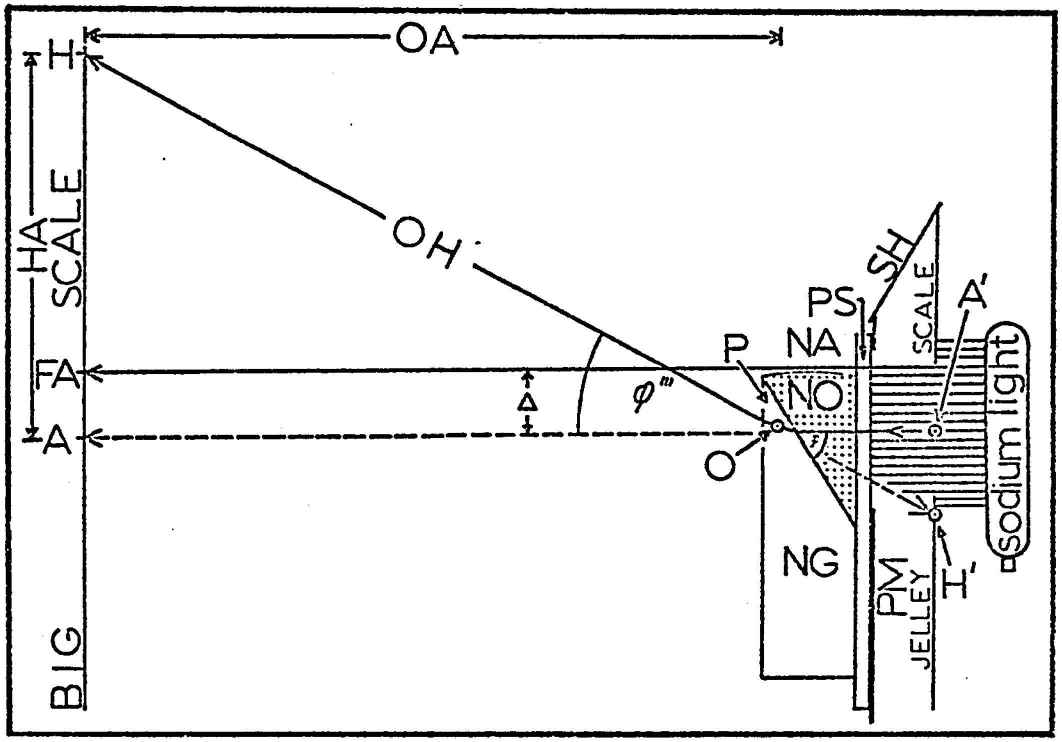

Figure B2. Big Jelley optics.

The following abbreviations are used in the text , in this, or in the next figure:

A = the point at which unrefracted beam O-A hits the vertical scale normally. A' = the point at which the ray to be refracted crosses the Jelley refractometer scale. Delta = the distance from A to the point above A where light shining from above the oil hits the scale at FA. FA = the false A obtained when light passes over the oil on the prism. H = the point where refracted beam O-H hits the scale. H' = the point where the virtual image created by O-H may be seen on the Jelley scale. HA = the vector from A to H. H'A' = the vector from A' to H'. NA = refractive index of air, here taken as 1.00029. NG = refractive index of prism glass, stated by manufacturer as 1.52012. NO = refractive index of immersion medium (usually oil). O = the point in the prism half-way between the two interfaces shown in the second of these two figures; as the refractometer is enlarged the conceptual, practical, and arithmetic differences between the prism and point O become vanishingly small and are ignored in calculations here. OA = the distance from O to A. O-A = the unrefracted ray traveling from A' to A. CH = the distance from O to H established by O-H. O-H = the refracted beam travelling from the prism to H. P = the prism region through which the refracted beam travels while between the two interfaces shown in the second of these 2 figures; the region is diagonally dotted in that figure. PM = the prism mount, a flat surface against which clips hold the prism slide when it is placed on the Jelley refractometer. PS = the prism slide on which the prism is cemented; PS attaches to the refractometer via the prism mount. PT = the prism trough which holds the immersion medium. SH = a shield placed between the tops of PM and the Jelley scale to prevent light diffracted at A' from being seen at the big vertical scale and confused with the refracted beam O-H.

One of the rays in Figure B2 passes through A' (on the plane connecting the centers of the slits in the Jelley refractometer scale and the prism mount) and is selected for discussion. When the selected ray passes normally from air into the glass of the prism slide, its velocity decreases. When it emerges from the glass to pass normally into the immersion medium held by the prism trough, its velocity is again decreased (the index of the immersion medium is taken here to be greater than that of the glass, which is the case most common to the present work; air, glass, and oil are not so labeled, but are identified by the symbol of their respective refractive indices).

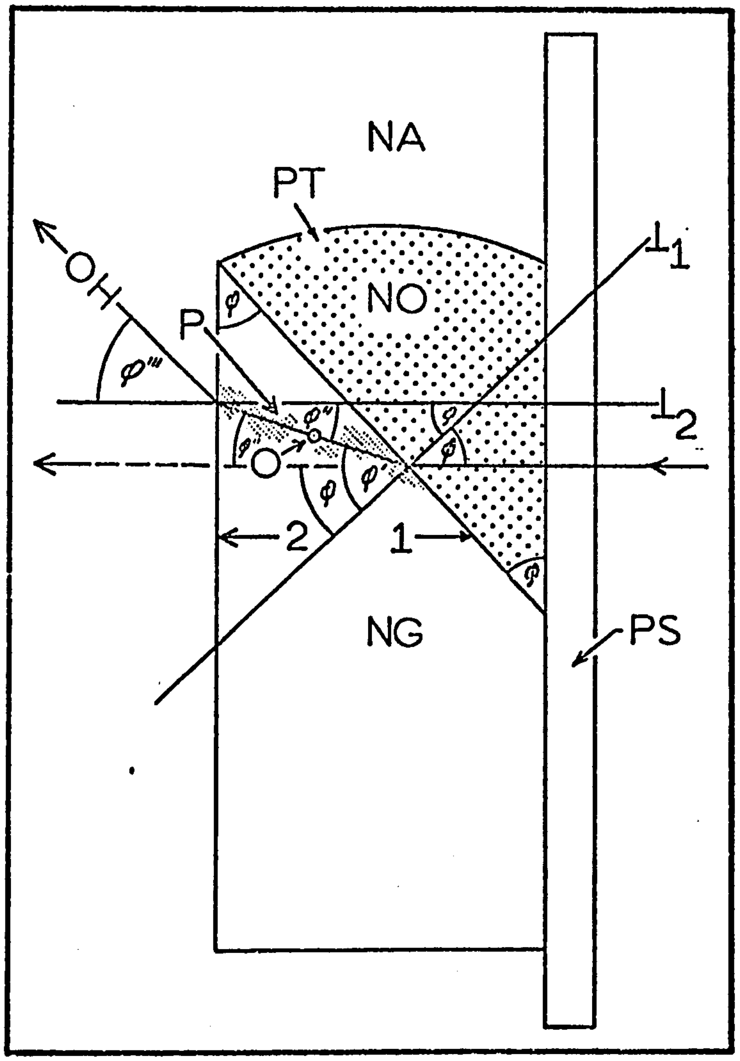

Figure B3. Prism optics.

A simplified treatment of what follows is given by Jelley (1934). The beam selected in Figure B2 is treated in Figure B3. The beam hits interface 1 at the angle ϕ to which the prism is cut. It is refracted according to Snell's law,

$$N \sin \phi = N' \sin \phi' .$$

Emerging from the prism at an angle to interface 2, the ray is again refracted; it is now called O-H. By geometry,

$$\phi = \phi' - \phi'' .$$

Application of Snell's law at interface 2 yields

$$NG \sin \phi'' = NA \sin \phi''' .$$

Likewise by application of Snell's law and the relation

$$\phi' = \phi + \phi''$$

at interface 1,

$$\sin \phi = (NG \sin(\phi + \phi''))/NO,$$

which may be rewritten

$$\sin \phi = NG(\sin \phi'' \cos \phi + \cos \phi'' \sin \phi)/NO .$$

The entire equation may be divided by sin to yield

$$NO/NG = \sin \phi'' \cot \phi + \cos \phi .$$

This may be rewritten

$$\cot \phi = (NO - NG \cos \phi'')/(NG \sin \phi'') \quad (1) .$$

Equation 1 is a general relationship. Use is made of it in the "Integration and calibration of stage-refractometer system" section.

CONSTRUCTION OF REFRACTOMETER AND INTEGRATION WITH STAGE.

MOUNTING OF THERMISTOR ON STAGE SLIDE.

A standard petrographic microscope slide is placed on the rotating stage and is held by Zeiss mechanical stage (serial number 4216454). The slide is moved to the extremes allowed by the mechanical stage while a felt-tipped pen is held under medium power (10X objective of N.A. 0.22 with 10X ocular) at the center of the field. The perimeter of the field available on a standard slide while held by the mechanical stage is thus drawn. The diagonals of the resulting rectangle cross and define the point at which a thermistor is to be placed.

A 1 mm hole is drilled with a water lubricated diamond bit. The thermistor is emplaced and held with epoxy resin. The wires are led to the edge of the slide and held with epoxy so thin that it does not interfere with the action of the slide on the stage. The leads are then connected to flexible wire which is suspended from above the entire microscope with enough play to allow full 360° stage rotation (but not much more). The leads then connect with the above described Wheatstone bridge. The slide can easily be built in a morning and is reused until, perhaps, it is destroyed accidentally. Such an accident occurred in this work when a soldering iron was used in an attempt to remove excess epoxy from the stage slide and thereby permit free play of the high power objective lens no matter what the stage rotation. The heat strained the glass and produced anisotropy in it. A short study showed that both uniaxial and biaxial optic figures appear quickly in glass as it is heated at the center of the slide with a soldering iron. The figures appear in the glass under crossed nicols and without the conoscope. The markedly biaxial figures so produced in quartz being used to calibrate the system necessitated building a new prism slide and submitting the entire system to recalibration.

MOUNTING OF THERMISTORS ON REFRACTOMETER PRISM SLIDE.

A thermistor bead is placed at each end of the trough of the Jelley refractometer prism so that each is in contact with the immersion medium in the prism trough. The leads from the prism form a vertex at the top of the prism slide, and the thermistors and glass encasing them and their leads for a length of 1/2" are affixed by clear epoxy resin.

To facilitate placement of immersion media into the prism trough, a short wire is affixed by epoxy so that a drop of oil placed on it is led to the prism trough. This avoids having the drop led to the outside of the prism system by following the outer sides of the prism leads.

Great care is needed during gluing to ensure that no epoxy resin enters the prism trough which will contain the immersion medium. Even though none enters immediately, some may be drawn into the trough by surface tension during curing, so it is better to use too little rather than too much resin.

CONSTRUCTION OF BIG REFRACTOMETER.

A Leitz Jelley refractometer is tilted to project a horizontal, unrefracted beam across the room where readings on a vertical scale are directly related to readings on the unmodified refractometer. Calibration of the entire scale is possible when a statistically significant number of readings on the big scale are averaged against concurrent readings on the small scale for an oil of high refractive index.

However, a different approach introduced here below relates known indices measured on the stage to known heights on the big scale. This removes the effects of the small scale from the calibration.

A scale is erected normal to the unrefracted beam as far as possible from the prism (in the present case 518.1 cm) within vertical and horizontal space limitations. The highest index of interest and the degree of precision desired determine the respective extremes necessary.

The prototype was assembled by placing the sodium light on a desk against the room wall. A wooden platform was glued to both floor and wall with contact cement. The tripod was placed on the platform, its steel prongs were dug firmly into the wood of the platform top, and the tripod was glued to the platform. The top part of the tripod comes mounted to the tripod base via a ball joint. The Jelley refractometer was mounted on a plywood base and the base was attached by C-clamps to the top of the tripod. The back of the Jelley refractometer was placed against the sodium vapor lamp. A wooden shield was placed between the tops of the Jelley scale and the prism mount to eliminate stray light effects at the big scale.

Two bookcases were cemented together back to back with silicone rubber to form a firm support for the scale. The edge of the bookcase farthest from the prism was made vertical with a plumb, level bubble, and large 45° triangle. Screws on the top of the tripod were adjusted to make the unrefracted beam arrive normal to the vertical edge of the bookcase. A large number of marks was made of the incoming beam height on the bookcase where the scale would be mounted. See below "Use of refractometer" for a description of how arriving beams are sighted. The center of density of these marks was found by eye and arbitrarily called A. Two wooden meter sticks were zeroed to A and glued in place. They serve as the platform on which the steel meter stick is mounted with C-clamps. They also provide reference marks with which to reposition the steel stick when necessary.

The distance OA (*Figure B2*) was measured with an uncalibrated steel tape. Ten measurements ranged between 16.995 ft and 17.001 ft, yielding a mean of 16.995 ft and a standard deviation of .002 ft. These convert respectively to 518.1 cm and 0.06 cm.

Slight vertical displacements of *H* as a function of varying placements of the prism on the prism mount were noticed. Therefore, chocks were placed on the back of the prism slide and on the front of the prism mount to ensure repeatable placement of the prism on the prism mount.

A white 3" X 5" card is folded lengthwise, accordian-style. One of the outer panels so created is laid along the edge of the steel meter stick. The other two panels are laid on the front of the steel meter stick, and the outer one of them is stuck to the meter stick with double-stick tape; this allows repositioning as necessary. The panel laid against the edge of the meter stick is surfaced with transluscent, pencil-accepting tape. This is in turn coated with white typewriter correction fluid. Use of the card is described in Appendix C under "Reading the big scale."

SYSTEM CALIBRATIONS.

Thermistor calibrations.

Thermistors are calibrated against thermometers over a temperature range from 0° C to 50° C. Calibration is performed in an aluminum block with a central chamber holding thermometer and both the stage slide and prism slide with their contained thermistors. Thermometers used are readable to hundredths of a degree C. Each thermometer is about 2 feet long and covers a range of about 12° C.

Data for thermistor calibrations consist of a large number of readings during both increasing and decreasing temperature changes, ohms to balance the Wheatstone bridge being read against thermometer temperatures. Polynomial regressions to the data for each slide's thermistors are done by BMD05R (Dixon, 1970).

Integration and calibration of stage-refractometer system.

Two refractive indices are taken as known. One is that of a precisely known Corning Glass Works glass of high index.[22] Its index for sodium light is 1.7548543. Corning's Senior Product Engineer John B. Helm writes (personal communication): "The Corning Glass Works method of determining the indices of a piece of glass utilizes 6 measurements at each of ten

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[22] "Precision Optical Glass, Code 8276, Type 755-276, " marked "EXTRA K-45."

distinct monochromatic spectral lines read on a Model C20 Guild-Watts spectrometer. These data are programmed into an I.B.M. 360 Model 40 computer to produce a six constant Sellmeier dispersion equation which best fits the data. Individual errors are averaged out and the curve smoothed. The individual indices produced for any wavelength are representative of the true indices of the glass with an accuracy in the seventh decimal place, and the data for any wavelength within the range of the original ten measurements is more accurate than that obtained by any system using only measurements at one wavelength to determine the index for that wavelength." A corollary statement can be made in support of using a substage variable bandwidth monochromator during work with minerals.

The other refractive index taken as known is that of omega in a perfectly clear crystal of quartz (origin unknown). An arbitrary assignment of index to the quartz omega was made on the basis of the work of Frondel and Hurlbut as reported in Deer <u>et al</u>. (1967b, p. 201). This most precise measurement made on a crystal of known purity gave a value of 1.544258 for quartz omega. Since Deer <u>et al</u>. mention in the same context work of others who have suggested rounding the value of quartz omega to 1.544 for purposes of calibration, but since the suggestion preceded the work of Frondel and Hurlbut, selection of the more recent and more precise measurement seems justified, especially since the number is used in double precision computer calculations in this work and since it rounds to the suggested 1.544 anyway. Unfortunately, independent corroboration of either the Corning glass or the quartz omega indices have not been obtained. But this should be no great detriment to the present work, for precision, not accuracy, is here most important as discussed elsewhere herein. And the constancy of the value of quartz omega from sample to sample is well known.

The goal is to relate for a given oil at a given temperature the height it projects on the big scale to the index it possesses both in the refractometer prism trough and under a cover slip on the stage slide.

Establishment of the number of ohms at which the Wheatstone bridge is balanced when either the Corning glass or the quartz omega matches an oil gives the temperature for each oil at which match of index is established on the stage. By calibration equations, the same temperature is determined for the refractometer prism, and the system is switched to the refractometer to balance at the indicated temperature for each oil. The height on the big refractometer scale is established for each oil at the respective temperatures. Thus, for two widely separated points on the refractometer scale, height is related to known index. Casting equation 1 into a specific form which pertains to this present system is the next step.

Angle phi is a property of the prism. It does not change as a function of the oil in use. NO of equation 1 is known precisely for two oils at temperatures matching the indices of the Corning glass and quartz omega respectively. Let the index of the oil matching the quartz omega index be NQO. Let the index of the oil matching the Corning calibration glass be NCCGO. Let phi double prime measured for NQO be QZPHIDP and let phi double prime measured for NCCGO be CCGPHIDP.

Since equation 1 sets the cotangent of phi equal to an expression whose only unknown is NG in both the cases of quartz omega and the Corning glass, measured values of QZPH and CCGPHI together with known values of NQO and NCCGO are entered in the right side of equation 1 separately for the case of quartz omega and the case of the Corning glass, and the resulting expressions are set equal to each other:

$$(\mathrm{NQO} - \mathrm{NG} \cdot \cos\mathrm{QZPHIDP})/(\mathrm{NG} \cdot \sin\mathrm{QZPHIDP}) = (\mathrm{NCCGO} - \mathrm{NG} \cdot \cos\mathrm{CCGPHIDP})/(\mathrm{NG} \cdot \sin\mathrm{CCGPHIDP}),$$

a single equation with a single unknown, NG.

NG may be found either mathematically or by iterative changes to NG in a computer program until the heights and indices measured respectively for Corning glass and quartz omega are made to match. The latter approach is used here.

Solving for NG in the present work yielded a value of 1.52143, significantly 0.00131 higher than the manufacturer's stated index of 1.52012 +/-0.0003 (Dr. Manfred Nahmmacher, personal communication). I have trusted the value of the arbitrarily chosen quartz omega index over that of the manufacturer's stated prism glass index in the current system. A program which generates a table of refractive indices for small increments in height on the big refractometer scale is available on request.

Construction and calibration of the entire, integrated prototype system was accomplished along with other work over a 6 month period.

APPENDIX C

USE OF PETROGRAPHIC LABORATORY

The limits of system calibration at present allow temperature changes from 15 to 50 degrees Celsius. The digital volt meter is most often adjusted to deviate no more than about 20 digits from the desired zero setting. Since each digit represents in the present system a temperature of 0.004° C, and since the system averages about the desired temperature, it is conservative to say that temperature on the stage is controlled to precisions of tenths and possibly to hundredths of a degree Celsius. The system produces constant, metered heat.

Whereas other studies (*e.g.* Smith, 1960) and the present one at its start have sought to work at closely controlled room temperatures to avoid heat gradients, heat gradients are now used extensively in this work both to change temperature quickly and to hold a desired temperature precisely. For instance, a high power objective close to the slide acts as a heat sink when the stage is above room temperature and as a heater when the stage is below room temperature. It is found that repeatable, useful results are obtained in any case since the thermistor is mounted with the oil and grains in the slide and controls the above-stage heater. It is sometimes helpful to turn off the air conditioner while heating the stage to a considerably higher temperature. Both stage and refractometer are at times cooled with dry ice. The system is dynamic.

USE OF ELECTRONICS.

Stage temperatures.

To cool the thermistor to a desired temperature, the stepped resistance is raised. This turns off the above-stage heater and the system begins to cool. If necessary, the substage heater can be turned down or off and dry ice can be used to hasten the process. When the resistance of the thermistor matches that of the stepped resistor, the minus indicator becomes active, turns on the above-stage heater, and cycles the infrared heat on and off to hold a temperature which averages about the one sought. Adjustment of the variable transformers quickly brings the system to a temperature equilibrium at the thermistor within tenths and at times thousandths of a degree Celsius. Conversely, to heat the stage, one may need only to lower the resistance set into the stepped resistor if the change desired is small. For very large changes in temperature, it may be necessary to turn the substage heater up, shine unfiltered white light up through the microscope, turn off air conditioning to reduce air motion, and cover the microscope to trap the heat. This sounds complicated but is easily done. Even though it generally takes longer to heat than to cool the stage, heating even over a temperature range of, say, 30^0 C usually takes no longer than a few minutes. When the temperature sought is reached, the above-stage heater begins to cycle on and off at about 1 second interals, and counting is begun. Further minor adjustments of variable transformers during the count permit extremely stable temperatures during the count.

Prism temperatures.

Temperature at the prism is monitored as for the stage; the above stage heater is moved and called the external heat source for the refractometer. The Wheatstone bridge is switched to the prism thermistors, and the system seeks a balance exactly as it does when monitoring stage temperatures. Readings of ohms for the same temperature are different, however, between the stage and the prism thermistors. This is because even though each is calibrated at the same time under the same conditions, each produces a different calibration curve.

CALIBRATION OF IMMERSION MEDIA

Calibration of each immersion medium used is made over a wide (10-50°C) temperature range. This permits temperature predetermination of a desired refractive index with which to compare indices of immersed grains. Equations relating refractive index to temperature for each medium so treated are generated by the packaged polynomial regression program BMD05R (Dixon, 1970).

USE OF REFRACTOMETER.

Introduction of oil to prism.

The prism is placed on the prism mount and a drop of oil is placed on the wire leading down to the prism trough. The oil flows by surface tension to the prism trough. Excess oil is led to the outside with a hand-held glass rod so that it does not flow over the front of the prism glass.

Reading the big scale.

For highly volatile media, two people may be used to ensure that the readings taken are not affected significantly by even brief time changes. One person introduces the oil to the prism trough, the other takes readings as soon as possible at H on the big scale. With practice, even one person can get good readings of oils even as high in index as 1.8.

Initial positioning of the folded 3" X 5" card on the big scale is accomplished by introducing the oil to be measured to the prism and sighting the beam O-H from behind the big scale. The card is placed and the prism is carefully cleaned while still in place so that it can remain at the desired temperature. Cleaning is readily done with twists of tissue. As soon as the medium whose index is to be determined is in the prism trough, a very sharp, thinly tapered, soft pencil is used to split the incoming beam at its apparent maximum intensity, and the position of H is marked 10 times as a matter of course for all H readings in this work. The marks are made on the panel of the card which lies against the side of the meter stick, and the observer is not able to see the marks made while sighting down beam O-H.

For corrections to drift of the refractometer during a series of calibrations, a series of 50 readings is taken at the start and another 50 at the end of each calibrating session. The prism is dismounted for these readings.. Thus, slight corrections for drift due to temperature, pressure, and humidity fluctuations are made to the heights measured during the session by simple trigonometry. The corrections so made are generally on the order of no more than .2 cm, representing refractive index corrections of no more than .00003 over the range of indices up to 1.8.

The card is folded back so that the dots placed on it by the observer lie in the same plane as the lines scribed on the meter stick, and two centimeter lines near the dots are carefully transcribed to the panel with the dots. These lines are labeled, and the card is removed from the meter stick. A Gerber scale (which divides lengths from 1 to 10 inches into 100 equal segments by moving a calibrated spring) is used to read the dots. The indicated heights of H are recorded to hundredths of a centimeter for each. The mean of the readings is found by Nova computer. The standard deviation of 10 such measurements is commonly on the order of 1 mm of height on the big scale.

Some comments on how best to sight the beam are in order. Best results are obtained when the stylus is held normal to the side of the meter stick at a comfortable arm's length. Bobbing the head slowly up and down and focusing on the beam at the prism, not at the big scale, maximum beam intensity is sought and marked with a dot. To eliminate bias it is best to settle on the beam alternately from above and below. A patch over the unused eye is sometimes helpful if a large number of readings is to be taken. Coating of the middle panel of the card with black avoids the possibility of prejudicing readings with stray marks which may have been made.

CARE OF CALIBRATED OILS.

Calibrated oils are precious. Great care is taken to eliminate contamination. Glass rods introduced to an oil are first quite thoroughly cleaned with acetone and then moistened with condensation from the breath and wiped with tissue. Oil vial caps are sealed with tape or silicon rubber for storage. The extremely toxic, volatile, and corrosive H series oils of Cargille Laboratories decompose even the bottle caps used by the manufacturer. Transfer to glass vials capped with polyethylene and sealed with silicon rubber after each use seems to provide a solution to the problem. The effects of curing silicone rubber so near the oil remain unknown.

DETAILED SUGGESTIONS FOR COUNTING INDICES.

Segregated mineral phase region index counts.

Randomly encountered indices.

Any counting method used to count indices of beta-prime is acceptable so long as each grain's index is encountered at random. Operators may find that varying the pattern in use preserves sanity. I do not mean to prescribe any particular pattern, but one used repeatedly in this work is to count first the grains on the vertical, then those on the horizontal crosshair. The perimeter is then examined. For crosshair and perimeter counts, all grains touching crosshair or perimeter are counted once only. So if a grain is in the field center, it is counted on the vertical, not the horizontal pass. Some grains on the perimeter do not extend into the field far enough to give unambiguous readings. They are ignored. After counting all grains cut by or tangent to crosshairs or perimeter, those remaining in the field are counted quadrant by quadrant proceeding counter-clockwise from the northeast quadrant. Use of such a pattern exhausts the field systematically. A new field is selected and the count continued. Adherence to such a pattern provides a constant check against subjectivity.

It is commonly best to use medium power, have the grains dispersed enough so that no more than about 10 fall in each quadrant of the field, and to examine each grain of each quadrant first under plane-polarized and then under cross-polarized light (to seek grains containing so little impurity that if they match the oil they otherwise go undetected). Having exhausted a field in such a manner, movement of one axis of a mechanical stage introduces a completely new field of grains (best located under crossed nicols) and the count is continued. Though statistically it does not matter whether or not the stage is set so long as each grain encountered has random orientation, the stage is locked at some convenient orientation for two reasons: 1. Operator bias is eliminated. 2. If the operator becomes interested in measuring some properties of anything in the oil, he can note the readings of the microscope and mechanical stages and return to the same point at will. Careful workers will not be bothered by movement of grains in the mount during this procedure. Moreover, in some work it is of interest to compare the randomly encountered index with that of a known vibration direction, in which case it is a convenience to have a set stage position. It is convenient to use a setting which allows a grain to travel along a cross-hair when the ocular is set with the cross-hairs at a 45^0 angle to the nicols.

Counts of index assignments are best accumulated on a mechanical point counter. In the case of randomly scattered grains, 100 grains are counted in each mount.

indices of known POD's.

In the case of oriented grains, 20 grains are counted in each mount unless the first 12 grains are assigned to the same category, in which case the count is discontinued.

The most convenient POD index to measure is usually beta, but circumstances might dictate other choices as for the choice of gamma-prime in this work on orthopyroxenes. The relations between DMEANBP and the mean alpha-prime of Tsuboi might prove interesting for the plagioclases, for example.

Operator bias was found to be more dangerous during work with oriented than with random grains, for the stage is free to rotate during the procedure, and it is the petrographer's training to recognize and select grains of low retardation when seeking optic axis figures.[23] However, the phase region examined may be so broad as possibly to select one composition out of a range if this technique is employed. Therefore, the method adopted has been to traverse the field under conoscopic conditions and to examine each new figure to see whether a desired orientation can be obtained. The first 12 or 20 such grains yielding useful figures are counted.

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[23] Optic axis figures are in fact very rarely used in the present work. In nearly all cases, even in feldspars, turning the stage produced noticeable changes in grain indices even when optic figures appeared so well centered that prior to this work I would not have hesitated to use the index measured at any stage rotation. This work makes almost exclusive use of the Kamb method on Bxax and Bxaz figures; rarely, the method of Tobi is possible (Bloss, 1961).

In traverses during a beta count, grains with ambiguous optic figures are rotated under plane polarized light through 360°. If the grain indices are in all positions of rotation assignable to the same category of L, E, or G, it follows that the beta index is also in that category, and a count is made in spite of the inability to align beta with the polarizer.

Other counting considerations.

When a sample is contaminated by a mineral with about the same refractive index, optic figures may provide the only trustworthy method of optical discrimination. Such a case occurs in the present work in sample P-8 where the feldspar occurs with rather abundant quartz. Usually, only grains having clearly biaxial figures and yielding the beta index are counted. Beta and beta-prime indices are taken from the same grain by choosing a set stage position to which each grain is turned for the beta-prime measurement following the beta measurement.

The count of beta-prime under these circumstances is limited to 20 rather than the usual 100. Although the possibility that the observer will show prejudice to the category found for beta when finding beta-prime for the same grain, the assignment to L, E, or G is usually clearcut. The occasional twenty grains per count of beta-prime by this method seem to have produced useful results. But the method is more time consuming than the standard method of obtaining 100 counts of beta-prime and is not recommended.

In samples containing highly-altered minerals (e.g. 52BE-29), only fresh grains which produce useful figures are used. This may bias the results of the present work when the results are compared to those produced by chemical analysis, microprobe, Xray, or other methods.

Twins at times cause a single grain to display distinctly different indices. In such cases each member is treated as a separate grain. When this occurs with polysynthetic twins, one count is given to each type of twin member.

The counting time required to produce the data for determination of DMEANBP by program CUM or its analog by probability paper graphics is the same--about 45 minutes per mineral phase per rock specimen, during which time the worker can obtain 100 counts of beta-prime in each of 4 media whose different indices are selected near the mean. Counts of indices in known POD's generally take somewhat longer due to the need of obtaining optic figures. However, the need of optic figures will become less important for determination of indices as determinative curves relating DMEANBP to known POD indices become generally available for various minerals.