Journal of Sedimentary Petrology, Vol. 49, No. 3, p. 0837–0868
Figs. 1–37, September, 1979

0022-4472/79/0049-0837/$03.00

FEATURES AND ORIGIN OF ITALIAN JURASSIC RADIOLARITES DEPOSITED ON CONTINENTAL CRUST[1]

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Abstract: Jurassic radiolarites that were deposited on continental crust and which are overlain and underlain by pelagic limestones were examined in four basins. Radiolarites studied range from *bedded chert*, where chert occurs in even, continuous beds separated by conscpicuous rhythmic shale interbeds, to *nodular-lumpy chert*, where chert occurs as isolated nodules in limestone at one extreme to lumpy beds of irregular thickness at the other extreme. Bedded chert formations are composed of microcrystalline quartz, clay minerals, and minor amounts of either hematite or organic matter pigment; nodular cherts contain in addition considerable micrite (altered coccolith ooze).

Chert nodules, lenses, and beds all formed by the diagenetic reorganization of silica almost entirely of biogenic origin, chiefly from Radiolaria. Nodular-lumpy chert beds and even some bedded chert formed by partial to complete replacement of limestone. Lumpy beds formed because compaction, dissolution of calcite, and replacement of calcite were not uniform in either time or place within a bed. Many even-bedded chert layers were originally silts or sands composed almost entirely of current-deposited Radiolaria.

The rhythmic bedding of radiolarite is the product of 1) episodes of rapid current-deposition (e.g., turbidity currents) of radiolarian sediment alternating with slow deposition of hemipelagic mud and 2) episodic growth of Radiolaria. Bioturbation blurs the evidence of these two different origins, but the following features indicate that many chert-precursor beds were current-deposited: sharp chert-shale bedding contacts, flute casts, graded beds, clay clasts, laminations and rapidly buried animal tracks and trails.

Water depths during radiolarite deposition are uncertain. Regional stratigraphic data, evidence of redeposited radiolarian sand, and acceptance of the Bosellini-Winterer model of carbonate dissolution surfaces during Late Jurassic time leads EFM to conclude that well-bedded radiolarite was deposited at depths close to the CCD (~2500 m) and that lumpy-bedded chert was deposited between the ACD and the CCD (1500 to 2000 m).

Features indicating the presence of evaporites (evaporite pseudomorphs, breccias formed by crystal growth, quartzine, lutecite), paleosoil fabrics, stalactite-stalagmite fracture fillings, and disbelief in the validity of the CCD in Late Jurassic time in the Tethys leads RLF to conclude that the Lombardy radiolarites were deposited in environments that were, in part, shallow intertidal mudflats where local precipitation and solution of evaporite minerals and occasional subaerial exposure took place.

INTRODUCTION

During the Mesozoic, a belt of radiolarian-rich sediment whose lithified product is bedded to nodular radiolarian chert or cherty limestone was deposited over a large part of the Tethys seaway, extending from the present Alps and Apennines through Greece and Turkey; radiolarites are found also in Indonesia. In Italy, radiolarian-rich sediment was deposited in two structural-stratigraphic settings: 1) on continental crust over- and underlain by pelagic carbonates in the southern Alps, non-Ligurian sequences in the Apennines, and Sicily; and 2) on ophiolites, probably oceanic crust, mainly in Liguria (Fig. 1). This report concerns the petrography and petrology of radiolarian chert deposited on continental crust, and is the second part of our comparative study of radiolarian chert deposited in these two contrasting settings (Folk, 1975; McBride, 1975; Folk and McBride, 1976, 1977; Folk and McBride, 1978b).

The rocks studied are chert-rich formations of two types: 1) bedded chert, where chert occurs in even, continuous beds separated by conspicuous rhythmic shale interbeds (Figs. 2, 3), and 2) nodular lumpy chert (or

[1]Manuscript received September 10, 1978; revised February 13, 1979.

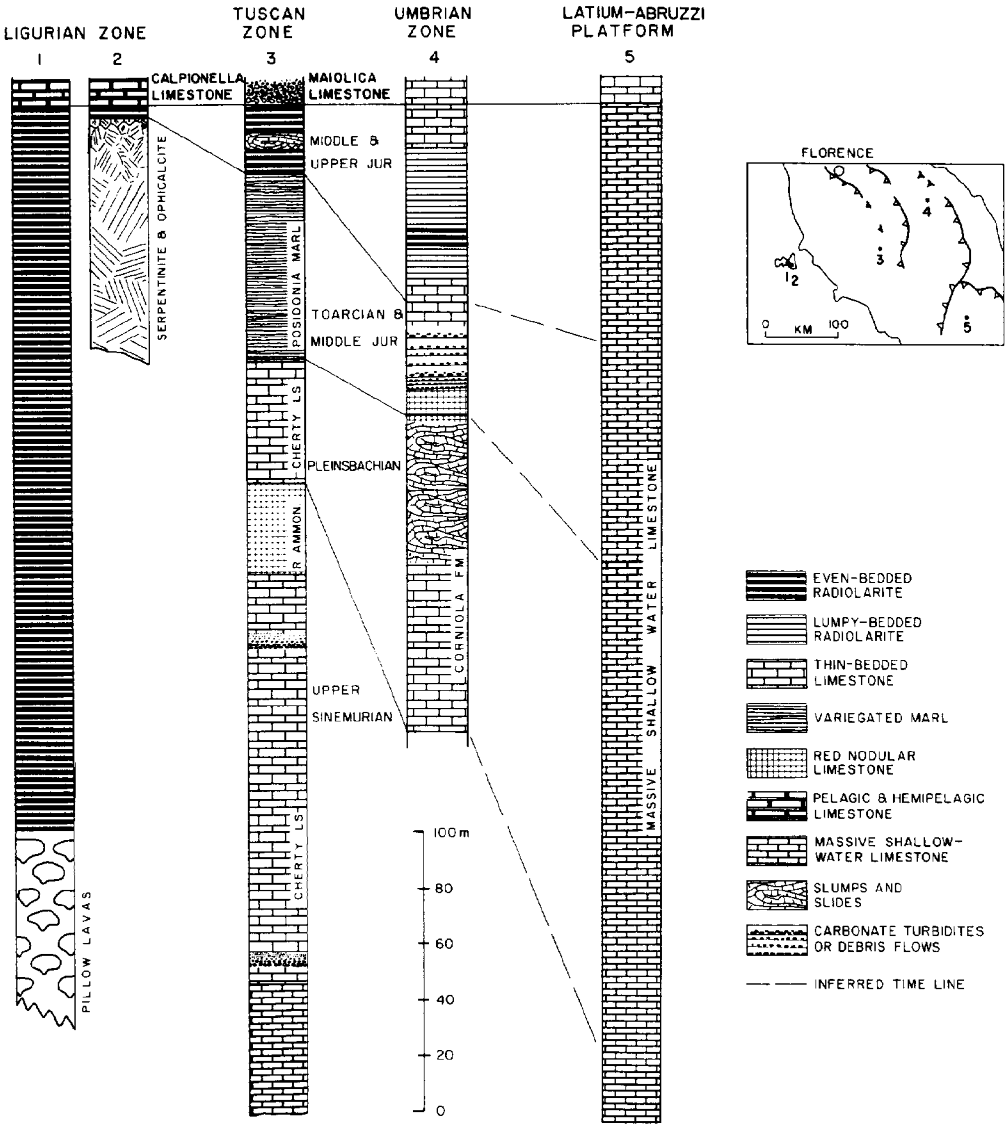

FIG. 1.—Stratigraphic sections illustrating the stratigraphic position of Jurassic radiolarites in central Italy. Radiolarite in the Ligurian zone (sections 1 and 2), presumably deposited on oceanic crust, has extreme thickness variations (see Folk and McBride, 1978b). Radiolarite is absent in the Latium-Abruzzi region, which remained a shallow shelf throughout Jurassic time. Early Jurassic rocks in the Tuscan and Umbrian zones are shallow-water carbonates also, but deeper-water facies follow in younger strata. Radiolarite apparently becomes younger eastward. (After Bernoulli et al., in press).

cherty limestone), where chert occurs as isolated nodules in limestone at one extreme to lumpy chert beds of irregular thickness at the other extreme (Figs. 4, 5). Shale interbeds are present also in nodular chert formations, generally as thin partings or beds less than 1 cm thick that rarely make up more than 2% of a given formation. In contrast, shale in bedded chert formations occurs in beds up to 50 cm thick and makes

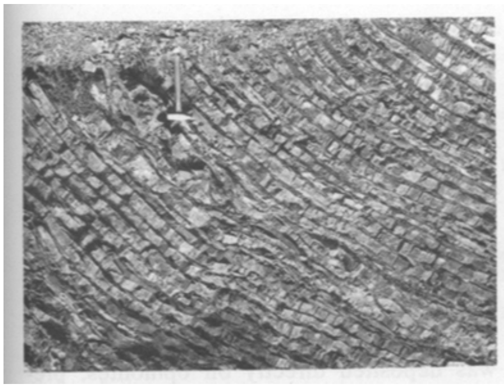

FIG. 2.—Even-bedded radiolarite in the Tuscan basin; thicker and lighter beds are chert, darker and thinner beds are shale. A slump sequence is visible by the hammer, 25 cm long. Beds are overturned. Monte Cetona, Tuscan basin.

FIG. 4.—Limestone beds with chert nodules and lenses and separated by shale partings at Burligo, Lombardy pre-Alps. Chert bodies are darker shades of green and red than their host rock. Hammer is 35 cm long.

up to 1/3 of a given formation. Bedded chert formations are composed almost entirely of microcrystalline quartz, clay minerals, and minor amounts of either hematite or organic matter pigment; nodular cherts contain in addition considerable micrite. Nodular and lumpy chert formations contain a greater variety of diagenetic textures and structures than bedded chert units. Variations in percentage of chert, limestone, and shale occur both vertically and laterally in most formations. Bedded cherts are predominately shades of reddish brown, but some are totally gray. Nodular cherts are red, green or gray, and are lighter shades with an increase in carbonate minerals.

The origin of radiolarites sandwiched between pelagic carbonates has been more controversial than those overlying ophiolites, probably because the ocean basins have not provided as close an analogy with Mesozoic radiolarites in pelagic sequences as they have for radiolarites overlying pillow basalts in ophiolite sequences. However, interest in pelagic rocks and associated cherts exposed in fold mountain belts has increased following the study of the wealth of data provided mainly by the Deep Sea Drilling Project (Alvarez, 1977).

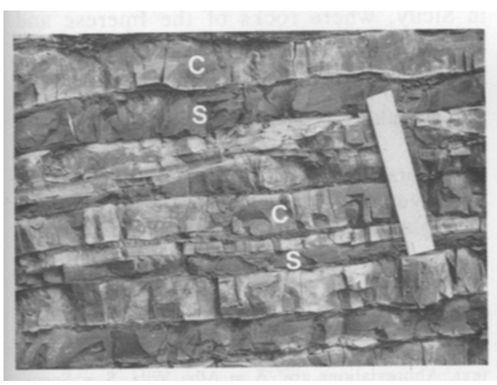

FIG. 3.—Close-up radiolarite shown in Figure 2 showing interbeds of chert (C) and shale (S). Note sharp contacts on all beds. Some beds are slightly undulose, but most are of uniform thickness. Beds are overturned; scale is 15 cm long.

FIG. 5.—Uneven-bedded radiolarite from the Lombardy pre-Alps at Burligo. Chert beds of uneven thickness are separated by shale partings and rare beds a centimeter thick. Hammer is 35 cm long.

The chief interest in radiolarites in general (reviews by Grunau, 1965; Garrison, 1974) has been the manner of silica accumulation (biogenic vs. chemical precipitate vs. altered ash) and depth of water during deposition. Radiolaria are ubiquitous in the chert beds, but dispute exists whether they were the chief source of silica. Depth interpretations from sublittoral to abyssal have been made for various radiolarian chert units, including those discussed herein. Remarkably few workers have addressed the problem of origin of the rhythmic bedding of chert-shale, one of the most diagnostic features of much radiolarite.

Major goals of our study were to evaluate sedimentological evidence of the environments of deposition of radiolarites deposited on continental crust, determine the source of silica, origin of the rhythmic bedding of radiolarite, and the diagenetic history of the siliceous sediment. Our study is based on a reconnaissance study of some of the better exposures of radiolarian chert from a number of different stratigraphic units in several tectonic elements. This approach enabled us to see a wide spectrum of radiolarian chert units from which to draw general conclusions, but did not permit us to interpret the sedimentary history at each location in the detail that it deserves. A regional petrographic study of Italian chert was recently completed by Parea (1970).

In Italy the term jasper (*diaspri*) is applied by the petrographer to red chert and by the stratigrapher to formations composed of red chert and shale; jaspery limestone (*calcare diasprini*) is applied by the stratigrapher to formations of limestone with red chert lenses and nodules; and radiolarite (*radiolariti*) is used by the petrographer for chert samples containing appreciable radiolarian ghosts (which applies to nearly all samples studied by us) and by the stratigrapher for formations that contain appreciable radiolarian chert.

GEOLOGIC SETTING OF RADIOLARIAN CHERTS

During Late Triassic and Early Jurassic time continental or microcontinental masses adjacent to the Mediterranean part of the Tethys were sites of shallow-water carbonate platform deposition. During Early Jurassic time, and associated with ocean spreading, these platforms were rifted and individual blocks subsided so that deposition changed first to "pelagic" limestone, than radiolarian chert or cherty limestone (largely Malm to Early Cretaceous). Following either uplift, a change in the CCD, or other conditions (Bosellini and Winterer, 1975; Hsü, 1976), deposition returned again to "pelagic" limestone (Cretaceous to Paleocene) and finally to flysch deposition, after which occurred the Alpine-Apennine episodes of crustal compression and mountain building. In the more internal part of the orogen radiolarite was deposited directly on ophiolites, presumed by most workers to be parts of the Triassic-Jurassic ocean floor. These radiolarites, most of which belong to the Ligurian realm, are described by Folk and McBride (1978b) and other works cited therein.

The stratigraphic units and the tectonic units to which the chert units belong that were studied by us are given in Table 1. The locations of the study areas are shown in Figure 6; representative stratigraphic sections are shown in Figure 7; and a schematic reconstruction of Italian tectonic units is given in Figure 8. During the Apennine orogeny, Ligurian and some Tuscan elements were thrust eastward over other Tuscan and Umbrian sequences, so that rocks once separated by 10's or 100's of kilometers are now superposed and compressed within a small area that makes up the major part of the Italian peninsula. A similar telescoping of tectonic-stratigraphic elements occurred in Sicily, where rocks of the Imerese and Sicani basins were thrust southward (R. Catalano, 1977, oral comm.).

ORIGIN OF CHERT BEDS—PREVIOUS INTERPRETATIONS

General reviews of the origin of radiolarites are given by Grunau (1965) and Garrison (1974) and for Italian rocks particularly by

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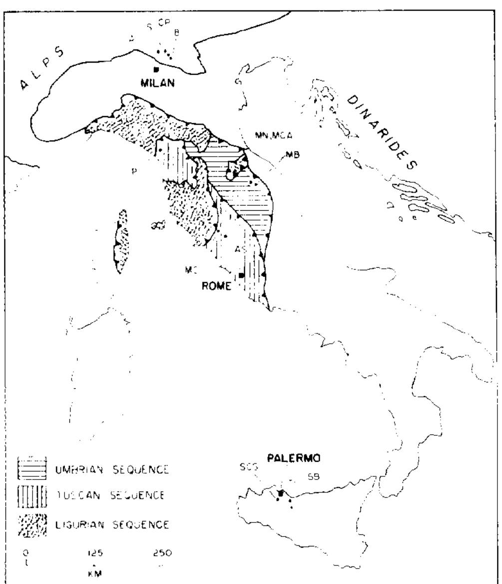
FIG. 6.—Map showing localities referred to in the text. Abbreviations are: A = Alba Villa, S = Sogno, CP = Col Pedrino, B = Burligo, P = Pontremoli, MC = Monte Cetona, AS = Acquasparta, MN = Monte Nerone, MCA = Monte Catria, MB = Monte (Fiume) Bosso, SCG = Santa Christina Gela, TI = Termini Imerese, SB = Sclafani Bagni. After Bernoulli, 1972.

TABLE 1.—*Stratigraphic Data for Radiolarite Units Studied*

Structural and Stratigraphic unit	Formation	Age	Thickness (M)	% Chert; % Shale % Limestone	Mean Thickness and 16th & 84th Percentiles of Chert & Shale Beds in mm (Poisson Distribution)
Lombardy					
Pre-Alps	Radiolarite	Late Callovian to Oxfordian	5–100	90:1:9	Chert 45, 11, 105 Shale 1, <1, 7
Tuscan Basin		Late Jurassic			
Allochthon		to Tithonian			
Mt. Cetona	Diaspri		30–40	80:19:1	Chert 33, 14, 59
Val Gordana	Diaspri		20	20:80:0	Shale 5, 16, 17
Rapolano					
Terme	Diaspri	?	30		
Vecchiano	Diaspri				
Monsummano	Diaspri				
Umbrian Basin					
Bosso Gorge	Calcari Diasprini	Oxfordian-Kimmeridgian	80	17:3:80	
Monte Nerone	Calcari Diasprini	Oxfordian-Kimmeridgian	4.5		
Monte Catria	Calcari Diasprini	Oxfordian-Kimmeridgian			
Acquasparta	Calcari Diasprini	Oxfordian-Kimmeridgian	48	15:1:84	
Imerese Basin					
S. Christina					
Gela	Diaspri	Lias-Dogger	~5	75:25:0	Chert 37, 19, 69
Termini					
Imerese	Diaspri	Lias-Dogger	~8	80:20:0	Shale 16, 5, 50
Sclafani	Diaspri	Mid-Late	90	70:30:0	
Bagni		Jurassic in lower part; Early			
		Cretaceous in upper part; separated by 35 m of limestone	50	25:15:60	



Conti (1958), Giannini et al. (1950), and Parea (1970). Parea summarized all previous work on Italian chert as part of a regional study of numerous formations with nodular, lenticular or bedded chert, so only a synopsis of ideas will be discussed here.

Nearly all workers accept the replacement of calcite by silica as the origin of nodules and lenses in limestone. Radiolaria are generally accepted as the most probable source of silica, although some authors have suggested connate, hydrothermal, or magmatic water as the supplier of silica.

There is no generally accepted origin for bedded chert among the rocks we studied. Most attention has been given the radiolarites overlying ophiolites, whose origin we have treated elsewhere (Folk and McBride, 1978b). Interpretations given for bedded chert units discussed herein include, with citations of the first worker to propose them:

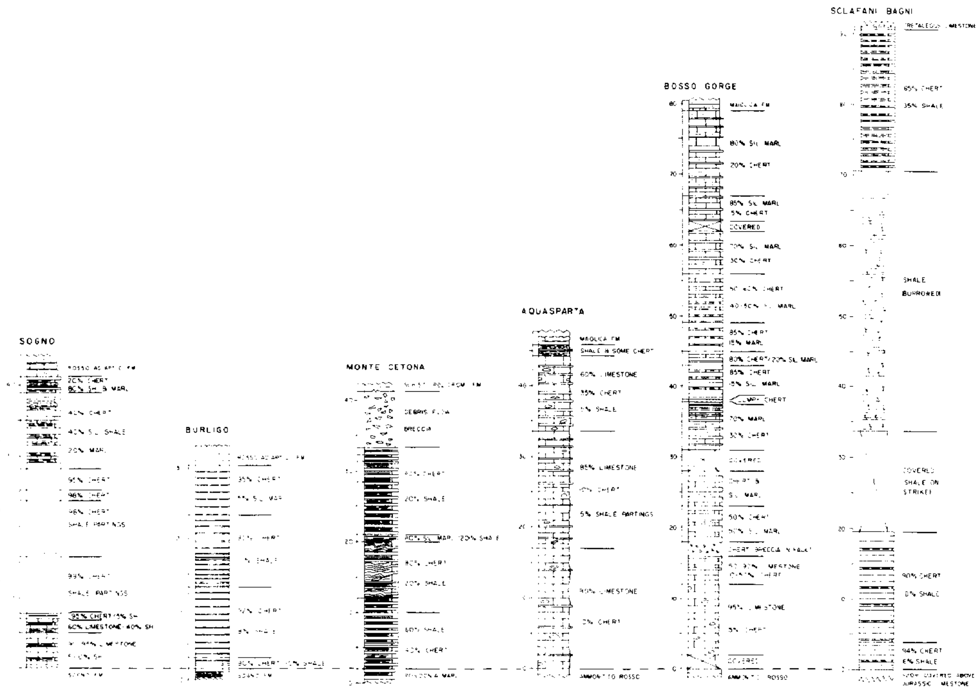


FIG. 7.—Representative measured sections of radiolarite. See Figure 6 for locations.

1) metasomatic (instead of metamorphic) substitution of an unspecified precursor (Parona, 1890)

2) entirely biogenic origin: Radiolaria were buried in a matrix of their own debris (Cocchi, 1871)

3) direct precipitation of silica from sea water with accidental entombment of Radiolaria (Giannini *et al.*, 1950)

4) complete replacement of limestone beds; silica derived principally by dissolution of Radiolaria and to a lesser extent of detrital silicates and perhaps during clay mineral diagenesis (Parea, 1970).

BEDDED CHERT

Study Areas

Examples of well-bedded radiolarite formations that we studied include two main but widely separated exposures from the Tuscan basin (Val Gordana and Mt. Cetona) and three radiolarite formations in Sicily from the Imerese basin (Table 1).

Bedding

All radiolarite formations are characterized by conspicuous rhythmic interbeds of chert and shale (Figs. 2, 3). Beds are so even and continuous in most places that the formations resemble the distinctive basin-plain facies of turbidite sandstone-hemipelagic shale sequences. Statistics on thickness of chert and shale beds and percentages of rock types in most formations are given in Table 1. Enigmatic stratiform breccias occur at two localities in the Tuscan basin and two localities in Sicily.

Exceptions to the even-bedded aspect of the radiolarite formations include 1) sequences up to 1 m thick of low-amplitude (rarely recumbent) folds and brecciated beds of soft-sediment slump origin, 2) rare starved current ripples, and 3) discontinuous or uneven beds whose shapes were produced during diagenesis. Examples of the latter type include beds whose original shape was modified by differential compaction, differential crystal growth, or differential dissolution, including stylolitization.

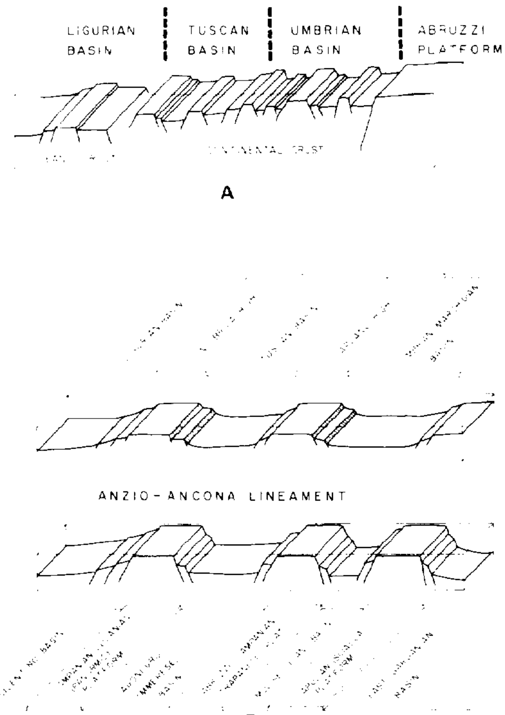


FIG. 8.—Schematic interpretive restorations of paleogeography and paleobathymetry during Late Jurassic time for north central Italy A) according to Bernoulli et al. (in press) and for north-central and south-central Italy B) according to D'Argenio and Pialli (1974). The names is parentheses in the lower diagram are tectonic elements in Sicily.

FIG. 9.—Radiolaria-rich chert shows the typical increase in clay toward its contact with the overlying shale. Absence of laminae and the presence of clay-rich burrows (arrows) suggest that many original laminae were destroyed by bioturbation.

About 90% of the chert beds have abrupt upper and lower contacts with their enclosing shale beds. Gradational contacts with shale over thicknesses of 2 to 3 mm are more common at the top of beds but occur also at the base of beds. Bedding surfaces, rarely well exposed, are either smooth or marred by small pits and mounds of uncertain origin (primary vs. diagenetic); but curved tracks of crawling animals occur at several localities, and flute casts occur at Mt. Cetona.

Considering red and green chert beds only, nearly all are texturally mottled in that clay is more abundant in local nebulous parts of a bed, but a few have crude parallel laminae. In about 10% of the samples the amount of clay increases upward (Fig. 9) to produce fine-tail grading; rare examples of reverse grading at the base (increase in clay toward the base) are found. Clay from adjacent shale beds was clearly introduced into proto-chert beds by bioturbation to form the normal and reverse graded beds. However, the possibility that bioturbation is an overprint on current-formed graded bedding cannot be ruled out, and a current-formed origin seems likely for a few specific examples. All starved-ripple beds sampled have lost all primary lamination also by either bioturbation or diagenesis.

In contrast to red chert beds, gray chert beds (all from Sicily) have from 5 to 40% by area of burrow mottles superimposed on crude laminae from 1 to 10 mm thick (Fig. 10). Laminae differ in the amount of Radiolaria, clay and grain size of microquartz. Burrow networks of *Chondrites* are common within chert beds and generally are subparallel with bedding.

Color

All formations are red or mottled red-green, except for two formations in Sicily

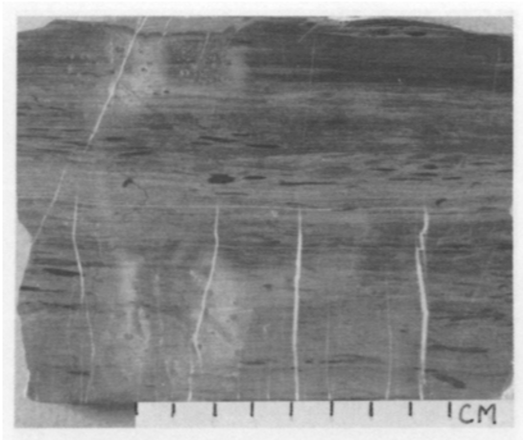


FIG. 10.—Laminated dark gray, organic-rich chert from the Imerese basin, Sicily. Burrows make up less than 5% of the slab surface.

that are gray to gray-green. The red ones are typically Munsell 10R 4/1.5-3, weak to moderate dark red-brown; hematite in micron-sized flecks mixed intimately with clay minerals and as rare large blebs up to a few microns imparts the red color in both chert and shale. Chlorite and illite, identified by XRD, impart the green colors, commonly 5GY 6-8/1 (very weak, very light yellow-green). Detrital organic matter and its diagenetic derivatives and minor pyrite mixed with clays impart the gray and the gray-green colors.

Field relations and thin sections clearly indicate that most, if not all, green or green-mottled beds of red jasper formations developed their color by the post-depositional reduction of hematite or a hematite precursor mineral, allowing the green color of the clay to show through. Green color occurs along vertical fractures, bedding planes, and as a rind on some beds. Many beds that are mottled red-green have more clay in the red parts of the rock; this suggests that bleaching of these areas was prevented because of the poorer permeability in the clay-rich areas. In addition, the larger blebs of hematite visible in thin section are present still in some green chert beds that lost all of their smaller grains of hematite pigment during the bleaching process. There are, however, a number of beds in several "red" formations that provide no direct evidence of having been red.

Red Chert

Red chert beds are 50%–75% Radiolaria (Fig. 11), 10%–30% microquartz cement, 10%–30% hematitic red clay, and some have several percent of other fossils and possibly silicified non-biogenic clasts. Fossils present in minor amounts include silicified thin shelled (pelagic) pelecypods, phosphatic and chitinous scraps of uncertain taxa, siliceous sponge-spicules and silicified spines of uncertain taxa. Radiolaria average 0.08 mm but reach 0.3 mm in diameter. The majority are spherical Spumellarians; tetrahedral and rod-shaped Spumellarians and possibly other orders are widespread minor forms. Radiolaria are composed largely of non-fibrous microquartz grains about 5–30 μm in diameter and are filled, in order of abundance, by non-fibrous microquartz, chalcedony, or red clay. Radiolaria that were flattened by compaction to prolate forms are rare in the cherts. Radiolaria are completely unsorted in terms of size except in the few laminated beds where laminae are composed of indistinct layers of different size and abundance of Radiolaria.

The non-fibrous microquartz that forms the cement in the chert beds is of variable size, chiefly from 5 to 20 μm, but of relatively uniform size in any given bed.

Clay is scattered unevenly among Radiolaria throughout the chert beds, as clay-filled

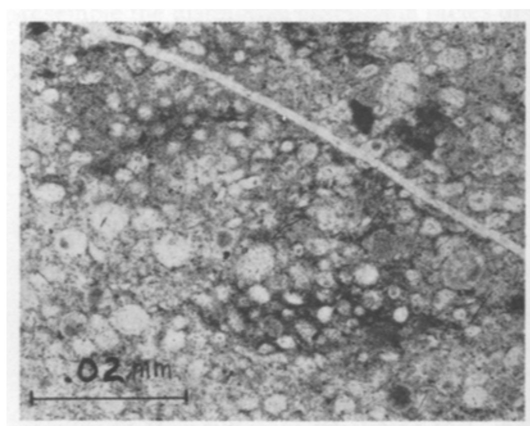


FIG. 11.—Red radiolarian chert in which Radiolaria, in various degrees of preservation, form essentially an intact framework. Microcrystalline quartz pigmented by hematite-stained clay is the groundmass. Dark patches are clay-rich burrows. Alba Villa, Lombardy pre-Alps.

burrow fillings (Figs. 9, 11) of elliptical shape (owing to compaction), and as rare isolated spherical particles that are either transported fecal pellets or clay intraclasts. Clay increases in abundance towards the margins of those beds that show reverse or normal grading (Fig. 9). Horizontal or subhorizontal clay "laminae" less than 1 mm thick but of discontinuous lateral extent are present in some beds. Some laminae look like current-formed clay laminae that were obliterated in places by burrowing activity, but others, those that have a low-angle inclination with bedding, are probably cross sections of *Zoophycos*-type burrows.

Hematite is abundant in minute shapeless flecks less than 1 m in diameter; none of it is in obvious cubes or framboids, thus it probably came into the sediment originally as hematite or hematitic clay, without a pyrite precursor.

Red Shale

Shale beds range from those that are 100% clay minerals (illite and chlorite) to those that are mixtures of microquartz (10% to 40%), Radiolaria (up to 15%), quartz and muscovite silt (up to 5%) and phosphatic and chitinous fossil scraps (trace amounts); a few beds have appreciable (up to 30%) micrite calcite. Fissility of shale decreases with an increase in microquartz or calcite; siliceous shale has a weakly developed conchoidal fracture, whereas calcitic shale has a hackly fracture. XRD analyses of three samples from the Lombardy region show that illite and dioctahedral chlorite make up about 80% and 20% respectively of the clay minerals; two samples have a trace of mixed-layer clays.

Most shale beds are completely structureless except for a good mass extinction of clay minerals. In beds that have detrital silt, the silt occurs as sparse laminae or in burrow nests. Additional evidence of bioturbation is that some mica flakes have a random orientation instead of parallel alignment with bedding. The sparsity of laminae and local evidence of burrows raises the possibility that the nearly homogeneous texture of shale beds is the result of intensive bioturbation.

Radiolaria in shale beds are poorly preserved in comparison with Radiolaria in chert beds; generally, only the central unornamented capsules of Spumellarians, somewhat flattened by compaction, are preserved in shale, and no non-spherical Radiolaria have been found in any shale samples. The preservation of essentially only the thick-walled central capsule of Spumellarians suggests that Radiolaria originally were more abundant in shale, but that many dissolved on the sea floor or during diagenesis. This supposition is supported by the occurrence and composition in several formations of siliceous shale nodules in non-cherty shale. Within the nodules Radiolaria, including Nasellariids, comprise up to 80% of the rocks, whereas in the adjacent shale Spumellerian capsules make up less than 10% of the rock and are the only forms present. Presumably, the nodules preserve more of the original fauna than does the shale host.

Green Chert and Shale

Green chert and shale beds are identical in texture with red chert and shale respectively. The only conspicuous mineralogical difference between red versus the green rocks is the presence of hematite in the red chert and shale and its absence in green rocks.

Gray Chert

Gray chert beds are crudely laminated and have less burrow mottles than red chert. Laminae are from 0.1 to 2 mm thick and differ in the relative abundance of Radiolaria, clay, and ultra-fine microcrystalline quartz (<5 μm in diameter). Common modes of laminae are 1) Radiolaria 50%, microquartz 48%, clay 2%, and 2) Radiolaria 10%, microquartz 80% and clay 10%; pyrite occurs in trace amounts.

Chlorite pellets up to 0.1 mm in diameter that locally make up to 30% by volume occur in some gray chert samples. According to Leone et al. (1975), the pellets are composed of Ib polytype chlorite that formed in unconsolidated mud before compaction and early diagenesis, either by replacement of original clay minerals or by precipitation from solution.

Gray Shale

Gray shale has on the average more muscovite and quartz silt than red shale, but this is a function of geography; all samples are from Sicilian basins. Plant fragments, pyrite framboids, and chitinophosphatic debris are important minor components. Some beds preserve a few silt-rich laminae where bioturbation was not complete.

Leone et al. (1975) report that clay minerals include random mixed-layer illite-montmorillonite, illite, and traces of chlorite of possible detrital origin.

Limestone

At several localities examined briefly (e.g., Rapolano Terme and Vecchiano, both south of Florence) there are several meters of section where limestone beds instead of chert make up the non-shale part of the rhythmic bedding. The limestone beds are composed of micrite (1–5 μm grains) with variable amounts of Radiolaria (5%–60%), all of which are completely replaced by calcite. Bedding types and other structures are similar to those in chert beds. Petrographic features of these limestone beds are similar to those described in more detail in the section on cherty limestones.

NODULAR-LUMPY CHERT

Study Areas

Formations composed chiefly of nodular-lumpy chert that we studied include the Radiolarite Formation of the Selcifero Group in the Lombardy Pre-Alps and the Calcareous Jasper Formation in the Umbrian sequence. Principal localities in the Lombardy region are Col Pedrino, Burligo, Sogno, and Alba Villa. Principal localities in the Umbrian region are the Bosso River gorge and Acquasparta; some observations come from Monte Catria and Monte Nerone.

Bedding and General Features

Although there are differences between the various stratigraphic units described here, some of the common aspects are summarized. The rhythmic aspect of these formations is not as conspicuous as in the even-bedded radiolarites because shale is not abundant, and limestone and/ or chert beds are thicker than chert beds in bedded chert formations. Shale beds, rarely greater than 5 mm thick, make up only about 2% of the lumpy chert formations. The rhythmic nature of these formations (Figs. 4, 5) is provided by alternations of limestone beds of different texture or composition, alternations of limestone and chert, and by alternations of limestone with thin but widespread shale laminae. Limestone and chert beds generally are thicker than 8 cm and are amalgamations of several sedimentation units (Fig. 12). Most shale beds are laterally continuous, but local pinchouts developed from either erosion, obliteration of clay layers by extensive bioturbation that mixed clay with radiolarian or carbonate ooze, or by "dilution" of clay layers by diagenetic addition of microquartz from adjacent beds.

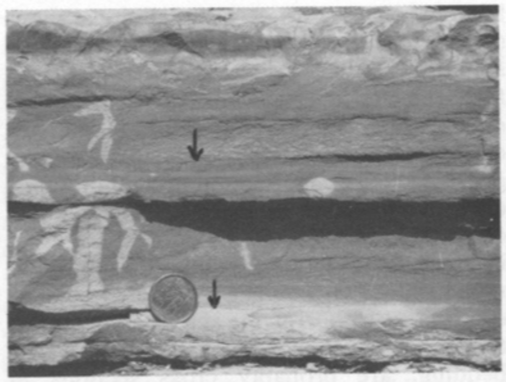


FIG. 12.—Sedimentation units, some with graded bedding (arrows at base of graded beds), in limestone of the Calcari Diasprini (Calcareous Jasper) at Bosso Gorge, Umbrian basin. The majority of the sedimentation units in the photo show evidence of current deposition. Coin is 2.5 cm in diameter.

The degree of lateral variation in bed thickness that produces the lumpy character of this type of chert generally increases as the amount of chert increases. Limestone beds that contain isolated chert nodules generally are of uniform thickness (Fig. 3), whereas chert beds have a lateral variation in thickness that ranges from 1.5:1 to 10:1 (Fig. 5).

Complete gradations exist in the following sequence: 1) isolated elliptical nodules of chert 1 to 5 cm long in the center of limestone; 2) uneven lenses of chert several meters long that occupy the middle part of limestone beds and that formed by lateral growth and coalescence of nodules; 3) beds of chert of

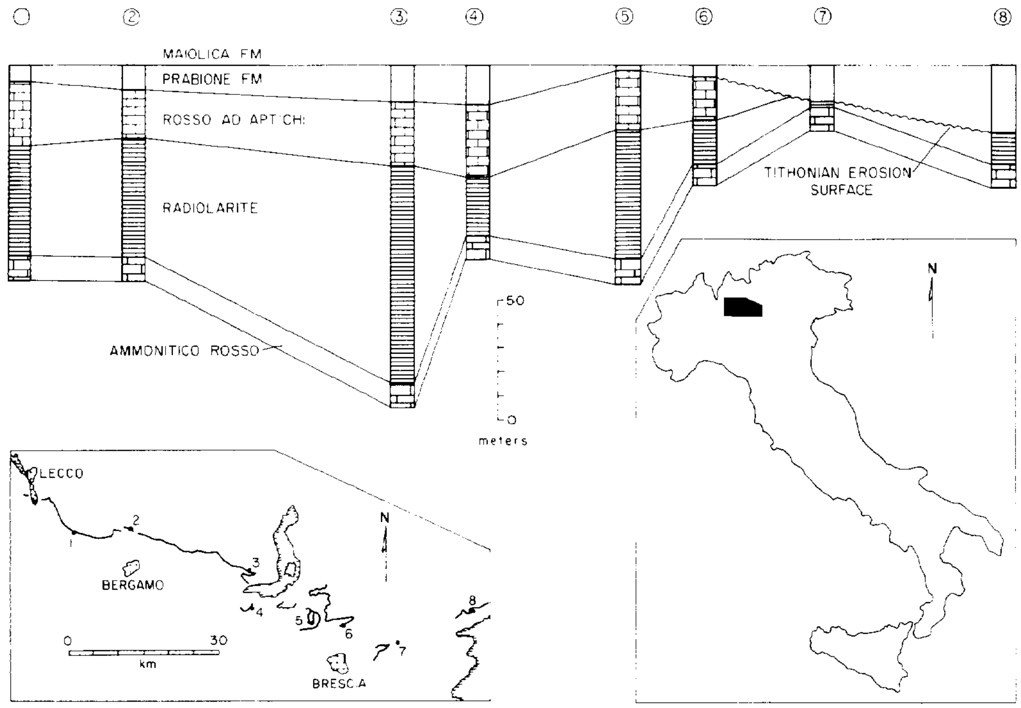


FIG. 13.—Stratigraphic cross section of the radiolarite and adjacent formations in Lombardy pre-Alps showing thickness variations resulting from deposition on fault-block topography and from post-Tithonian erosion (after Pasquarè, 1965).

uneven thickness. About 70% of chert nodules have an abrupt contact with the limestone host rock, others are gradational over a few millimeters. Some chert nodules contain concentric growth bands made visible by slight differences in abundance of hematite or calcite inclusions in chert; others possess a millimeter-thick white patina on their outer margin. Laminations, where present, pass continuously from limestone into adjacent chert nodules. These relations plus the occurrence of all gradations between nearly pure limestone to nearly pure chert indicate conclusively that chert formed by the replacement of carbonate beds.

At most locations there are distinct vertical variations in abundance of chert, uniformity of bedding, thickness of beds, and thickness of the formation. From a regional study of the Radiolarite Formation in the Lombardy region, Pasquarè (1965) recognized and mapped several facies on the basis of such lithic variations (Fig. 13), and inspection shows that a similar procedure could be done in Umbria.

Chert beds have abrupt upper and lower contacts with shale, and bedding surfaces of chert have a variety of small pits and mounds of uncertain origin and rare trace fossil tracks or burrows (Fig. 14). Limestone beds have contacts with shale that are either abrupt or apparently gradational, but the contrast developed by weathering of limestone and calcitic shale is commonly not strong enough to discern clearly whether the contact is abrupt or gradational.

Recumbent folds less than 0.5 m thick of slump origin are found at most sections studied but are not common features. Several crackle breccia beds about 0.5 m thick and also of slump origin occur at the Col Pedrino locality. Breccia beds of probable debris-flow origin up to 0.5 m thick at Monte Catria contain pebbles of locally derived chert and limestone in addition to limestone of the underlying formation (Ammonitico Rosso).

FIG. 14.—Elongate burrow or crawl mark on top of chert bed, Lombardy pre-Alps.

Two widespread diagenetic features that we found in the chert beds of this facies are domal structures and chalcedony-filled fractures.

Color

The Radiolarite Formation of Lombardy is 80% red to red brown and 20% green to gray green. The Calcareous Jasper Formation at Acquasparta is nearly all red, but at the Bosso Gorge it is 50% pale green to gray. Pigments are the same as in well-bedded radiolarites. Red and green colors are most intense in chert beds and fade to pastel pink and pale green respectively with an increase in calcite. Some nearly pure limestone beds are cream colored. Because of similar evidence cited for the well-bedded radiolarites, most green chert in the lumpy-nodular radiolarites formed by post-depositional reduction of hematite or a hematite precursor mineral. However, several meters of section in the lower part of the Radiolarite Formation in Lombardy and several sequences at the Bosso Gorge section show no evidence of having been red. Laminations are more common in green chert beds, suggesting less bioturbation, an event favored by anoxic or oxygen-poor bottom water. This supports the idea that some green beds were never red.

Limestone

Limestone beds (Fig. 12) are composed principally of micrite with variable amounts, in order of abundance, of Radiolaria, pelagic pelecypods, hematitic clay, chitinophosphatic and calcite skeletal parts of uncertain affinity, clay pellets or clasts, quartz and mica silt and ammonite aptychi (calcite). The abundance of these components differ in individual sedimentation units, most of which are only a few millimeters thick. Micrite makes up as much as 98% of a few sedimentation units, but Radiolaria are essentially ubiquitous in abundance greater than 5% but less than 50%. With an increase in microcrystalline quartz, generally accompanied by many Radiolaria, limestone grades into chert; with an increase in red clay, limestone grades into "marl" and finally shale.

Poorly preserved coccoliths are common in the micrite fraction of limestone in the Lombardy Radiolarite (I. Premoli-Silva, 1977, oral comm., so we suspect that most micrite in the limestones under study is the diagenetic product of altered coccoliths. Pasquarè (1965, p. 129), thought some carbonate in the Selcifero Group of the Lombardy region is detrital, having been eroded from local topographic highs. Dolosparite occurs at the Bosso Gorge section as pods and local lenses up to 10 cm thick. In beds where Radiolaria comprise less than about 30% of the rock, the Radiolaria, slightly flattened by compaction, are generally replaced by microquartz with a chalcedony center.

Most limestone beds, those delimited by shale partings, are multiple sedimentation units (Fig. 12) as shown by differences among layers in the abundance of non-micrite components. These sedimentation units range from a placer of chitinosphosphatic scraps 0.04 mm thick to rare graded beds 20 cm thick; most sedimentation units are less than 8 cm thick. Grading (Fig. 12) is developed by an upward decrease in abundance (rarely decrease in size) of Radiolaria. Some sedimentation units are laminated regularly by alternations of fewer or more Radiolaria or pelecypod valves, but most are structureless except for the nearly universal overprint of bioturbation. Burrows, nearly without exception, are parallel to subparallel with bedding and appear as mottles that disrupt the primary stratification. Recognizable burrow density ranges from absent to 100% by volume and averages about 30%. Burrows are discernable by shape and by differences in texture and composition of burrow fillings from host rocks.

Valves of pelagic pelecypods, locally called filaments because they are only a fraction of a millimeter wide but up to 10 cm long, are conspicuous skeletal grains in many rocks and locally form placers of self-supporting grains. They lie parallel with bedding except where disturbed by bioturbation. Most retain their identity during silicification.

Chert

Chert occurs as nodules, lenses, and beds composed of microcrystalline quartz, and for the most part, contains moderately well preserved ghost textures of the limestone bed that it replaces. During replacement, some Radiolaria and small carbonate skeletal grains lose their identity, and micrite grains are replaced by non-fibrous microquartz grains that range from less than 1 μm to 15 μm. Radiolaria, probably preserved as internal molds, are composed of coarser microquartz than host chert; many central parts of Radiolaria are filled by chalcedony. Chert masses range from those devoid of calcite to those with about 40% unreplaced calcite inclusions. The only chert type that does not have a limestone analog is that composed of 80% grain-supported Radiolaria.

Differential permeability parallel with bedding in carbonate beds and permability barriers formed by shale partings controlled the shape and development of chert bodies. Nodules and lenses are elongate parallel with bedding, and beds of limestone that are nearly completely replaced by chert show that the top and bottom of each bed are the last rocks to be replaced.

Whereas limestone beds with or without chert nodules are generally uniform lateral thickness, chert beds commonly display uneven thickness, that is, lumpy bedding (Fig. 5). Within a thickness of several meters, the thicker parts of some beds are compensated by the thinner parts of subjacent beds, suggesting that a random factor controlled the thickness variation.

Hemispherical Mounds.—The most spectacular chert thickness irregularities are sharply defined hemispherical mounds from 10 to 50 cm across, with a relief of from 1 to 10 cm (Figs. 15–17), often reddish compared to surrounding non-red cherts. Laminae, where present, conform to the shape of individual mounds. Most have convex upward form, and the majority of the red mounds are broken by a septarian-like network of radial, radial-concentric, or irregular prismatic fractures (Fig. 17) that are filled with green siliceous shale from overlying beds or rarely by chalcedony and megaquartz. The fracture pattern resembles that atop salt domes. In several, the red chert in the mounds seem to have become brittle while the green or gray sediment was still soft.

FIG. 15.—Mound structure in a chert bed; convex form is almost always up. Did the structure form by differential compaction or expansive growth of the mound? Sclae divisions are centimeters. Burligo, Lombardy pre-Alps.

FIG. 16.—Mound structure (8 cm thick) and uneven chert beds separated by shale partings. The red chert beds have developed a white patina from weathering. Bosso Gorge, Umbrian basin.

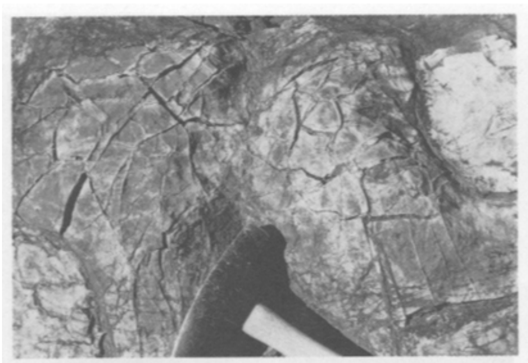


FIG. 17.—Top surface of mound structures in red chert showing septarian fractures that were filled by green clayey chert. Exposed part of hammer is 10 cm long. Burligo, Lombardy pre-Alps.

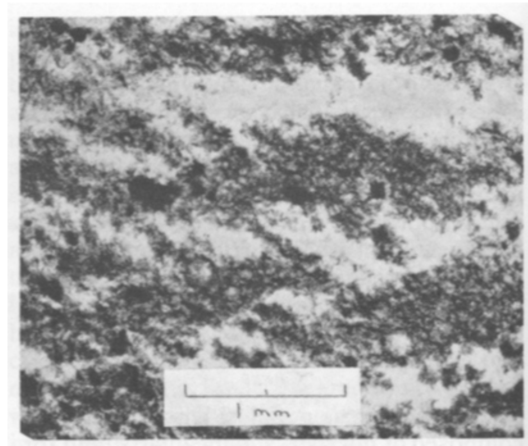


FIG. 19.—Ordinary light. "Stretch marks" showing the softness of the mother radiolarian sediment (dark); openings filled with clear chalcedony and quartz. Observe the en echelon distribution of the openings; photo corresponds to the relations on the right side of the mound in Figure 18. Specimen 74-Alb-21.

Most of the domes also contain along their flanks an en echelon series of "stretch-marks" (Figs. 18, 19), irregular, mainly horizontally-oriented openings that are arranged in zones concentric with the dome margin. These stretch marks resemble the markings on expanded human skin; they have "curdled" walls whose irregularities match across the open space (Fig. 19), thus the sediment must have been very soft at the time. The openings occur at a uniform spacing of about 1 mm over lateral distances of several centimeters, and are 0.1–0.4 mm wide. The openings are now filled mainly with chalcedony, but also contain occasional geopetal heaps of red, clayey chert pellets (crystal size about 1 μm) sometimes containing Radiolaria. Thus, the openings formed penecontemporaneously with the sediment and at some stage were empty. The final fill is normal length-fast chalcedony. The septarian-like cracks discussed above have sharp margins and cut across the stretch marks, and formed after the domes were more lithified.

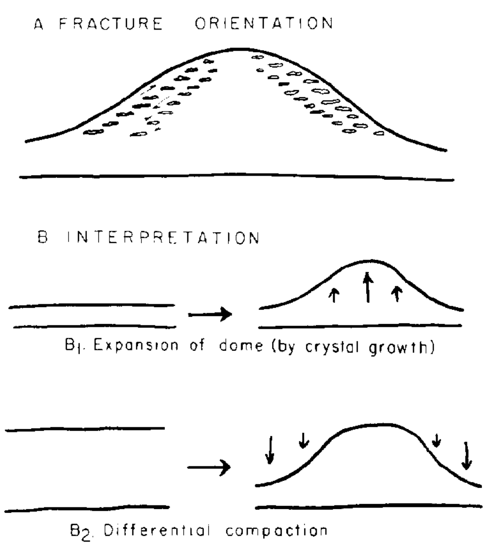


FIG. 18.—Orientation of stretch marks in hemispherical domes. En echelon orientation indicates that the outer layers sheared upward toward the peak of the dome. The domes can be explained either by expansion of a thin bed by crystal growth, or alternately by differential compaction leaving a circular less compacted region.

Dynamically, the en echelon orientation of the stretch marks could indicate either that the dome rose, or that the surrounding sediment layer compacted. Thus there are two explanations (Fig. 18):

1. Starting with an initially flat thin bed, localized doming occurred (as in the formation of salt domes or laccoliths). This could be done by growth of salt or gypsum crystals (Assereto and Kendall, 1977), ice crystals, or perhaps by gas generation. Ice crystals growing in clay can cause uniformly spaced expansion fractures with the same irregular surfaces (Taber, 1930).

2. Starting with a thick flat bed, compaction occurred except in the area of the domes, which were perhaps more indurated by selective cementation. Compaction could be caused by dissolution of carbonate and/or Radiolaria in areas adjacent to the mound.

RLF favors mechanism (1) as it seems simpler to make isolated circular domes on a flat bed exposed at the surface by expansion, and this seems the easiest way to explain the stretch marks, their en echelon orientation, and the septarian cracking. The reason for oxidation and precocious lithification of the mounds is not clear, but the two processes are probably related in origin. EFM favors mechanism (2) in view of the lack of compulsive evidence of expansive crystal growth.

Aside from color and pigmenting agents there is no basic difference between red, green or gray chert. There are few clay-rich green cherts, suggesting that bleaching solutions avoided the less permeable clayey rocks. Rare beds of black chert from the Bosso Gorge section contain pyrite framboids and cubes and phosphate in the form of anastomosing stringers and chitinophosphatic scraps.

Shale

Shale is composed of various mixtures of clay minerals (chiefly illite and chlorite), micrite, microcrystalline quartz, and similar skeletal, detrital and pigmenting material as present in limestone. Optically the bulk clay mineral (~80%) has very low birefringence, an index near Canada Balsam, and is in almost invisibly small crystals. Scattered in this are shreds of 5–15 μm illite flakes with straw yellow birefringence, and about 5% of quartz silt. Radiolaria, flattened slightly by compaction and preserved chiefly as molds of central capsules, rarely exceed a few percent. Burrow mottles are ubiquitous and abundant and obscure nearly all primary textures. Laminae are rare, but clay minerals and pelecypod valves have a fair preferred orientation parallel with bedding. Microstylolites of low relief are present locally, even in shale that now lacks calcite. The latter occurrence suggests that calcite was lost by dissolution during burial diagenesis.

Shale beds rarely exceed 1 cm thick, and the thicker ones are all highly calcitic. Most beds can be traced laterally the extent of outcrops, implying wide lateral extent. Pinchouts into limestone are abrupt by wedgeout, which suggests that clay was here removed by erosion. Pinchouts into chert nodules are gradual and local, because the shale layers continue on the opposite side of the nodules. Thin sections of the nodules show the clay minerals are dispersed in microquartz matrix. Either the clay in the nodule was dispersed within the carbonate sediment by bioturbation prior to chertification, or silica was preferentially precipitated in the initially porous mud to "dilute" the clay content.

ORIGIN OF CHERT BEDS—PRESENT INTERPRETATION

Combining evidence of previous workers with that uncovered by our work, plus the results of studies of siliceous rocks and chert gathered by the DSDP, we conclude that the chert nodules, lenses and beds all formed by the diagenetic reorganization of silica almost entirely of biogenic origin, namely from Radiolaria. In limestone beds with chert nodules and lenses the chert formed by replacement of calcite grains of uncertain but possibly biogenic origin. Simple dissolution of radiolarian opal was the immediate major source of silica to the interstitial water. Complete replacement of some limestone beds resulted in the development of chert beds, generally of uneven thickness because compaction, dissolution of calcite and replacement of calcite were not uniform in either time or place within a bed.

In addition, many chert beds of even-bedded formations also formed largely by the replacement process. The dark gray Sicilian chert beds have considerable matrix of microquartz possessing the same grain size and texture as microquartz of replacement origin in nodules in other formations, and it is likely that the gray beds originally had considerable micrite. However, we disagree with Parea (1970) that *all* radiolarian chert beds are of replacement origin. Many red chert beds at Monte Cetona have textures that suggest they initially were silts or very fine sands composed of mostly transported Radiolaria plus a few mud intraclasts or fecal pellets. The most likely means of chertification of these beds was by dissolution of Radiolarian opal followed by precipitation of opal A' or opal C-T as cement around remaining Radiolaria (cf. Hein et al., 1978) and also as fillings of radiolarian molds. With time, opal A' and opal CT altered to microquartz. Evidence from Tertiary oceanic deposits (Hein et al., 1978) suggests that from 5 to 25 m.y. were required to complete the transformation. We agree with Parea's (1970, p. 694) statement that it is difficult to estimate the original carbonate content of beds of chert.

A considerable amount of silica is necessary to convert a radiolarian silt, with an initial porosity of at least 70%, to essentially nonporous chert, or to form nodules and lenses of chert by replacement origin in limestone. Some silica, as suggested by Parea (1970), is released during clay mineral diagenesis (e.g., montmorillonite → illite + quartz) and some silica came from siliceous sponge spicules, but the bulk of it was almost certainly derived from Radiolaria. We are not convinced by the arguments of some authors (e.g., Passerini, 1965, p. 264) that because Radiolaria are abundant and many are well preserved and show no corrosion, that they could not have been the source of silica. As noted by Garrison (1974, p. 369), most Radiolaria are preserved as molds, formed by first dissolution and then backfilling. Thus, it is likely that even chert beds with abundant well-preserved Radiolaria have undergone much shuffling of silica of radiolarian origin.

Probably most silica came from Radiolaria in the current-deposited beds; however, two lines of evidence suggest that considerable silica came from Radiolaria in the hemipelagic shale interbeds. First, Radiolaria in shale beds are poorly preserved and show evidence of dissolution: generally, only the filled central capsule is preserved. This style of preservation indicates that these individuals were not dissolved at the sea-fllor interface because dissolution of the test was preceeded by infilling of the capsule by microquartz. Although considerable Radiolaria undoubtedly dissolved before being buried (cf. Hurd, 1973), some were entombed to provide a source of silica during burial diagenesis. The second line of evidence is the chert-rich nodules (siliceous shale) found in shale beds in two formations. Radiolaria are abundant (up to 70% by volume) in one nodule, but in laterally equivalent shale make up only 10%. If, as it seems, this nodule is a concretion that preserves more of the original composition of the mud than the adjacent shale, this is strong evidence that at least some mud beds were initially rich in Radiolaria.

The original thickness of beds of clay, carbonate mud and siliceous ooze must have been reduced considerably by the combination of physical compaction (repacking of grains) and dissolution-reprecipitation processes. The latter process was most important in siliceous ooze. For example, if all silica for induration of an ooze bed 10 mm thick with a porosity of 70% came from within the bed, its thickness would have been reduced to 3 mm. Essentially no textural evidence of this compactional process is preserved. In contrast, laminae 1 cm apart in a chert nodule are only 5 mm apart in the laterally enclosing limestone host bed. This evidence of differential compaction attests to a minimum thickness reduction of 50% for this carbonate mud bed. If the hemispherical domes are the result of differential compaction, some record 90% reduction in bed thickness based on a comparison of maximum versus minimum thickness of the objects and their host beds.

Parea (1970, p. 694) noted that there is conflicting evidence of the time of silicification of nodules and beds, and we concur. Fractures filled with soft-sediment (green chert that fills fractures in red chert), presence of internal sediment in largely silica-filled fractures, and compactional drape around domes and other nodules argues for early silicification. However, we differ among ourselves in our interpretation of "early" as being in part syn-sedimentary (RLF) versus after moderate burial (tens of thousands to several million years after deposition, EFM). Both Parea (1970, p. 694) and we found examples of chert nodules abutting late tectonic fractures, attesting to silicification probably during Tertiary time. In our experience such examples are rare, and we think most silicification was complete before Tertiary orogenesis. An alternate interpretation is that fracturing occurred in early lithified limestone nodules that subsequently were replaced by chert.

ORIGIN OF BEDDED CHERT CYCLES

Four hypotheses (Fig. 20) are considered for the origin of the rhythmic chert-shale interbeds: 1) diagenetic segregation of silica from initially nearly homogeneous siliceous mud, 2) episodes of rapid and slow production of Radiolaria in surface waters with a constant rate of mud deposition; 3) episodes of current-deposition of radiolarian silt with a constant rate of mud deposition, and 4) episodes of current deposition of mud with a constant rate of Radiolaria deposition.

The first hypothesis was suggested by Davis (1918, p. 393–402) to explain the rhythmic bedding in the radiolarites of the Franciscan Group in California, and by Giannini et al. (1950) and Pasquarè (1965) to explain the chert-shale cycles in the Tuscan and Lombardian radiolarites respectively. Segregation of silica from clay or calcite is inferred to have taken place when the sediment was a gel, a condition that has never been proven to exist in marine sediments. Whereas there is considerable evidence of mobility of silica during diagenesis in Italian rocks under study, the style of stratification, internal structures and abrupt contacts of most beds described herein, including those with sole marks, discredits this hypothesis as an important origin of stratification for these rocks.

The second hypothesis assumes cyclic control of the productivity of Radiolaria by variations in some limiting factor (nutrients, temperature, etc.). This explanation is favored by Garrison and Fischer (1969) and Fischer (1977) for the Oberalm Radiolarite of Austria, where a periodicity of about 80,000 years is computed for each couplet. However, the abrupt contacts between most chert and shale beds seems contrary to slow deposition, because burrowing animals would almost certainly have thoroughly worked this interface.

In both chert and shale beds and at their contacts where bioturbation has not obliterated primary stratification there is evidence of current deposition, and we believe the evidence warrants the conclusions that mud was the hemipelagic "background sediment" and most radiolarian-rich layers were deposited by currents and accumulated rapidly. Evidence for current deposition of chert beds includes:

1. Sharp top and bottom contacts with shale, which implies, especially at the base of each chert bed, an abrupt rather than gradual change in depositional process.
2. Casts of animal tracks and burrows are preserved on the sole of chert beds. To preserve a surface populated by vagile animals requires rapid deposition of the covering bed.
3. Presence of laminae in some chert beds. The laminae are the product of deposition by currents that produced a degree of hydraulic sorting.
4. Presence of primary graded beds, which are most commonly produced by turbidity currents and other currents of waning velocity.
5. Presence of clay clasts.
6. Examples of starved current ripples.
7. Flute casts.

Shale beds in the cycles under discussion also have laminae of probable current origin, but because the shale is similar with shale of so-called pelagic or hemipelagic origin in basinal facies throughout the Tethys, we believe it is the background deposit that records the slowest rate of accumulation. This is supported indirectly by the greater abundance of chitinophosphatic debris in shale than in chert; i.e., the insoluble chitinophosphatic material is more abundant in sediment that records the slowest accumulation rate.

There is little evidence to determine the types of currents that transported and deposited what was essentially beds of radiolarian silt. Some beds have characteristics of turbidites, others have characteristics of contourites (starved current ripples), and others are non-diagnostic. However, we stress the importance of turbidity currents because of the lateral continuity of beds, similarity in overall rhythmic style of cyclic bedding with turbidite chert beds in the Ligurian sequence (Folk and McBride, 1978), and the opportu-

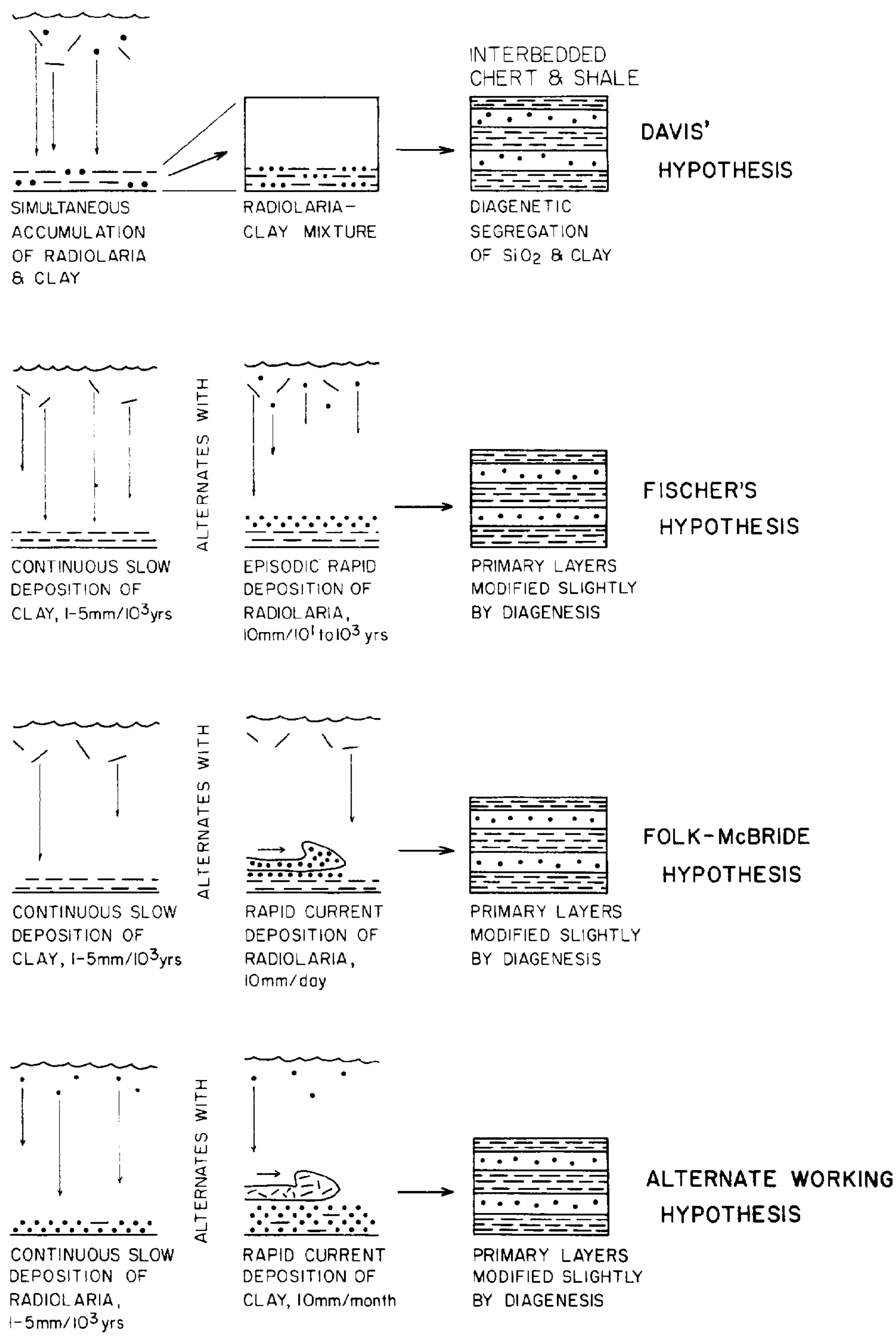


FIG. 20.—Diagram of four hypotheses of the origin of chert-shale rhythms. Davis's (1918) and Fischer's (1977; also Garrison and Fischer, 1969) hypotheses have been presented elsewhere.

nity for turbidity currents to develop in basins characterized by strong topographic irregularity and tectonically active margins (cf. Nisbet and Price, 1974).

We do not reject the possibility that some chert beds are unreworked pelagic deposits (hypothesis 2), but because of the evidence cited we favor hypothesis 3 as the more important process. Bioturbation has severely modified primary stratification to obliterate the primary evidence that would enable a better estimate to be made of the proportion of true pelagic beds to current-deposited beds. Moreover primary lamination might have been destroyed during the shuffling of silica and calcite during diagenesis in the same manner that laminations were destroyed in current-deposited limestone beds of the Cretaceous Calpionella Limestone (Andri and Fanucci, 1975). In the radiolarites studied, about 80% of the stratification in the red chert and shale beds has been destroyed and about 40% in the gray chert and 80% in the gray shale beds. The difference between extent of bioturbation in cherts is presumably due to a greater population of animals in the well oxygenated environment where red sediment accumulated. Notable, however, is the scarcity of burrowing *across* the proto chert-shale contacts. It is difficult to explain this by the pelagic theory, but not difficult by the current-deposition theory, where a blanket of current-deposited sediment might either kill the benthic population or encourage it to repopulate the new surface. Burrowers, which worked parallel with bedding, probably found more food available in the newly deposited bed than in the buried mud (shale) layer, and had little desire to work in the interface between them.

Using paleomagnetic reversals to establish chronostratigraphy, Arthur (1977) reports for pelagic carbonate-shale cycles in Umbria burrowed by *Chondrites*-type animals, that primary features less than 100 years duration in black shale were destroyed and that primary features up to 10,000 years duration were destroyed in interbedded limestone. Using average rates of accumulation of Apennine radiolarites (Schlager, 1974, p. 66) of 3–9 mm/1000 years, each millimeter-thick layer records 100 to 330 years time, which presumably would have been sufficient for burrowers to destroy all primary features if deposition were by slow pelagic accumulation.

ORIGIN OF NODULAR-LUMPY CHERT

The presence of chert nodules and lenses in limestone beds produces the nodular aspect of this type of radiolarite or radiolarian limestone. Evidence that the nodules formed by the replacement of limestone (or carbonate mud) has been presented. We found no clues that suggest why certain parts of a bed were replaced preferentially.

The lumpy aspect of beds that are now entirely chert may have developed before silicification. Because no chert-free limestone beds possess the same lumpy character as the lumpy radiolarite beds, the evidence favors the origin of the major part of the lumpiness during silicification and concomitant differential compaction.

Bosellini and Winterer (1975, p. 280) suggest that "knobby calcareous radiolarite" of the Mediterranean Tethyan region accumulated above the CCD but below the calcite lysocline (CLy; the depth below which calcite dissolution increases abruptly), and that early diagenetic calcareous nuclei and insoluble siliceous sediments were differentially compacted to produce wavy-bedded or nodular calcareous radiolarite. The authors do not indicate what bedding features developed at the sea floor and what features developed after burial. We suggest that the lumpy forms that developed upon differential compaction probably needed several meters or tens of meters of overburden, and took place in a diagenetic environment different from that at the time of deposition. Our inability to tie down the time of silicification prevents clarification of this problem. Parea (1970, p. 694) also reports conflicting evidence on the time of silicification. Drape over chert mounds suggests "early" chertification, whereas nodules oriented along fractures suggests a "late" origin. Probably chertification took place over a long time span (cf. Hein et al., 1978).

Thin shale beds are ubiquitous and form conspicuous partings in both nodular cherty limestone beds and lumpy chert beds. The chert-shale or limestone-shale rhythms pose the same problem of origin as the rhythms of the well-bedded chert and shale. Graded bedding and laminations of current origin indicate that many nodular limestone beds and what are now lumpy chert beds were deposited by turbidity currents and other marine currents. However, the depositional processes of shale and of many limestone and chert beds is uncertain. Most shale beds have sharp contacts with enclosing chert or limestone beds, but rarely could samples of the contact be obtained for thin section study to check for abruptness of the contact or degree of bioturbation. It is tempting to interpret the shale beds as the slowest hemipelagic deposit and to infer that limestone and chert beds of uncertain origin include both pelagic deposits and unrecognized current laid deposits. The ultimate cause of the rhythms (other than turbidite rhythms) is unknown.

FRACTURE FILLS AND BRECCIAS

General Features

At almost all outcrops of chert examined, we found some chert beds cut by fractures that are now filled by either sediments from adjacent beds (Fig. 17) or by chemically precipitated forms of silica, often recording a complex paragenesis. In addition, strata-bound breccias of spectacular fabric are present at several localities. Some fractures and breccias formed when the sediment was only partly lithified, and all formed prior to the latest stage of thrusting and orogenesis because in places they are cut by younger tectonic quartz-filled or calcite filled fractures. Early fractures are filled with microcrystalline or chalcedonic quartz, later tectonic ones only by megaquartz. Major features of the two types of breccia are described below. Separate interpretations are given for the features on whose origin we disagree.

Sediment-filled Fractures.—These fractures occur in red chert beds, particularly hemispherical domes (Fig. 17), as near-vertical cracks from 1 to 10 mm wide that are filled with green clayey chert from adjacent beds that oozed into the cracks like toothpaste. The darker chert infill is made of cryptocrystalline microquartz ($<1\ \mu m$), whereas the red chert host is made of microquartz averaging 10 μm. Fractures either taper and die out downward within each bed or cut only one bed and die out in enclosing shale beds.

These fracture-fills are similar in geometry and composition to those in the Caballos Novaculite of Texas (McBride and Folk, 1977), and had a similar origin. Before deep burial, early-lithified red chert fractured, and the fractures filled immediately by unlithified green clayey chert. Either clay or organic matter retarded the lithification of siliceous sediments, a conclusion made earlier from the Caballos (McBride and Folk, 1977, p. 1273; Folk and McBride, 1978a, p. 126–129).

Silica-filled Fractures.—Most silica-filled fractures are sheet-cracks (term of Fischer, 1964); that is, fractures subparallel with bedding in chert; they are most abundant in lumpy chert beds (Fig. 21) and in mounds. In hemispherical mounds they are roughly parallel with the outer surface of the nodules. Fractures are mostly straight, from 1 to 10 cm long, up to 5 mm wide, and die out within a bed; a few are curved, and some are perpendicular to bedding. Some fractures have straight sides that cut through Radiolaria and detach sliverlike pieces, whereas others are slightly sinuous and weave around Radiolaria.

The main filling is chalcedony (length-fast fibrous microquartz) but locally is quartzine

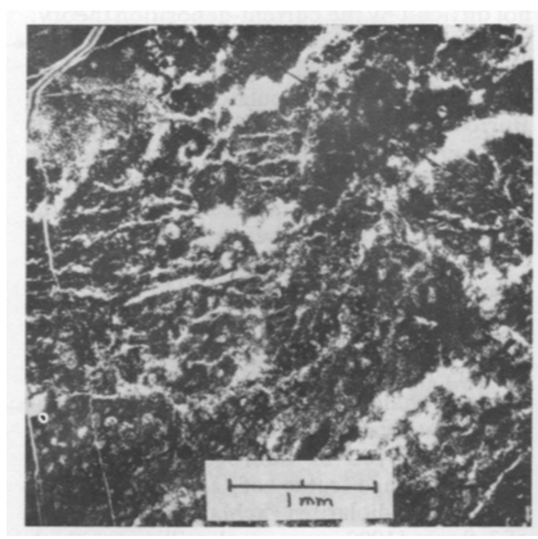


FIG. 21.—Ordinary light. Irregular soft-sediment fractures mainly parallel with the bedding, in dark radiolarite. Curdled fabric probably due to desiccation, and resembles soil fabrics. Specimen 74-Sog-4.

(length-slow fibrous microquartz) or zebraic chalcedony (cf. McBride and Folk, 1977). A few fractures have geopetal internal sediment a few grains thick of pellets of red clayey chert (0.05 to 0.1 mm diameter), larger soft intraclasts of radiolarian ooze, and some sharp, angular shards of more brittle, red radiolarite.

An unusually well-developed system of silica-filled fractures occurs in a quarry exposure at Alba Villa, Lombardia. Several beds of chert up to 30 cm thick underwent brecciation (probably associated with submarine slumping) and injection of ochre-colored chert during an early stage of deformation, and later underwent brittle fracturing and infilling by internal sediment, chlorite, and both fibrous microquartz and quartz in a complicated fashion. Examples of paragenetic sequences of the dominately silica-filled fractures are given in Table 2. Some fractures widen into cavities from 1 to 3 cm in diameter. These cavities are filled generally with chalcedony, quartzine and zebraic chalcedony, lutecite (Fig. 23), and finally with megaquartz. Cube-zone quartz (Fig. 24) alternates with the lutecite. In one spectacular example (74-Alb-23-1), the chalcedony forms very nearly perfectly oriented "stalactites" 1-2 mm long by 0.5 mm wide hanging vertically down from the presumed roof of the cavity (Figs. 25–27); and on the bottom of the cavity are stubby growths like stalagmites in minature. Some of the "stalactites" curve or fork dendritically like helictites. They have a central whitish thread but no trace of organic structure can be seen in thin section. Other specimens (ALB-m-1, ALB-m-3, ALB-m-10) also

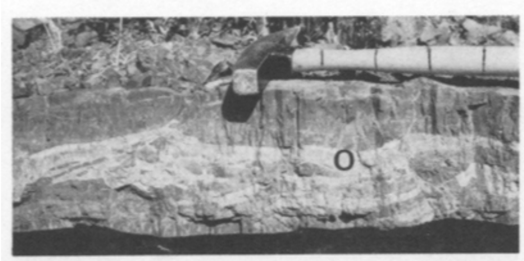


FIG. 22.—Internally brecciated chert bed from Santa Christina Gela, Imerese basin. The outer margins of the bed were lithified and then locally brecciated; the unlithified center part of the bed, which is ochre-colored chert (O), flowed to accommodate local changes in volume. Scale divisions on handle are 5 cm long.

TABLE 2.—*Sequence of Fracture Fills from Samples at Alba Villa, Lombardia (1 = oldest event, etc.)*

Sample ALB-m-1.

1a. Internal sediment, clasts up to 0.1 mm in diameter, composed of microquartz grains 0.02 mm in diameter.
1b. Internal sediment composed of cryptocrystalline microquartz grains.
2. Finely fibrous chalcedony rim cement.
3. Internal sediment, clasts up to 1.0 mm.
4. Spherulitic chalcedony crust and stalactites now recrystallized to megaquartz; brown zones outline spherulitic ghosts.
5. Cube-zoned megaquartz cement.
6a. Quartzine bands 0.3 mm thick, cloudy.
6b. Like above, clear.
7. Megaquartz cement to fill remaining pores.

Sample ALB-M13

1. Non-fibrous microquartz layer 5 μm thick.
2. Internal sediment including Radiolaria; geopetal fabric.
3. Finely fibrous spherulitic chalcedony layer 0.5 mm thick.
4. Hematite coating 1 μm thick of underlying chalcedony layer.
5. Medium-fibrous chalcedony up to 2 mm thick in a single layer.
6. Megaquartz.
7. Non-fibrous quartz crystals (0.2 mm long) about 1 layer thick.
8. Megaquartz filling of remaining pores.

Sample ALB-M10

1. Thin chalcedony crust.
2. Second fracture.
3. Crust of chlorite, locally vermiform, on upper and lower walls of fracture.
4. Internal sediment: pelletoidal grains.
5. Possibly roof-fall of chlorite—or simultaneous growth of chlorite and coarse fibrous chalcedony in thin bands.
6. Non-fibrous microquartz fills last pores.

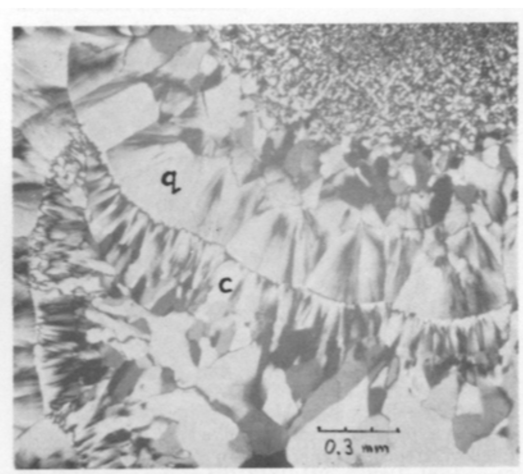


FIG. 23.—Polarized light. Alternating layers of length-slow quartzine (q), chalcedony (c) and megaquartz in a cavity. Specimen ALB-M-1.

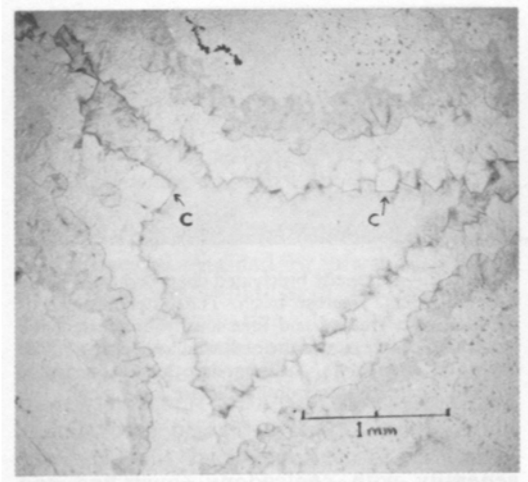


FIG. 24.—Ordinary light. Cavity filling of chalcedony followed by quartz with pseudocubic zoning (c). Specimen ALB-M-1.

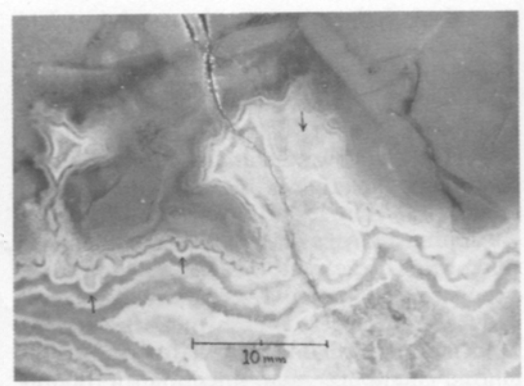


FIG. 26.—Rock slab, detail of Figure 25. An upward embayment of the main cavity, lined with downward-hanging microstalactites (arrows).

contain curving "filaments" (Fig. 28) in the cavity-fill chalcedony—some are chlorite, some are tiny hollow tubes and some are chalcedony fingers.

Origin of Fracture Fills (EFM)

Sheet cracks formed long enough after deposition for chert beds to be brittle and adjacent shale beds to be lithified because even the fractures that reach shale bedding planes were filled initially by water instead of clay, i.e., the shale beds were too stiff to flow into the fractures. This suggests burial of hundreds of meters at the time of fracture development. Internal sediment must have been produced by spalling from the fracture walls or, rarely, from adjacent beds.

The composition of pore fluids that cemented the fractures at Alba Villa changed repeatedly as attested by the complex fracture fill sequence. Probably enough changes in water composition took place during burial diagenesis (expulsion of water by compaction), ionic filtration through clay, diagenesis of opaline Radiolaria, etc.) to effect the changes recorded. I see no compelling evidence to suggest subaerial exposure or vadose diagenesis. The stalactite-like objects are elongate growths of spherulitic chalcedony into open cavities that need not have

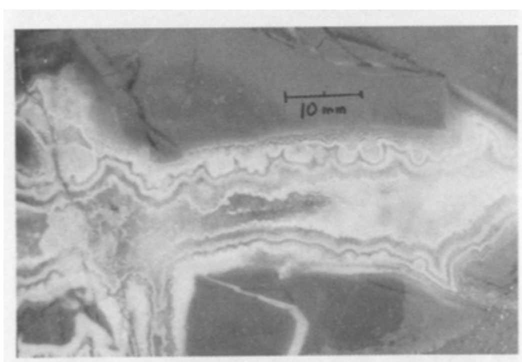


FIG. 25.—Rock slab. Mother radiolarite (dark) fractured in a quasibrittle manner (like hard cheese); cavity filled with repeated generations of clear quartz and milky fibrous silica. The cavity shows obvious geopetal asymmetry, with miniature stalactites hanging down from the upper surface and only an irregularly bumpy lower surface. Specimen 74-Alb-23-y.

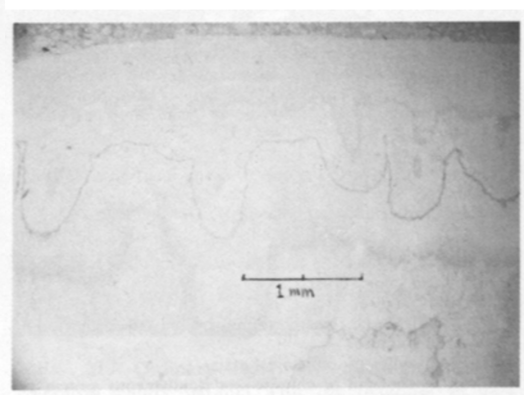


FIG. 27.—Ordinary light. Detail of stalactites on the cavity roof. Specimen 74-Alb-23-y.

FIG. 28.—Ordinary light. Stubby filaments of unknown origin that occur in some chalcedony-filled cavities. Specimen 74-Sog-4.

been vadose cavities. Because lutecite and quartzine can form in environments unrelated to evaporite deposits (e.g., Amaral, 1974; S. Mazzullo, 1978, oral communication), their presence at Alba Villa was probably controlled by partciular ions in the pore fluids (cf. Millot et al., 1963; Keene, 1975).

Origin of Fracture Fills (RLF)

Sheet-cracks formed penecontemporaneously with sedimentation, though some developed while the sediment was still soft and curdly, others occurred after it was brittle (probably like hardened cheese). Some of these cracks resemble the soft irregular curving cracks common in soils (Fig. 21; Freytet, 1971, 1973; McBride and Folk, 1977). The brittle straight sheet-cracks may perhaps have resulted from buttressed expansion of the sediment when it was more rigid (cf. Patton and Folk, 1978) caused by some mechanism such as recyrstallization of salts.

The larger cavities in the breccias at Alba Villa have every appearance of having formed in a vadose environment, with the chalcedony stalactites formed by water dribbling from the roof of air-filled cavities. The presence of length-slow and zebraic chalcedony and pseudo-cubic zoned quartz generally means a sulfate rich environment or alkaline paleosoil (Folk and Pittman, 1971; McBride and Folk, 1977, Folk and McBride, 1978a; Milliken, 1977). Chalcedony stalactites are known from a number of geodes (Robertson and Brooks, 1951, p. 175) and caves (Anderson, 1930; Swartzlow and Keller, 1937; Deal, 1964; and Broughton, 1972, 1974) and in at least one (Broughton, 1973) the chalcedony is length-slow as the result of having replaced gypsum. A. W. Walton (pers. comm., 1976) has found stubby opal stalactites 1 mm long underneath an outcrop of sandstone in Tennessee.

Other Ochre-chert Breccias.—In addition to the two breccia beds at Alba Villa mentioned previously, ochre-chert breccia beds were seen at only two other localities. The breccias developed entirely within single beds. Although each records multiple episodes of brecciation and healing, at least the earliest stage of deformation took place while part of the bed was soft.

The complexity of origin of these ochre-colored chert breccias is illustrated by the one at Santa Christina Gela, Sicily.

The breccia bed (Fig. 22) is exposed over a lateral distance of 5 m and varies between 5 to 8 cm thick. The main part of the bed is as the host for the brecciated internal part of the bed, which is ochre chert. The ochre chert has an irregular thickness, locally makes up nearly the entire bed, but elsewhere pinches out. Textural relations indicated the following sequence of events for this bed:

1. Differential lithification of a radiolarian-rich sediment;
2. Development of vertical polygonal fractures through the entire thickness of the bed (polygons from 10–30 cm) and plastic flow of part of the bed both within and up and down along the fractures;
3. Alteration of the unlithified sediment; development of curdles and short (maximum length 1 cm) curved shrinkage cracks;
4. Precipitation of chalcedony in shrinkage cracks;
5. Formation of short brittle fractures in the ochre bed; local development of crackle breccia;
6. Filling of fractures of previous event by chalcedony, chlorite, and megaquartz;
7. Development of tectonic fractures (now all quartz filled) through the entire bed.

Jasper-quartz Breccia.—Only one breccia of this type was found by us in Jurassic radio-

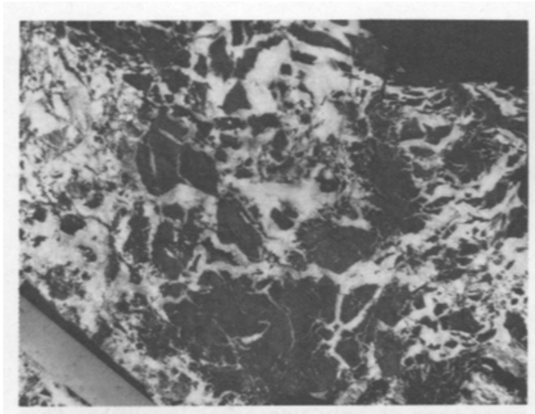


FIG. 29.—Spectacular jasper breccia composed of fractured red radiolarian chert in a white quartz cement. The breccia pieces that have moved only a short distance from the mother rock would fit back together, but the pieces separated the farthest from the mother rock have either rotated or changed shape and cannot be refitted. Scale divisions are in inches. Pontremoli, Tuscan basin.

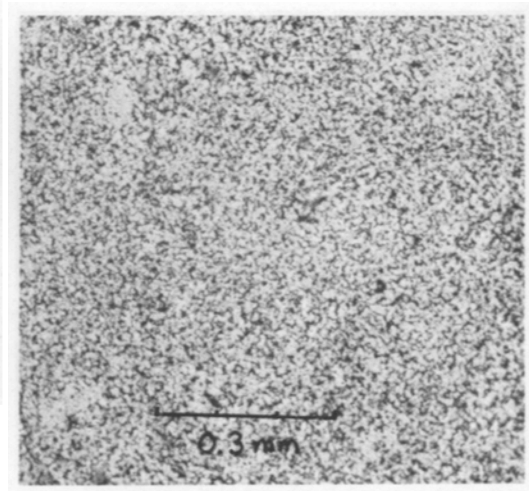


FIG. 30.—Ordinary light. Strange fabric of mother radiolarian chert in the pontremoli breccia. Tiny quartz crystals lie in a matrix of hematite. Compare with Figure 31. Specimen 74-Pont-brecc.

larites of continental crust association (Valgordana near Pontremoli). This breccia (Fig. 29) is a single bed of irregular thickness (average 4 m) which occurs near the top of a 20-m-thick sequence of radiolarite. The top has a very irregular lumpy surface on several scales, like a head of broccoli. The major lumps are 2–3 m in diameter, with relief of up to 1 m; minor lumps are 0.2–0.4 m in diameter. The host rock is jasper, color 10R 4/3 (moderate dark red-brown), that has an "exploded" or brecciated fabric with the spaces between angular fragments filled with white quartz (Fig. 29); about 50% by volume of the rock is fracture-fill. Shards of red chert appear to be surrounded by a white chalcedony crust uniformly 1 mm thick. In the top 0.5 meter of the bed, fractures occur in concentric shells.

The jasper contains Radiolaria in a matrix of microcrystalline quartz pigmented by 1 μm shapeless flecks of hematite. Some areas of the jasper consist of a curious fabric: loaf-shaped crystals of quartz 4–15 μm long, subelongate parallel to c axis, with <1 μm hematite flecks in the interstices (Fig. 30). Similar fabric occurs in silcretes developed on serpentine in New Caledonia (RLF, personal obs., slide #TK-352-RXPc), that contain identical 4–18 μm quartz crystals in hematite (Fig. 31). The radiolarite has a curdled structure and is riddled by common sheet-cracks. A younger generation of brittle fractures are also abundant, many of them parallel with the bedding; these must have formed prior to post-lithification tectonism, because they are often filled with geopetal accumulations of chert mud and pellets and some Radiolaria, and broken fragments of former chalcedony crusts. Fillings of the

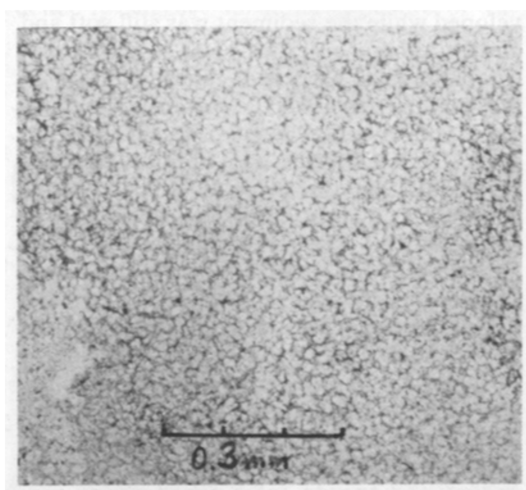


FIG. 31.—Ordinary light. Quaternary red silcrete (jasper) developed upon serpentine, New Caledonia. Tiny quartz crystals are surrounded by dark hematite. Specimen TK-352-RXPc.

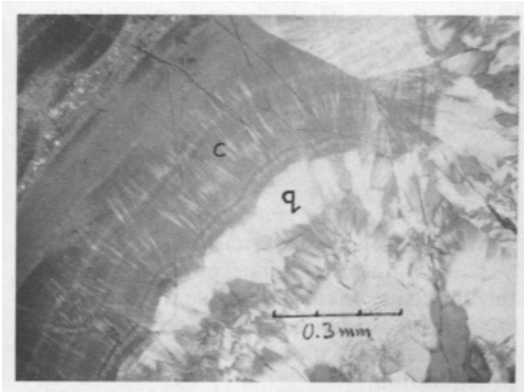


FIG. 32.—Crossed nicols, gypsum plate. Pontremoli breccia: cavity fill with length-slow quartzine (q) and length-fast chalcedony (c). Specimen 74-Pont-z.

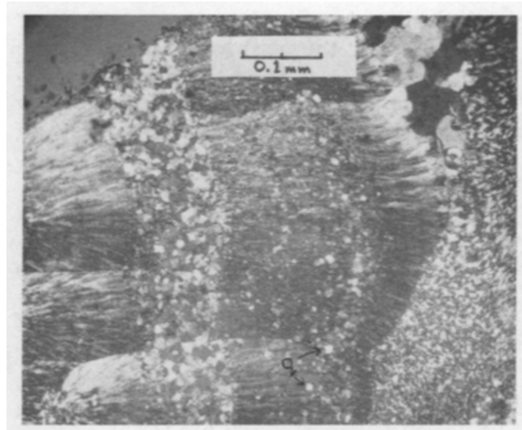


FIG. 34.—Crossed nicols, gypsum plate. Cavity fill of chalcedony with zones of tiny pseudocubic quartz crystals (square in the thin section, q). Specimen 74-Pont-brecc.

cavities include bands of chalcedony, quartzine (Fig. 32), lutecite (Fig. 33), zebraic chalcedony and abundant micro-zoned quartz (but this quartz is not obviously pseudo-cubic). A curious occurrence, hitherto unknown to us, is the presence within some chalcedony crusts of a zone with a thick scattering of very tiny squares (actually pseudo-cubes) of quartz 10–25 μm in diameter (Fig. 34). These "squares" have symmetrical extinction oriented with c-axes subparallel with that of the enclosing chalcedony.

Sample 74-Pont-y has an unusual bed of reverse-graded pisolites that show slight fitting of shapes (Fig. 35). The nuclei are angular pieces of red radiolarian chert ranging from 0.1 to 3 mm. Each nucleus is dispersed (floating in three dimensions) and surrounded by a rind of microcrystalline quartz constantly 0.5 mm thick, and the diameter of the

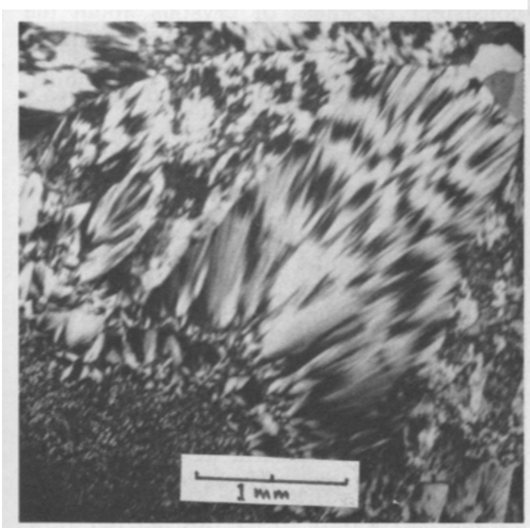


FIG. 33.—Crossed nicols. Zebraic chalcedony. Specimen ALB-M-1.

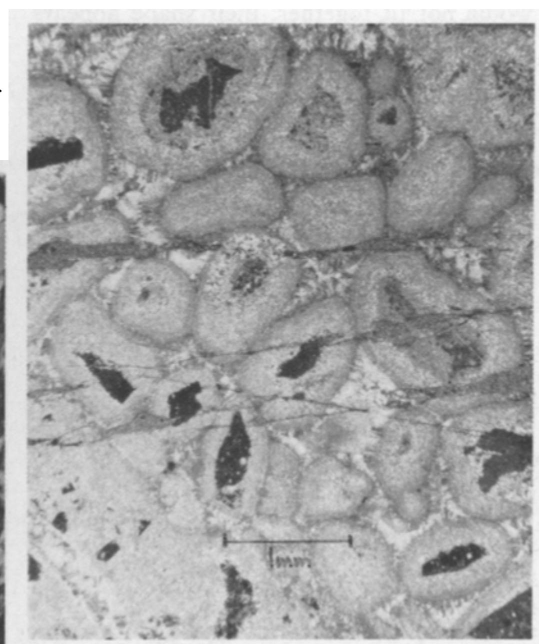


FIG. 35.—Ordinary light. Fitted pisolites developed about dark, angular pieces of red radiolarian chert. Specimen 74-Pont-z.

total pisolite thus produced ranges from 1 mm (bottom of the bed) to 7 mm at the top of the bed. It is as if each clast were surrounded by a coat of microquartz that grew in situ, displacing the clasts while they all remained touching. Thus, they grew somewhat in the manner of pisolites or cave pearls.

One of the Medici chapels in the church of San Lorenzo, Florence, contains ornamental slabs up to 1 × 3 m of the types of breccias described here. Although verification of the source of these breccias could not be obtained, they are identical in color and texture to the Pontremoli-type breccia. The large polished surfaces exposed in the chapel show that the density of brecciation is uneven; hand-sized areas of unbroken jasper occur amongst circular pockets of breccia with many curved cracks. Isolated cracks are surrounded in places by 30 cm of undeformed radiolarite, whereas thick zones of closely-spaced cracks are 1 m across. A common feature is that breccia fragments close to mother wall rock clearly would fit back together like pieces of a puzzle to form compact rock, whereas breccia fragments displaced a centimeter or more from the wall rock and now isolated in white quartz would not fit together; their shape appears modified.

Origin of Jasper Breccia.—(EFM) The confinement of these breccias to individual beds, the presence of internal sediment, and the fact that both the breccias and overlying and underlying beds are cut by the same tectonic fracture system indicates the breccias formed by unusual events during diagenesis and prior to late tectonic events. The geometry of single cracks and of curved multiple-arm cracks suggests the cracks developed by shrinkage. Additional support for shrinkage comes from the textures in the Medici chapel. Uneven shrinkage of breccia fragments can explain why the older fragments, those farthest from host rock walls, cannot be visually restored to a compact unit.

Uneven shrinkage of chert beds during lithification was unusual, as shown by the rarity of these breccias. Possibly an unusual consistency of protochert developed, and shrinkage occurred when opal Radiolaria converted to microquartz. The filled cavities in parts of the breccia seem too large to have been completely open; perhaps infilling took place concomitant with shrinkage. The idea that the breccias formed instead by expansion (see below) is attractive, but I find no compelling evidence of precursor minerals in the quartz-filled areas. Desiccation during subaerial exposure is rejected as a possibility because there is no evidence of an unconformity or of regression-transgression.

The complex sequence of cavity filling in the breccias, including those at Alba Villa, suggests that changes in the composition of pore fluids took place during the episode of precipitation.

Origin of Jasper Breccia. (RLF) In its features the jasper breccia at Pontremoli closely resembles the red jasper bed in the Devonian Caballos Novaculite of Texas (McBride and Folk, 1977, Folk and McBride, 1978a). Both units are essentially a breccia of red jasper with white quartz, have very uneven thickness patterns and lumpy upper bedding surfaces. Both show soil-like curdling and irregular sheet-cracking, and cavities filled with pseudocubic quartz, lutecite, quartzine and zebraic chalcedony. These indicate that the material probably formed in a hypersaline environment; the brecciation is most readily ascribed to initial slight shrinkage on desiccation (forming hairline cracks, often concentric). Subsequent expansion occurred by saline mineral growth within the fractures, to produce an exploded fabric, with the consistent thickness of crystals about the shards. This is what also produces the lumpy upper bedding surface. At some stage the evaporite minerals were replaced by silica.

MISCELLANEOUS DIAGENETIC FEATURES

Stylolites

Stylolites with amplitudes less than a millimeter are common minor features in many samples of limestone and chert; all are nearly parallel with bedding. Hematite or clay forms the insoluble residue along the seams. Most stylolites, including those in chert, probably formed by the dissolution of calcite. Dissolution of microquartz did take place locally, because some Radiolaria have sutured-dissolution contacts. However, "Occams razor" suggests that dissolution of calcite was the major event.

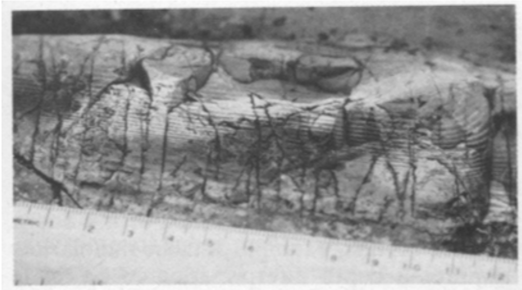


FIG. 36.—Chert bed of replacement origin showing color bands that have progressively increasing thickness. Although the laminae are primary, the spacing is probably the result of combined effects of compaction and dissolution-precipitation. Burligo, Lombardy pre-Alps; scale numbers are centimeters.

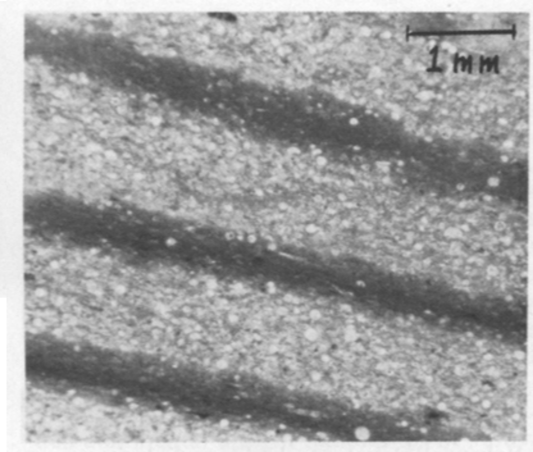


FIG. 37.—Cherty limestone containing rhythmic laminae of partly chertified radiolarian-rich micrite (light) and hematite-stained clay with few Radiolaria (dark). Rocks like this are probably the precursor of chert with pin-stripe bedding, although not all show the increased-spacing effect. Acquasparta, Umbrian basin.

Pin-Stripe Beds

Thin chert beds that diplay beautiful parallel light-dark color laminations (Fig. 36) are rare occurrences in many outcrops of lumpy nodular chert. The striking feature is that the spacing of either one or both laminae increases in thickness in a regular manner towards the tops, rarely bottoms, of the beds much in the fashion of Liesegang bands in a gel. Similar beds in the Caballos Novaculite were termed pin-stripe beds by Folk (1973, p. 718), who interpreted them as silicified evaporite and dolomite varves (see also Lowe, 1975). The Italian pin-stripe beds formed differently, by the replacement of laminated radiolarian-rich calcareous ooze. Thinner laminae poor in Radiolaria and containing cryptocrystalline microquartz alternate with thicker laminae rich in Radiolaria and composed of micrite (Fig. 37) that has been partly replaced by microquartz. Thus, much of the original content of these beds was probably calcite ooze. The geometric spacing of the laminae of differential permeability and thickness when silica, dissolved from Radiolaria, diffused upward and precipitated selectively in the more permeable layers. The resultant thickness of layers was controlled more by diffusion behavior and nucleation rate of silica than by original thickness.

It is not clear whether the Italian laminae were current-formed or are varves, but we believe their present thickness is the result of diagenetic processes instead of depositional processes.

Pseudowood Nodules

Several localities in the Lombardy region, notably Alba Villa, contain rare beds of chert up to 35 cm thick that display closely spaced concentric fractures that resemble the structure of petrified tree trunks in cross-sections. Remarkably uniform spacing of the bands exists for thicknesses of 10 cm. The concentric patterns are the elliptical cross-sections of spheroidal bodies from 10 to 25 cm in diameter, because, unlike wood, no long sections of bands are present.

The bands are fractures generally less than 2 mm wide that were filled generally by first a thin rind of medium-fibrous chalcedony, and lastly by megaquartz. The walls of the fractures are irregular, match across the opening, and pass around it but not through Radioalria. Fractures cut across bedding without deflection.

The curved fractures formed when thicker than normal chert beds underwent a stage of shrinkage at a time when they had a "cheesy" consistency. The nodules have features in common with some contraction spheroids from the Monterey Formation (Taliaferro, 1934), but we find no evidence of a gel precursor as suggested by Taliaferro for the nodules he examined. The diagenetic process during which the pseudo-wood nodules formed is not clear, but greater than normal bed thickness seems to have been important.

ENVIRONMENT OF DEPOSITION

Previous Work

The subject of the environment of deposition of the radiolarites is controversial. Because of the unique lithic and faunal character of radiolarites, lack of shallow water benthic fossils, and perhaps influenced by the early "abyssal" label attached to radiolarites associated with ophiolites by Steinmann (1905), many workers interpreted the radiolarites treated in this report as deep-water deposits also (e.g., Giannini and others, 1950; Merla, 1951; Trumpy, 1955, 1957; Pasquarè, 1965). However, specific water depths were not mentioned, and it is uncertain if all authors equated "deep" with abyssal (>4000 m). However, discussion of the depth problem with various European sedimentologists and stratigraphers and published reports (e.g., Fazzuoli and Maestrelli-Manetti, 1973) indicate that many of them favor the interpretation of deposition at bathyal depths (200–4000 m), and many favor the shallow end of the depth range. The position of radiolarite on continental crust and the presence of intercalated tongues of carbonate debris shed from adjacent shallower water platforms are the chief lines of evidence cited for shallow water.

Bosellini and Winterer (1975) and Hsü (1976) interpret depths from 2000–2500 m based on inferences of depth of dissolution surfaces, the sequential arrangement of facies and of basin geometry.

Present Interpretation-General Comment

The different radiolarites that we studied were undoubtedly deposited in a considerable range of water depths, and depth may have also varied considerably during deposition of individual formations. However, we present here some general conclusions and divergent opinions. The absence of a modern or Late Tertiary example of these radiolarites requires a depth interpretation to be made on inferences about the maximum and minimum depth range of deposits. Table 3 summarizes the depth values that we indidivudally assign to various criteria.

Present Interpretation—EFM

The presence of only a pelagic fauna, lack of unequivocal shallow-water textures and structures, and "basin-plain" aspect of many radiolarites suggests they were deposited in marine basins that were deeper than 500 m. That the basins had considerable local relief is indicated by abrupt lateral changes in thickness of radiolarites and adjacent formations. The presence of turbidites composed of displaced pelagic sediment in radiolarite formations indicates that the most common adjacent "highs" were also sites of pelagic deposition; therefore, the ultimate site of deposition was deeper than the first-cycle pelagic deposits.

The Jurassic paleogeographic interpretation proposed by Bernoulli and others (in press) for the northern and central Apennines provides a working model that explains the depth differences of the Ligurian, Tuscan, and Umbrian basins (Fig. 8, this report) which is consistent with interpretations (summarized in Table 3) that I favor. The Sicilian radiolarite basins and the Lombardy basin may be analogous to the Tuscan and Umbrian basins, or perhaps better compared with the

TABLE 3.—*Contrasting Interpretation of Evidence for Water Depth*

	EFM		RLF	
	Bedded Chert	Lumpy-nodular Chert	Bedded Chert	Lumpy-nodular Chert
Fossils	>150 m	>100 m	>10 m	peritidal
Bedding Style	>150 m		>10 m	evaporitic
Sedimentary Structures	>100 m		>10 m	to
Breccias	not definitive		>10 m	100 m or
Associated Strata	100–3000 m		>100 m	more deep
Calcite Compensation Depth (CCD)	~CCD	<CCD	inapplicable	inapplicable

basin-platform model of D'Argenio and Pialli (1974; Fig. 8, this report).

In the reconstruction of Bernoulli and others (in press), the Italian embryonic continental margin underwent block-faulting beginning in early Liassic with the development of a number of carbonate platforms and marginal troughs and plateaus. The troughs and plateaus subsequently subsided to depths where only pelagic sediment accumulated, part of which was radiolarite. Concomitantly, oceanic crust developed in the Ligurian basin; the radiolarites deposited on it are discussed elsewhere (Folk and McBride, 1978a). Bernoulli and others (in press) document in the Tuscan-Umbrian basins a west-to-east "transgression" of pelagic rocks, i.e., the oldest pelagic rocks in a sequence get younger eastward. With continued subsidence, maximum depth attained in the Tuscan basin was greater than maximum depth in the Umbrian basin. The abundant pelagic pelecypods in the Umbrian basin and scarcity of them in the Tuscan basin, and presence of abundant carbonate ooze (now limestone) in the Umbrian basin supports this idea if the calcite compensation depth (CCD) controlled the presence or absence of carbonate ooze. Although there is no independent proof of the existence of the CCD at this time, data are consistent with its existence and of its control of calcite deposition.

Problems concerning the existence of a CCD and other dissolution surfaces and its importance in controlling carbonate accumulation during Late Jurassic time was discussed elsewhere (Bosellini and Winterer, 1975; Hsü, 1976, Folk and McBride, 1978b). The spectrum of pelagic rocks of Late Jurassic-Early Cretaceous age, including nodular limestones with ammonites (*Ammonitico rosso*), even-bedded limestones that contain only the calcite opercula of dissolved aragonite phragmocones (*Rosso ad Aptici*), and chert is the best evidence that dissolution surfaces existed during the time in question. The arguments in favor of the Tethyan Mesozoic model proposed by Bosellini and Winterer (1975) are compelling (i.e., the aragonite and calcite lysoclines and compensation depths were present but much compressed compared with their present ranges; the CCD was approximately 2500 m deep).

If our interpretation that many of the chert beds in radiolarite are "resedimented" is correct, the most reliable clue to water depth based on dissolution surfaces lies in the carbonate content of indigenous shale beds instead of the composition of chert beds.

Thus, water depth in the Ligurian basin, which is devoid of calcite in radiolarite, was entirely below the CCD (probably greater than 2500 m); water depth in the Tuscan basin, which contains traces of calcite, was between the CLy and the CCD (probably 2000 to 2500 m); and water depth in the Umbrian basin was between the ACD and the CLy (probably 1500 to 2000 m). By extrapolation of these ideas, most well-bedded continental margin radiolarites of Jurassic age in Italy were deposited at approximately 2000 to 2500 m, whereas lumpy-bedded continental margin radiolarites were deposited in water depths between 1500 and 2000 m.

Most lumpy-bedded radiolarite formations contain several meters of even-bedded chert and shale that occur at random position in the section. This variation in bedding style in a vertical sequence probably reflects fluctuations in rate of calcite supply, depth changes of the basin floor, or variations in diagenesis. If these stratigraphic variations are controlled by fluctuating dissolution surfaces, it supports the contention of Bosellini and Winterer (1975, p. 281) that these surfaces were originally much closer to each other than at the present.

Present Interpretation—RLF

The thick radiolarian cherts that fill troughs in the Ligurian outcrops we studied (Folk and McBride, 1978a, 1978b) are devoid of complex sedimentary structures (domes, fracture fillings, breccias) or curious forms of silica; they are even-bedded, sometimes graded, and bedding surfaces are smooth. We both agree that they were deposited at least in part as turbidites below wave base, in basins probably 100 m or more deep.

The sedimentological monotony of these true "deeper-water" cherts contrasts notably with the wide variety of curious sedimentary structures, fabrics, fracturing, problematical filaments and unusual evaporite-related forms of silica common in the Lombardian outcrops. I take this to mean that the Lombardy radiolarites were deposited in environments that were in part shallow intertidal mudflats, with local precipitation and subsequent solution of evaporite minerals and even occasional subaerial exposure.

Among the features found exclusively among the Lombardian and Appenine cherts are the following. Soft-sediment sheet-cracks, analogous to structures in peritidal "birdseye" limestones or paleosoils, were caused by alternating wetting and drying. Lumpy bedding, and bedding surfaces dimpled with irregular depressions are probably the result of bioturbation but are not indicative of any particular depth. However, the hemispherical mounds were formed by localized growth of crystals (evaporites most likely) that expanded the sediment and formed "stretch-marks"; the evaporite crystals later dissolved. Synsedimentary breccias were produced by major crystallization of evaporite minerals, causing an expanded fabric by the force of crystal growth; later these evaporites were dissolved out or replaced and the resulting space was occupied by forms of silica usually indicating evaporitic conditions or alkaline paleosoils: lutecite, quartzine, zebraic chalcedony and zoned quartz. Internal sediment and pisolites also favor a shallow or exposed environment.

Some larger cavities were filled with gravitationally-oriented chalcedony ministalactites and contain filaments and evaporitic forms of silica such as pseudocubic-zoned quartz, quartzine, and zebraic chalcedony. The stalactites are a vadose feature and indicate that at least some of the radiolarites were subaerially exposed during Jurassic time.

No such features have yet been described from modern deep-sea sediments and until they are, the most reasonable course is to consider that they in fact did form in shallow water as all analogues do.

I think the concept of the CCD has no validity for Jurassic radiolarites. Even in the open ocean the CCD varies greatly with geologic time (see Folk and McBride, 1978b), being a function of relative productivity rates of siliceous versus calcareous plankton, organisms, amount of terrigenous influx, solution rate of calcareous organisms, which is in turn a function of temperature and depth of water. And the early Tethys seaway was in no sense analogous to a modern ocean; it was more similar to the Red Sea as it represented the beginning of the continental split between Africa and Europe. Furthermore, calcareous plankton had just begun to evolve at this time. Thus, it is fallacious to extrapolate the present open-oceanic CCD back 140 million years into the Jurassic and assume that it applies equally well to a narrow seaway surrounded by landmasses.

My analysis of the time during radiolarite deposition is as follows. As the Tethyan seaway widened, local tectonism exposed subaerial ridges of unstable ophiolite and other rocks. These weathered rapidly to produce a large amount of hematitic clay which muddied the surrounding narrow seaway. Aided by the large amount of silica liberated by tropical weathering, extensive radiolarian blooms occurred. A siliceous, hematitic, clayey radiolarian ooze accumulated at all depths from intertidal mudflats to depths of perhaps several hundred meters. The shallowest environments became the sites of evaporite crystallization, and these areas were locally subaerially exposed. Because of the lack of diatoms competing for silica, the Radiolaria occupied all the marine ecologic niches at depths from a few hundred meters up to the surface. There were small amounts of calcareous plankton, but they were overwhelmed by siliceous organisms and by terrigenous mud so that they were dissolved, probably after burial. The narrow tropical seaway had a fluctuating salinity and the high suspended load and soft mud bottom made it inhospitable to calcareous megafauna during Tithonian time. The environment was basically "polluted" by effluent from weathering ophiolite.

As the subaerially-exposed ophiolites disappeared by erosion or tectonic subsidence, the supply of hematitic clay and silica was cut off. The Tethys seaway widened and became less restricted and muddy. By the beginning of the Cretaceous enough calcareous plankton had evolved to be able to overwhelm the shallow oceanic waters, and deposition of typical pelagic chalks began in the Tethys. Thus, I adopt a "terrigenous-rate-of-supply" argument instead of a "depth-of-water" argument to explain the shift from Tithonian radiolarites to Cretaceous carbonate oozes.

ACKNOWLEDGMENTS

Invaluable help in this study was provided in Italy by the late Riccardo Assereto, Raimondo Catalano, Roberto Colacicchi, Gabriele Caranante, Bruno D'Argenio, Milvio Fazzuoli, Vittoria Ferreri, Maurizio Gaetani, Marco Leone, Piero Manetti, Patrizia Massano, and Gian Clemente Parea. Financial support was provided by the National Science Foundation (Grant GA-40862) and the Owen-Coates Fund and other funds of the Geology Foundation of the University of Texas at Austin. EFM also acknowledges the National Research Council (CNR) of Italy and the University Research Institute of The University of Texas at Austin.

REFERENCES

ALVAREZ, WALTER, 1977, Pelagic carbonates: Geotimes, v. 22, no. 4, p. 16–17.

AMARAL, E. L., 1974, Oxidation of pyrite: a key factor in the formation of authigenic feldspar and chert cement in the St. Peter Sandstone (Abs.): Geol. Soc. America Program with Abs., v. 6, p. 1018.

ANDERSON, C. A., 1930, Opal structures and stalagmites from a lava tube in northern California: Am. Jour. Sci., v. 20, p. 20–26.

ANDRI, E., AND FANUCCI, F., 1975, La risedimentazione dei calcari a calpionelle liguri: Boll. Soc. Geol. Italia, v. 94, p. 915–925.

ARTHUR, M. A., 1977, Sedimentology of Gubbio sequence and its bearing on paleomagnetism, *in* Giampaolo, Pialli, ed., Paleomagnetic stratigraphy of pelagic carbonate sediments: Mem. della Soc. Geol. Italia, v. 15, p. 9–20.

ASSERETO, R. L. A. M., AND KENDALL, C. G., 1977, Nature, origin and classification of peritidal tepee structures and related breccia: Sedimentology, v. 24, p. 183–210.

BERNOULLI, DANIEL, 1972, North Atlantic and Mediterranean Mesozoic Facies: a comparison, *in* Hollister, C. D., Ewing, J. I., et al., Initial Reports of the Deep Sea Drilling Project: Washington, v. 11, p. 801–871.

———, KÄLIN, OTTO, AND PATACCA, ETTA, in press, A sunken continental margin of the Mesozoic Tethys: the northern and central Apennines, *in* Symposium sur la Sedimentation Jurassique est European: Assoc. des Sedimentologists Francais, Paris.

BOSELLINI, ALFONSO, AND WINTERER, E. L., 1975, pelagic limestone and radiolarite of the Tethyan Mesozoic: A genetic model: Geology, v. 3, p. 279–282.

BROUGHTON, P. L., 1972, Silicification processes in solutional limestone caves in the Hartville Uplift Area of Wyoming (Abs.): Geol. Soc. America Program with Abs., p. 458.

———, 1973, Replacement of gypsum by length-slow chalcedony in the karst subsurface: Caves and Karst, v. 15, p. 21–23.

———, 1974, Silica Deposits in Eastern Wyoming Caves: Nat. Speleol. Soc. Bull., v. 36, no. 3, p. 9–11.

COCCHI, I., 1871, Descrizione geologica dell'Isole d'Elba: Mem. Descr. Carta Geol. d'Italia, v. 1, p. 141–302 (none-vide).

CONTI, SERGIO, 1958, Diaspri, ftaniti e radiolariti. Relazioni genetiche e rapporti di giacitura con le formazione ofiolitiche: Pubbl. Ist. Geol. Univ. di Genova, Quaderno no. 11, ser. B., p. 1–65.

D'ARGENIO, BRUNO, AND PIALLI, GIAMPAOLO, 1974, Tentativo di correlazione fra unità paleogeografiche mesozoiche dell'Appenninno meridionale e settentrionale: Atti dell'Academia Pontaniana, Nuova Serie, v. 23, p. 23–26.

DAVIS, E. F., 1918, The radiolarian cherts of the Franciscan Group: Univ. California. Pub. Geology, v. 11, no. 3, p. 235–432.

DEAL, D. E., 1964, Scintillites: A variety of quartz speleothems: Nat. Speleol. Soc. Bull., v. 26, p. 29–31.

FAZZUOLI, MILVIO, AND MAESTRAELLI-MANETTI, ORNELLA, 1973, I nuclei Mesozoici di Monsummano, Montecatini Terme e Marliana (Prov. di Pistoia): Mem. Soc. Geol. It., v. 12, p. 39–79.

FISCHER, A. G., 1964, The Lofer Cyclothems of the Alpine Triassic: Kansas Geol. Survey Bull., v. 169, p. 108–149.

———, 1977, Pelagic sediments as clues to earth behavior, *in* Giampaolo, Pialli, ed., Paleomagnetic stratigraphy of pelagic carbonate sediments: Mem. Soc. Geol. Italia, v. 15, p. 1–18.

FOLK, R. L., 1975, Jurassic radiolarian cherts of Liguria, Italy and the case for exposure of ophiolite ridges (Abs.): Geol. Soc. America Program with Abs., v. 7, no. 7, p. 1077.

———, AND MCBRIDE, E. F., 1976, Possible pedogenic origin of Ligurian ophicalcite: A Mesozoic calichified serpentine: Geology, v. 4, p. 327–332.

———, AND ———, 1977, Poisson bed thickness distribution and turbidite-pelagite thickness correlation, Jurassic Radiolarites, Liguria, Italy (Abs.): Amer. Assoc. Petroleum Geologists Bull., v. 61, p. 785.

———, AND ———, 1978a, Origin of the Caballos Novaculite: p. 101–130 *in* Mazzullo, S. J., ed., Tectonics and Paleozoic Facies of the Marathon Geosyncline, West Texas: Soc. Econ. Paleontologists Mineralogists, Permian Basin Sect., 1978 Field Conf. Guidebook, Pub. No. 78-17, 271 p.

———, AND ———, 1978b, Radiolarites and their relation to subjacent "oceanic crust" in Liguria, Italy: Jour. Sed. Petrology, v. 48, p. 1069–1102.

———, AND PITTMAN, J. S., 1971, Length-slow chalcedony: a new testament for vanished evaporites: Jour. Sed. Petrology, v. 41, p. 1045–1058.

FREYTET, PIERRE, 1971, Palèosols rèsiduels et palèosols alluviaux hydromorphees dans le Crètacè supèrieur du Languedoc: Rev. Geogr. Phys. et Geol. Dyn., v. 13, p. 245–268.

———, 1973, Petrography and paleo-environment of continental carbonate deposits with particular reference to the Upper Cretaceous and Lower Eocene of Languedoc (Southern France): Sed. Geology, v. 10, p. 25–60.

GAETANI, MAURIZIO, 1975, Jurassic stratigraphy of the southern Alps, *in* Squyres, Coy, ed., Geology of Italy: Earth Sci. Soc. Libyan Arab Republic, Tripoli, p. 377–402.

GARRISON, R. E., 1974, Radiolarian cherts, pelagic limestones, and igneous rocks in eugeosynclinal assemblages, *in* Hsü, K. J., and Jenkyns, H. C., eds., Pelagic Sediments on Land and Under the Sea: Int. Assoc. Sedimentologists, Spec. Pub., no. 1, p. 367-399.

———, AND FISCHER, A. G., 1969, Deep-water limestones of the Alpine Jurassic: *in* Friedman, G. M., ed., Depositional environments in carbonate rocks: Soc. Econ. Paleontologists Mineralogists Spec. Pub. No. 14, p. 20–54.

GIANNINI, E., PIERUCCINI, R., AND TREVISAN, L., 1950, Calcari con liste di selce e diaspri. Ipotesi geologiche e geochimiche sulla loro origine: Mem. Soc. Toscana Sci. Nat., Sr. A., v. 57, no. 9, p. 49–71.

GRUNAU, H. R., 1965, Radiolarian cherts and associated rocks in space and time: Ecl. Geol. Helv., v. 58, p. 157-208.

HEIN, J. R., SCHOLL, D. W., BYRON, J. A., JONES, M. G., AND MILLER, JACQUELYN, 1978, Diagenesis of late Cenozoic diatomaceous deposits and formation of the bottom simulating reflector in the southern Bering Sea: Sedimentology, v. 25, p. 155-182.

HSÜ, K. J., 1976, Paleoceanography of the Mesozoic Alpine Tethys: Geol. Soc. America Spec. Paper No. 170, 44 p.

HURD, D. C., 1973, Interaction of biogenic opal, sediment and sea water in the central equatorial Pacific: Geochim. et Cosmochim. Acta, v. 37, p. 2257–2282.

KEENE, J. B., 1975, Cherts and porcellanites from the North Pacific, DSDP Leg 32, *in* Larson, R. L., and Moberly, R., et al., 1975, Washington, Initial reports of the Deep Sea Drilling Project, v. 32, p. 429-508.

LEONE, MARCO, ALAIMO, ROSARIO, AND CALDERONE, SALVATORE, 1975, Genesis of chlorite pellets from Mesozoic bedded cherts of Siciliy: Jour. Sed. Petrology, v. 45, p. 618–628.

LOWE, D. R., 1975, Regional controls on silica sedimentation in the Ouachita System: Geol. Soc. America Bull., v. 86, p. 1123-1127.

MCBRIDE, E. F., 1975, Origin and features of Jurassic radiolarites, Italian Alps (Abs): Geol. Soc. America Program with Abs., v. 7, no. 7, p. 1193-1194.

———, AND FOLK, R. L., 1977, The Caballos Novaculite revisited: Part II; Chert and Shale Members and synthesis: Jour. Sed. Petrology, v. 47, p. 1261–1286.

MERLA, GIOVANNI, 1951, Geologia dell'Appennine Settentrionale: Bull. Soc. Geol. Italia, v. 70, no. 1, p. 95–382.

MILLIKEN, K. L., 1977, Silicified evaporite nodules from the Mississippian rocks of southern Kentucky, and northern Tennessee [Unpub. Masters Thesis]: Austin, Univ. Texas, 121 pp.

MILLOT, GEORGE, LUCAS, JACQUES, AND WEY, RAYMOND, 1963, Research on evolution of clay minerals and argillaceous and siliceous neoformation, *in* Clays and Clay Minerals, Proc. 10th Nat. Conf., p. 399-412.

NISBET, E. G., AND PRICE, I., 1974, Siliceous turbidites: bedded cherts as redeposited ocean-ridge derived seiments, *in* Hsü, K. J., and Jenkyns, H. C., eds., Pelagic sediments on Land and Under the Sea: Int. Assoc. Sedimentologists Spec. Pub. no. 1, p. 351-366.

PAREA, G. C., 1970, Ricerche sulla genesi delle rocce silice non detritiche: Mem. Soc. Geol. Italia, v. 9, p. 665–707.

PARONA, C. F., 1890, Radiolari nei noduli selciosi del calcare giurese di Cittiglio presso Laveno: Boll. Soc. Geol. Italia, v. 9, p. 132-175.

PASQUARÈ, G., 1965, Il Giurassico superiore nelle Prealpi Lombarde: Riv. Italian Paleont. e Stratigraf., Mem. 11, 238 pp.

PASSERINI, PIETRO, 1965, Il Monte Cetona (provincia di Siena): Boll. Soc. Geol. Italia, v. 83, no. 4, p. 219-338.

PATTON, E. B., AND FOLK, R. L., 1978, Buttressed expansion of granite and the development of grus (Abs.): Geol. Soc. America Program with Abs., NE Section, Boston, p. 79.

ROBERTSON, P., AND BROOKS, M., 1951, Geodes of Warsaw Formation: The Mineralogist, v. 19, p. 186–190.

SCHLAGER, WOLFGANG, 1974, Preservation of cephalopod skeletons and carbonate dissolution on ancient Tethyan sea floors, *in* Hsü, K. J., and Jenkyns, H. C., eds., Pelagic Sediments on Land and Under the Sea: Int. Assoc. Sedimentologists Spec. Pub. No. 1, p. 49–70.

STEINMANN, G., 1905, Geologische Beobachtungen in den Alpen. II. Die Schardtsche Überfaltings theorie und die geologische Bedeutung der Tiefseeabsätze und der ophiolithischen Massengesteine: Ber. Natürf. Ges. Frieburg, v. 16, p. 18–67.

SWARTZLOW, C. R., AND KELLER, W. D., 1937, Coralloidal opal: Jour. Geology, v. 45, p. 101-108.

TABER, STEPHEN, 1930, The mechanics of frost heaving: Jour. Geology, v. 38, p. 303-317.

TALIAFERRO, N. L., 1934, Contraction phenomena in cherts: Geol. Soc. America Bull., v. 45, p. 189-232.

TRÜMPY, R., 1957, Quelques problems de palèogéographie alpine: Bull. Soc. Géol. France, 6th Ser., v. 7, p. 443-461.

———, 1955, Wechselbeziehungen zwischen Paleogeographie und Decken-bau: Vierteljahrsschr. Naturf. Gesell. Zurich, v. 100, p. 217-231 (non-vide).