bonado, however, variable amounts of mineral inclusions fill part of the pores and no evidence was found of inclusions within the crystallites themselves. Examination of the outer surfaces and fractured surfaces of carbonados yields only limited information on the number and location of these inclusions whose size and distribution were obtained by contact radiography with high-resolution plates. The number of inclusions varied greatly from sample to sample, but the stone shown in Fig. 1A is a representative example. Electron-probe microanalysis showed that the most frequently encountered type of inclusion contained the elements silicon, aluminum, potassium, and iron. Minor amounts of phosphorus, sulfur, calcium, titanium, copper, zinc, zirconium, tin, and cerium as well as traces of magnesium, lanthanum, praseodymium, neodymium, and hafnium were also detected. The distribution of the most frequent elements was mapped by means of x-ray area scans such as the ones shown in Fig. 3. The combinations in which the elements occur were determined from goniometer scans over a large number of discrete spots 2 to 3 μ in diameter (Table 1).

Several carbonados were heated in a quartz boat to 800°C in order to burn away the diamond. The residue (3 percent) was a pale-yellow powder; its x-ray diffraction diagram revealed only monazite, rutile, and hematite, but analysis by x-ray fluorescence confirmed the elements listed in Table 1. The heat evolved by the combustion of the diamonds apparently caused melting of all the silicates and the formation of glasses and cerium phosphate; only rutile and hematite were unchanged.

Aside from strong diamond *hkl* lines, powder x-ray diagrams of crushed carbonado contained a considerable number of weak nondiamond lines, caused by a complex mixture of minerals, the identification of which was considerably facilitated by the microprobe data. These minerals are listed in Table 1; most of them are silicates with minor amounts of phosphates, carbonates, titanates, oxides, and sulfides. It was estimated that at least 80 percent of the inclusions are composed of orthoclase, often in association with hematite. With the exception of chloritoid, which is metamorphic, most of the minerals listed in Table 1 are either primary or common accessory constituents of igneous rocks which are normally associated with diamond. Pseudomalachite, covellite, anhydrite, rosasite, and parisite are secondary minerals of hydrothermal origin.

Assumptions concerning the geochemical history of carbonado may thus be made on the basis of the mineral inclusions it contains in easily detectable amounts. For example, the presence of minerals such as allanite and corundum are indicative of a deep-seated igneous origin, and chloritoid is regarded as an indication of the dynamic metamorphism of rocks. A secondary ore such as covellite results from an enrichment process related to a descending solution. It may thus be assumed that the carbonados were originally formed in basic magmatic rocks that were later subjected to metamorphic and erosional processes resulting in eventual detrital deposits. The relatively low percentage of ultrabasic mineral inclusions in carbonado is indicative of long exposure to an erosional environment. The unusual combination of orthoclase, an acidic igneous mineral, with more basic minerals such as gehlenite could indicate that an initial basic mineral containing gehlenite intruded into granitic rock mass rich in orthoclase. In certain instances, however, a mellilite such as gehlenite is represented in a high-temperature low-pressure sanidinite metamorphic facies. Therefore the gehlenite could also have formed by contact metamorphosis of existing rock debris with intruding diamond-bearing magma. Such an interpretation is in agreement with the geological conditions at the site of carbonado deposits.

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References and Notes

1. W. A. Roth, G. Naeser, O. Dopke, *Chem. Ber.* **59**, 1397 (1926).
2. W. Gerlach, *Z. Anorg. Chem.* **137**, 331 (1924).
3. E. Brandenberger, *Schweiz. Mineral. Petrogr. Mitt.* **10**, 490 (1930).
4. C. R. Fettke and F. C. Sturgis, *Amer. Mineral.* **18**, 172 (1933).
5. P. F. Kerr, D. L. Graf, S. H. Ball, *ibid.* **33**, 251 (1948).
6. R. N. Wentorf and H. P. Bovenkerk, *Astrophys. J.* **134**, 995 (1961).
7. M. E. Lipschutz and E. Anders, *Science* **134**, 2095 (1961); M. E. Lipschutz, *ibid.* **138**, 1266 (1962); *ibid.* **143**, 1431 (1964); L. F. Trueb, *J. Appl. Phys.* **39**, 4707 (1968).
8. J. C. Branner, *Eng. Mining J.* **87**, 981 (1909).
9. One of us (L.F.T.) thanks the Explosives Department of E. I. du Pont de Nemours & Co., Eastern Laboratory, Gibbstown, N.J., for the carbonado samples and support of this work during his association with the company.

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Microphotometric Determination of Preferred Orientation in Undeformed Dolomites

Abstract. *Preferred orientation was observed in certain undeformed dolomites with a microphotometric technique. The preferred direction of the* c-*axis was found to be perpendicular to the bedding planes. The degree of orientation is rather slight, but is considered significant due to the fact that thousands of crystals are included in each measurement. It is suggested that the preferred orientation was acquired during an early diagenetic stage of dolomitization, when the individual crystals could rotate and adjust their position so that their maximum cross section tended to lie horizontally.*

Petrofabric analysis of no more than 45 limestones and dolomites have been reported (*1*). The results of these studies, summed up by Johnson (*1*) as "isotropism is the rule, anisotropism the exception," and the tedious work involved in carrying out a conventional petrofabric analysis discouraged further research on the subject.

Microphotometric techniques which were introduced in recent years as an aid to the petrofabric studies of sandstones, lavas, and shales (*2–4*) are simple and reliable. The advantage of this method lies in the fact that the orientation of many thousands of crystals (depending on the crystal size and the field diameter) is readily integrated to give a meaningful result. In this way, the time element involved in carrying out the measurements and computing the results is reduced to a minimum, and the significance of the analysis is increased. The microphotometric method is therefore an ideal tool for detecting preferred orientation in rocks whose fabric is only slightly organized and which are not considered appropriate for conventional petrofabric analysis.

I checked for anisotropism 74 thin sections of various dolomites taken from an Upper Cretaceous section in northern Israel. Some of the rocks are thinly bedded to laminar, and their mosaic is composed of anhedral to subhedral crystals, 2 to 150 μ in size. The rocks were examined in sections cut perpendicular or parallel to the bedding planes.

The light-sensing equipment used in my study consists of a photoconductive cell, a stabilized d-c variable voltage source (up to 100 volts), and a milliammeter. Each thin section was measured twice; first between crossed Nicols and, second, under plane-polarized light.

The measurement taken between crossed Nicols is valuable for observing even small deviations from random orientation, as expressed by the ratio of minimum to maximum light intensities [I_{min}/I_{max} (*3*)] during rotation of the thin section. This measurement does not give a unique preferred direction, and, in order to distinguish between the fast and slow rays, Martinez (*4*) suggested the use of a gypsum plate in the optical system. This is essential when dealing with rocks which are composed of low birefringent minerals (such as quartz or feldspars), but is of no advantage in the examination of highly birefringent minerals, such as dolomite. The measurement taken under plane-polarized light, however, is particularly suitable in those cases (as well as for pleochroic minerals), as it makes use of the fact that the absorption of light by a mineral depends on its vibration direction and index of refraction (*5*). In uniaxial carbonate minerals, the intensity of transmitted extraordinary rays (that is, vibrating parallel to the *c*-axis) is greater than that of the ordinary rays and thus the preferred *c*-axis direction can be directly determined.

I compared the microphotometric results with those obtained by petrofabric analysis. Two thin sections were subjected to conventional petrofabric analysis in two dimensions (*5*). In each slide the orientation of 500 crystals was determined and their vectorial mean (*6*) computed (Fig. 1). The resultant vectors computed from the petrofabric measurements lie rather close to the photometric mean. It may be noted that the discrepancy is larger where the degree of preferred orientation is lower (Fig. 1b), a fact which is attributed mainly to the low significance of the petrofabric result.

The significance of the petrofabric analysis could be made to approach that of the photometric method if the number of observations made were increased considerably; however, the effort would be impracticable.

The results of the microphotometric measurements can be briefly summarized as follows. (i) Preferred orientation was revealed in most of the sections cut perpendicular to the bedding planes. The degree of preferred orientation (expressed as I_{min}/I_{max}) is usually more pronounced in rocks which have marked lamination, and reach values of 0.90. The preferred direction of the *c*-axis was, in all cases, found to be perpendicular (or almost so) to the bedding traces. (ii) No preferred orientation was detected in sections that were cut parallel to the bedding plane.

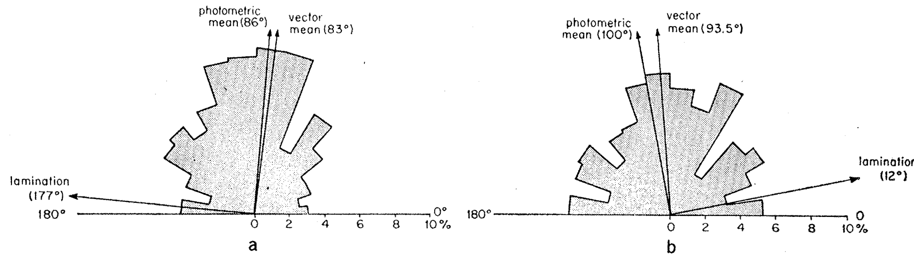

Fig. 1. *c*-Axis distribution (500 observations) and vector mean of two samples, compared with the photometric mean. (a) Sample UF 320; photometric data: approximately 5,000 crystals, $I_{min}/I_{max} = 0.92$; (b) sample UF 78; photometric data: approximately 120,000 crystals, $I_{min}/I_{max} = 0.99$.

On considering possible explanations of the kind of preferred orientation encountered in the dolomites, I discarded an epigenetic process because no indications of deformation or recrystallization are present. Alternatively, therefore, it looks as though the preferred orientation was acquired during a diagenetic process.

In order to interpret this phenomenon, the pertinent data concerning the evolution of the dolomitic mosaic (*7*) of the studied rocks should be given. (i) The dolomites were formed during a diagenetic process of replacement of aragonitic or calcitic mud. (ii) Individual dolomite crystals started their growth within the carbonate mud as isolated nuclei some tens of microns apart. Initially, they developed euhedral, rhombohedral forms, retaining them through successive growth until adjacent crystals came into contact. From then on, each crystal developed compromise boundaries and thus became anhedral.

Accordingly, to explain the preferred orientation, the following process is suggested as having taken place. The habit of the dolomite crystals in the examined rocks (as well as in other sediments) is the rhombohedron $\{10\bar{1}1\}$, for which the *c*-axis is shorter than the other three axes (*8*). The stable position of a nonspherical grain in a soft medium is such that its maximum cross section lies horizontally. A dolomite crystal can be regarded as a discoidal body whose maximum cross section is perpendicular to the *c*-axis, and the *c*-axis of which would therefore tend

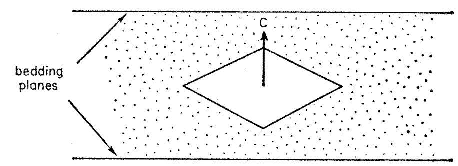

Fig. 2. Stable position of a discoidal rhombohedron in a muddy sediment.

to align itself vertically in a muddy medium (Fig. 2).

The main factor which may interfere with this tendency is the burrowing activity of benthic animals and the resulting mixing of the sediment. Thinly laminated rocks bear evidence of minimum disturbance (as compared with the poorly laminated or thickly bedded rocks) and their better organization is thus explained. The results of this study suggest that preferred orientation in dolomites may be more common than was previously thought.

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References and Notes

1. B. Sander, *Contributions to the Study of Depositional Fabrics, Rhythmically Deposited Triassic Limestones and Dolomites* (1936), E. B. Knopf. Transl. (American Association of Petroleum Geologists, Tulsa, Okla., 1951); R. B. Hohlt, *Colo. School Mines Quart.* **43**, 4 (1948); F. A. Johnson, thesis, University of Chicago (1951).
2. J. D. Martinez, *Indian Miner* **6**, 97 (1965); *Tulane Stud. Geol.* **3**, 165 (1965).
N. R. Morgenstern and J. S. Tchalenko, *Proc. Roy. Soc. Ser. A* **300**, 218 (1967).
4. J. D. Martinez, *Bull. Amer. Ass. Petrol. Geol.* **42**, 588 (1958).
5. B. Sander, *Einführung in die Gefügekunde der geologischen Körper*, part 2, *Die Korngefüge* (Springer-Verlag, Berlin, 1950).
6. W. C. Krumbein, *J. Geol.* **47**, 673 (1939); J. R. Curray, *ibid.* **64**, 117 (1956).
7. E. Sass, thesis, Hebrew University of Jerusalem (1966).
8. C. Palache, H. Berman, C. Frondel, Eds., *Dana's System of Mineralogy* (Wiley, New York, ed. 2, 1951), vol. 2. They mention that $c : a = 0.8322$.
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