[American Journal of Science, Vol. 253, August 1955, Pp. 433-461]

American Journal of Science

*AUGUST 1955*

# ZIRCONS IN ROCKS
# 1 SEDIMENTARY ROCKS

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ABSTRACT. This is the first of a series of three contributions dealing with zircons in rocks. The present paper describes the size and shape distribution of zircons in sediments. Methods of concentration of zircons in crushed rock samples are summarized and methods of measurement of zircons discussed. Zircon has been shown to be a highly resistant mineral in sedimentary processes. Its relative stability in the sedimentary cycle is attributed to its resistance to chemical attack, small size, and lack of cleavage. However, there is evidence that alkaline solutions may corrode zircons. Minute zircon fragments are probably dissolved and complex zirconium anions may then be adsorbed, e.g. on hydrated ferric oxides. Thus it is believed that in shales only part of the total zirconium is present as zircon, while in oceanic clays zircon accounts for only a small proportion of total zirconium.

In sedimentary transport or upon reworking of sediments, zircons are repeatedly rounded, broken, and again rounded. In sandstones the majority of zircons are well-rounded grains, and both sharply euhedral crystals and angular fragments are usually in the minority. In siltstones increased proportions of broken grains are encountered. In shales the majority of zircons are angular fragments and rounded grains are in the minority. Generally sharply terminated, euhedral zircons are subordinate in sediments, and those present are small rather than large. Another general observation is that the average elongation ratio of sedimentary zircons is less than 2.0. A third general rule is that the average size of zircons decreases from arenites to lutites. Exceptions to all three generalizations may be found.

The stability of malacons is not as high as that of clear zircon. Accordingly, sandstones and siltstones contain few malacons, but considerable proportions of the zircons of shales may be gray, brown, or black. Possibly formation of malacon is promoted in minute grains by solutions present in shales.

Studies of zircon size and shape distribution in sediments are usually not particularly useful in paleogeographic investigations; as a rule variations in size and shape are minor, even when traced over large distances. Pronounced changes indicate different sources of sediments. The relative proportions of heavy nonopaque minerals are generally more revealing in sedimentary petrographic studies.

Finally, a few selected examples are given to illustrate the role of zircon in sediments; (1) Kalahari sands of the Bechuanaland Protectorate, (2) arenites of the Cape system, Cape Province, Union of South Africa, (3) Permian arenites of New Mexico, Oklahoma, and Texas, and (4) miscellaneous zircon studies given in the literature.

## INTRODUCTION

Accessory minerals of sedimentary, igneous, and metamorphic rocks have held the interest of geologists for a long time, and a voluminous literature on the subject has accumulated. Zircon was singled out at an early stage as the mineral of greatest interest among the accessories. It is the most abundant, indeed practically ubiquitous, in rocks most suitable for study of accessory minerals, i.e. silicic and intermediate igneous rocks, arenaceous sediments, and their metamorphic equivalents such as quartzites, gneisses, and granulites. In addition certain special qualities were ascribed to zircon, such as its being one of the least refractory minerals and most resistant to chemical weathering and abrasion.

The early studies were generally qualitative and not always objective.[1] This soon resulted in pronounced differences of opinion which eventually caused doubts regarding the hardy qualities ascribed to zircon, the validity of conclusions based on this type of work, and finally even the significance of zircon studies. This situation has persisted more or less to the present time. Good reviews of the literature are given by Reed (1937) and Hoppe (1951).

The introduction of statistical methods in petrology made it possible to place studies of accessory minerals on a semi-quantitative footing. For zircon. the relative abundance, color. habit. dimensions. elongation ratio. degree of rounding. and other properties can now be determined on a rough quantitative basis for each rock, and the resulting data compared with those of another rock or suite of rocks. Such positive expressions of zircon properties can replace vague and unconvincing statements concerning the prevalence of particular peculiarities of zircons which supposedly characterize a rock or a series of rocks.

The aim of the present contributions is to outline methods in statistical zircon studies. to indicate their significance to understanding of petrogenetic processes. and to stimulate further detailed studies in this field. This will be done in part by reference to such studies in the literature. and in part by the use of selected examples studied by the writer and others in the United States and South Africa. In turn will be discussed: (1) zircons in sediments. (2) zircons in igneous rocks, and (3) zircons in metamorphic rocks. Portions of these papers are admittedly speculative. but it is hoped that those who disagree will be provoked to provide data from zircon studies. rather than arguments. to disprove these speculations.

ACKNOWLEDGMENTS

In 1947 the writer initiated his long term program of zircon studies mainly as a result of Read's provocative series of addresses on the subject of granite (1939; 1943; 1944; 1946; 1948a; 1948b; 1949; 1951; 1955). Smithson's interesting investigations of sediments in England using semiquantitative methods of study of accessory minerals (1939; 1941; 1942). and Coetzee's applications of Smithson's techniques in his study of Archaean metamorphic rocks of the Orange River valley in South Africa (1942a: 1942b). Throughout the years these studies were pursued as by-products of other researches. first at the University of Cape Town. South Africa. next at the Geological Survey, Lobatsi. Bechuanaland Protectorate. and finally at

[1] Starting with the work of Thürach (1884), a large number of zircon studies have been published. However, methods of concentration used often resulted in the loss of the smaller zircons and malacons. After the introduction of statistical methods in petrology (Niggli, 1924), zircon studies also became less qualitative (e.g. Zerndt, 1927; Wasserstein, 1933). However, the emphasis of these studies was on crystal habit of zircons (thereby largely eliminating rounded zircons) rather than shape (rounding) and size. They will, therefore, be quoted more extensively in the two later papers of this series than in the present one. It is of interest to note here that, for instance, Zerndt (1927, p. 373) remarked that, "Die meisten Zirkone in den beiden Quartziten sind *natürlich* stark abgerundet" (italics are the present writer's).

Columbia University, New York. Numerous persons collaborated in obtaining rock samples, or made useful data available to the writer, or contributed by correspondence or in discussions. Although the list of names is too long to give here in full, the writer would like to acknowledge his debt to them all for their cooperation, their interest, and their friendly and constructive criticism.

## METHODS

*Separation of zircon.*—About 500 grams of the rock are crushed to pass through a U. S. Standard 80 mesh (0.22 mm opening) sieve under which is a 100 mesh (0.16 mm opening) sieve. Thus the sample is divided into two portions which are treated separately. Tests indicate that the number of zircons broken by crushing is surprisingly small when the maximum diameter of the grains is less than ½ mm (as it usually is). Particularly if crushing is done mechanically, unusually high proportions of small, broken grains indicate that broken or cracked grains are present in the rock. The powders are placed in 500 cc beakers, water is added and the mixture vigorously agitated, then left to stand for 3 minutes and the water carefully decanted. This is repeated two or three times, after which the washed samples are dried. Next the powders are transferred to 500 cc pear-shaped separatory funnels one-quarter filled with bromoform. More bromoform is added and the mixture thoroughly stirred with a glass rod with paddle-shaped end. During the separation the rod is inserted at intervals of 10-15 minutes to various depths and rotated to agitate in turn the heavy fraction, the material adhering to the sides of the funnel, and the light fraction. The funnel itself is also rotated and slanted at intervals to allow the material adhering to the sides to slide down. The separation is usually complete after 1-1½ hours, when the heavy fraction is filtered off, washed with alcohol, and dried.

For studies of sedimentary heavy residues, slides are prepared from the heavy fractions according to instructions given below, but for specific zircon studies it is more convenient to purify the heavy residues further by magnetic separation and boiling with HCl.

For the magnetic separation the heavy fractions are transferred to a Frantz isodynamic separator. It is best to separate first the strongly magnetic minerals, for which purpose appropriate settings are chosen. The strongly magnetic fraction (mainly magnetite) is set aside, and the less magnetic fraction is run through slowly with different settings to separate all the weakly magnetic minerals. The resulting more magnetic fraction (mainly ilmenite and ferromagnesians) is run through several times with the same settings to augment the nonmagnetic fraction. The latter is then run through once more to obtain a final clean separation. If the sample is a mafic rock (e.g. dolerite), it will be necessary to run both strongly and moderately magnetic fractions through repeatedly to obtain any zircons at all. Patience then becomes a virtue.

To obtain a further concentration of the zircon fraction, the material is finally boiled with conc. HCl for 10-15 minutes to remove apatite and monazite, washed, and dried. If the final residue is very small it consists largely of zircons. if large there may be present considerable proportions of such minerals as garnet, fluorite, or barite.

At this stage the coarse and fine fractions may be combined or mounted separately, depending on the type of work contemplated. If the amount of final residue cannot be mounted conveniently on one slide. sampling of the residue becomes necessary. The all too frequent practice of tipping part of the residue out of a storage tube onto the slide is to be condemned. as excellent gravitative separations of minerals and of grain sizes are effected by this simple method. Instead, the sampling procedure suggested by Hutton (1950. p. 643) is preferred. It consists of passing the residue through a funnel with a small opening onto a glass surface, thus obtaining a conical heap of residue which is halved with a razor blade. The half removed is passed anew through the funnel and again halved. until a fraction is obtained of suitable size to mount in its entirety on a slide. Mounting is done with stiff Canada balsam, avoiding an excess of balsam. else much of the residue will move toward the sides of the slide on pressing down the cover glass, or will slide down to one side on vertical storage. Care should also be taken in distributing the grains evenly over the slide, avoiding both too high and too low a concentration of grains. In these respects a little practice goes a long way.

*Zircon measurements.*—Various measurements can be made. and the choice is determined solely by the particular interest and aims pursued in the study. The percentage total heavy residue has been called the *heavy minerals index* (Brammal and Harwood. 1923. p. 40) and is obtained by weighing the original sample and the heavy fraction of the bromoform separation. For most rocks it should correspond roughly with the *color index* of the mode (Shand. 1947, p. 233). The nonmagnetic fraction can similarly be determined and called the *nonmagnetic heavy minerals index.* Relative amounts of the various minerals present can be ascertained by linear traverses with a mechanical stage at regularly spaced intervals covering the entire slide, and counting 300 grains. The amounts may be expressed as volume percentages or after recalculation. as weight percentages of the total residue. The weight percentage of zircon with respect to the total heavy fraction may be called the *zircon index.*

The size of the grains may be determined by measurement with an ocular micrometer of both maximum and minimum diameter of each grain encountered in linear traverses with a mechanical stage at regularly spaced intervals covering the entire slide, care being taken that intervals are wide enough to exclude previously measured grains. Measurements of 200 grains are normally sufficient (Poldervaart and von Backström, 1950, p. 436-437). Broken grains are excluded in these measurements. If the grains are euhedral their length is measured along the *c* axis and their width at right angles thereto. If the grains are rounded the greatest length may or may not coincide with the *c* axis; the width is again measured at right angles to the length. Lengths. widths. and elongation ratios are best analyzed according to the method described by Smithson (1939, p. 349-351) using a moving average of 4 units and moving at intervals of 2 units. Corrections advocated by Smithson need not be applied if all zircons in the microscope field are measured and spaced intervals cover the entire slide. Final results for lengths and widths should be expressed in mm and frequency percentages, and are conveniently represented graphically. The shapes of these frequency curves and number and positions of maxima are of interest in zircon studies.

Various specific properties of zircons in concentrates may be noted by counting the number of grains which exhibit these properties in a total of 200-300 grains encountered in linear traverses at regularly spaced intervals. For ease of comparison the results may be expressed as percentages. Of especial interest may be for example:

(1) The number of euhedral, versus rounded, versus broken grains.

(2) The number of colorless zircons, versus hyacinths (purple), versus malacons (brown to black).

(3) The number of zircons with a conspicuous crystal face (e.g. the basal pinacoid), versus those without this face.

(4) The number of euhedral zircons with rounded cores, versus those without such cores.

(5) The number of highly elongated ($L/B > 4$), moderately elongated ($L/B$ 2-4), or slightly elongated ($L/B$ 1-2) grains.

Such counts are more rapid and less tedious than detailed measurements and yet give results of much significance in particular studies. Of especial interest is the proportion of rounded versus sharply euhedral grains. Allen (1944, p. 72) has introduced the term *zircon abrasion index*, being the percentage euhedral crystals (in relation to rounded grains and excluding broken grains). Thus defined the term is not a happy one, and the writer prefers the suggestion of Eckelmann (1954) to call the *zircon rounding index* the percentage of rounded versus euhedral grains (again excluding broken grains). In determining the zircon rounding index especial attention should be given to the terminations of grains; although the grains may show good crystal faces their terminations may be well rounded, and such crystals are rounded, not euhedral.

## HARDY QUALITIES OF ZIRCON

Zircon is one of the most resistant of the accessory minerals of sediments, to both chemical attack and abrasion. Table 1 is taken from Smithson (1950, p. 14) and shows relative stabilities of common accessory minerals in sediments. The order of stability was determined both experimentally and empirically.

Table 1 seems to indicate general agreement as to the hardy qualities of zircon in the sedimentary cycle. Yet zircon is not a very hard mineral (H: 7½), and Freise (1931) found that the abrasive resistance of zircon was less than that of such minerals as epidote, garnet, staurolite, rutile, and tourmaline, and of the same order as quartz and apatite. Resistance to chemical attack, the small size of crystals, and the absence of cleavage equally account for the apparent stability of zircon in the processes which make and transport sediments. Another factor is the relative ease with which crystals or broken fragments are modified to more resistant and chemically more inert rounded grains.

TABLE 1
Stability of Accessory Minerals

| Mechanical Action | Chemical and Mechanical Action | Chemical Action | | | | |
|---|---|---|---|---|---|---|
| Abrasion tests | Marine shore sands | Subterranean strata | | Weathering (?) | Weathering of rocks and soil minerals | |
| Freise (1931) | Thoulet (1913) | Pettijohn (1941) | Smithson (1941) | Sindowski (1949) | Goldich (1938) | L. and C. Dryden (1946) |
| | | Rutile | | | | |
| | Zircon | Zircon | Zircon | Zircon | | Zircon |
| | Rutile | | Rutile | Rutile | | |
| Tourmaline | | Tourmaline | Tourmaline | Tourmaline | | Tourmaline |
| | | | Apatite | | | |
| | | Monazite | Monazite | | | Monazite |
| Staurolite | | | | | | |
| Augite | | | | | | |
| Garnet | | Garnet | Garnet | | | |
| | Biotite | Biotite | | | Biotite | |
| Olivine | | | | | | |
| Apatite | Apatite | Apatite | | | | |
| | | Staurolite | Staurolite | Staurolite | | |
| Kyanite | | Kyanite | Kyanite | Kyanite | | Kyanite |
| | Amphiboles | Hornblende | | Amphiboles | Hornblende | Hornblende |
| | | | Ferromag-nesian minerals | | | Staurolite |
| | | | | Garnet | | Garnet |
| | Pyroxenes | Augite | | Augite | Augite | |
| | | | | Apatite | | |
| | Olivine | Olivine | | Olivine | Olivine | |
| Monazite | | | | | | |

However, this stability is only relative; i.e. zircon generally persists longer than most other minerals. In a finely divided state zircon inevitably loses its stability. In the presence of a solvent, minute particles might dissolve and might again crystallize on larger grains as authigenic growths. Several examples of such zircon outgrowths are reported in the literature (Butterfield, 1936; Smithson, 1937; Tyler et al., 1940; Bond, 1948a; Hutton, 1950), peculiarly enough all from zircons in relatively coarse-grained arenites. It might be expected that in finer-grained sediments (siltstones, shales) zircon outgrowths would be less rare, but so far they have not been observed in such sediments (e.g. Karroo siltstones, Malmesbury semi-pelites, and Pretoria shales, South Africa; Permian siltstones from the Delaware basin, Texas). The problem of zircon outgrowths cannot be regarded as solved until more is known of conditions under which they originated. It may be significant that Hoppe (1951, p. 71-73) has described intergrowths of zircon and xenotime and drawn attention to their close similarity to these zircon outgrowths. Confirmation is needed that the outgrowths are in all instances zircon and not xenotime.

Nonetheless it is clear that eventually zircon is taken into solution. Rankama and Sahama (1950, p. 566) note that, despite the apparent stability of zircon, there is a definite zirconium cycle in nature. Dorothy Carroll (1953, p. 111) observes that zircons in lateritic soil profiles are frequently strongly corroded, and ascribes this to attack by alkaline solutions. Strock (1941, p. 863) attributes the high zirconium content of Saratoga Springs mineral waters to solution of zircon in the country rocks by the carbonated, saline, and lime-rich solutions.

Abundance data for zirconium in sediments are few. The abundance of zircon in sandstones is probably of the same order as that in granite, but subject to large variations, depending also on the amount of reworking of the sediments. Shaw (1954a, p. 1163; 1954b, p. 1179) gives the abundance of zirconium in shales as 200 p.p.m. Yet zircon crops from shales are relatively small, and it is suspected that a considerable proportion of zirconium in shales is not present as zircon. Cherts contain no zirconium (Maxwell, 1953). The abundance of zirconium in oceanic red clay is given by Hevesy and Würstlin (1934, p. 309; Atlantic samples) as 140 p.p.m., and by Young (1954) as 230 p.p.m. The chocolate brown clays of the South Pacific, high in fine-grained pyroclastics, average about 220 p.p.m., and the light buff North Pacific clays about 150 p.p.m. zirconium (Gustaf Arrhenius, personal communication, Nov. 19, 1954). Yet zircon is rarely observed and the zirconium content of the clays varies with iron, indicating sorption of complex zirconium anions on hydrated ferric oxides (Revelle et al., 1955). Thus zirconium in oceanic clays, which may be regarded as the end products of the sedimentary cycle, is not present as zircon.

### SIZE AND SHAPE OF SEDIMENTARY ZIRCONS

The implications of table 1 are clear: (1) Away from source, with repeated reworking, or traced back in geologic time, both the total amount of accessory minerals and the number of mineral species ("richness" of mineral assemblage) are likely to diminish (Pettijohn, 1941). (2) If a sediment is traced away from its source or is reworked repeatedly, the proportion of zircon relative to other accessory minerals is likely to increase gradually. Various uses have been made of these observations; it suffices here to refer to Smithson's studies (1941, 1942) of Mesozoic arenites of Yorkshire.

Assuming an original source in which the zircons are prismatic crystals with sharply pointed pyramidal terminations, it would appear likely that the sharp points would be rounded off relatively rapidly during sedimentary transport. Further away from the source, and more slowly, the grains would tend to become more rounded in shape, by rounding of both original prismatic crystals and angular chips and fragments resulting from breakage (fig. 1). Yet further away from source there would probably be increasing amounts of small, roughly equidimensional, angular fragments, in addition to well-rounded grains. Finally there would be a predominance of minute, angular fragments over rounded grains, and much fine zircon flour which normally would not be recovered in heavy mineral separations. The same effects would be produced by repeated reworking without much lateral transport. The effect

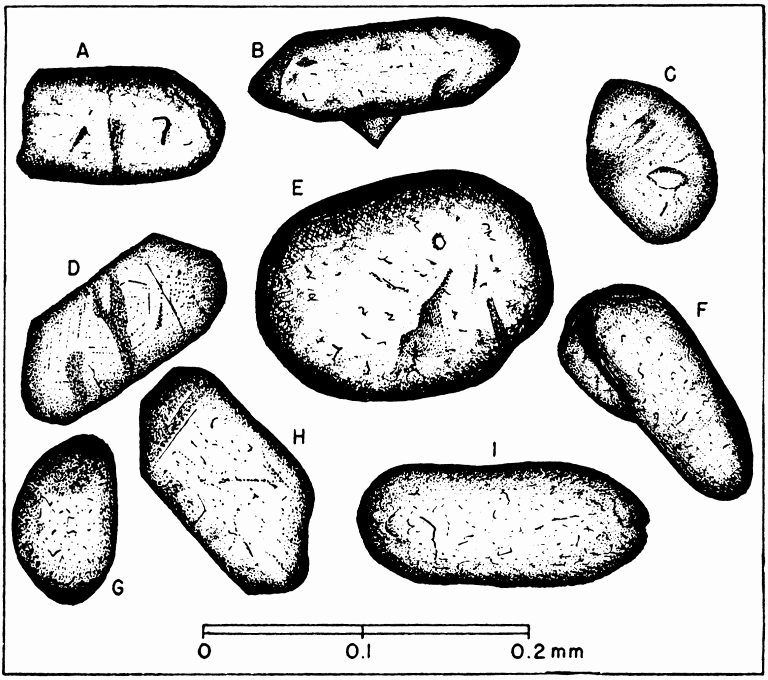



Fig. 1. Habit of zircons in sandstones.
A. Fractured grain with rounded end.
B. Partly rounded grain with sharply euhedral outgrowth.
C., G. Rounded grains in which terminal faces can still be faintly seen.
D. Partly rounded, partly euhedral, zoned grain.
E. Well-rounded grain.
F., I. Well-rounded but elongated grains.
H. Fractured grain, partly euhedral and partly rounded.

of grain-size of zircons should be considered, as well as distance from source or amount of reworking prior to final deposition. Larger grains would tend to round more rapidly than smaller crystals. The latter may be carried further or reworked to a greater extent without losing their sharply euhedral original shapes.

These predictions are generally realized in studies of zircons in various sediments. On the whole, sorting of sediments is reflected also in sorting of their zircons. Well-sorted sediments yield zircon length- or elongation-frequency curves with one narrowly defined maximum, whereas ill-sorted sediments may yield zircon curves with broad peaks or several maxima, depending also on zircon size distribution in the source rocks. The inequidimensional character of zircon in most source rocks generally results in zircons separated from a particular size grade of a sediment being longer than conforms with the average diameter of quartz of that size grade. The size of zircons which passes through a sieve is determined by the widths of the grains rather than their lengths.

In arkoses there are usually many zircons with sharp as well as rounded terminations, but in most sandstones angular zircon fragments and sharply terminated crystals are subordinate to grains with well-rounded terminations. In both arkoses and sandstones the average longest diameter of zircons is generally 0.15-0.25 mm. In most siltstones there is an appreciable proportion of angular zircon fragments in addition to rounded grains. Generally the average longest diameter of zircons is 0.05-0.15 mm. In most shales the proportion of zircons recovered is relatively small, rounded grains are subordinate to angular fragmental grains, while sharply terminated crystals are rare or absent. The average longest diameter of zircons is usually 0.02-0.07 mm.

It is to be noted that in the series arkose-sandstone-siltstone-shale, the largest proportions of sharply terminated zircon crystals are to be found in arkoses and siltstones, the euhedral grains being large (length $>$ 0.12 mm) in the former and small (length $<$ 0.10 mm) in the latter.

Rounding and breakage of primary crystals results in a rapid decrease in average elongation ratio of zircons in sediments when traced away from their source, or when repeatedly reworked. In most igneous rocks the average elongation ratio of zircons is less than 3.0. Accordingly, the average elongation ratio of zircons in most sediments is less than 2.0, and approaches 1.0 in fine-grained sediments. However, some igneous rocks may contain small, slender zircons with elongation ratios much in excess of 3.0. Their significance will be discussed later. Sediments derived from such rocks commonly contain zircons with rounded terminations, but with elongation ratios greater than 2.0, even when transported over considerable distances or reworked repeatedly. Apparently the small size of the zircons prevents much breakage in spite of their slender form.

The above observations allow for certain general conclusions which are at least statistically true, although exceptions may be found:

(1) Zircons of sediments are predominantly grains with rounded terminations, or angular fragments, but sharply pointed, euhedral crystals are generally subordinate.

(2) The average elongation ratio of such zircons is generally less than 2.0.

(3) The average size of zircons in arenites decreases toward that of lutites, while at the same time the proportion of rounded grains decreases and that of angular fragments increases.

Studies of zircon size and shape distribution are not particularly useful in paleogeographical investigations of sediments. Generally it is found that, e.g. the same sandstone sequence, even when traced through a considerable distance, contains zircons of the same or similar size and shape distributions. For such investigations the relative proportions of the heavy nonopaque minerals, including zircon, and the size distribution of other common accessory minerals (e.g. garnet, staurolite, kyanite, sillimanite, andalusite) may yield more satisfactory results. However, data on zircons in sediments form the basis for zircon studies of metamorphosed or granitized rocks. Hence there is a real need for information of this type.

TABLE 2

Characteristic Nonopaque Heavy Minerals in Kalahari Sand Surface Samples from Ukwe Pan to Kanye

| Index | L | L | L | P | P | P | L | P | P | L | P | P | P | L | P | L | L | L | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 196 | 197 | 198 | 292 | 285 | 291 | 200 | 286 | 283 | 203 | 287 | 284 | 290 | 205 | 282 | 206 | 207 | 208 | 289 |
| Distance from Ukwe Pan (miles) | 32 | 36 | 46 | 113 | 130 | 133 | 137 | 147 | 176 | 194 | 195 | 201 | 208 | 218 | 231 | 246 | 276 | 288 | 303 |
| Zircon | 23 | 25 | 36 | 40 | 41 | 35 | 36 | 43 | 42 | 41 | 52 | 50 | 39 | 43 | 47 | 44 | 46 | 48 | 48 |
| Tourmaline | 22 | 26 | 27 | 29 | 29 | 33 | 30 | 25 | 28 | 30 | 23 | 21 | 32 | 32 | 26 | 33 | 33 | 30 | 29 |
| Staurolite | 41 | 36 | 22 | 20 | 22 | 19 | 20 | 18 | 20 | 18 | 15 | 16 | 19 | 15 | 17 | 16 | 14 | 15 | 15 |
| Kyanite | 6 | 6 | 8 | 5 | 3 | 4 | 4 | 4 | 3 | 4 | 3 | 5 | 4 | 4 | 3 | 3 | 2 | 2 | 2 |
| Rutile | 8 | 7 | 7 | 6 | 5 | 9 | 10 | 10 | 7 | 7 | 7 | 8 | 6 | 6 | 7 | 4 | 5 | 5 | 6 |

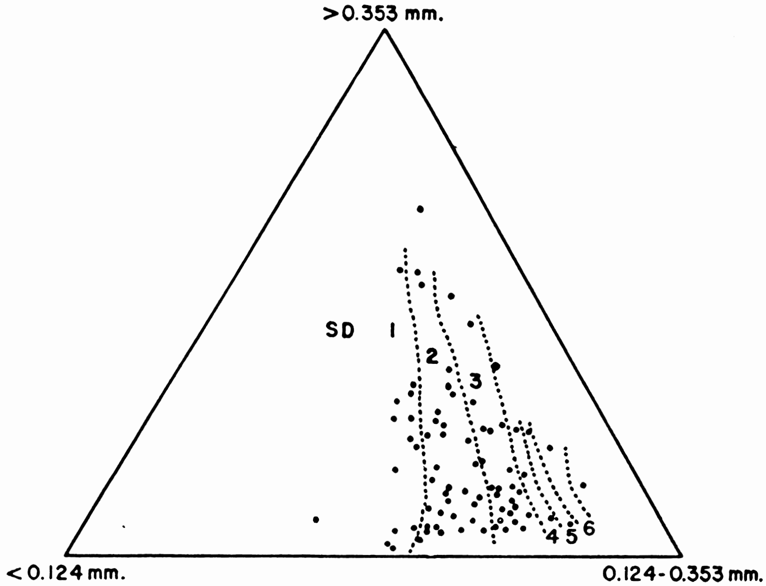



Fig. 2. Size distribution of quartz grains in Kalahari sands, Bechuanaland Protectorate.

### MALACONS IN SEDIMENTS

Little is known of the role of malacons in sediments. Gross observations on heavy residues of arenites indicate that brown or black zircons are relatively rare; hence it may be concluded that the stability of malacon is lower than that of clear or colorless zircon, and that the former crystals break more easily and are also more easily attacked by solutions. The Precambrian Mahalapye granite in the Bechuanaland Protectorate (Poldervaart and Green, 1954) contains a high proportion (about 75 percent) of brown and black zircons. In places the granite is overlain by highly feldspathic grits, arkoses, and sandstones which so closely resemble the granite that their local derivation can hardly be in doubt. Heavy residues of the sediments confirm this; the proportion of euhedral crystals with sharp terminations is relatively high (about 20 percent) and they are identical in shape and size to the colorless zircons of the granite (rather small, squat crystals with a small basal pinacoid). However, only some 25 percent of the grains are brown, indicating relatively rapid dissolution of malacon in the formation of the sediments.

Siltstones are in this respect similar to sandstones, i.e. they contain relatively few malacons. On the other hand, shales often contain a considerable proportion of gray, brown, or black zircons. Probably original malacons fracture easily to minute grains which are carried further and thus concentrated in sediments of finest grain-size. This may be a contributing factor, but it cannot be the only reason for the paucity of malacons in sandstones and siltstones and their relative concentration in shales, since they are probably also more easily attacked by solutions than clear zircons. The writer suggests that water under favorable conditions may promote the production of malacon.

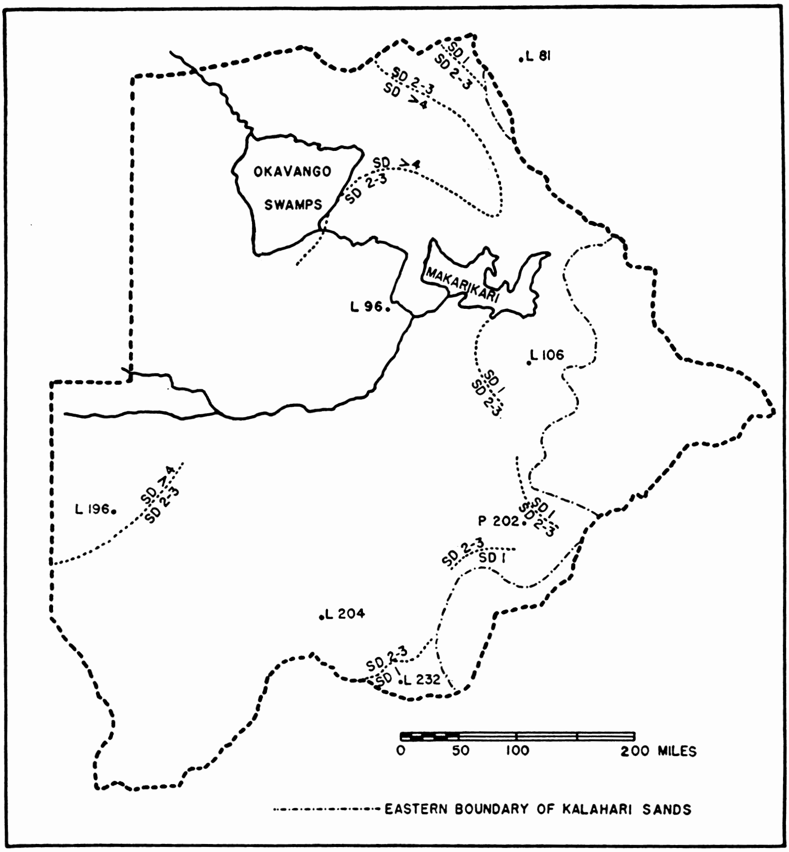



Fig. 3. Geographic distribution of SD (sand-dust) ratios in Kalahari sands, Bechuanaland Protectorate.

Thus he interprets the apparent concentration of brown and black zircons in shales as due in part to their formation during and after deposition, facilitated by both the solutions contained by shales and the extremely small size of the majority of zircons present. This will be discussed further in the second paper of this series.

## EXAMPLES

*Kalahari sands. Bechuanaland Protectorate*[2].—The present work was done on about 100 samples with a wide geographic spread. Considering the large area involved the number of samples is woefully small, and this study can only be regarded as a reconnaissance.

[2] Data given here are derived in part from an unpublished report by the writer while at the Geological Survey of the Protectorate. Permission of the Director is acknowledged for publication of these results.

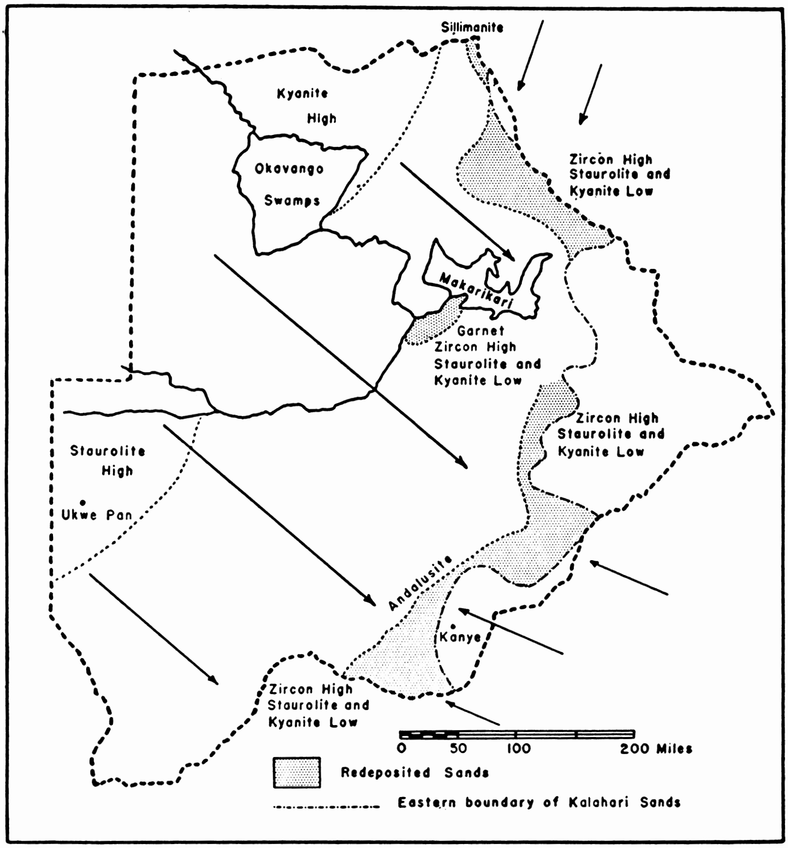



Fig. 4. Geographic distribution of nonopaque heavy minerals in Kalahari sands, Bechuanaland Protectorate.

Sieving results indicate that the sands are uniformly well sorted. Figure 2 shows percentages of the quartz fractions $>$ 0.353, 0.124-0.353, and $<$ 0.124 mm diam. for 77 samples plotted on a triangular diagram. The lines drawn separate fields for which $\text{SD} = \dfrac{\text{weight percent } 0.124\text{-}0.353 \text{ mm}}{\text{weight percent} < 0.124 \text{ mm}}$ equals 1, 2, 3, 4, etc. Figure 3 is a sketch map of the Protectorate on which the distribution of SD (sand-dust) ratios is indicated geographically. The proportion of dust increases in a general southeasterly direction.

Typical nonopaque heavy minerals of Kalahari sands are zircon, tourmaline, staurolite, kyanite, and rutile. Minerals such as garnet, sillimanite, andalusite, epidote, augite, and hornblende may be present locally. Figure 4 indicates the geographic distribution of differences in proportions of these minerals. Sands with high staurolite and kyanite proportions are found in the western and northwestern parts of the Protectorate and seem to be differentiated from one another. Proportions of these two minerals decrease in a

Table 3

Diameters of Largest Staurolite, Zircon, and Andalusite Grains in Kalahari Sand Series Ukwe Pan to Kanye

| Index | L 196 | L 197 | L 198 | P 292 | P 285 | P 291 | L 200 | P 286 | P 283 | L 203 | P 287 | P 284 | P 290 | L 205 | P 282 | L 206 | L 207 | L 208 | P 289 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance from Ukwe Pan (miles) | 32 | 36 | 46 | 113 | 130 | 133 | 137 | 147 | 176 | 194 | 195 | 201 | 208 | 218 | 231 | 246 | 276 | 288 | 303 |
| Diam. largest staurolite (mm) | 0.66 | 0.48 | 0.60 | 0.41 | 0.52 | 0.42 | 0.38 | 0.64 | 0.50 | 0.51 | 0.46 | 0.32 | 0.36 | 0.42 | 0.48 | 0.45 | 0.51 | 0.36 | 0.68 |
| Diam. largest zircon (mm) | 0.33 | 0.37 | 0.31 | 0.30 | 0.34 | 0.30 | 0.33 | 0.28 | 0.36 | 0.40 | 0.46 | 0.26 | 0.30 | 0.39 | 0.30 | 0.39 | 0.39 | 0.48 | 0.32 |
| Diam. largest andalusite (mm) | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 0.29 | 0.52 | 0.56 | 0.44 |

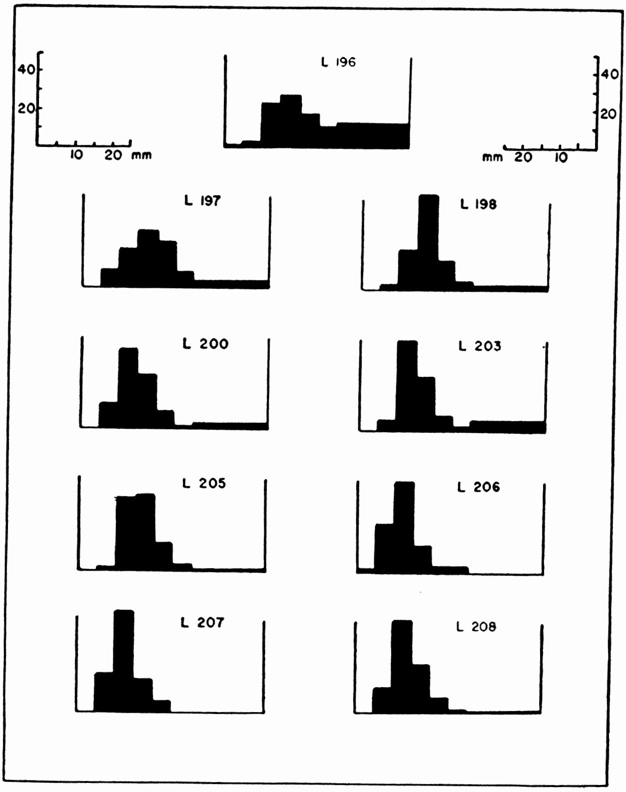
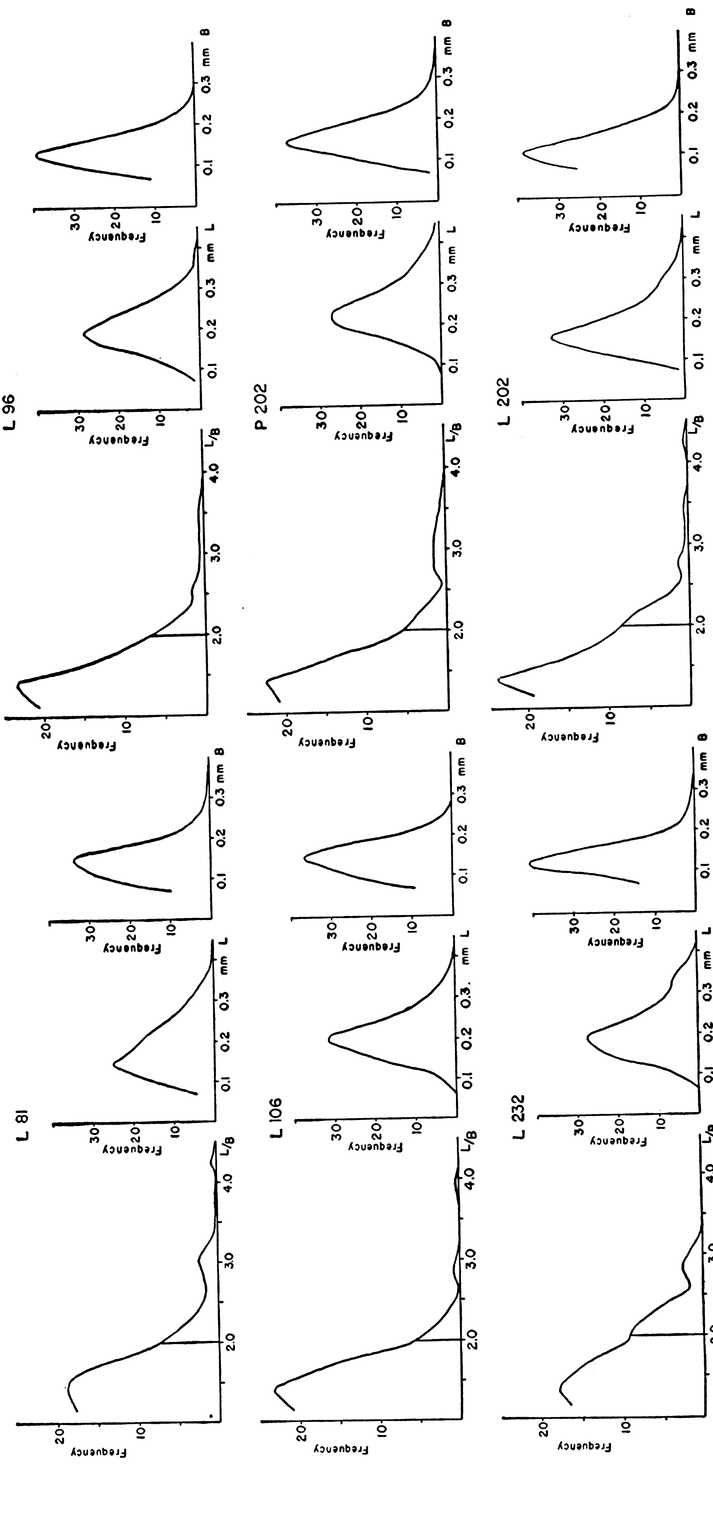



Fig. 5. Histograms of maximum diameter of 100 staurolite grains in series of Kalahari surface sands from Ukwe Pan to Kanye.

general southeasterly direction while that of zircon increases. In the southeast and east sands are encountered which contain andalusite, epidote, augite, and hornblende, in addition to the typical minerals of Kalahari sands. Since

TABLE 4
Relation between Elongation and Length of Zircons in Kalahari Sand Sample L 196

| L/B | L 0.05-0.10 mm | L 0.10-0.15 mm | L 0.15-0.20 mm | L 0.20-0.25 mm | L 0.25-0.30 mm | L >0.30 mm |
|---|---|---|---|---|---|---|
| 1.0-2.0 | 97 | 80 | 92 | 71 | 27 | 10 |
| 2.0-3.0 | 3 | 18 | 7 | 24 | 17 | 3 |
| 3.0-4.0 | — | 2 | 1 | 4 | 5 | 1 |
| 4.0-5.0 | — | — | — | — | 1 | 1 |
| 5.0-6.0 | — | — | — | 1 | — | — |
| total | 100 | 100 | 100 | 100 | 50 | 15 |
| > 2.0 | 3 | 20 | 8 | 29 | 23 | 5 |


L 96
P 202
L 202
L 81
L 106
L 232

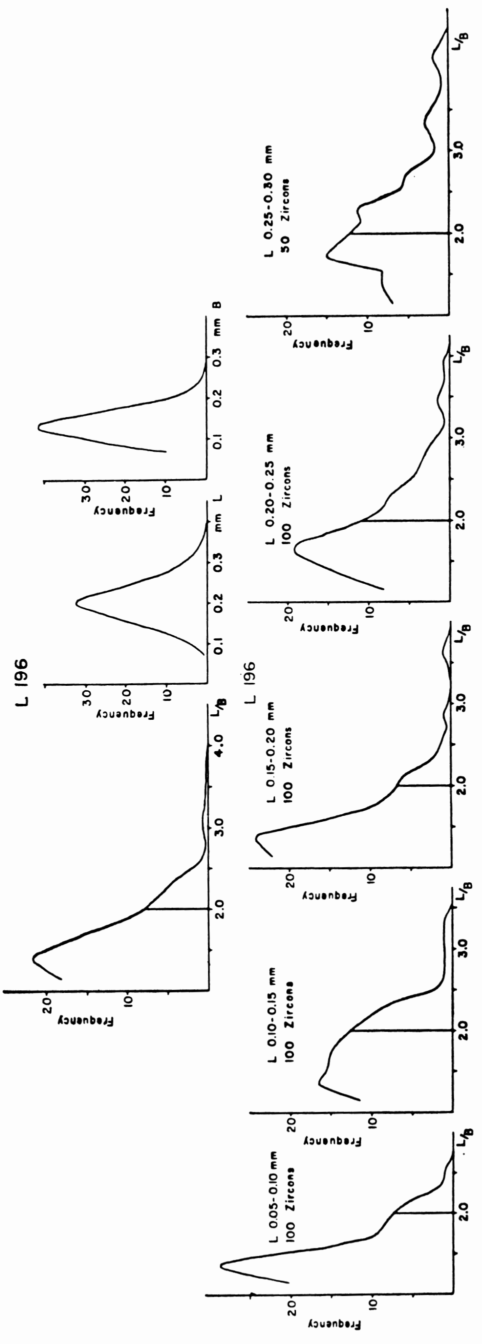



Fig. 6. Zircon size-frequency curves of 7 samples of Kalahari sands (for locations see figure 3).

andalusite increases eastward these sands are regarded as redeposited and blown back into the Kalahari basin from the Bushveld region (a likely source for the andalusite) after the main Kalahari phase. A similar belt of redeposited sands is recognized in the northeastern parts of the Protectorate. characterized by sillimanite. epidote. augite. and hornblende. These sands are thought to have been blown back from Southern Rhodesia in a southerly or southwesterly direction (Bond, 1948b). A small patch south of Makarikari is also regarded as redeposited and is characterized by garnet. epidote. and hornblende. Its derivation is uncertain.

Table 2 shows percentages (exclusive of other minerals) of typical heavy residue minerals in a characteristic series of surface samples from Ukwe Pan to Kanye (locations indicated on figure 4). Table 3 lists diameters of the largest staurolite. zircon, and andalusite grains found in this series. Evidently there is no systematic variation in maximum size (cf. Bond. 1948b). Histograms of 100 staurolite grains measured for 9 samples of the series also show lack of systematic variation (fig. 5).

Two hundred zircons were measured for each of 7 representative samples with a wide geographic spread. Sample locations are indicated on figure 3. All zircon grains were found to be well rounded. Figure 6 shows zircon elongation-. length-. and width-frequency curves for the samples.[3] Also shown are elongation-frequency curves for 5 length ranges of zircons of one sample (L 196). Further data concerning the relation of elongation and length of zircons are given in table 4. These illustrate the points made in previous sections of this paper. It is also evident that there is little variation in size distribution of zircons in the sands. despite transport over considerable distances.

Preliminary conclusions from this study are: The Kalahari sands were originally derived from a source. or sources in Southwest Africa or Portuguese Angola. and blown in a general southeasterly direction. Subsequently the sands were in part blown back into the Kalahari basin. resulting in fringe areas of redeposited sands in the southeast. east. and northeast. It is noteworthy that evidence for a post-Acheulean. pre-Levallois age for the sands (E. J. Wayland, personal communication. 1951) comes chiefly from these fringe areas and leaves in doubt the age of original distribution of the Kalahari sands. Much work remains to be done. It seems to the writer that detailed archeological and sedimentary petrographical studies of cave deposits (King. 1951). coupled with $C^{14}$ age determinations as far as possible, should be most profitable in this research.

*Arenites of the Cape system in Cape Province. South Africa.*—For general information on this sedimentary sequence. the reader is referred to du Toit (1939). De Villiers (1942) published a detailed structural study of part of the Cape Folded Belt and also (1945) discussed more general aspects of the Cape orogeny. Coetzee (1942a. 1942b). and Conradie and Rabie (1945) studied heavy residue minerals of samples of Table Mountain sandstone. and

[3] Using Smithson's method, frequency percentages are obtained at regular intervals, e.g. for L/B at 1.15, 1.35, 1.55, etc. No specific points are shown on the curves which were faithfully drawn through all the points obtained.

TABLE 5

Relation between Elongation and Length of Zircons in Table Mountain Sandstone Sample from Schoenmakers Kop

| L/B | L 0.05-0.10 mm | L 0.10-0.15 mm | L 0.15-0.20 mm | L 0.20-0.25 mm | L >0.25 mm |
|---|---|---|---|---|---|
| 1.0-2.0 | 99 | 167 | 44 | 10 | — |
| 2.0-3.0 | 1 | 33 | 53 | 52 | 2 |
| 3.0-4.0 | — | — | 2 | 33 | 2 |
| 4.0-5.0 | — | — | 1 | 5 | 1 |
| 5.0-6.0 | — | — | — | — | 1 |
| total | 100 | 200 | 100 | 100 | 6 |
| > 2.0 | 1 | 33 | 56 | 90 | 6 |

TABLE 6

Characteristic Nonopaque Heavy Minerals in Cape Sediments at Wuppertal

| | | Zircon | Rutile | Brookite | Tourmaline | Monazite |
|---|---|---|---|---|---|---|
| Witteberg series (base) | | 55 | 16 | 20 | 9 | - |
| Bokkeveld series | | | | | | |
| $S_5$ | top | 64 | 19 | 9 | 4 | 4 |
| | middle | 56 | 25 | 12 | 3 | 4 |
| | bottom | 54 | 24 | 16 | 2 | 4 |
| $S_4$ | top | 59 | 22 | 9 | 7 | 3 |
| | middle | 56 | 21 | 16 | 4 | 3 |
| | bottom | 66 | 17 | 5 | 7 | 5 |
| $S_3$ | top | 70 | 17 | 3 | 9 | 1 |
| | middle | 69 | 17 | 6 | 4 | 4 |
| | bottom | 66 | 18 | 4 | 8 | 4 |
| $S_2$ | top | 69 | 24 | 1 | 5 | 1 |
| | middle | 70 | 23 | 1 | 6 | + |
| | bottom | 73 | 20 | 2 | 4 | 1 |
| $S_1$ | top | 72 | 18 | 4 | 6 | + |
| | middle | 80 | 14 | + | 6 | + |
| | bottom | 81 | 7 | + | 11 | 1 |
| Table Mountain series (top) | | 54 | 30 | - | 15 | 1 |

Swart (1950) investigated Cape sediments around Wuppertal. Present data are largely derived from the last three papers with the addition of results for two samples of Table Mountain sandstone obtained by the writer.

Figure 7 shows the geographic distribution of the samples discussed here. Figure 8 gives zircon elongation-frequency curves for Table Mountain Sandstone samples from two localities and different horizons, measured by *Coetzee*

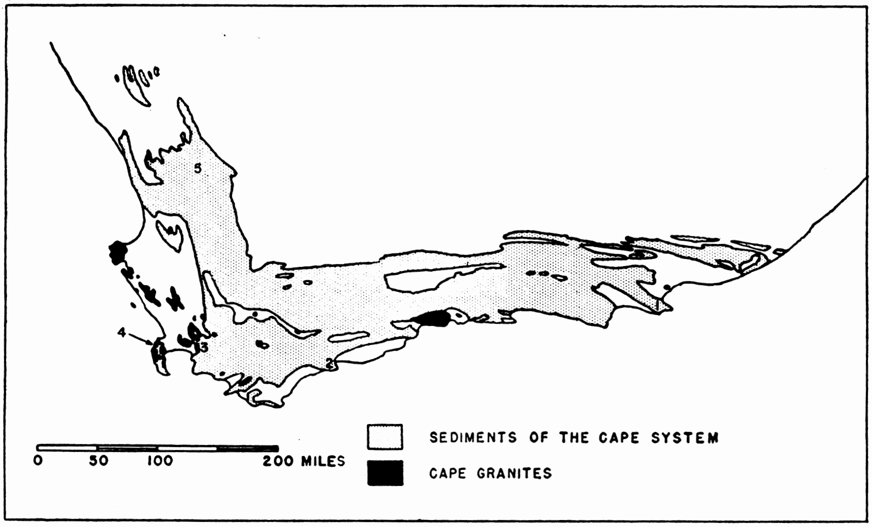



Fig. 7. Geographic distribution of samples of Cape sediments examined.
1. Table Mountain sandstone, Schoenmakers Kop, near Port Elizabeth.
2. Table Mountain sandstone, Mosselbay.
3. Table Mountain sandstone, base of series, Botmanskop, near Stellenbosch.
4. Table Mountain sandstone, just above lower shale band, Cape Town.
5. Cape sediments, Wuppertal district.

(1942b) and Conradie and Rabie (1945). and complete zircon size-frequency curves for two other samples measured by the writer. Also shown are elongation-frequency curves for four length ranges of zircons of one sample (Schoenmakers Kop). Further data are given in table 5. Figure 9 gives zircon elongation-frequency curves for Cape sediments of the Wuppertal district measured by Swart (1950). Table 6 lists percentages of nonopaque heavy minerals in the Wuppertal samples given by Swart (1950).

Conclusions reached in preceding sections are well illustrated by these data. This is not the place for a detailed discussion of conditions of deposition of the Cape sediments. nor are there probably sufficient data for such a discussion. nor is the writer the best qualified to do so. However. one point deserves mention here. The so-called Cape granites (Scholtz. 1946; Walker and Mathias. 1947; Potgieter, 1950) are characterized by highly elongated "needle" zircons often with unusually steep pyramidal terminations. probably (331).[4] No other granites in southern Africa examined by the writer possess zircons of this habit and with such steep pyramid faces. Zircons of the Table Mountain samples usually have rounded terminations, but many are long and bar-shaped. There is a small proportion of grains in which pyramidal faces can still be recognized, although points and edges are usually rounded off. These zircons show the same steep pyramid faces and leave little doubt that the grains are in large part derived from the Cape granites. Swart (1950, p. 441)

[4] See further the second paper of this series.

remarks that in the arenites of Bokkeveld and Witteberg age from Wuppertal, zircons with steep pyramidal faces are not frequent. This may indicate a different principal source for these sediments but the similarity of elongation-frequency curves for the Witteberg and Table Mountain sandstones should be noted. More systematic work of this nature is needed. The Table Mountain sandstone seems to be an accumulation of beach sands, reworked repeatedly but not transported far, and derived in large part from the Cape granites.

*Permian arenites of New Mexico, Oklahoma, and Texas.*—Data given here were obtained by Mr. J. P. D. Hull, Jr. during his research work on these sediments at this University. The writer is indebted to him for making these data available for this paper.

King (1948, p. 83-84) has summarized information concerning the Guadalupian series of the Delaware Basin of western Texas. Some 3000 feet of well-sorted sand and silt were here deposited in deep water of the fore-reef environment of the basin. Arenites are common also throughout the larger Permian basin of the southwest-central United States. Lang (1937, p. 888-890) and Newell et al. (1953, p. 185-186) have suggested that the sands were derived from distant sources of older arenites.

Locations of the 6 samples discussed here are given in figure 10. Stratigraphers disagree on correlation of some of the Permian units, but the samples represent approximately the base of the middle Guadalupian series, or the base of the Cherry Canyon formation (Adams et al., 1939, p. 1676). Typical nonopaque heavy minerals are zircon, tourmaline, apatite, rutile, and garnet, with minor amounts of staurolite, anatase, and sphene.

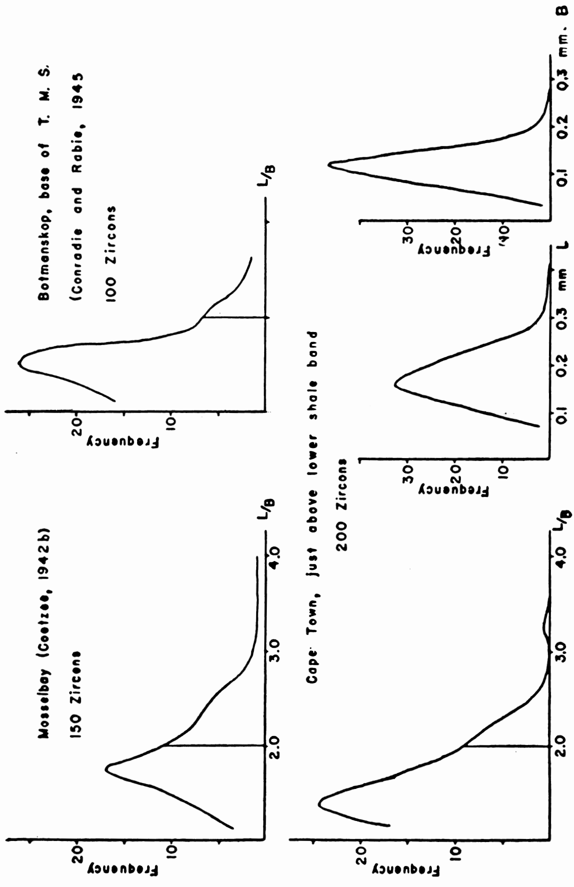
Figure 11 shows zircon elongation-, length-, and width-frequency curves for the 6 samples. Several samples contain a small proportion of highly elongated, needle-shaped zircons with well-rounded terminations. However, the maximum elongation-frequency in all cases is well below 2.0.

Table 7 shows data obtained for a sample of the Glorieta sandstone member of the Permian San Andres formation, from Glorieta Mesa, near Rowe, San Miguel County, New Mexico. The sample consists for 72 percent of fine sand (0.250-0.125 mm). It was graded into 5 portions by sieving and elutriation, and zircons were separated from each portion. Grains are divided into 3 classes; (1) essentially euhedral crystals, including those with slightly rounded terminations, (2) well-rounded grains, and (3) fragmental grains, including those with slight rounding of sharp edges and points. Results are given in percentages on counts of 200-400 zircons.

TABLE 7

Distribution of Zircons in Glorieta Sandstone Sample

| Grade (mm) | 0.177-0.125 fine sand | 0.125-0.088 very fine sand | 0.088-0.062 | 0.062-0.044 silt | 0.044-0.031 |
|---|---|---|---|---|---|
| Class 1 | 0 | 0 | 0 | 2 | 5 |
| Class 2 | 87 | 78 | 66 | 47 | 20 |
| Class 3 | 13 | 22 | 34 | 51 | 75 |


Mosselbay (Coetzee, 1942b)
150 Zircons
Botmanskop, base of T. M. S.
(Conradie and Rabie, 1945
100 Zircons
Cape Town, just above lower shale band
200 Zircons
Frequency
L/B
2.0
3.0
4.0
0.1
0.2
0.3
mm L
mm. B

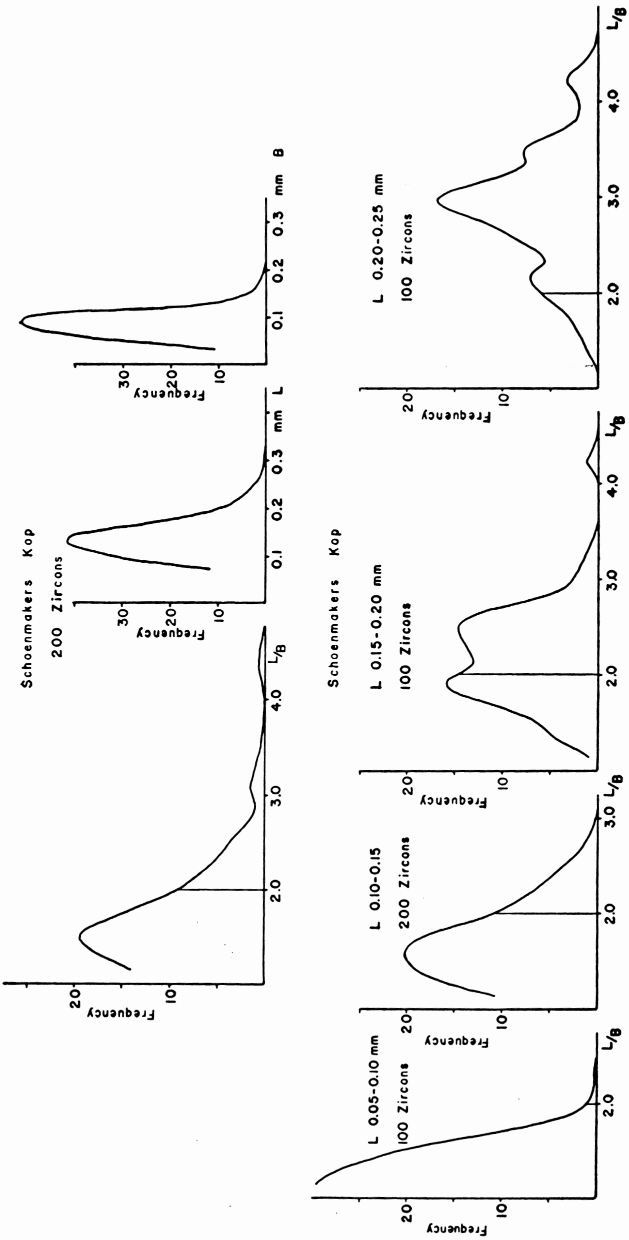



Fig. 8. Zircon size-frequency curves of 4 samples of Table Mountain sandstone (for locations see figure 7).

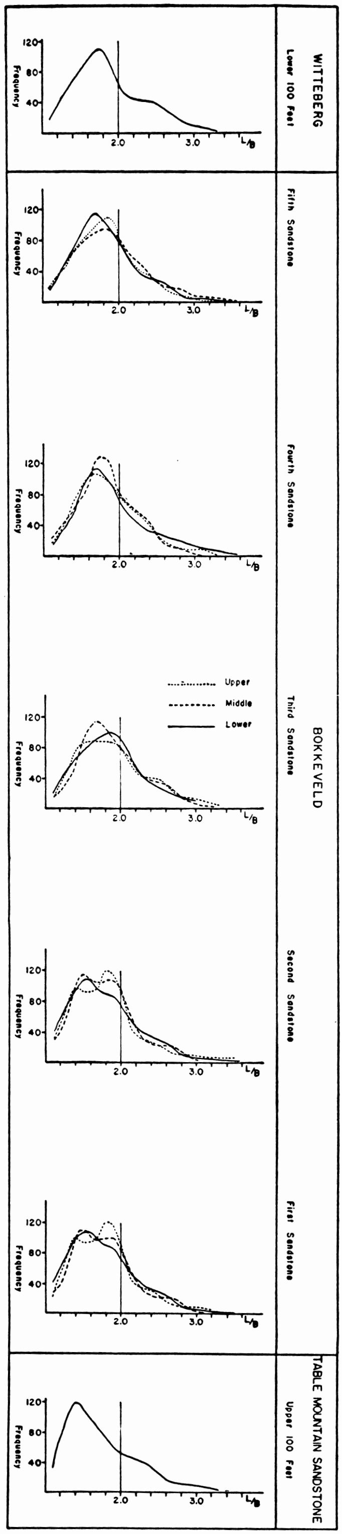



Fig. 9. Zircon elongation-frequency curves of Cape sediments of the Wuppertal district (after Swart, 1950).

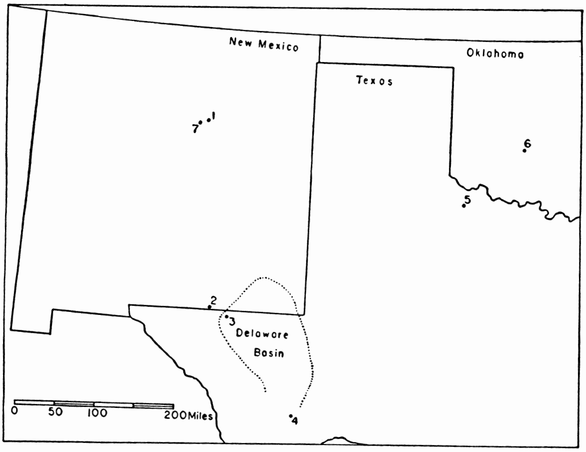



Fig. 10. Geographic distribution of samples of Permian arenites in the southwest-central United States.

1. Base of Glorieta sandstone, south of Romeroville, San Miguel County, New Mexico.
2. Base of Cherry Canyon, Brokeoff Mountains, Otero County, New Mexico.
3. Base of Cherry Canyon formation, Guadalupe Canyon, Culberson County, Texas.
4. Just above third limestone member of Word formation, Glass Mountains, Brewster County, Texas.
5. Base of San Angelo sandstone, south of Quanah, Hardeman County, Texas.
6. Base of Duncan sandstone, southwest of Fletcher, Comanche County, Oklahoma.
7. Base of Glorieta sandstone, Glorieta Mesa, near Rowe, San Miguel County, New Mexico.

Figure 12 shows zircon elongation-. length-, and width-frequency curves for the 4 largest size portions of table 7. The smallest size portion contained insufficient unbroken grains for evaluation. The "sieve ranges" are also indicated. It may be noted that (1) sieving results in sorting of zircons by width rather than length, (2) "sieve ranges" may depart markedly from width ranges of zircons, especially for the smaller sieve openings, and (3) the maximum elongation frequency increases from 1.2 to 1.6, the curves also widening toward greater elongation ratios, with decreasing size of zircons. The last is in keeping with the observation that small, slender zircons will remain unbroken, despite long transport or repeated reworking.

*Examples from the literature.*—Few publications give specific frequency curves for zircon measurements. Rao (1953a) published data for the lower Cuddapah quartzites (Precambrian) and also (1953b) for the upper Gondwana sandstones, both from Madras. Henzen (1950) gave data comparing the Rooiberg arenites of the Rooiberg and Stavoren-Vlakfontein areas in the Transvaal, South Africa. Apart from contributing to local geologic problems, these studies fully confirm conclusions reached in preceding sections of this paper.

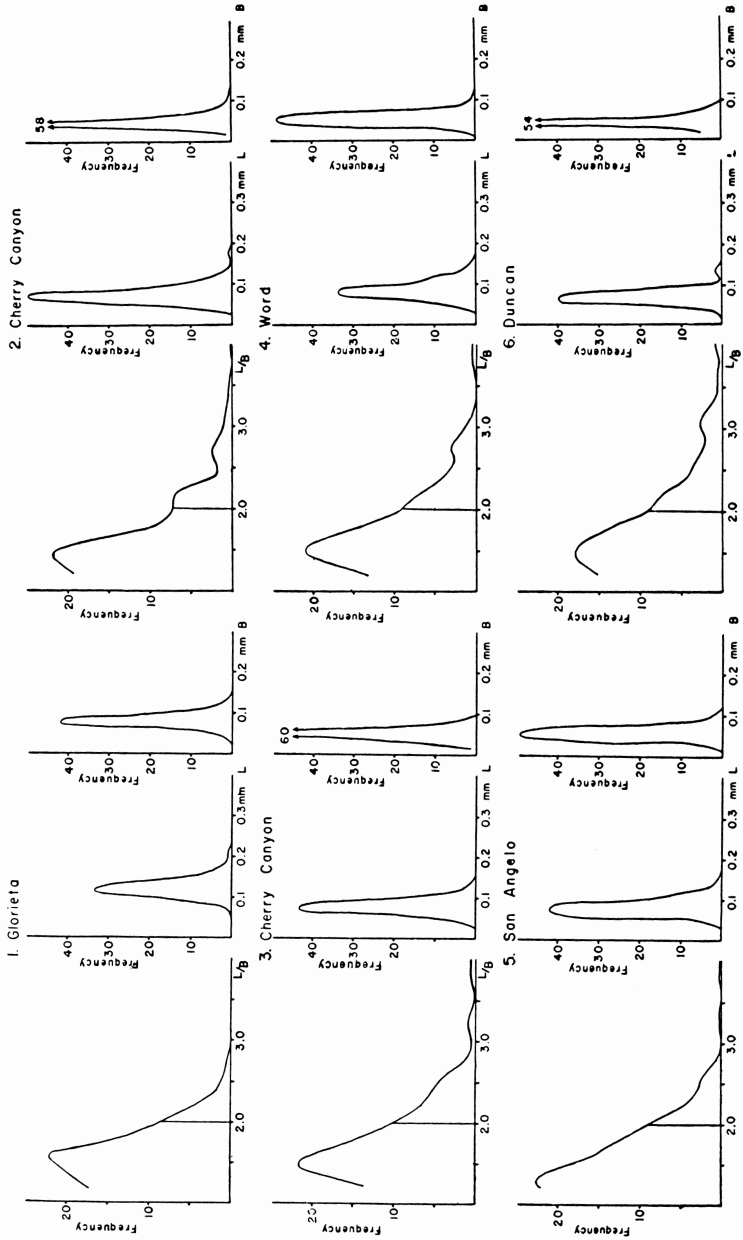



Fig. 11. Zircon size-frequency curves of 6 samples of Permian arenites (for locations see figure 10).

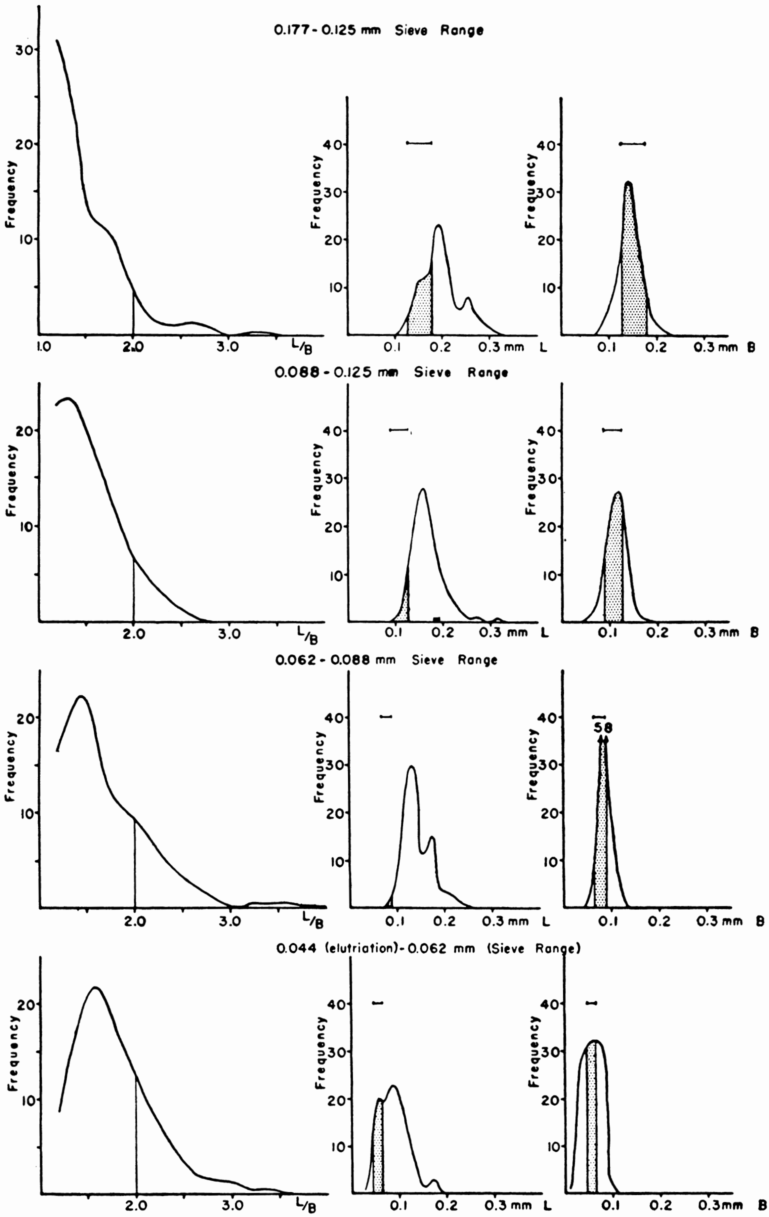



Fig. 12. Zircon size-frequency curves for 4 size fractions of a sample of Glorieta sandstone, Glorieta Mesa, near Rowe, San Miguel County, New Mexico.

REFERENCES

Adams, J. E., et al., 1939, Standard Permian section of North America: Am. Assoc. Petroleum Geologists Bull., v. 23, p. 1673-1681.

Allen, P., 1944, Statistics in sedimentary petrology: Nature, v. 153, no. 3872, p. 71-74.

Bond, Geoffrey, 1948a, Outgrowths on zircon from Southern Rhodesia: Geol. Mag., v. 85, p. 35-40.

———, 1948b, The direction of origin of the Kalahari sand of Southern Rhodesia: Geol. Mag., v. 85, p. 305-313.

Brammal, A., and Harwood, H. F., 1923, The Dartmoor granite; its mineralogy, structure, and petrology: Mineralog. Mag., v. 20, p. 39-53.

Butterfield, J. A., 1936, Outgrowths on zircon: Geol. Mag., v. 73, p. 511-516.

Carroll, Dorothy, 1953, Weatherability of zircon: Jour. Sedimentary Petrology, v. 23, p. 106-116.

Coetzee, C. B., 1942a, The petrology of the Goodhouse-Pella area, Namaqualand, South Africa: Geol. Soc. South Africa Trans., v. 44, p. 167-206.

———, 1942b, Metamorphosed sediments from the Goodhouse-Pella area, Namaqualand, South Africa: Royal Soc. South Africa Trans., v. 29, pt. 2, p. 91-112.

Conradie, W. F., and Rabie, L. P., 1945, A petrographic investigation of the heavy residues associated with the alluvial cassiterite from Kuils River, C. P.: Univ. Stellenbosch Ann., v. 22, sec. A, p. 105-134.

de Villiers, J. E., 1942, The geology of the Baviaans Kloof: Geol. Soc. South Africa Trans., v. 44, p. 151-161.

———, 1945, A review of the Cape orogeny: Univ. Stellenbosch Ann., v. 22, sec. A, p. 183-208.

Dryden, A. L., Jr., and Dryden, Clarissa, 1946, Comparative rates of weathering of some common heavy minerals: Jour. Sedimentary Petrology, v. 16, p. 91-96.

du Toit, A. L., 1939, Geology of South Africa, 2d ed.: London, Oliver and Boyd.

Eckelmann, F. D., and Kulp, J. L., 1954, The sedimentary origin and stratigraphic equivalence of the so-called Cranberry and Henderson granites in western North Carolina: Columbia University thesis.

Freise, F. W., 1931, Untersuchung von Mineralen auf Abnutzbarkeit bei Verfrachtung im Wasser: Min. pet. Mitt., v. 41, p. 1-7.

Goldich, S. S., 1938, A study in rock weathering: Jour. Geology, v. 46, p. 17-58.

Henzen, M. R., 1950, A comparative petrographic study of the sediments of the Rooiberg and Stavoren-Vlakfontein areas: Univ. Stellenbosch Ann., v. 26, sec. A, p. 307-322.

Hevesy, G. von, and Würstlin, J., 1934, Die Häufigkeit des Zirconiums: Zeitschr. anorg. allg. Chemie, v. 216, p. 305-311.

Hoppe, Günter, 1951, Die akzessorischen Schwermineralien in Eruptivgesteinen am Beispiel des Ramberggranites und anderer Harzer Gesteine: Geologica, no. 9.

Hutton, C. O., 1950, Studies of heavy detrital minerals: Geol. Soc. America Bull., v. 61, p. 635-716.

King, L. C., 1951, The geology of the Makapan and other caves: Royal Soc. South Africa Trans., v. 33, p. 121-151.

King, P. B., 1948, Geology of the southern Guadalupe Mountains, Texas: U. S. Geol. Survey Prof. Paper 215.

Lang, W. T. B., 1937, The Permian formations of the Pecos Valley of New Mexico and Texas: Am. Assoc. Petroleum Geologists Bull., v. 21, p. 833-898.

Maxwell, J. A., 1953, Geochemical study of chert and related deposits (abst.): Geol. Soc. America Bull., v. 64, p. 1452.

Newell, N. D., et al., 1953, The Permian reef complex of the Guadalupe mountains region, Texas and New Mexico: San Francisco, W. H. Freeman Company.

Niggli, P., 1924, Lehrbuch der Mineralogie, Band 1: Berlin, Gebr. Borntraeger.

Pettijohn, F. J., 1941, Persistence of heavy minerals and geologic age: Jour. Geology, v. 49, p. 610-625.

Poldervaart, Arie, and von Backström, J. W., 1950, A study of an area at Kakamas (Cape Province): Geol. Soc. South Africa Trans., v. 52, p. 433-495.

Poldervaart, Arie, and Green, D., 1954, An outline of the geology of the Bechuanaland Protectorate: Internat. Geol. Cong., Algiers, 1952, Assoc. Service Géol. Africains, 1e. Pt., fasc. 20, p. 53-66.

Potgieter, C. T., 1950, The structure and petrology of the George granite plutons and the invaded pre-Cape sedimentary rocks: Univ. Stellenbosch Ann., v. 26, sec. A, p. 323-412.

Rankama, K., and Sahama, T. G., 1950, Geochemistry: Chicago, Univ. Chicago Press.

Rao, C. G., 1953a, Statistical studies in the heavy mineral assemblages of the Gulcheru and the Pulivendla quartzites of the lower Cuddapah formations (Precambrian)

near Rayalacheruvu, Anantapur district, Madras: Mysore Univ. Jour., sec. B, v. 13, p. 247-258.
————, 1953b, Statistical studies in the heavy mineral assemblages of the Sriperumbudur and the Satyavedu stages (upper Gondwana) near Madras: Mysore Univ. Jour., sec. B, v. 13, p. 259-269.
Read, H. H., 1939, Metamorphism and igneous action: British Assoc. Adv. Science, sec. C, p. 223-251 (presidential address).
————, 1943, Meditations on granite. Part I: Geologists' Assoc. London Proc., v. 54, p. 64-85 (presidential address).
————, 1944, Meditations on granite. Part II: Geologists' Assoc. London Proc., v. 55, p. 45-93 (presidential address).
————, 1946, This subject of granite: Science Progress, v. 34, p. 659-669.
————, 1948a, Granites and granites, *in* Gilluly, James, chairman, Origin of granite: Geol. Soc. America Mem. 28, p. 1-19.
————, 1948b, A commentary on place in plutonism: Geol. Soc. London Quart. Jour., v. 104, p. 155-205 (presidential address).
————, 1949, A contemplation of time in plutonism: Geol. Soc. London Quart. Jour., v. 105, p. 101-156 (presidential address).
————, 1951, Metamorphism and granitisation: Geol. Soc. South Africa Trans., v. 54, annexure.
————, 1955, Granite series in mobile belts: Geol. Soc. America Mem. (in press).
Reed, J. C., 1937, The study of accessory minerals in igneous and metamorphic rocks: Am. Mineralogist, v. 22, p. 73-84.
Revelle, R., et al., 1955, Pelagic sediments of the Pacific: Geol. Soc. America Mem. (in press).
Scholtz, D. L., 1946, On the younger Precambrian granite plutons of the Cape Province: Geol. Soc. South Africa Trans. and Proc., v. 49, p. xxxv-lxxxii (presidential address).
Shand, S. J., 1947, Eruptive rocks, 3rd ed.: New York, John Wiley & Sons.
Shaw, D. M., 1954a, Trace elements in pelitic rocks. Part I, Variation during metamorphism: Geol. Soc. America Bull., v. 65, p. 1151-1166.
————, 1954b, Trace elements in pelitic rocks. Part II, Geochemical relations: Geol. Soc. America Bull., v. 65, p. 1167-1182.
Sindowski, F. K. H., 1949, Results and problems of heavy mineral analysis in Germany; a review of sedimentary petrological papers, 1936-1948: Jour. Sedimentary Petrology, v. 19, p. 3-25.
Smithson, Frank, 1937, Outgrowths on zircon in the middle Jurassic of Yorkshire: Geol. Mag., v. 74, p. 281-283.
————, 1939, Statistical methods in sedimentary petrology, pts. 1, 2, 3: Geol. Mag., v. 76, p. 297-309, 348-360, 417-427.
————, 1941, The alteration of detrital minerals in the Mesozoic rocks of Yorkshire: Geol. Mag., v. 78, p. 97-112.
————, 1942, The middle Jurassic rocks of Yorkshire; a petrological and paleogeographical study: Geol. Soc. London Quart. Jour., v. 98, p. 27-59.
————, 1950, The mineralogy of arenaceous deposits: Science Progress, v. 38, p. 10-21.
Strock, L. W., 1941, Geochemical data on Saratoga mineral waters, applied in deducing a new theory of their origin: Am. Jour. Sci., v. 239, p. 857-898.
Swart, B., 1950, Morphological aspects of the Bokkeveld series at Wuppertal, Cape Province: Univ. Stellenbosch Ann., v. 26, sec. A, p. 413-479.
Thoulet, J., 1913, Lithologie sous-marine: Inst. Océanographie Paris Ann., v. 5, fasc. 9, p. 1-14.
Thürach, H., 1884, Über das Vorkommen mikroskopischer Zirkone und Titanmineralien in den Gesteinen: Phys. Mediz. Ges. Würzburg, Verh., Band 18, no. 10, p. 203-284.
Tyler, S. A., Marsden, R. W., Grout, F. F., and Thiel, G. A., 1940, Studies of the Lake Superior Precambrian by accessory mineral methods: Geol. Soc. America Bull., v. 51, p. 1429-1537.
Walker, Frederick, and Mathias, Morna, 1947, The petrology of two granite-slate contacts at Cape Town, South Africa: Geol. Soc. London Quart. Jour., v. 102, p. 499-521.
Wasserstein, Benno, 1933, Zur Petrogenesis des Burgsandsteins zwischen Nürnberg und Weissenburg: Neues Jahrb., Beilage-Band 70, Abt. B, p. 335-392.
Young, E. J., 1954, Trace elements in recent marine sediments (abst.): Geol. Soc. America Bull., v. 65, p. 1329.
Zerndt, J., 1927, Mikroskopische Zirkone als Leitmineralien: Acad. polonaise sci. Bull. internat., sér. A, p. 363-377.

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