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Figs. 1–4, March, 1969

PETROLOGY OF SILICEOUS ROCKS IN THE MISHASH FORMATION (NEGEV, ISRAEL)[1]

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ABSTRACT

The main rock types of the Campanian Mishash Formation in Israel are: (1) homogeneous chert; (2) chert spheroids; (3) heterogeneous (brecciated) cherts; (4) porcelanites. Zones of preferred orientation were detected in the heterogeneous cherts, and two alternative models are suggested to explain both the brecciation and the formation of preferred orientation. The cherts in the Mishash formation are mostly products of early replacement of carbonate and sometimes phosphate sediments. Apatite seems more resistant to silicification than calcite. Some of the siliceous rocks (homogeneous cherts, spheroids) may have been formed by primary precipitation of silica.

INTRODUCTION

Cherts, porcelanites, and silicified varieties of carbonate rocks form the bulk of the Campanian (Upper Cretaceous) Mishash formation in Southern Israel and its equivalent Quatrane Formation in Transjordan. The thickness of the Mishash formation varies between a few meters on structural highs in the Northern Negev to 130 meters in synclines in the Southern Negev. The Mishash formation is a part of a siliceous-phosphatic facies extending from Syria in the north (the Soukhne formation) through Israel and Jordan to Egypt in the South (Picard 1943).

The petrography of some of the siliceous rocks—in particular of the chert breccias—was discussed by Krusch (1911), and Lees (1928).

LITHOSTRATIGRAPHY

Four stratigraphic units have been distinguished in the Northern Negev (Kolodny 1967). These are from bottom upwards: (1) Brown Chert and Porcelanite Unit; (2) Brecciated Chert Unit; (3) Siliceous Phosphorite Unit; (4) Main Phosphorite Unit. This scheme does not hold in the southernmost part of Israel (the Eilat area), and no detailed information is available on the lithostratigraphy of the Quatrane Formation in Transjordan.

ROCK TYPES

a. Homogeneous Chert.—All the chert in the lowest unit is homogeneous, in sharp contrast to the overlying chert breccias (fig. 1A). The color is usually brown, with the center of strata or nodules often being black due to a higher (up to 1.3%) content of organic matter. In upper units light-colored cherts, including extremely pure white chert, are also common. Brown chert forms beds 10–30 cm thick, interbedded with biomicritic limestone and porcelanite. Pinch and swell structures are common. On surfaces of contact with surrounding rocks, silicified fossils are beautifully exposed. They include mainly gastropods, bivalves, and ammonites (*Baculites*).

The dominant component of homogeneous chert is micro- and crypto-quartz. Chalcedonic varieties of quartz are common, especially as vein infillings. The chalcedony fibers usually are length fast. Translucent flakes of clay, limonite, and organic matter are abundant. The Mishash chert has been claimed to be devoid of any micro-fauna. This sterility has been invoked in discussions of its origin (Reiss, 1962). Closer examination of thin sections, however, proves that most of the homogeneous cherts are quite rich in foraminiferal ghosts. Foraminiferal cavities are infilled with coarser drusy quartz. Limonite also tends to concentrate in those cavities.

b. Spheroids.—The term spheroid was introduced by Taliaferro (1934) for concentric structures in cherts described by him from the Monterey and Franciscan formations of California. Spheroids are a characteristic component of the Brown Chert and Porcelanite Unit (fig. 1 B, C). Their shape varies from almost spherical to disclike. The discs lie parallel to bedding planes, their diameter varying between a few centimeters and half a meter. The concentric appearance is caused by alternation of broad (2–5 cm) brown micro-quartz bands with

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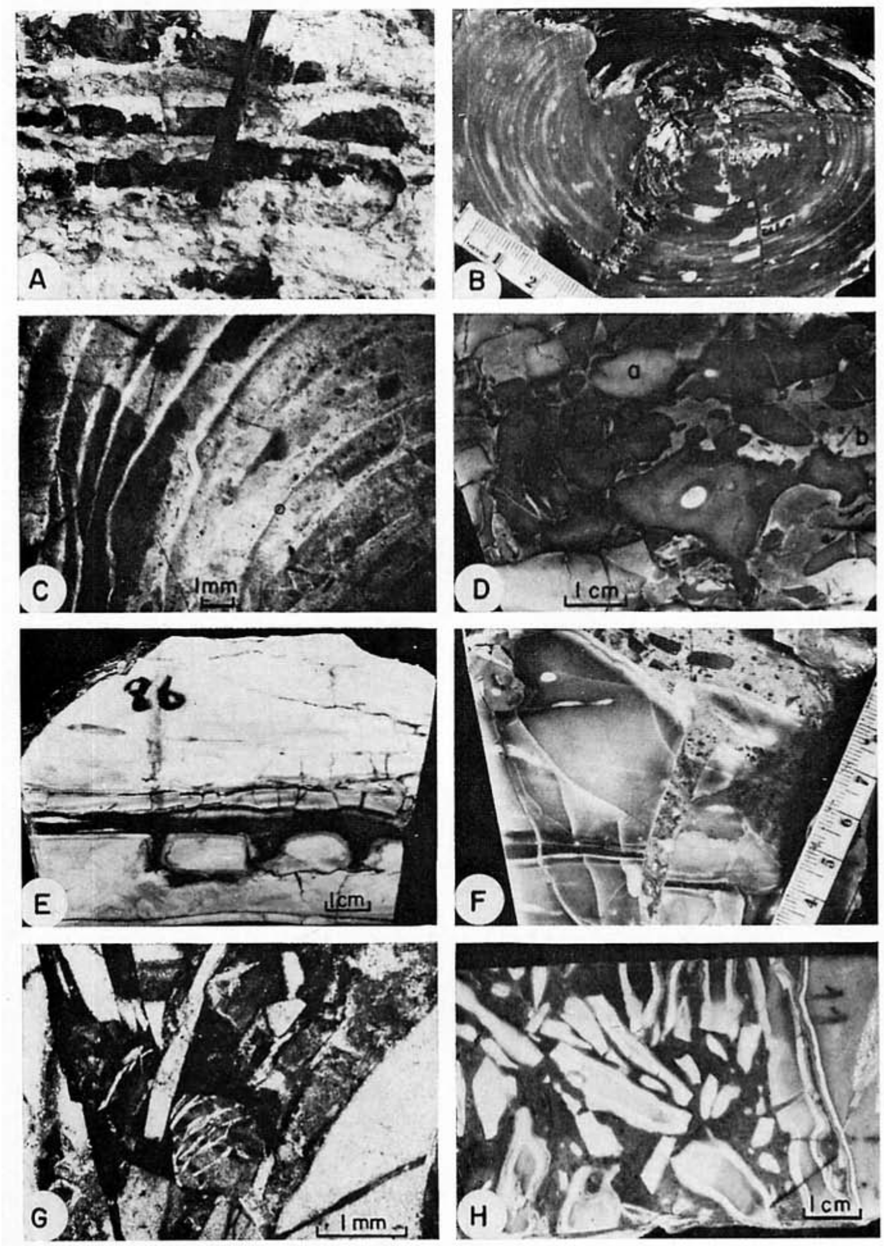

FIG. 1.—A Close-up of the Brown Chert and Porcelanite Unit; Black chert; White porcelanite; Gray-limestone. B. Spheriod from the Brown Chert and Porcelanite Unit. C. Thin section of spheroid. Transparent narrow bands are chalcedony. Plain light. D. "Spotty Chert"; a-fragments; b-matrix. E. "Torn Chert"; initial stages of rupture are seen; there is almost no displacement of fragments. F. Displacement of a horizontal layer in a "Torn Chert" and infilling of the open gap. G. Infilling of the open gap in figure 1F; the matrix is cryptocrystalline. Crossed Nicols. H. "Splinter Chert". In the upper (right on the photograph) part, a layer is seen in initial stages of rupture.

thin (0.1–2 mm) transparent chalcedonic bands (fig. 1C). Taliaferro (1934) considered spheroids as a contraction phenomenon in dehydrating siliceous gel. The chalcedonic bands were explained as infillings of concentric tension cracks upon contraction toward the center.

c. Heterogeneous Chert.—The term "heterogenous" includes here what is usually termed as "brecciated chert" as well as "spotty chert." In all the heterogeneous types one can easily distinguish two components: "fragments," and "matrix" or "cement." In most cases both components are micro-quartz. Usually the boundary between a fragment and the matrix is sharp, but gradual transition has also been observed. Trace elements (Ti, Fe, Mg, and V) and organic matter are more enriched in the "matrix" than in the "fragments."

Usually the matrix is finer-grained than the fragments and is much richer in pigmented materials, phosphoritic detritus, and foraminifera.

The chemical resistance of the matrix differs from that of the fragments. During erosion the matrix is preferentially destroyed leaving behind the fragments, sometimes creating the impression of a true, clastic breccia. Many fragments are surrounded by a white translucent band resembling the patina surrounding chert gravels in river beds. The occurrence of a similar band around irregular amoeboid "fragments" which obviously never underwent clastic transport excludes a possibility of origin by weathering.

The geometry of the heterogeneous cherts may serve for further subdivision: in "spotty chert" (fig. 1D), chert "fragments" of irregular form are enveloped in a matrix, usually cherty as well. In a few cases the matrix is calcitic with large amounts of phosphatic detritus. "Fragments" in spotty cherts show various degrees of separation and rupture (fig. 1E). Samples where this kind of displacement is most evident are classified as "broken chert." That the fragments were actually broken apart and displaced is well evidenced by: (1) the excellent fit of boundaries between two counterparts of a torn fragment; (2) the displacement of linear and planar structures (veins and bedding) (fig. 1F); (3) collapse of overlying fragments into open gaps (fig. 1G); (4) appearance of drusy quartz or calcite in these gap areas. The plane of dislocation is always perpendicular to the bedding plane, but no further regularity was observed in the offset directions. In sections perpendicular to the bedding, a parallel linear pattern is observed, whereas irregular fragments appear in the plane parallel to bedding. "Splinter chert" (fig. 1H) is the term describing a variety of breccia in which no boundaries can be matched, and traces of bedding planes are not recognizable. In this variety there appears to have been considerable relative displacement of the fragments.

d. Porcelanite.—Porcelanite was defined by Taliaferro (1934) as "impure, usually opaline rock having the texture and appearance of unglazed porcelain." It occurs mainly in the lowest units of the Formation. Phosphatic porcelanite occurs also in the third unit underlying the main phosphorite unit. The porcelanite is white to grayish, brittle, and very light. Its bulk density ranges from 0.9 to 1.8, with porosity up to 50 percent and a permeability 0.08 md. It usually contains 30–80 percent SiO_2, the rest being calcite and quartz. Under the microscope it is isotropic, with an index of refraction varying between 1.458 and 1.462. Microfossils which are abundant in porcelanite are infilled by micro-quartz. Porcelanite shows a quite sharp 4.02Å peak of α-cristobalite in X-ray diffractograms. The petrology and origin of porcelanite were discused in more detail by Kolodny and others (1965).

e. Carbonates.—Throughout the Mishash Formation, carbonates are interbedded with cherts. These are usually sparse biomicrites with *Bulliminidae* predominating among the microfossils. Dolomite is a common constituent of the Mishash Formation, especially in the Judean Desert.

f. Phosphorites.—Phosphate minerals are abundant throughout the entire formation. The concentration of phosphate increases from the bottom upwards, and culminates in the Main Phosphorite Unit, the uppermost unit of the Mishash Formation where phosphorite is exploited commercially.

As in the case of carbonates, this work is not concerned with the description of phosphates as such (see Gross and others, in press). A short description is, however, necessary for the subsequent discussion of silicification phenomena.

The major phosphate mineral is francolite. Francolite occurs as bone fragments, ovulites (fecal pellets ?) 0.1–0.4 mm in diameter, and larger pellets (2–5 mm) which have been termed locally "corprolites."

In several cases, large (1–10 cm) intraclasts of micritic limestone occur in the phosphorite.

Only very rarely is the cement apatitic. Usually it is calcitic (micrite or sparite). Underlying the Main Phosphorite Unit, the typical phosphorite cement is siliceous. Here one can observe many transition stages from pure calcitic to completely siliceous cement. Opal also forms phosphorite cements.

STRUCTURES AND TEXTURES

Throughout the Mishash Formation the rocks are well bedded. Thickness of beds varies from a few centimeters to 3–4 meters. At the contact between cherts and other rocks, one frequently observes a smooth upper border and an irregular lower border of the chert bed. Such morphology has been attributed in the past to either silica supply from above (Dietrich and others 1963) or to gravitative settling during consolidation (Gundoff, 1963). "Pinch and swell" structures are common.

Foliation is caused mainly by uniformly oriented flakes of clay and organic matter as well as by foraminiferal tests.

Gravitative sedimentary microstructures.—Phosphatic ovulites and pellets in the matrix as well as splinters of chert behave as clastic material, and give rise to gravitational microstructures. The most prominent feature is accumulation of detrital material on top of cherty fragments in breccias (fig. 2A). Similar structures from sedimentary breccias were described by Sanders (1954). This type of structure indicates that while the breccia fragments were already lithified, the matrix was still muddy, so that detrital grains could sink through it. Microfaults which cause offset in fragments turn into flexures in the matrix.

Zones of preferred orientation.—In homogeneous cherts and in fragments of chert breccias the orientation of quartz crystallites is random. In twelve out of the approximately 150 thin sections examined, areas were found in the matrix which showed a high degree of preferred orientation. This is apparent under crossed nicols by uniform extinction of the entire zone (fig. 2B), as well as by the gypsum plate effect which indicates a preferred orientation of the c-axes normal to foliation planes. The preferred orientation in the chert breccias has been studied by Wenk and Kolodny (1968). They found that: (1) The observed fabric shows axial symmetry with the symmetry axis approximately perpendicular to foliation. (2) The strongest preferred orientation is observed between layers of fragments; the degree of preferred orientation is much weaker in "gaps" between fragments of the same layer.

Carbonate-chert (and apatite-chert) relationship.—Originally calcareous silicified fossils are abundant. Silicification is often restricted to fossils. The void space in the fossils is infilled by drusy quartz. Replacement of sparry calcite infilling of fossils by chert has also been observed. Both micritic and sparrite cement may become silicified. It is very difficult to establish replacement of micrite and the only useful criterion is cross-cutting of bedding planes by microquartz. When sparry calcite is replaced, relics of carbonate (fig. 2C) as well as ghost structures are observed. The replacing phase is usually microquartz, but often fibrous chalcedony was observed to replace a sparrite cement. When large calcite crystals have been replaced, one usually sees common extinction of isolated calcite areas which are relics of a previously single crystal.

When dolomite is silicified the evidence for replacement is much more clear-cut; dolomite rhombohedra may be partly replaced by microquartz (fig. 2D).

In the first stages of silicification of phosphorites, only the calcite cement is affected. It is replaced by micro-quartz. The general texture remains the same as in calcitic phosphorite. Figure 2E shows a thin section in which the silicification front forms a central east-west line. Nothing but the cement differs on both sides of the boundary. Limestone intraclasts in the phosphorite are affected only slightly by silicification. This may indicate that the replacement occurred quite early in the diagenetic history of the rock prior to consolidation of the sediment. Silicification of an already lithified rock probably would not distinguish between cement and intraclasts, as both were fine-grained calcite.

Only after all the calcite has been replaced does silicification affect apatite grains. In most cases after ovulites have been replaced, a ghost of the organic matter which was contained in the ovulite is left. When recrystallization of a siliceous phosphorite occurs (as evidenced by relatively coarse-grained chert) the ovulite texture is destroyed. In such cases partially silicified ovulites are the products (fig. 2F).

Usually, whenever partial silicification occurs, impurities (limonite, organic matter) are concentrated at the boundary between chert and carbonate. Swett (1965) interpreted a similar phenomenon as exclusion of these impurities from the siliceous phase upon replacement.

No relic carbonate has been observed in homogeneous cherts. In brecciated chert the matrix is in many cases calcitic. (Compare figures 3A and 3B.) A phenomenon which I would like to relate to brecciation (see below) is the occurrence of parallel bands of chert in limestones (fig. 3C). These bands are sometimes fractured

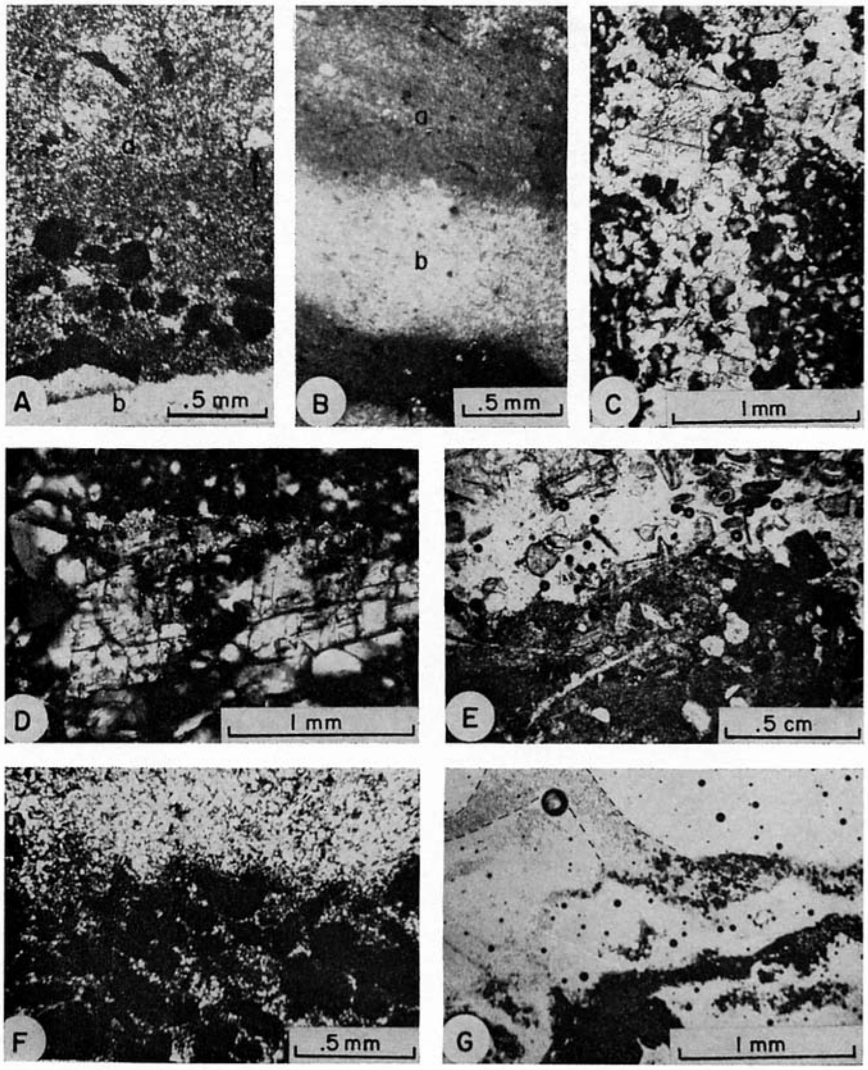

FIG. 2.—A. Detrital phosphate (a) in the matrix of a "Spotty Chert." The isotropic detrital particles are concentrated in the lower part of the matrix zone resting on a fragment (b). Crossed Nicols. B. Preferred orientation in "Torn Chert"; a-matrix; b-fragments. The matrix zones are at extinction. Foraminifera are more abundant in the matrix (small white spots in dark areas). Crossed Nicols. C. Replacement of sparry calcite by chalcedony. Crossed Nicols. D. A rhombohedron of dolomite, half replaced by chalcedony. Crossed Nicols. E. Phosphorite; the upper part is calcitic, the lower silicified; it is only the cement that differs on both sides of the boundary. Plain light. F. A front of recrystallization cuts through an ovulitic phosphorite. Some of the ovulites are partly destroyed. Crossed Nicols. G. Areas of calcitic matrix in a spotty chert. The calcite is being replaced by micro-quartz, leaving behind "trails" of impurities (marked area). Plain light.

and pulled apart in the same manner as the fragments of the chert breccias (fig. 3D).

In some of the breccias with relic carbonate matrix, a dark band occurs in the siliceous part of the matrix in continuation of calcite bands (fig. 2G). I consider this as evidence for a second stage of silicification. The calcitic matrix, which was enriched in impurities during the first stage, is now completely silicified.

DISCUSSION

Environment and Mode of Silica Deposition

A possible environment of deposition of the Mishash formation has been suggested by Kolodny and others (1965). On the basis of stratigraphic data and the tectonic framework of the area, they envision a physiography of semiclosed silled basins bordered by a continent of

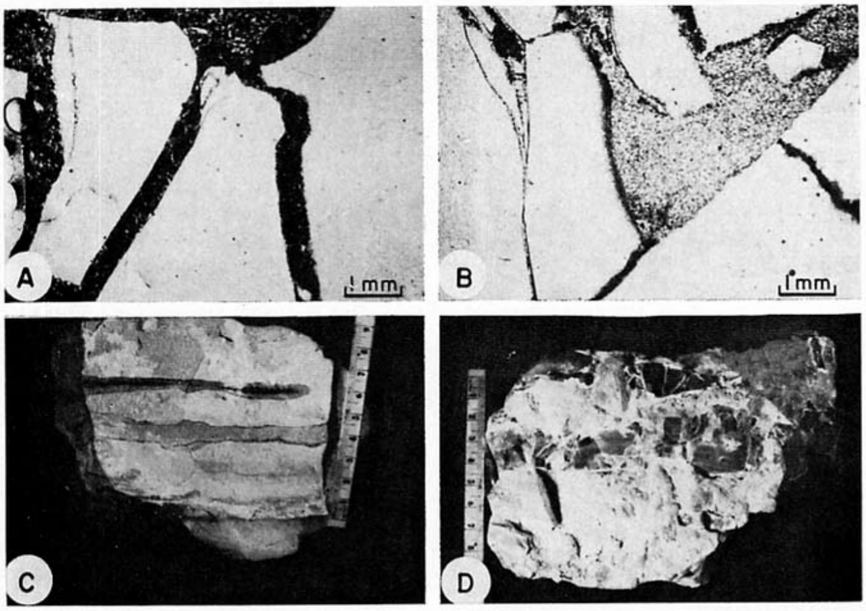

FIG. 3.—A. "Torn Chert." Note the fit of boundaries. The matrix is ovulitic calcite. Plain light B. "Torn Chert" similar to 3A, but with siliceous matrix. Crossed Nicols. The difference between 3A and 3B is more spectacular when stained with Alizarin Red S. C. Chert layers in limestone. The upper chert layer has a black core rich in organic matter. D. Tearing apart of chert layers in limestone (see fig. 4).

low relief. Such an environment may be responsible for the necessary high concentrations of silica without resorting to volcanism, no signs of which are known in contemporaneous sediments of the area, or to concentration of silica by siliceous organisms which are absent in Mishash sediments. Interstitial waters may reach specially high SiO_2 concentrations and these waters are the medium which would deposit the solid siliceous phase.

The presence of porcelanite shows that at least in some cases the solid phase was opaline.

It is not always possible to decide whether the chert (micro-quartz) replaced carbonate or crystallized from amorphous silica gel, opal being another crystallization product (into α crystobilite) of the same gel. In most heterogeneous cherts, as well as in the case of siliceous phosphorites, there is good evidence that silica did replace carbonate and phosphate minerals; no opal appears in these rocks. On the other hand, no relic calcite has been observed in the homogeneous cherts of the Brown Chert and Porcelanite Unit. Spheroids may be an indication of a former gel stage of these rocks (Taliaferro 1934). Thus one cannot exclude the possibility that chert may be the end product of two different paths—in the lower unit it may be essentially primary, crystallizing from a silica gel, whereas in the Brecciated Chert Unit it is a product of diagenetic replacement of carbonate.

Origin of Chert Breccias

Brecciated chert is not a peculiarity of the Mishash Formation. It is a rather common and typical feature of chert formations all over the world. Among 28 regional papers on chert, 14 mention brecciation (Bramlette 1946, Dietrich and others 1963, Goodwin 1956, Logan and Chase 1961, Rapson 1962, and others noted below).

Lees (1928) attributed the brecciation in Palestinian cherts to shattering of original limestone by impregnating chert layers, and a later second stage silicification. Picard (1931) considered the breccia a result of dehydration (syneresis) of a primary gelatineous sediment. A similar hypothesis was advanced by Rapson (1962) when studying the chert breccias of the Rocky Mountain Group in Alberta, Canada, and by Goodwin (1956) for breccias in Pre-Cembrian cherts in the Lake Superior area. Gignoux and Avnimelech (1937) drew an analogy between brecciation in cherts and formation of similar textures in permafrost soils. There the brecciation is caused by an increase in volume of the matrix due to ice crystallization and ice-soil segregation. They suggest that in the case of cherts, the increase in matrix volume occurs by introduction of additional siliceous solutions into the matrix.

Restricting one's approach to textural arguments only, several facts and conclusions can be noted:

1. There is a strong correlation between the occurrence of brecciated textures in cherts and silicification phenomena.
2. Several arguments have been presented to show that at a certain stage the matrix of the chert breccias were soft, whereas the fragments were rigid.
3. Breccia fragments which are now separated were once continuous bands (fig. 1, E,F,H). The separation between fragments is always of tensional character. All stages of separation from a crack to a wide gap can be observed (fig. 1 E, F), and no thrusts or folds in fragments have ever been found. The relative displacement of fragments occurs usually in lines parallel to the bedding.

The above-mentioned characteristics of the breccias practically rule out a possibility of an erosive or tectonic origin of the breccia. Occurrence of preferred orientation in the matrix but not in the fragments suggests that the breccias formed during some stage of diagenesis. Assuming that different geometrical patterns of breccias represent different stages of breccia formation, I suggest that the sequence of brecciation may have been somewhat like that of figure 4.

Whereas the geometrical relations of the breccias are evident, and the kinematic sequence can be conceived, as represented on figure 4, it is far from simple to suggest a dynamic model for the breccia formation. Explaining the preferred orientation of quartz in the matrix is here of uppermost importance. This feature cannot be ascribed to regional tectonics–the Mishash Formation is essentially undeformed as a unit. The only significant disturbances which should be noted are intraformational folds in the Mishash cherts; these however, were formed after brecciation commenced (Kolodny, 1967).

From symmetry considerations (Paterson and Weiss 1961) it might be expected that the causes responsible for the preferred orientation were axially symmetric–as is the fabric–with the axis perpendicular to the foliation.

An uniaxial stress with a major vertical axis may be a result of vertical compression or of horizontal tension.

Uniaxial compression, when applied to normal alternating beds of differing competence, has for many years been accepted as the cause of boudinage in metamorphic rocks (Wegmann, 1932; Ramberg, 1955). Several types of evidence have been presented above to show that at some stage of diagenesis the breccia fragments were rigid, whereas the matrix was less competent. The kinematic sequence of figure 4 may therefore be considered as reflecting the following genetic stages:

a. Deposition of a calcitic mud
b. Selective silicification of the carbonate sediment in parallel bands. The nonsilicified mud remains incompetent.
c. Separation of the competent siliceous bands due to vertical stress which is applied to the sequence. The stress is probably related to the load of overlying sediments. Deviations from hydrostatic stress may occur due to some strength of incompetent layers.
d. Due to thixotropic properties of the mud, the separated fragments form the extremely irregular breccia pattern. According to Boswell (1961, p. 92), the addition of low amounts of silica to carbonate mud increases the thixotropy considerably. This is how a texture similar to that of figure 1H could develop from the type represented by figure 1E.

The timing of silicification is critical for development of preferred orientation in the matrix. Obviously two stages of silicification are necessary to produce a breccia in which both fragments and matrix are quartz. Should the second stage of silicification occur late in the rock's history, say after stages "b" or "c" (above), no preferred orientation could be expected in the micro-quartz, since a pseudomorph quartz fabric after the calcite is unlikely to occur. If, on the other hand, the silicification started again while the matrix was still incompetent and undergoing deformation, a preferred orientation in the matrix may develop.

McCrossan (1958) called for a boudinage-related mechanism to explain sedimentary features which are morphologically very similar to chert breccias. Furthermore, pinch and swell structures, which are genetically related to boudinage (Ramberg, 1955) are very common in the Mishash Formation (as well as in other siliceous formations).

The analogy between chert breccias and metamorphic boudinage cannot be drawn too far. For stress to occur so that boudins are formed, not only is an anisotropic load necessary, but a lack of restraint on the sides must be required too, so that stress can develop. Our sedimentary sequence was probably not subjected to wholesale flattening. If it were, one should find some shortening features in the sequence to compensate for the stretching. Intraformational contor-

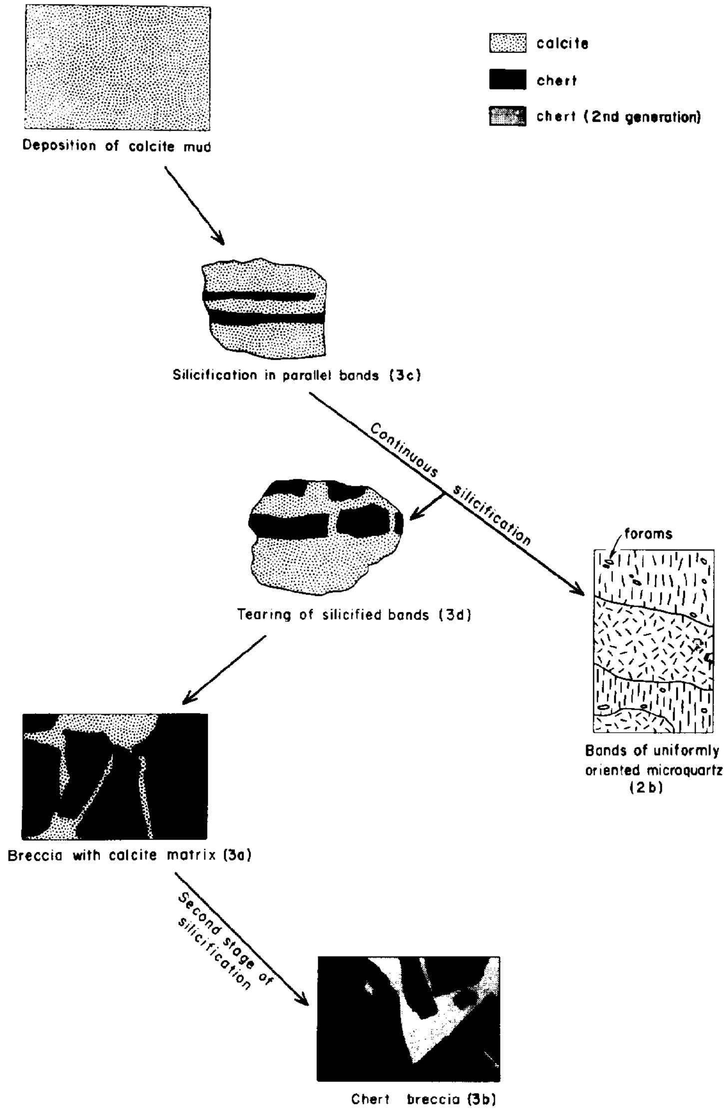

FIG. 4.—Flow chart of hypothetical stages of Brecciated Chert formation. The numbers in brackets refer to figures in this text.

tions which occur in the Mishash and other chert formations may represent such shortening. It appears, however, that these contortions formed after brecciation commenced (Kolodny, 1967).

The same deviatoric stress as in axial compression can be achieved by axial symmetric horizontal extension. The driving force for such a process may be contraction of a siliceous sediment upon aging. That such contraction occurs has been shown both by experimental work (Ilea, 1955, p. 41), by observation on ancient cherts (Taliaferro, 1934), and on recent siliceous sediments (Peterson and Van der Borch, 1965). The contraction is probably mainly due to syneresis–a spontaneous release of water by a gel upon aging which can occur in a water saturated environment. As mentioned before, Rapson (1962) suggested that syneresis may be one of the reasons for brecciation of cherts. An alternative model was suggested by Dr. G. Oertel:

a. Starting with a sequence of alternating siliceous and carbonate layers, the siliceous layers begin to shrink. Layers which are infinitely laterally extended are torn apart, and with continuing syneresis more cracking develops. These cracks are not unlike normal mud cracks, often wedge-shaped, due to a propagating moisture gradient away from the forming crack. (See fig. 1 E, F, H.)

b. The formation of preferred orientation in the matrix can be explained if one assumes a second silicification. After becoming siliceous the matrix begins to contract at a time when the fragments have already turned into rigid chert. The contracting matrix is not completely free to move, but adheres to the surfaces of the rigid fragments; a stress pattern will develop, entirely dictated by the local geometry of the fragment surfaces. This pattern will be that of compression perpendicular to the fragment surface and tension parallel to this surface. Near a fragment surface parallel to the bedding, the stress field will therefore be similar to the one obtained in the boudinage model, and may produce a c-axis maximum normal to the bedding.

CONCLUSIONS

In light of the long-standing controversy of "primary" versus "replacement" cherts, the bicausalistic approach seems most promising for the case under discussion: some of the cherts have formed by replacement of carbonate while others precipitated as primary silica. If one is ready to admit primary precipitation of chert at all, it is most likely to occur in a silica-saturated environment and to follow the dissolution of the carbonates formerly existing in the sediment. Or one can imagine a water body from which silica is being precipitated while replacement takes place in the underlying sediment.

Heterogeneous cherts are the result of secondary silicification. Some of them, the "spotty cherts," may be just results of irregular silicification patterns. Others, the chert breccias, are the result of a diagenetic process in which once continuous laminae of chert have been disrupted, and the incompetent siliceous matrix between them attained preferred orientation.

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