# Silica Saturation in Cenozoic Basalt [and Discussion]

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# Silica saturation in Cenozoic basalt

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Cenozoic basalts are conspicuously either over- or undersaturated with respect to silica. Undersaturated basalts are strongly dominant in the mediterranean areas and in oceanic islands other than Hawaii. Oversaturated basalts are strongly dominant in Hawaii and throughout the circumoceanic environment. Both over- and undersaturated basalts are abundant on the continents. Silica-saturated basalts are dominant only in the submarine ridges, where fresh representatives of either of the other saturation types are still unknown.

Experimental work suggests that initial or early melting fractions of basalts or their plutonic equivalents or precursors would usually be either over- or undersaturated regardless of the saturation state of the starting material. The bimodal distribution of silica saturation in Cenozoic basalts is thus compatible with, and provides little basis for preference among, a variety of Earth models in which basaltic lavas are presumed to be early melting fractions of pre-existing solid materials.

## 1. Assumptions and reservations

If present applications seem to fall more in the realm of speculation than hypothesis, it is nevertheless hardly to be doubted that petrological inquiry into the relations between volcanism and the structure of the Earth will at some point profit from a summary of what is actually known about the frequency distribution and geographic incidence of relative silica saturation in Cenozoic basaltic rocks. Individual studies rarely involve sampling sufficiently extensive to throw much light on frequency distributions, but useful information of this kind can sometimes be obtained by pooling data from large numbers of such studies. The characterization of a frequency distribution reached in this fashion will scarcely be as satisfactory as one yielded by a sampling designed specifically for the purpose. Even if we knew how to design such a sampling plan for the Cenozoic basalts of the world, however, it seems rather unlikely that its execution could be financed; for the foreseeable future, reliance on a literature search seems unavoidable. The practical problem is not whether but how such a search should be conducted.

Questions concerning the strategy and tactics of the petrographic literature search are numerous and difficult. Even a cursory examination of them would leave little time for discussion of substantive issues. But those expected to entertain and perhaps even accept a conclusion are entitled to information about the premises on which it is based, and in this instance the ‘premises’ are essentially the principles guiding the literature search.

The basic datum is what is ordinarily called a full or complete rock analysis, one containing values quoted to the second decimal for the oxides traditionally regarded as essential by petrologists, namely, $SiO_2$, $Al_2O_3$, $Fe_2O_3$, FeO, MgO, MnO, CaO, $Na_2O$, $K_2O$, $TiO_2$, $P_2O_5$, $H_2O$. Some years ago it occurred to me that a complete collection of published analyses of Cenozoic volcanics would provide excellent material for experimentation in electronic storage and retrieval of petrographic data. I then felt quite confident that there could not be more than a couple thousand such analyses in print. With a still incomplete tape library containing well over 9600 of them, I am now prepared to settle for something less than an exhaustive sampling.

The sampling is, nevertheless, sufficiently extensive that inadequate literature coverage can hardly be responsible for serious bias.

How well the sample population of published analyses 'represents'—i.e. how accurately it samples—the target population of rock compositions, I do not know. Nor, I think, does anyone else. The presumptions underlying the whole corpus of petrographic knowledge are that the samples we bring home do indeed give us sound information about the much larger amounts of exposed material we leave *in situ*, and that, in similar fashion, the exposed rock in an area gives us sound information about the vastly larger volume of contiguous unexposed material. This, in purposely vague language, is the unavoidable chain on which all ordinary petrographic inference hangs, and one unable to accept it could scarcely be a petrologist. But if the numerical data of petrology are to be treated in synoptic studies as numbers rather than as observations that merely look like numbers, this vague characterization will not do. Specifically, we shall have to agree, at least provisionally, about systematic weights reflecting the reliability and, for lack of a better term, 'representativeness', of the data.

Assigning numerical weights to analyses culled from the literature is an exceedingly arbitrary business. Except for rare instances of extreme incompatibility between announced mineralogy and chemical composition, I exclude from the tape library no 'complete' analysis that has appeared under circumstances in which its perpetrator may be presumed to have undergone prepublication or to have accepted the hazard of postpublication, criticism. In terms of reliability, then, the system admits of only two weights, zero and one.

Questions bearing on the 'representativeness' of analyses arise in at least three not quite independent forms. First, there is the circumstance that some areas have been visited and sampled many times. An astonishingly large proportion of the analyses of lavas from oceanic islands, for instance, are from just two groups, the Hawaiian and Canary archipelagoes. If our objective is inference about oceanic islands as a whole, it could be argued that analyses of specimens from these two groups should receive smaller weight than those from other oceanic islands. Aside from the fact that this is a curious way in which to reward the diligence and industry of the geologists involved, however, there seems no sensible way in which to assign actual numerical weightings.†

Secondly, whether or not there are differences in the numbers of analyses available for them, and granting that on grounds of presumed reliability all accepted analyses are to be given unit weight, certain areas are much better described and mapped than others. Surely one would wish to weight results from well described areas more heavily, but again, as with the grading of reliability, the assignment of actual weights other than zero and unity would involve innumerable arbitrary, unverifiable and largely subjective judgements, judgements which would surely differ widely in time and among observers.

Finally, if it were possible it would surely be desirable to incorporate geological considerations in a systematic weighting scheme. Granting that conventional field techniques are capable of yielding sound numerical estimates of the relative volumes of identifiable volcanic map units, however, the scale and detail of the mapping varies widely among the source references and

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† A similar problem arises in connexion with certain recent studies, chiefly of submarine basalts, in which several analyses are presented, from the skin inward, for the same nodule or pillow. These studies are of considerable interest in their original context, but clearly a nodule that has been analysed $n$ times should not enter the library as $n$ specimens. Published studies of this sort are still uncommon, and the manner in which the analyses they contain are incorporated in the tape library does not materially affect the sample frequency distributions discussed here.

many lack maps entirely, most of the text discussions give only broad qualitative appraisal of the relative abundances of the different rock types, and in those rare instances in which numerical estimates are given they are usually unaccompanied by clear descriptions of how they have been reached. Most critically, the variable to which the weighting factor would be applied, the ternary ratio which characterizes the silica saturation, is one which varies considerably from specimen to specimen and is not known before analysis. At the scale of individual areal studies, in sum, I believe it is at present quite impossible to incorporate geological considerations in a systematic weighting scheme.

Broad regional or provincial petrographic distinctions would be no less difficult to handle, for the reasons that the weights to be assigned the various environments of Cenozoic volcanism are quite unknown and the allocation of specific volcanics to specific environments is so often a matter of taste. What, for instance, is the relative (numerical) importance of the oceanic island, circumoceanic and mediterranean environments? Is Iceland an oceanic island? Is Japan oceanic, continental or marginally continental? Is the Comores archipelago oceanic or mediterranean? Is the chain of volcanoes extending from the deep water of the Gulf of Guinea northward far into the African mainland to be considered continental or oceanic?

The assignment of unit weight to all accepted analyses certainly seems the only currently practical procedure, but none of the cited objections to it may be dismissed as trivial. Together they constitute ample reason for caution in ascribing significance to distinctions between rock types based on small differences in mean or dispersion of one or more chemical or normative variables. The normative differences to be described here, however, are pronounced and remarkably persistent. They would survive even unrealistically extreme weighting procedures designed to suppress them.

In one important respect unit weighting of analyses runs counter to standard petrographic practice and conviction. Early in our training as petrologists we are taught that alkaline rocks are much rarer than subalkaline ones. The very high incidence of alkaline rocks among Cenozoic specimens for which analyses are published is then usually dismissed as a joint consequence of the somewhat irrational interest petrologists take in these handsome rocks and of the curious tendency of alkaline derivatives (phonolites, trachytes, peralkaline rhyolites, etc.) to occur as small discrete plugs in or thin cappings over enormous masses of subalkaline lavas. Nothing in this would appear to account satisfactorily for the fact that 43 % of the now more than 2400 available complete analyses of Cenozoic basalts are *ne*-normative.† In view of this result it is surely reasonable to conclude that alkaline basalts, despite their scarcity in pre-Cretaceous time, are comparable in abundance to subalkaline ones throughout the Cenozoic, and that is the position taken here.

## 2. Raw material

The sample was drawn from all available analyses of rocks described in the source references under names whose principal nouns are shown in table 1. Only complete analyses with less than 54 % of $SiO_2$ and norms containing *an* but no *he* or *c* were selected. The $SiO_2$ criterion was adopted as a protection against gross clerical error. The *an*, *c* and *he* restrictions exclude, respectively, peralkaline, peraluminous and perferric materials which, among rocks called basalt, would almost certainly be either extensively altered or poorly analysed.

† This figure is for analyses of specimens most petrologists would call basalts; it includes no phonolites, trachyandesites, nephelinites, leucitites or melilite rocks.

The incidence of accepted analyses, by rock name, is shown in table 1. 77 % of the accepted analyses are of rocks in whose names the principal noun is either basalt, diabase, dolerite or tholeiite; in 7.8 % of the accepted analyses, the principal noun of the rock name is basanite; in 2.3 % it is tephrite or teschenite; in 2.5 % hawaiite, and in 3.9 % trachybasalt or trachydolerite. In only 6.5 % is it other than one of these.

TABLE 1. PRINCIPAL NOUNS IN NAMES OF 2413 CENOZOIC BASALTS

| name | frequency | name | frequency |
|---|---|---|---|
| basalt | 1570 | limburgite | 40 |
| basanit-e, -oid | 187 | diabase | 23 |
| tholeiite | 171 | mugearite | 17 |
| dolerite | 92 | lamproite | 16 |
| trachybasalt | 86 | teschenite | 13 |
| hawaiite | 59 | tachylyte | 12 |
| tephrite | 43 | trachydolerite | 9 |
| ankaramite | 42 | all others | 33 |

The current version of the tape library contains 2413 analyses satisfying the test criteria, and the first practical problem is to isolate these from the 7200 that do not. This is accomplished by a program that reads and tests all analyses in specified (geographic) regions of the library tape, and enters the required normative and chemical variables for each accepted analysis in the appropriate logical record of a mass storage file, referred to below as the 'problem file', the records of which are also sequenced geographically. A second program sorts the analyses contained in any desired record(s) of the problem file on the basis of assigned ranges of $H_2O$ content, Fe oxidation, and amount and *an* content of normative plagioclase, and compiles the sample frequency distribution of saturation parameters in those which pass muster. The first step of the process, preparation of the problem file from the library tape, consumes considerable machine time; generation of sample frequency distributions from all or any part of the problem file is astonishingly rapid.

## 3. SATURATION PARAMETERS AND THE SATURATION DIAGRAM

Applying the initially mineralogical or modal terminology of Shand (1947) directly to chemical composition, we may distinguish three levels of 'silica saturation'. A rock containing more silica than is required to permit the casting of all alkalies, alkaline earths, and molar excess of FeO over ($Fe_2O_3+TiO_2$) as a mixture of feldspar and alumina-free pyroxene will be referred to as 'oversaturated' with silica, and one with silica insufficient for this purpose but sufficient or insufficient to permit recasting of the same oxides as a mixture of olivine, pyroxene and feldspare will be called, respectively, 'saturated' or 'undersaturated'. In the simple basalt tetrahedron of Yoder & Tilley (1962), the 'plane of saturation' separates our saturated and oversaturated classes and the 'plane of critical undersaturation' separates the saturated and undersaturated classes.

In the CIPW combining conventions, the norm of an oversaturated basalt will contain *Q*, the norm of an undersaturated basalt will contain *ne* and the norm of a saturated basalt will contain neither. A more direct molar statement of the rules determining the saturation class of a particular analysis may be of interest, since the norm is used here not as a means of predicting or rationalizing mineral associations, but merely as a convenient summary of molar relations often of mineralogical interest. The molar inequalities

$$FeO > (Fe_2O_3+TiO_2) \tag{1}$$

and

$$(CaO-3P_2O_5) > (Al_2O_3-R_2O) > 0 \tag{2}$$

apply almost without exception to basaltic rocks which have escaped extensive surficial or hydrothermal oxidation. When they hold, the CIPW rules for the appearance of $Q$, *ol* and *ne* may be put in the surprisingly simple form shown in table 2, in which $R_2O$, RO and $R_2O_3$ denote oxides of metals that are, respectively, univalent, divalent or more than divalent. In the interest of simplification the ratio $CaO:P_2O_5 = 3:1$, instead of the more exact 10:3, has been assumed for apatite, which is rarely more than a very minor part of the norm. It is also tacitly assumed that less CaO than (FeO + MgO) is available for (*px* + *ol*), certainly a safe assumption in rocks of this sort.

TABLE 2. MOLAR AND NORMATIVE CONDITIONS DETERMINING SILICA-SATURATION LEVEL

| saturation class | molar criterion | presence (+) or absence (0) of normative indicators | | |
|---|---|---|---|---|
| | | *ne* | *ol* | $Q$ |
| I | $SiO_2 > A$† | 0 | 0 | + |
| II | $A \geqslant SiO_2 \geqslant B$‡ | 0 | + | 0 |
| III | $B > SiO_2$ | + | + | 0 |

† $A = 5R_2O+RO-R_2O_3+2(Al_2O_3-P_2O_5)$.
‡ $B = 5.5R_2O+0.5(RO-R_2O_3)+Al_2O_3-P_2O_5+CaO$.

Each line of table 2 defines one of the silica-saturation classes. The norm of an analysis satisfying condition I will contain $Q$, the norm of one satisfying II will contain neither $Q$ nor *ne* and the norm of one satisfying III will contain *ne*. The classification may be represented graphically, following Tilley & Muir (1962), by three ternaries, one of which has a common edge with each of the others. Members of class I project in the ternary *Q-hy-di*, of II in *hy-di-ol* and of III in *di-ol-ne*.

We are, alas, accustomed to loosely defined and rather uninformative rock names. But I do not think most of us are aware of just how unsatisfactory the situation is in the basalt family. The relative silica saturation of a basalt is surely one of its more important geochemical characteristics, yet the names commonly applied to Cenozoic basaltic rocks convey little information on this score, and what little they do convey is quite likely to be wrong. Of the 2413 analyses considered here, for instance, the names given to 696 pretty clearly imply membership in classes I or III. The names of the remaining 1717 are compatible with membership in class II, and this, I imagine, is why many of us presume that basalts are commonly saturated with respect to $SiO_2$. Or perhaps it is the other way round, and the naming simply reflects prior conviction. In point of fact, however, 65% of the rocks whose names are compatible with membership in class II are not members of that class![†]

Class II analyses are by no means rare. They are found in considerable numbers in every

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[†] In this tally it is assumed that the name tholeiite implies membership in class I, whereas alkali dolerite and alkali basalt imply membership in class III; neither assumption is strictly correct, so the proportion of rocks whose saturation class is not correctly and unambiguously indicated by their names is actually higher than indicated above.

major environment, but are dominant only in the recently discovered and still very sparingly sampled submarine ridges. In this environment, curiously, unoxidized and reasonably unaltered representatives of classes I and III are virtually unknown. In every other major environment, as is evident from table 3, sample density is clearly greatest in either class I or class III.

Table 3. Sample densities of Cenozoic basalts in saturation classes I, II and III

| environment | class I | II | III |
|---|---|---|---|
| Hawaii, (271) | 147 | 63 | 61 |
| oceanic islands other than Hawaii, (422) | 58 | 98 | 266 |
| circumoceanic,† (507) | 330 | 122 | 55 |
| mediterranean,‡ (275) | 42 | 46 | 187 |
| continental Asia, Europe, Africa,§ (514) | 170 | 141 | 203 |
| Australia, New Zealand, North and South America, (340) | 35 | 57 | 248 |
| submarine ridges, (84) | 7 | 74 | 3 |
| totals | 789 | 601 | 1023 |

† Includes also Indonesia, Pacific Japan, West Indies, Scotia Arc.
‡ Includes European Mediterranean, Japan Sea, China Sea, Bering Sea.
§ Includes also Madagascar.

## 4. THE SAMPLE FREQUENCY DISTRIBUTION OF SATURATION PARAMETERS

The program that compiles the sample frequency distribution of saturation parameters first determines in which ternary of the Tilley–Muir diagram an accepted analysis projects and then finds the 10 % cell in which it falls. A '10 % cell' is a triangle each of whose edges is 10 % of the analogous edge of a main saturation ternary. There are 100 such nonoverlapping cells in any ternary, and each cell is thus 0.33 % of the area of the saturation diagram. The processing of an accepted analysis continues until the cell in which it projects is identified. A counter assigned to this cell is then incremented, and processing of a new analysis begins. The results of the completed tally are printed out in a format which duplicates, as nearly as the line and character spacing of the printer permit, the geometry of the Tilley–Muir saturation diagram. The entries, however, are not points marking the projections of individual analyses or averages, as in conventional applications of the diagram. Rather, they are numbers, the frequencies of analyses projecting in each of the subtriangles. The centre of the units digit of each such frequency is at the centre of its subtriangle. The centres, of course, follow a hexagonal pattern.

In the accompanying figures, which are at the same time numerical and graphical ternary frequency distributions, the following graphical conventions are used:

(1) Cells containing no analyses are unmarked. In most of the distributions this produces a sharp contrast between the 'occupied' and 'empty' regions of the diagram. What is taken to be the boundary between these regions is shown by a line, the number 1 contour. With exceptions noted in 3, below, at least one analysis projects in every cell whose centre lies on or within the number 1 contour.

(2) Within the occupied region a contour interval linear in the square roots of observed frequency is used. A cell whose centre lies on or within the second contour contains at least four analyses, one whose centre is on or within the third contour contains at least nine analyses, and so on.

(3) A carat over an entry indicates a positive, and an inverted carat under an entry a negative, deviation from the local contour pattern. Two or more adjacent deviations of like sign are usually outlined by a contour.

The purpose of these conventions is to direct attention to regions of high sample density without either exaggerating them or concealing noise, of which there is usually a considerable amount.

Figure 1 shows the distribution of silica-saturation parameters in 660 basalts of the oceanic islands;† the tendency toward bimodality is already clear even though the number of analyses is little more than twice the number of cells in the diagram. The addition of 272 mediterranean† basalts to the oceanic-island data, as shown in figure 2, somewhat enlarges the occupied area but changes the main pattern very little. Now if such a pattern is not materially changed by the insertion of additional data, it can only be strengthened. Thus, for instance, the number of analyses in the area within the number 3 contour increases from 158 to 183 in class I and from 212 to 303 in class III. Of the 275 mediterranean basalts, only 46, or 17 %, lie in class II.

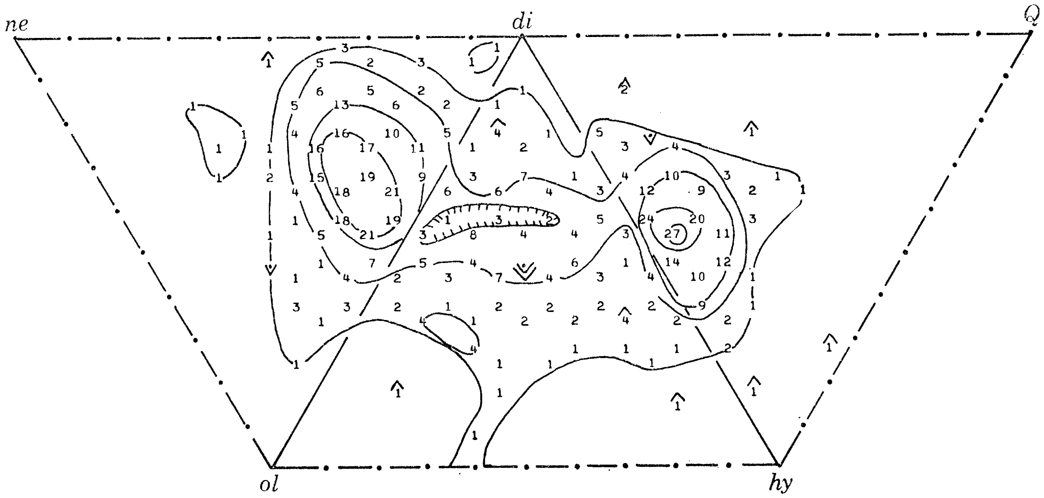

FIGURE 1. Distribution of normative silica-saturation parameters of 660 oceanic-island basalts, Tilley–Muir projection.

Pooling the data from all environments nearly triples the number of analyses, with results shown in figure 3; the addition of 1481 analyses broadens and intensifies the maxima somewhat but scarcely shifts their locations. On the whole, the contouring provides a rather consistent summary of the sample frequency distributions, and the pattern it suggests is abundantly clear. Strong point maxima are centered near $Q_{10}di_{45}$ in class I and $ne_{20}di_{50}$ in class III. There is no indication of a maximum in class II and, indeed, there are many negative deviations scattered through the occupied region of this class.

Before attempting any interpretation of this strikingly bimodal distribution we must first show that it is neither an artefact of projection nor a consequence of neglecting to exclude atypical, oxidized, or hydrated materials. The latter possibility is easily disposed of. Restriction of the sample to analyses in which the molar ratio $Fe_2O_3/(FeO+Fe_2O_3) < 0.25$, total $H_2O <$ 2.0 %, and normative plagioclase is at least 50 % *an* reduces the number of analyses from 2413

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† The terms 'oceanic-island', 'mediterranean', 'circumoceanic', etc., are used here essentially as defined in Chayes & Velde (1965).

to 1110, so that contours are in general reduced in value. Nevertheless, as shown in figure 4, the general pattern of concentration is virtually unaffected.

The possibility that the pattern is an artefact of projection is not so readily evaluated. In general, it will always be possible to choose a projection in which no pattern will emerge in a frequency distribution constructed with a given origin and class width. The practical concern, however, is whether a pattern found in one projection relevant to a particular problem will be either distorted beyond recognition or suppressed in another equally relevant projection. Since not all relevant projections are known at any given time, no definitive answer is possible. But it is worth noting that the pattern of the frequency distribution of silica-saturation parameters of Cenozoic basalt established in the Tilley–Muir projection (figure 3) is readily recognizable in the Coombs projection (figure 5), in which *hy* is not a component and the ternary ratios are cast up from molar amounts rather than mass percentages (Coombs 1963). The average content per cell in the occupied region of figure 3 is 14.1 in class I, 14.9 in class III and 7.9 in class II; the analogous averages for figure 5 are 17.4, 20.1 and 12.0. The Tilley–Muir projection shows

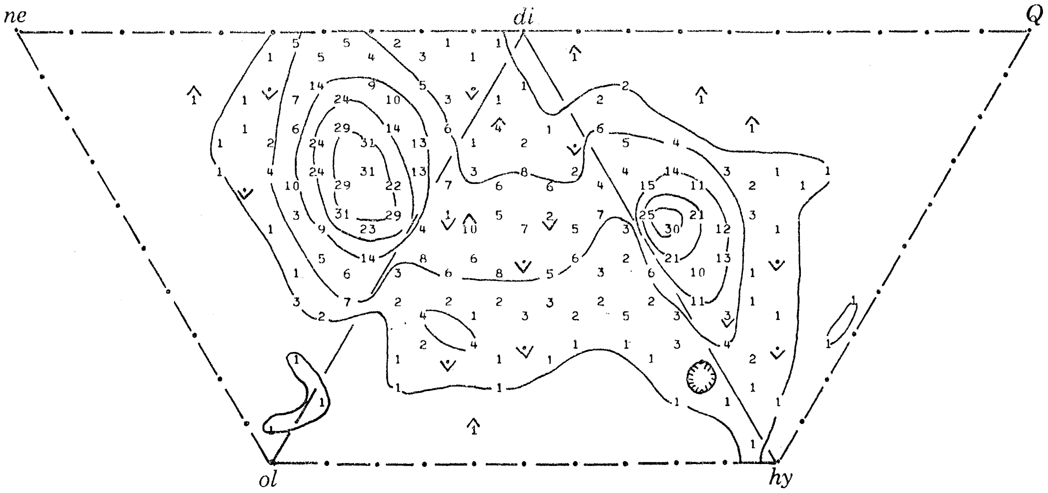

FIGURE 2. Distribution of normative silica-saturation parameters in 932 mediterranean and oceanic-island basalts.

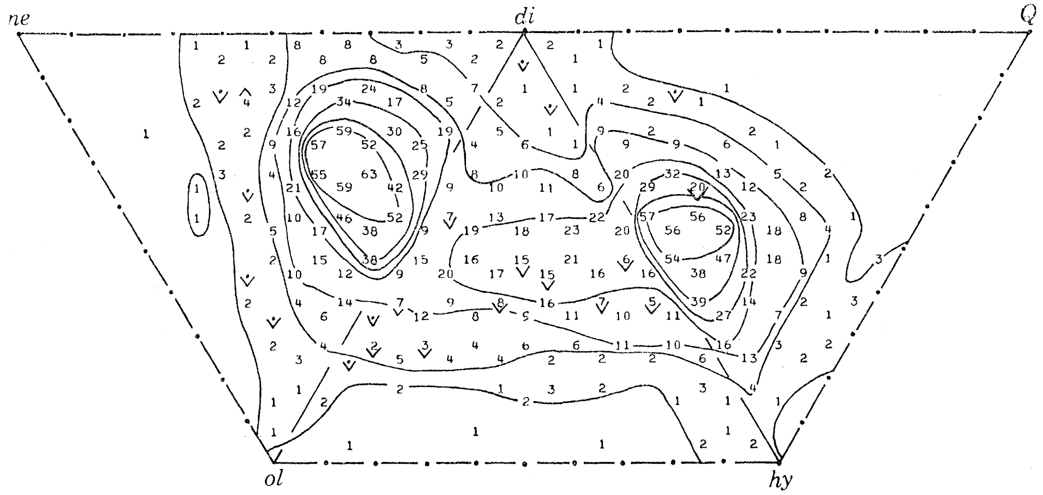

FIGURE 3. Distribution of normative silica-saturation parameters in 2413 Cenozoic basalts, all localities.

two quite distinct maxima connected by a rather flat gently sloping ridge; the Coombs projection shows a steep walled maximum in class III and, in class I, a highly asymmetric maximum whose skewed flank extends into class II. But the overall similarity of the pattern in the two projections is quite obvious.

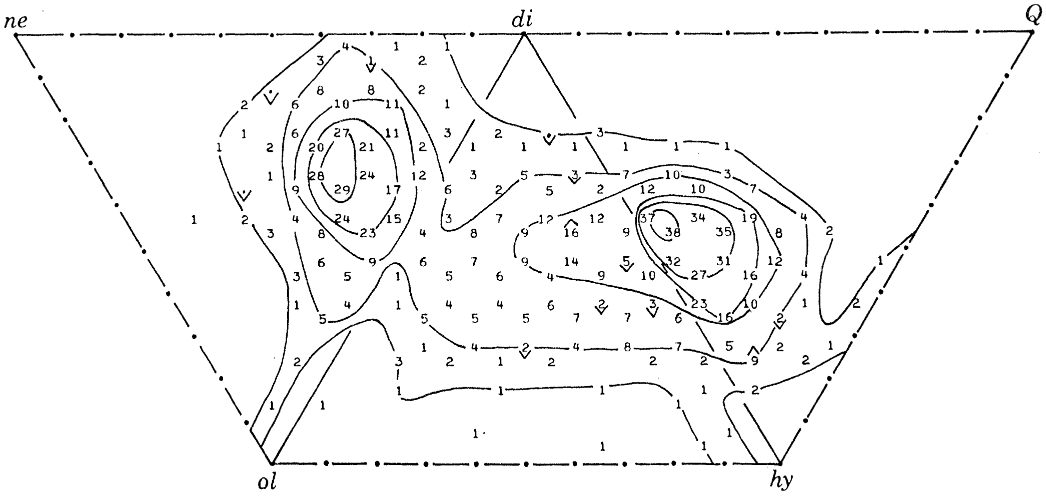

FIGURE 4. Data of figure 3 after exclusion of 1303 analyses in which molar $Fe_2O_3/(Fe_2O_3+FeO) > 0.25$, total $H_2O > 2\,\%$, or normative plagioclase is less than 50 % *an*.

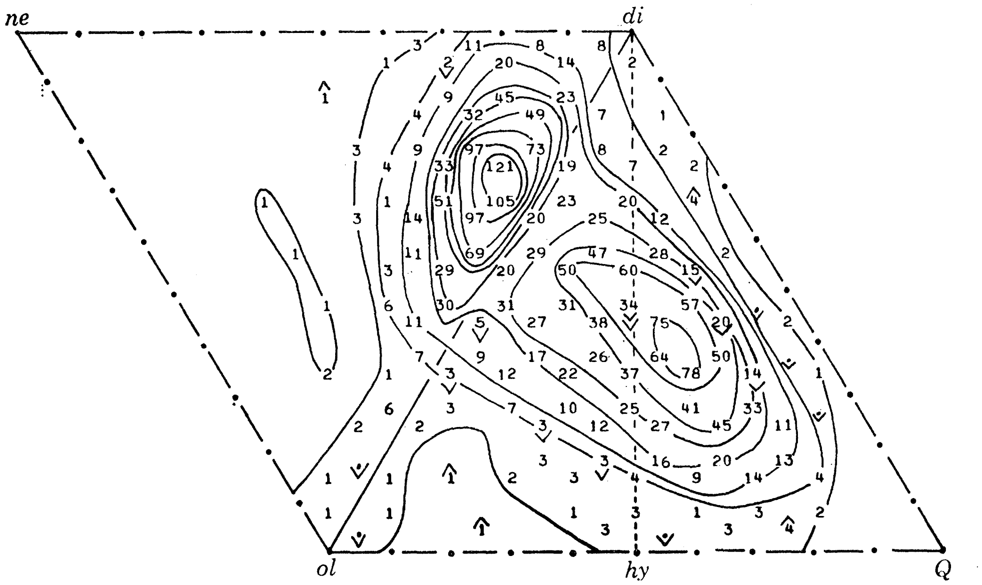

FIGURE 5. Data of figure 3 plotted in the Coombs projection.

## 5. SILICA SATURATION IN THE PARENT MATERIAL(S) OF BASALT

Making every allowance for real or imagined sampling bias, it seems a reasonable inference from the work of the preceding sections that there are two distinctly different immediately parental materials for the bulk of Cenozoic basalt, one a little oversaturated, the other appreciably undersaturated in silica. Whether these two 'proximate' parents themselves have a common parent, and at what remove, is a moot question, one on which the sample frequency distribution of silica-saturation parameters in Cenozoic basalts may in fact throw very little light.

If current speculation about the depths at which they form is correct, basaltic magmas must be generated by local melting of normally solid crust or upper mantle. If this melting goes to completion in a closed system, the composition of the resulting magma must of course be that of its parent. It may be that the maxima shown in the figures represent essentially complete melts of different parental materials, but it is impossible to account in this fashion for the paucity of saturated materials relative to over- and undersaturated ones unless, of course, such a paucity characterizes the region of the crust or mantle in which basalts are generated. This is perhaps not altogether impossible but seems exceedingly unreasonable.

If we start from a solid and do not wish to melt it completely, we must partially melt it and, by tectonic means, separate the liquid from the residual solids. Chemical petrology offers no special insight into the means by which the second step is to be accomplished, but a considerable body of experimental data suggests that partial melting might account for the bimodal distribution of silica saturation in basalts if the melts could indeed be separated from the residual solids.

Specifically, although initial melts of under- or oversaturated basaltic materials would evidently inherit the silica-saturation state of their respective parents, it has been suggested by a number of workers (Yoder & Tilley 1962; Yoder & Schairer 1964; Kushiro 1968) that, depending on the pressure at which it formed, the initial melt of a saturated basalt or its mantle precursor would be either over- or undersaturated with respect to silica. The most extensive discussion of this aspect of partial melting is by Green & Ringwood (1967), who give a detailed bibliography.[†] Thus a series of meltings of varying extent and at unsystematically varying pressure should lead to a bimodal distribution of silica saturation in the separated liquids *whether the parent materials are homogeneously saturated with respect to silica or vary widely in this respect.*

## 6. SILICA SATURATION IN BASALTS OF THE SUBMARINE RIDGES

In four of the seven groups for which tallies are listed in table 3 basalts of class III, and in two of those of class I, are strongly dominant; in all but one of these there is a more than two-fold excess of analyses of the dominant class, whether I or III, over those of class II. In the basalts of the submarine ridges, as already noted (Chayes 1965), the situation is drastically different. Of the 84 analyses available as of this writing, 74 project in class II and the ten which fall in classes I and III are without exception highly oxidized and hydrated.

The process outlined in the preceding section assumes a wide range of silica saturation in the basalt-generating region of the crust or mantle, for there seems little reason to suppose that part of the Earth any less heterogeneous in this respect than the visible portion of the lithosphere. It is to be noted, however, that a similarly bimodal distribution of silica saturation ought to characterize the liquids generated by application of the same process to a silica-saturated parent material, whatever its compositional variability in other respects. If we ignore materials balance questions to which there are at present no sound answers, or evade them by postulating an essentially unlimited reservoir of parent material, the submarine ridge basalts might qualify as either the extrusive equivalent or partial melt of such a parent.

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[†] In their view, however, although 'under restrictive conditions' the partial melt may itself be quartz-normative, it usually is not; rather, oversaturated magmas originate by subsequent fractionation of saturated partial melts formed at appropriate pressures.

It is perhaps tempting to suppose that the whole ocean is floored by material like that found along the ridges, for a material whose extrusive equivalent is present in such magnificant abundance could hardly be in short supply at depth. Despite much propaganda in recent years about the enormous volume and monotonous compositional uniformity of submarine basalts, however, very little is actually known about them. Even those of the submarine ridges have been sampled in only preliminary fashion, and concerning basalts away from the ridges there is, at this writing, almost no published information.

## 7. Silica saturation in Cenozoic volcanics

It is clear that if silica saturation is bimodally distributed in Cenozoic basalts, then it must be similarly distributed throughout Cenozoic volcanics as a whole. By definition, phonolites, tinguaites, nephelinites, leucitites and melilitites will project in class III, as will most trachyandesites and some trachytes. It has recently been shown (Chayes 1969), on the other hand, that nearly all andesites project in class I, and this of course will also be true of dacites, rhyolites and many trachytes. This about exhausts the list of volcanic rocks which are more than sports or oddities; there seems little doubt that in the Cenozoic volcanic dispensation as a whole, materials saturated with respect to silica are far less abundant than those that are either over- or undersaturated.

## 8. Source references

One of the hazards of literature searches is that they generate large bibliographies of little or no concern to the vast majority of readers. In the near future I hope to submit the bibliography of source references to a documentation service, so that copies will be available at reasonable cost. Readers who notify me of their interest will be informed of developments along this line. The bibliography below includes only works to which reference is made in the text.

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## *Discussion*

Dr P. W. Lipman. I am concerned that limitations of the sample distribution are more serious than stated in Dr Chayes's Introduction. For example, in the previous lecture Professor Walker estimated that about 75% of the world's active volcanism is submarine—mainly abyssal tholeiite erupted along spreading ocean ridges. Yet this group of basaltic activity is represented by only about 60 out of 2400 samples in your suite—about 2.5%—and they plot in the gap between your alkalic and subalkalic groups. Would not introduction of almost any reasonable volume factor result in disappearance of the bimodal distribution plot?

Dr F. Chayes. Whether or not 75 %—or 50 %, or 90 %—of the world's active volcanism is submarine I do not pretend to know, and I cannot help wondering how Dr Lipman can know, from analyses of 60 specimens or so, that this vast amount of unsampled material is 'mainly abyssal tholeiite'. But even if he is right on both counts, he would simply be confirming what I suggested, namely, that there is indeed a remarkable difference between submarine ridge basalts and other basalts.

His specific question, it seems to me, is quite unanswerable if we follow practices common in most sciences. For how can we fix on a 'reasonable volume factor' for an unknown amount of material of unknown composition? If we could do so, then of course we would have no need to sample and analyse the material. In this way we could dispense entirely with field petrologists. Is this what Dr Lipman has in mind?