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Radiolarian Cherts and Associated Rocks in Space and Time

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with 6 figures in the text and 1 plate (I)

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ABSTRACT

Radiolarian cherts and associated rocks occur throughout the geological column from Cambrian to Eocene-Lower Oligocene. Major periods of chert deposition were the Ordovician, Silurian, Devonian, Upper Jurassic and Upper Cretaceous.

Radiolarian cherts and associated sediments such as pelagic limestones, siliceous shales, graded lime-grainstones, sandstones, greywackes and coarse clastics, which occasionally show graded bedding, were deposited in the eugeosynclinal part of major geosynclines. In accordance with KÜNDIG's views, the eugeosynclinal sedimentary fill can be subdivided into perennial cherts, pelagic limestones, siliceous shales, and catastrophic olistostrome-turbidite rocks.

In the Tethys geosyncline, two main periods of chert deposition are known: Upper Jurassic in the Mediterranean area, and Upper Cretaceous in the Near, Middle and Far East. Cherts were also formed during the Palaeozoic in the Caledonian trough, the Ural geosyncline, the Tasman geosyncline, and a few minor basins, and during late Palaeozoic, Mesozoic and mainly late Mesozoic in the Circumpacific belt.

Ophiolites, intermediate igneous rocks, tuffs and tuffaceous breccias are usually found together with radiolarian cherts and related sediments. In a few cases it can be proved that the emplacement of ophiolites is more or less syntemporaneous with chert deposition, and that a petrogenetical connection must exist. In other cases, however, a direct ophiolite-chert relationship is not obvious. Cherts not associated with ophiolites are rather the exception to a general rule.

The present world-wide review corroborates STEINMANN's original concept that cherts were deposited in deep-sea basins, characterized by strong tectonic mobility, which facilitated intrusion and extrusion of basic and ultra-basic magma. Excess silica and hematite supply and carbon dioxide exhalations in connection with ophiolitic magmatism are an additional characteristic of syntemporaneous ophiolite-chert assemblages.

The main periods of chert genesis, i.e. Ordovician, Silurian and Devonian, Upper Jurassic and Upper Cretaceous, were characterized by a tropical to sub-tropical, moist climate. The theory is advanced that there is probably a close relationship between tropical palaeoclimate, abundant growth of radiolarians in surface water and the predominant red colour of cherts.

Chert-ophiolite belts have a structural style of their own, which is mainly due to vertical tectonics and gravity sliding during the basinal and the orogenic phase.

A new nomenclatural system is proposed to designate ophiolite-chert associations.

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PREFACE

At the suggestion of Professor Dr. J. CADISCH, from 1943 to 1946 I chose to investigate the geology of the area of Arosa (Grisons, Switzerland) as a subject for my thesis. As a result of Professor CADISCH's inspiring guidance I directed most of my field and laboratory work towards a comprehensive study of the radiolarian chert-ophiolite problem not only in the Arosa area, but in other parts of the Swiss Alps as well. From 1953–1956 I made a further effort to gain a better understanding of the chert problem in the Central Alps, and once again Professor CADISCH gave me his valuable advice and rendered me every help possible to facilitate materially my investigations. – When I was requested to contribute an article to an Eclogae volume in honour of Professor CADISCH's 70th birthday, I accepted gladly and decided immediately to prepare an article on the regional aspects of the radiolarian chert problem. Although I am aware that I have no original contribution to offer, I thought it would be useful to compile data from literature on the world-wide occurrence of radiolarian cherts and associated rocks, and discuss the implications of such a comprehensive review. Field excursions in ophiolite-radiolarite areas of California, Turkey, Iran, Oman and Portuguese Timor have enabled me to add a few personal observations and remarks.

I owe a great debt of gratitude to Professor CADISCH, who first stimulated my interest in the chert problem. I also wish to express my sincere thanks to the BATAAFSE INTERNATIONALE PETROLEUM MAATSCHAPPIJ N.V., The Hague, for permission to publish the present article, to my colleagues who have contributed to the present study by supplying published reference and personal experience, and to Mr. E. G. EVERETT for critically reviewing the manuscript.

1. Introduction

The frequent association of radiolarian cherts, red shales, pelagic limestones and clastics on the one hand with peridotites, serpentinites, gabbros, diabases, spilitic pillow lavas and their metamorphic equivalents on the other hand, has been recognised and described in literature for more than 80 years: PANTANELLI (1880) and LOTTI (1886) probably gave the first explanation of chert-ophiolite relationships. MOLENGRAAFF (1900) incorporated under the name of Danau Formation a variety of rocks ranging from diabase-tuff, diabase, and diabase-porphyrite to quartzite, chert, clay-slate, and sandstone, which he saw for the first time typically developed in the area of the great lakes in Central Borneo. DAVIS (1918) in his classical work on the radiolarian cherts of the Franciscan Group in California devoted a full chapter to the occurrenc of radiolarian cherts and related rocks in many parts of the world. STEINMANN (1905, 1927) emphasised the frequent association of ophiolites with cherts from the Mediterranean mountain chains. Many more contributions of a general nature were made by a great number of authors, among which should be mentioned TALIAFERRO (1933), BRAMLETTE (1946), ROUTHIER (1946), GRUNAU (1947), WENK (1949), CORNELIUS (1951), CADISCH (1953), KÜNDIG (1956), CONTI (1958), GANSSER (1959), IRELAND (1959), KÜNDIG (1959), GRUNAU (1959), and TRÜMPY (1960). Strangely enough, no effort has ever been made before to put the observations from many parts of the world together in order to arrive at a broad view of the complex aspects of the chert problem. The present article, therefore, aims at compiling some of the known facts, especially on age, lithology, palaeontology, and thickness of radiolarian cherts and associated sediments, and age of the ophiolites, on a world-wide scale. No claim, however, is made to complete coverage.

A world-wide review and its graphic presentation is considered a prerequisite to clarify some typical environmental and genetic relationships of the radiolarian chert association. In the main the following specific problems will be considered: Basin configuration and bathymetry – Pre-orogenic basin history – Time relationship between cherts, associated sediments and ophiolites based on palaeontological and other critical evidence – Post-orogenic tectonic position and structural style – The role of coarse clastics and turbidites – Origin of silica and ferric iron, also in relation to climatic belts – Origin of ferrous iron in relation to ophiolites – Chert-limestone sedimentation and possible ophiolitic influence – Chert stratification – Red and green colour.

The literature on cherts is of an uneven quality. It is not too often that a factual account is found on lithology, thickness, palaeontology and field relationship of radiolarian cherts and associated rocks. This may, of course, be due to one of a number of reasons. Many chert occurrences are found in virgin forests (as for example in Borneo, Celebes, Ceram, Timor, Guatemala, Colombia), where only scanty observations are possible. In addition, some of these areas have only been visited by petroleum geologists, whose attention was directed towards oil-geological problems and not to radiolarian rocks. Other well-exposed areas such as southern Iran and Oman are not easily accessible to earth scientists not concerned with petroleum operations and have, therefore, only been looked at superficially. The Mediterranean regions, the Alps and the Coast range of California, however, are the areas which have been studied in some detail. In this connection the very valuable work done by BLUMENTHAL (1963) and NEBERT (1959) in Turkey, and DUBERTRET (1953) in south-eastern Turkey and Syria should also be mentioned.

The interpretation of field observations in areas where radiolarian cherts and associated rocks are exposed, is by no means easy. The geological history of eugeosynclinal basins in which ophiolitic intrusions and extrusions frequently occur, is very complex (KÜNDIG, 1956, 1959). In addition, the rock content of these basins was subjected to a considerable amount of vertical uplift and tectonisation during major orogenic phases, which has made original complex relationships even more enigmatic due to incompetent folding, overthrust and gravity sliding phenomena. The factual statements, gaps in knowledge, theories and speculations offered in this article have to be regarded in this context.

2. Radiolarian Cherts and Associated Rocks in Space and Time, a World-Wide Review

The following is a brief and mainly factual account on world-wide occurrences of radiolarian cherts and associated rocks and their stratigraphic position. The principal facts are summarized in Plate I, and the text is restricted to a few supplementary remarks. Eugeosynclinal sediments are discussed, and only occasional mention is made of radiolarian rocks of other origin.

Radiolarian cherts and associated sediments were deposited mainly in Paleozoic and Mesozoic leptogeosynclines (TRÜMPY, 1955), or the eugeosynclinal parts of orthogeosynclines (STILLE, 1940a). Whereas the Northwest European Caledonian trough is only of minor importance for the deposition of cherts, the eugeosynclinal parts of the Tethys geosyncline can be regarded as the major sedimentary basin for chert genesis. The classical chert-ophiolite occurrences in the Mediterranean area, including the Alps and the Carpathians, are well known. The chert-ophiolite associations in the eastern part of the Tethys between the Middle East countries and the Malayan archipelago have not yet been studied in great detail, so that knowledge of them is rather scanty, although major contributions toward their understanding could be made in well exposed desert countries such as Iran and Oman. Radiolarian cherts and green rocks are found in great variety and different ages in the Circumpacific Belt, especially in Japan, and the Coast Range of California, the Ural geosyncline, and the Tasman geosyncline of Eastern Australia.

A review by countries is thought to be more desirable for ease of reference than a description of the major eugeosynclinal basins.

GREAT BRITAIN

In the northern Highlands (Scotland) chert layers are found in the Upper Cambrian to Lower Ordovician Durness Limestone (PHEMISTER, 1960, p. 50). The Durness Limestone represents very fine calcareous mud which accumulated so slowly that the fossils were partially dissolved before being covered up. The layers and nodules of chert are probably due to redeposition of silica derived from solution of siliceous organisms. Sponge Spicules have been observed in some of the cherts.

In the Southern Uplands (southern part of Scotland) the Lower Ordovician (Arenig) is composed of black shales and variously coloured cherts interbedded with coarse agglomerates associated with beds of tuff; in the lower part there are flows of spilitic lavas poured out of submarine volcanoes. Near Ballantrae (PRINGLE, 1948, p. 10) the following general succession can be observed:

	Feet
Red, green and grey radiolarian cherts interstratified with tuffs and volcanic breccias	70
Coarse agglomerates and tuff containing a thin band of black shale with graptolites	720
Spilitic lavas associated with breccias and tuff; near the top are thin seams of black shales with fossils	700

The age of the lavas and pyroclastic materials has been determined by the occurrence of graptolites in the interbedded mudstones and shales, and the sediments occupy a position within the zone of *Didymograptus extensus*. Many of the lava flows exhibit the pillow structure characteristic of spilites. A detailed account of the pillow-lavas and rocks associated with them is found in the classical paper of DEWEY & FLETT (1911).

The Lower Ordovician cherts and spilitic lavas can be interpreted as a typical eugeosynclinal association of the Caledonian trough.

Radiolarian cherts together with mudstones and black shales are also found in the Caradoc (PRINGLE, 1948, p. 16) in the Girvan area (Southern Uplands).

Fig. 1. Geographic distribution of radiolarian cherts and associated rocks.

Occurrences shown in Plate I

1a, 1b	Great Britain	12, 13	Germany	22	Oman	31	Australia
2	Morocco	14, 15	Yugoslavia	23	India-Tibet	32	California
3	France	16	Poland	24, 25	Borneo	33	Nevada
4	Corsica	17	Greece	26	Celebes	34	State of New York
5, 6, 7	Switzerland	18	Cyprus	27	Ceram	35	Guatemala
8, 9	Italy	19	Turkey	28	Timor	36	Colombia
10	Elba	20	Syria	29	Japan	37	U.S.S.R.
11	Austria	21	Iran	30	Philippines		

Occurrences mentioned in the text

A	Norway	F	Sumatra
B	Spain	G	Malay Peninsula
C	Hungary	H	New Guinea
D	Burma	I	New Zealand
E	Andamans-Nicobars		

(No claim is made to complete coverage.)

In the Lower Carboniferous Millstone Grit of North Wales (Smith & George, 1961, p. 63) some of the shale bands of the Holywell Shales are highly siliceous and pass into pure cherts. Most of the goniatite zones of the Millstone Grit are present. The environment of the Millstone Grit as a whole was estuarine with marine intercalations.

NORWAY

In the Norwegian part of the Caledonian geosyncline Middle Ordovician cherts occur in the Trondheim area (Holtedahl, 1960, p. 156–157). They are found as intercalations of basaltic greenstones, which often show pillow structures indicating submarine eruption.

MOROCCO

Upper Jurassic radiolarian cherts occur in the imbrication zone of Jebel Musa west of Ceuta, which is superimposed by the Flysch nappe of Beni-Ider in the northern Rif (Durand Delga et. al., 1962, Durand Delga & Villiaumey, 1964). The red and green cherts are underlain by purple silex-bearing limestones, which contain perisphinctidae of Dogger to Lower Malm age, and overlain by whitish marly limestones with silex. At the base of these marly limestones a tintinnid-fauna was found, which is composed of *Calpionella alpina*, *Calpionella elliptica*, and *Tintinnopsella carpathica*, associated with *Stomiosphaera minutissima* and *Cadosina fusca*. The authors ascribe a Berriasian age to this association. As no further details are given in the paper by Durand Delga & Villiaumey (1964) on tintinnid distribution, it is an open question whether and to what extent Upper Tithonian is represented in the marly limestones.

The cherts of the Rif show a typical Mediterranean facies and can easily be compared with similar deposits in Spain, Italy, Yugoslavia, and Greece.

FRANCE

Radiolarian cherts, marbles and ophiolites are found in the «schistes lustrés» zone of the French Alps (Barbier, Bloch, et al., 1963, Lemoine, 1955, 1961) and in the so-called Gondran series situated between the «zone briançonnaise» and the «schistes lustrés» zone (Lemoine, 1953). The cherts and marbles are believed to range from Upper Jurassic into Neocomian. Pillow-lavas frequently occur in the ophiolitic suite, which consists of serpentinites, gabbros, and prasinites.

SPAIN

Radiolarites are found in the Camarote unit in the Penibeticum north-east of Algeciras, in southern Spain (Didon, 1962). No reference is made to their age, but apparently they are Upper Jurassic like those of the Rif, as they are overlain by Berriasian limestones as well as breccias with *Trocholina*, and underlain by marls and limestones of Lias age.

Liassic cherts associated with nodulous, red, silex-bearing limestones, marls and limestone breccias are mentioned from the Liassic zone of Tajarillo de Gaucin in southern Spain (Dürr et al., 1962, Blumenthal, 1931, 1931–1933). The age is given as Hettangian-Sinemurian based on ammonites.

CORSICA

Radiolarian cherts are found in north-eastern Corsica, namely in the Balagne nappe (BODENHAUSEN & SPIJER, 1962, TERMIER & MAURY, 1928) and in the «schistes lustrés» zone (BROUWER, 1963; NETELBEEK, 1951). From the Balagne nappe BODENHAUSEN & SPIJER (1962) describe a thick mass of spilitic pillow-lava, which is locally overlain by fine-grained limestones with *Calpionella*, sponge spicules and radiolaria, or by a rhythmic alternation of graded limestones with radiolarian-spongolithic cherts and siliceous shales. The graded limestones are interpreted as a turbidity current deposit. The Upper Jurassic-Lower Cretaceous age of the limestone-chert association is asserted by the occurrence of *Calpionella alpina* in the pelagic limestones, a conclusion reached already by most previous authors. According to BROUWER (1963) the extrusion of the basic igneous is thought to have taken place between Middle Jurassic and Tithonian.

NETELBEEK (1951) emphasises the close association of red and green radiolarian cherts with spilites in the «schistes lustrés» zone, to which he attributes a genetic relationship. Magmatic eruptions and exhalations supplied silica and carbon dioxide to the sea-water, which favoured the formation of siliceous rocks and at the same time prevented precipitation of calcium carbonate. Chert genesis is believed to be merely dependent on syntemporaneous spilitic extrusions and not on bathymetric conditions. Consequently, a time correlation of chert beds in different areas is rejected. Gabbros and serpentinites also occur in the «schistes lustrés» unit. The age of the ophiolites cannot be assessed. The are syntemporaneous with the cherts, which cannot be dated.

SWITZERLAND

The radiolarian cherts and associated rocks of Switzerland are known in great detail. Apart from accurate descriptions of local occurrences (RENZ, 1920; SENN, 1924; CORNELIUS, 1935; JEANNET, 1938–40; CADISCH, 1940; SCHWARTZ CHENEVART, 1945; GRUNAU, 1947b; GEIGER, 1948; STAUB, 1948; RENZ, 1949; GEES, 1955; BERNOULLI, 1960, and others) regional views and a discussion of the chert-ophiolite problem are offered by WENK (1949), CADISCH (1953), GRUNAU (1947a, 1947b, 1959), and TRÜMPY (1960).

Radiolarian cherts and associated rocks are found in the higher penninic, austroalpine and southern alpine structural units of the Central Alps. Geographically they are located in the Simmen-nappe south-west of the lake of Thun, in the «Klippen» area east of Schwyz, in the higher penninic and austroalpine nappes of south-eastern Switzerland (especially in the Arosa and St. Moritz area), and in the southern alpine, dinaric realm south of Lugano.

The radiolarian cherts of the Central Alps are mainly Upper Jurassic and upper Middle Jurassic. The upper age limit is Lower Tithonian or even basal Upper Tithonian, as the cherts are overlain by pelagic, tintinnid-bearing limestones containing the Upper Tithonian-Berriasian association *Calpionella alpina, Calpionella elliptica* and *Tintinnopsella carpathica* together with *Stomiosphaera moluccana* WANNER and *Cadosina fusca* WANNER (see DOBEN, 1962). The lower age limit cannot be properly defined. In the Simmen-nappe, ammonoids indicating Aalenian and Bajocian age were found in limestones and shales underlying the cherts. In the southern alpine sector Aalenian ammonoids and Bajocian pelecypods (*Posidonomya alpina* GRAS) occur in red limestones and marls (Ammonitico rosso). No Middle Jurassic fossil evidence can be given from south-eastern Switzerland. From the foregoing it follows that the lower age limit of the cherts is Bathonian, at least in some areas. It seems probable, however, that the basal part of the cherts does not strictly represent a sharp time line all over the Central Alps.

A difference in lithology can be recognised between higher penninic-austroalpine cherts on the one hand and southern alpine radiolarites on the other. Austroalpine cherts are in most cases carbonate-free, and southern alpine cherts are usually interbedded with marly and calcareous layers.

Ophiolites are restricted to the penninic realm. Austroalpine and southern alpine units are ophiolite-free. However, mention should be made of the controversy over the structural position of the zone of Arosa, where an almost classical association of cherts, serpentinites and spilites occurs. TRÜMPY (1960) correlates the zone of Arosa with the higher penninic Platta-nappe, whereas CADISCH (1953) and others claim a lower austroalpine position. The age of the penninic ophiolites is thought to be late Jurassic-Cretaceous. In the zone of Arosa a few arguments could be advanced by GRUNAU and HÜGI (1957) in favour of a late Jurassic intrusion of peridotites and serpentinites and an Upper Cretaceous extrusion of a spilitic pillow-lava.

In order to reconstruct the Middle and Upper Jurassic palaeogeography of the higher penninic, austroalpine and southern alpine units, it is necessary to unravel an area of complex nappes. As already pointed out above, such an undertaking is controversial and serious errors can be made in assigning each tectonic unit its proper position in the orthogeosyncline. TRÜMPY (1960) recently offered a most valuable contribution of a palinspastic reconstruction, especially of the western part of the Swiss Alps. For the south-eastern part following TRÜMPY's (1960) suggestions, it is possible to arrive at the following unravelled Upper Jurassic-Berriasian palaeogeographic units in a NNW–SSE direction:

1. Penninic Falknis unit (ALLEMANN, 1957)
   Upper Tithonian-Berriasian: Tintinnid limestones (eugeosyncline)
   Lower Tithonian: Falknis breccia showing a distinct graded bedding (slope)
   Sequanian-Kimeridgian: Comparatively shallow carbonates (platform)
2. Penninic Sulzfluh unit (CADISCH, 1953)
   Lower Tithonian: Oolitic limestone (platform)
3. Higher Penninic Arosa unit (TRÜMPY, 1960)
   (Upper Cretaceous: Extrusion of spilitic pillow-lava)
   Upper Tithonian-Berriasian: Tintinnid limestones (eugeosyncline)
   Upper Jurassic up to Lower Tithonian: Radiolarian cherts and serpentinites-peridotites (eugeosyncline)
4. Austroalpine units
   Upper Jurassic: Radiolarian cherts, partly with intercalations of breccias. No ophiolites (eugeosyncline)
   (In the upper austroalpine realm of the Piz Lischanna area near Schuls, Lower Engadin, an Upper Kimeridgian limestone is found which contains a fauna of

ammonoids and aptychi. This so-called «*Acanthicus*-limestone» cannot be interpreted as being of shallow water origin.)

5. Southern alpine unit
   Upper Tithonian-Berriasian: Tintinnid-Nannoconus limestones (Biancone) (eugeosyncline)
   Bathonian-Lower Tithonian: Radiolarian cherts. No ophiolites (eugeosyncline)

Assuming that the above order is more or less correct, it becomes evident that in the Upper Jurassic the Falknis-Sulzfluh units (in the sense of CADISCH, 1953) represent an unstable platform-edge and partly already a continental slope. Pelagic sedimentation reigned at least in the Falknis area during Upper Tithonian-Berriasian. True eugeosynclinal conditions prevailed in the higher penninic, austro-alpine and southern alpine realm during the Upper Middle and Upper Jurassic including early Cretaceous. This of course does not mean that the bottom of the eugeosyncline could not have been differentiated into submarine swells and basins.

In conformity with KÜNDIG's (1956, 1959) views it is not surprising that a major ophiolite zone occurs in the Arosa area between the Falknis-Sulzfluh shelf and slope and the Arosa trough, or that a most enigmatic ophiolite-sediment mixture is found there. Earlier authors always explained the complexity of the zone of Arosa by tectonic arguments. The author, who mapped part of the area (1947b) as a student, was never satisfied with a mere tectonic explanation, but could not at that time offer a better solution to the problem. In the light of present knowledge, the temptation is to compare Upper Jurassic sedimentary conditions within the zone of Arosa with those of the «coloured melange» in Turkey, Iran, and Oman. The chaotic aspect of the area is due to its palaeogeographic position in the slope-trough transition zone, where sliding, turbidity phenomena, and ophiolite activity produced a gigantic breccia of rocks of different ages. Thrusting and gravity gliding during the Tertiary paroxysms contributed to even more complexity.

ITALY

The Upper Jurassic radiolarian cherts of Italy occur in the southern, dinaric zone of the Alps and in the northern part of the Appenines, especially in the area between Genoa and Florence, where they are associated with ophiolites. A great number of authors have contributed to the description and interpretation of the genesis of the classical chert occurrences in northern Italy, among whom are: PANTANELLI (1880), STEINMANN (1905), LOTTI (1947), GIANNINI, PIERRUCINI, & TREVISAN (1950), MERLA (1951), CONTI (1958), GRUNAU (1959), BERNOULLI (1960), AUBOUIN (1963), and GÖRLER & REUTTER (1964). The author is fully aware that this list is by no means complete and the reader will find additional literature references in MERLA (1951) and CONTI (1958).

The radiolarian cherts of the dinaric zone are found along the southern slopes of the Alps, especially in Lombardy (area of the lakes of northernmost Italy) (AUBOUIN, 1963). Well-exposed sections are described in great detail from the Torrente Clivio close to the Swiss border (Canton Ticino) by SENN (1924), GRUNAU (1959) and BERNOULLI (1960). The upper part of the Torrente Clivio chert sequence is red-brown to grey-red, well-bedded, nodular, with marly, red-brown limestone cover at the top and bottom of individual beds. The lower part consists of thinly stratified, greenish-grey and light red, siliceous limestone. The cherts are overlain by white, so-called Biancone limestone, which contains the following microfossils (GRUNAU, 1959): *Calpionella alpina, Calpionella elliptica, Tintinnopsella carpathica, Tintinnopsella oblonga, Tintinnopsella cadischiana; Stomiosphaera moluccana, Cadosina fusca; Nannoconus steinmanni, Nannoconus globulus; Spumellaria* and *Nassellaria*. The tintinnid association is typical for Upper Tithonian-Berriasian age. At the bottom of the chert sequence follows downwards the so-called Ammonitico rosso, which consists of red-brown limestones and marls. In some places *Posidonomya buchi* ROEMER and *Posidonomya alpina* GRAS (SENN, 1924) were found in nodular marls just below the cherts. These pelecypods indicate an Upper Bajocian age. In other places Aalenian ammonoids such as *Dumortieria evolutissima* occur in the highest beds of the Ammonitico rosso. From the foregoing it becomes evident that the top of the cherts is probably Lower and possibly even basal Upper Tithonian, whereas the lower time limit seems to vary from Bajocian to Bathonian. According to BERNOULLI (1960), a differentiation into basins and swells characterised the paleogeography of this area from Middle Lias onward to Bajocian. The basinal areas are characterised by more or less continuous sedimentation, and the swells by disconformities due to non-sedimentation and/or early erosion. Uniform conditions prevailed when the cherts began to deposit on rocks of slightly different age. This view makes the siliceous sedimentation coincide with a rather sharply defined time limit (Bathonian). SENN (1924) on the other hand believed that the lower part of the cherts was diachronous and would partly replace the upper Ammonitico rosso. The author is more inclined to subscribe to BERNOULLI's views, which, in a modified form, conform to his own interpretation (GRUNAU, 1959).

Submarine slumping and gliding phenomena were not observed in the radiolarian cherts, but are characteristic for the Liassic siliceous limestones (personal communication by D. BERNOULLI), the lower Dogger (red-brown marls and limestones), and the basal part of the Biancone limestone (GRUNAU, 1959, p. 65).

No ophiolites are associated with the radiolarian cherts of northernmost Italy.

The classical chert-ophiolite association of the Toscana in the northern Apennines was described as early as 1880 by PANTANELLI. He interpreted the cherts as deep-sea deposits. So did STEINMANN (1913), who mentions a typical Upper Jurassic radiolarian chert-red clay-pelagic limestone section from Figline in the Ripa valley close to Florence, overlain by tintinnid-bearing limestone and underlain by serpentinite, ophicalcite and gabbro, which intruded into the sediments. Detailed and accurate observations on the cherts of an area north of La Spezia were made by VAN DER WAALS (1946). In the Toscanides about 100 m. of Upper Jurassic chert occurs, which is overlain by Upper Tithonian-Neocomian tintinnid-limestone, and underlain by Upper Liassic limestones and shales with *Posidonomya bronni*. The following sequence could be observed in the Ligurides:

Neocomian-Tithonian	Limestones with shales; tintinnids
Upper Jurassic	Diabase
	Radiolarian cherts and siliceous shales, predominantly red, with coarse detritic beds containing gabbro and serpentinite at the base

Gabbro
Serpentinite

MERLA (1951), in his paper on the synthesis of the northern Apennines, gives a full account of the Jurassic-Lower Cretaceous stratigraphy, which can be summarised as follows:

Autochthonous

Berriasian-Tithonian	White and grey limestones with chert nodules Calpionella alpina
Tithonian-Lusitanian	Light yellowish, green, red and violet cherts, and siliceous limestones *Lamellaptychus beyrichi* (OPPEL) *Belemnites semisulcatus* MÜNST.
Lusitanian-Callovian	Stratified siliceous limestones
Callovian-Bathonian	Stratified siliceous limestones *Posidonomya alpina* GRAS
Bajoccian-Sinemurian	Stratified siliceous limestones Ammonoids

Allochthonous Argille Scagliose Formation

Serpentinite-gabbro-diabase, Upper Jurassic chert and tintinnid limestone are elements of the Argille Scagliose Formation.

New observations on the age of the ophiolites, associated breccias and olistostromes in the northern Apennines were made by GÖRLER & REUTER (1964). It can be shown that an Upper Jurassic and lowermost Lower Cretaceous age for the ophiolites can only be maintained for the area north of Genoa and the coastal strip between Sestri Levante and Levanto. In the remaining areas an Upper Albian to Upper Turonian age of some ophiolite occurrences seems probable. Age dating was made possible by a study of the associated ophiolite-, ophiolite-sedimentary- and sedimentary breccias, which in some places contain siliceous limestones with pelagic foraminifera. The breccias are intercalated with shaly sandstones, and show distinct grading and flute casts. A turbidity origin is assumed and a strong submarine relief postulated. Ophiolites probably extruded along tension faults bordering the deeper part of the basin.

It appears to the author that many more detailed observations will have to be made before the complex conditions as described above are properly understood. Analogous geological conditions are known from Turkey (KÜNDIG, 1959), Iran (GANSSER, 1959) and Celebes (KÜNDIG, 1956), but have never been studied in great detail.

SICILY

SCHMIDT et al. (1959) described radiolarian cherts, calcilutites, siliceous shales and rocks of a basaltic composition from the Madonie mountains in northern Sicily. These rocks, which are grouped under the name of Crisanti Formation, range from Jurassic to ?Aptian.

ISLAND OF ELBA

A classical radiolarian chert-ophiolite association from the eastern part of the island of Elba was described by LOTTI (1886) and has been re-examined by TREVISAN (1951) and BODECHTEL (1963). Upper Jurassic limestones, radiolarites and ophiolites occur in a zone of imbrication.

The «STEINMANN Ophiolitic Trinity» (STEINMANN, 1927) is well developed and consists of serpentinite, diabase-spilite, and gabbro. The diabase-spilite shows pillow-structure and is interpreted as submarine extrusion of a diabase sheet. Serpentinite and gabbro were intruded after the spilite extrusion.

Radiolarian cherts are found in superposition of the ophiolites. Their thickness bears a direct relation to the ophiolite thickness and therefore it is inferred that a genetic connection between the two rocks must exist.

The radiolarian cherts, which can be as thick as 300 m, are believed to be Upper Jurassic. No fossil evidence is given for their lower age limit. The upper age boundary is probably Lower Tithonian or lowermost Upper Tithonian, as the cherts grade upwards into dark limestones, shales, marls, and finally tintinnid-bearing limestones with *Calpionella alpina* and *Calpionella elliptica*, which are indicative of Upper Tithonian-Berriasian.

AUSTRIA

The palaeogeographic, stratigraphic and structural complexities of the Eastern Alps have resulted in an almost infinite number of controversial discussions, which have recently been thoroughly reviewed and synthesised by TOLLMANN (1963). The nappe architecture is unravelled and the Mesozoic basinal areas are shown in palinspastic reconstruction. A subdivision is made into a Helvetic, a Penninic, a Lower, Middle, and Upper Austro-alpine and a Southern Alpine realm. The Middle and Upper Jurassic of the Austro-alpine and Southern Alpine realm are characterised by radiolarian cherts, breccias, sandstones, shales, and limestones with Aptychus and Acanthicus. Ophiolites are not associated. Middle and Upper Jurassic cherts are also recorded from the Helvetic zone of Grestenen, where they occur together with *Aptychus*-bearing marls and limestones.

The Upper Jurassic chert breccia of the Sonnwend Mountains, situated about 40 km north-east of Innsbruck, deserves special mention. Its genesis has been discussed by WÄHNER (1903), AMPFERER (1908), HERITSCH (1915), SPENGLER (1935), and WEYNSCHENK (1949). The association of coarse clastics with radiolarian cherts, as typically exposed in the Sonnwend Mountains, has been a controversial subject in alpine geology from the beginning of this century until about the mid-fifties. Radiolarian cherts were believed by some authors (e.g. STEINMANN, 1913, 1925) to be abyssal sediments, whereas breccias were generally thought to be shallow deposits. In order to solve this controversy, authors like WÄHNER (1903) favoured the idea of a tectonic origin of the Sonnwend coarse clastics. AMPFERER (1908) and SPENGLER (1935), however, emphasised the primary-stratigraphic nature of the Sonnwend breccia, and WEYNSCHENK (1949) considered the breccia with associated cherts and limestones as being a shallow-water sediment. In 1950 KUENEN and MIGLORINI published their important article on turbidity currents as a cause of graded bedding, followed by a number of contributions on the same subject by KUENEN and other authors (see comprehensive bibliography in BOUMA and BROUWER, 1964). In the light of the present knowledge on turbidites, the coarse and fine breccias of the Sonnwend Mountains, which show distinct graded bedding (GRUNAU, 1959, p. 90), can be interpreted as submarine slope deposits. A shallow-water origin of the associated cherts and limestones has lost much of its former attraction and can probably be discarded.

GERMANY

Silurian and Devonian siliceous slates and cherts («Kieselschiefer») occur in the Frankenwald, a Hercynian massif in central-eastern Germany, situated about 220 km east of Frankfurt a. M. (GREILING, 1958). The thickness of the Silurian siliceous rocks is 40–50 m only, whereas the Devonian «Kieselschiefer» reach a thickness of 200–350 m, which is the thickest development in the Paleozoic in Central Europe.

The Silurian siliceous rocks are intercalated with comparatively thick layers of shales. The Devonian «Kieselschiefer» show almost a complete lack of shaly inter-layers and their colour is grey, green, red, and subordinately, black.

The siliceous slates and cherts consist of concretionary lenses, which in a lateral direction do not extend over more than 20 m. A close connection between diabase volcanism and «Kieselschiefer» genesis has been emphasised by SCHWAN (1952) and other authors. The siliceous rocks are thickest in areas of active volcanism. They become thinner and less frequent in areas of minor volcanic activity.

A number of «Kieselschiefer» proved to be quartzkeratophyric tuffs. Transitions to genuine siliceous rocks exist. Some siliceous slates and cherts are of organic origin and consist of radiolarians and other siliceous organisms.

The origin of the silica of many «Kiselschiefer» is still obscure.

Upper Jurassic radiolarian cherts are found in the Bavarian Alps close to the Austrian border, about 80 km south-east of Munich, in the austroalpine tectonic unit of the northern «Kalkalpen» (DOBEN, 1962). The thinly laminated, red radiolarian cherts are about 10–20 m thick. Their lower limit is thought to coincide with the Dogger-Malm boundary. Their upper limit is given as Upper Kimeridge-Lower Tithonian, as they are superimposed by red, marly boulder beds («Geröll-mergel»), limestones, marly limestones, and marls, which, in their basal part, show a «*Lombardia*» microfacies (BRÖNNIMANN, 1955) with Saccocoma alpina (Lombard), followed by an Upper Tithonian ammonoid fauna with *Virgatosphinctes*(?) *transitorius* (OPPEL), *Berriasella chomeracensis* (TOUCAS) and other *Berriasellae*. Together with and above the ammonoids a tintinnid association consisting of *C. alpina* and *C. elliptica*, also of Upper Tithonian age, is found.

The cherts occur in a strongly folded and imbricated zone. No association with ophiolites can be observed. The red, marly boulder beds («Geröllmergel») on top of the cherts are interpreted as being a submarine erosional phenomenon.

YUGOSLAVIA

The Dinarides of Yugoslavia are subdivided into an external and an internal part. The Mesozoic sediments of the external part were deposited in a miogeosyncline; those of the internal part were deposited in a eugeosyncline characterised by ultrabasic igneous rocks and a subsidence in excess of syntemporaneous sedimentation (CIRIC, 1963).

The radiolarian cherts of the Dinarides are mainly of Triassic and Jurassic-Lower Cretaceous age (CIRIC, 1963; MARKOVIC, 1958; PILGER, 1939).

Triassic cherts. The so-called porphyrite-chert formation of Ladinic age con-consists of andesites-basalts and their tuffs, grey and red cherts, shales, tuffaceous sandstones and limestones. This formation is found all over the Dinarides of Yugoslavia and also in northern Albany. In areas where volcanic activity took place during the Middle Triassic, calcareous sedimentation with intercalation of chert continues into the Upper Triassic (CIRIC, 1963, p. 569).

Upper Jurassic-Lower Cretaceous cherts. From Upper Lias to Valanginian typical eugeosynclinal sediments developed in the internal Dinarides. They are composed of radiolarian cherts, flysch-like clastics, and tuffs, associated with diabase, gabbro and peridotite of Jurassic age (CIRIC, 1954). In the external Dinarides, reef limestones were formed at the same time.

The author regrets that much valuable literature on the diabase-chert problem of Yugoslavia was not accessible to him, so that the facts summarised above do not provide a very satisfying picture.

HUNGARY

ELEMER (1960) describes Callovian-Oxfordian radiolarites associated with shales from Hungary. The sequence is 70 m thick.

POLAND

Radiolarian cherts occur in the zone of the klippen of Pieniny, which extends from the Vienna area over a distance of some 500 km to the massif of Marmaros in the eastern Carpathians. According to BIRKENMAJER (1960) the klippen zone of Pieniny consists of four to five nappes, which were thrust on the sub-pieninic sedimentary unit before the Upper Senonian transgression took place. This concept is contested by KSIAZKIEWICZ (1963), who believes that the folding and overthrust of the Pieniny units are post-Paleogene, but at the same time Ksiazkiewicz admits that no satisfactory hypothesis can be presented which would reconcile the known facts.

The radiolarian cherts are fully developed in the series of Pieniny and become thinner in the so-called mixed series. They completely disappear in a northerly direction. In the series of Pieniny, the cherts are underlain by Middle Jurassic limestones and marls and overlain by silex-bearing limestones with Aptychus dated as Tithonian-Neocomian.

It can therefore be said that the cherts represent Upper Jurassic not including Tithonian (? or Upper Tithonian). In the mixed series, the Upper Jurassic cherts are associated with nodular limestones (KSIAZKIEWICZ, 1963), which at the top contain *Calpionella alpina* LORENZ and *Calpionella elliptica* CADISCH.

GREECE

Jurassic to Lower Cretaceous radiolarian cherts occur in the Pindos zone (AUBOIN et al., 1963), an allochthonous tectonic unit, which extends from the western part of the Peleponese in a northerly and then north-north-westerly direction into Albania. The Pindos zone is characterised by pelagic, siliceous and calcareous sediments, which, on the flanks of the original depositional basin, pass into limestone micro-breccias. Red and green radiolarian cherts attain a thickness of 250–300 m. A Jurassic to Lower Cretaceous age is ascribed to them. Ophiolites are found on the flanks of the basin.

Jurassic radiolarites are also found in other hellenic zones such as the Ionian zone, the subpelagonnian zone, and the zone of Vardar. In the latter zone (Thessaloniki area) ophiolites up to 3000 m thick are well developed and consist of dolerites, peridotites, pyroxenites, gabbros, pillow-lavas, and rocks of a basaltic composition. Their age is probably Jurassic. In an imbricated area of the Vardar zone (BRUNN, 1960, 1961) a gigantic mixture of limestones, ophiolites, and shales was observed which could be compared with the Ankara melange or the Coloured melange in Iran.

The hellenic zones are interpreted as being a system of deep basins separated by swells. During the Jurassic-Lower Cretaceous, radiolarian cherts developed in the basins and shallow carbonates on the swells. Gliding occurred on the flanks, and shallow sediments moved down the slope into the deeper parts of the basin where they interfingered with pelagic sediments. Calcareous microbreccias or «flank-breccias» originated this way.

CYPRUS

Radiolarian cherts and associated rocks, including Upper Cretaceous pillow-lavas, occur in south-west Cyprus in the foothill belt south of the basic igneous massif on the Troodos Mountains (HENSON, BROWNE, & MCGINTY, 1949; GASS, 1958). The cherts belong to the Mamonia Formation, which can be summarised as follows (HENSON, BROWNE, & MCGINTY, 1949, p. 6–8):

A continuous section was not observed, since the beds have been subjected to violent deformation, mainly faulting, and are penetrated by igneous extrusions. For the same reason a measurement of thickness was not attempted. The aggregate thickness, however, was estimated at not more than 600 ft. The section consists of:

(a) Laminated silts and sandstones, interbedded with limestones with a cherty texture and containing abundant spicules and radiolaria. An Upper Triassic fauna containing *Daonella*, *Halobia* and *Monotis* indicating Carnic-Noric age, was collected from radiolarian limestones in the type area.

(b) Massive to medium and thin-bedded limestones with some sandstones.

(c) Siliceous limestone interbedded with banded and nodular chert; some chalky limestones and grits also occur.

(d) Red beds, red marls, shales with bands of hornstones, thin-bedded, red radiolarites with intercalations of basic igneous rocks and tuffs, and laminated sandstones towards the base of the section.

The age of the Mamonia Formation is considered to be Upper Triassic.

Pillow lavas overlie the Mamonia Formation along the southern foothills of the Troodos Mountains. Field evidence indicates a Middle-Upper Cretaceous age. The basic igneous rocks may even be contemporaneous with the Senonian lavas (roches vertes) of Lattaquia (Dubertret, 1953).

From a regional comparison of radiolarian cherts and associated rocks in Turkey, Syria, Iran, and Oman it would seem to the author that the Mamonia Formation in Cyprus could be interpreted as an Upper Cretaceous «Coloured melange» association, which contains exotics of Triassic and possibly even other ages. The clastic sediments could probably be interpreted as turbidites mixed with pelagic cherts and limestones. Such a concept is thought to have a rather high degree of probability, but more detailed field work is necessary before definite statements can be made. The author recently had a discussion on the subject with Mr. McGinty, who found the above views acceptable.

TURKEY

Radiolarian cherts, olistostromes and ophiolites are typically developed in south-eastern Turkey, especially in the Kurdish Taurus between Malatya, Adyaman and Ergani (Kündig, 1956, general reference). Cherts not associated with ophilites (Nebert, 1959) are found in south-eastern and western-central Anatolia (Bursa, Tavsanli, Kütahya). A Coloured Melange-type ophiolite-olistostrome mixture is well known from northern Turkey (Ketin, 1962, 1963) and was called Ankara Melange by Bailey & McCallien (1953).

Kündig (1956) describes sill-like ophiolite bodies consisting of diabase, spilite, pillow-lavas and tuffs, and also chains of serpentine lenses in the lower part of the sequence. Crumpled radiolarites are found with the ophiolites, together with blocks and slabs of mainly Middle Cretaceous and older limestones. In a later paper, Kündig (1959, p. 10) presents a schematic section showing the relationships between sediments and ophiolites in south-eastern Turkey which can be summarised as follows: The ophiolites are restricted to a short paroxysm in Maestrichtian time. They fill up a short-lived subsidiary trough situated on the epicraton. The trough content consists of up to 95 % ophiolites and only a small fraction of radiolarites and shales. The ophiolite complex rests on and is normally interbedded with Cretaceous sediments which are only gently folded. Radiolarites occur as a normal lateral continuation of the ophiolites, and their age is supposed to be Lower Maestrichtian. Flanking blocks are Palaeozoic limestones of the shelf edge and a down-thrown younger block with Mesozoic limestones.

Based mainly on observations in south-eastern Turkey, Kündig (1959) developed a more general scheme for the configuration of the shelf edge and the eugeosynclinal environment. He emphasises that ophiolites occur mainly at the hinge zones and may, like the sediments, glide into the eugeosynclines.

The radiolarian cherts of the Taurus (Blumenthal, 1956, 1963) are probably not synchronous. Upper Cretaceous age is probable in many cases, but there is also some evidence for Lower Cretaceous and Upper Jurassic (Blumenthal, 1963, p. 616).

The genesis of the radiolarian cherts of Turkey has been fully discussed by NEBERT (1959), who came to the conclusion that the silica of the cherts is of inorganic origin, and related to exhalations during the final phase of basic and ultrabasic magmatism. Evidence against the deep-sea nature of the Turkish cherts was put forward by BAILEY a MC CALLIEN (1953), BLUMENTHAL (1956) and TROMP (1948).

SYRIA

The radiolarian cherts and associated ophiolites of north-western Syria (Bassit and Kurd Dagh) and the bordering area of south-eastern Turkey (Hatay) have been carefully described by DUBERTRET (1953). The ophiolitic suite consists of peridotites, serpentinites, gabbros, dolerites and pillow-lavas and is interpreted as a submarine flow (DUBERTRET, 1953, p. 170) of Maestrichtian age. Dolerites and pillow-lavas are overlain by intensely folded red cherts in isolated lenses associated with blocks of sediments ranging from Palaeozoic over Jurassic, Aptian, Cenomanian-Turonian to Senonian. In some places, the cherts are found outside the ophiolitic belt lying directly on Senonian marls. Their age is very likely to be Maestrichtian, but it does not seem entirely excluded that they might range into the Paleocene.

IRAN

The ophiolite belt of the internal Zagros Mountains (GANSSER, 1959, p. 669) extends in a NW–SE direction from Kurdestan (N. Iraq/Iran) to the area north of Bandar Abbas. Its eastern continuation is found in Beluchistan, south of the Djaz Murian basin and east of the Lut desert. Ophiolites are also present in central Iran (Nain) and the eastern part of the Elburz Mountains south of Meshed.

Radiolarian cherts are often associated with the ophiolites as well as chaotic block zones, which were called «Coloured Melange» by GANSSER (1955, p. 286). The Coloured Melange of Beluchistan has been described in detail by GANSSER (1959, p. 668–674). His observations can be summarised as follows. The ophiolitic portion of the Coloured Melange consists of diallage peridotite, serpentinite, ophicalcite, olivine basalt, diallage gabbro, diabase, diorite, pillow lava and spilite. On top of the ophiolites are found isolated blocks and lenses of red radiolarian chert, red marly limestone, siliceous limestone, white coral-bearing reef-limestone, rudist limestone, and white limestone, which are Cretaceous and Jurassic. Upper Cretaceous Globotruncana-bearing marly limestones are the youngest fossil-dated element of the sedimentary blocks. The Coloured Melange is transgressively overlain by thick flysch-like shales and sandstones with block-flysch at the base. The flysch is mainly Lower Oligocene and partly also Middle Eocene. Consequently, the upper age limit of the Coloured Melange is Lower Eocene, but it is believed that the ophiolites and radiolarites are mainly of Maestrichtian age.

In 1949, GRAY thought he had found evidence of large-scale over-thrusting during Upper Cretaceous in part of the Zagros Mountains. Thrust-sheets made up mainly of radiolarian cherts and serpentinites and including fossiliferous rocks of Triassic age, are shown to have been extensively over thrust upon Cretaceous rocks, including Cenomanian limestones and marlstones probably of Senonian age. Marine Maestrichtian and younger rocks were deposited upon the thrust-sheets and were later folded, together with the sheets themselves and the underlying autochthonous rocks. Subsequent erosion of the cover has exposed the thrust-sheets over wide areas and in places has exposed the underlying autochthonous rocks in tectonic windows of which a striking example, the Dalnashin Window, was described in detail by GRAY (1949). HENSON (1951) remarks that evidence such as adduced by GRAY (1949) to demonstrate the existence of Cretaceous thrust sheets in south-western Iran requires critical review, as similar occurrences in Cyprus, north-western Syria and Oman are almost certainly autochthonous. In this context it is worth mentioning that GANSSER (1955) also criticises DE BOECKH's (1929) radiolarite nappe, which he prefers to call imbrication-zone. The author of this paper had an opportunity to fly over the Dalnashin area and the Coloured Melange outcrops east of Bandar Abbas, and also examined the latter on the ground, together with P. HEYBROEK and R. COOK. It was concluded that local thrusting, reverse faulting and, to some extent, gravity sliding on a minor scale could be observed at the contact between the Coloured Melange and younger sediments in the area east of Shamil-Minab in Mekran (southern Iran), but no evidence for large-scale thrusting could be found. In the Dalnashin area the assumption of the existence of an ophiolite-radiolarite nappe can no longer be maintained, if an Upper Cretaceous age and incompetent folding of the radiolarites and the Coloured Melange nature of the ophiolite-olistostrome mixture is accepted.

Radiolarite and ophiolite pebbles are common in the Plio-Pleistocene Bakhtiari conglomerates in the area bordering the Zagros foothills to the south-west. No conclusions can yet be drawn from this observation, as the study of the distribution of pebbles in the molasse-like Bakhtiari sediments has not been undertaken.

OMAN

The mountain zone along the east coast of Oman appears as a detached orogenic arc with the overall structure of a complex geanticline (MORTON, 1959). It exposes huge masses of Upper Cretaceous ophiolites, radiolarian cherts and associated sediments, so that the Oman Mountains might be considered as one of the world's classical areas for a thorough and detailed study of chert-ophiolite-olistostrome occurrences. For a variety of reasons, however, such an investigation has never been initiated and the information available is more of a regional and generalised nature. Apart from LEES' (1928) classical paper on Oman, only scanty literature reference is available. The most noteworthy publications are those by HUDSON, McGUGAN & MORTON (1953), HUDSON, BROWNE, & CHATTON (1954), and especially MORTON's (1959) review of the geology of Oman.

Cherts and associated sediments were called Hawasina Series by LEES (1928, p. 599) and the ophiolites given the name Semail Igneous Series (LEES, 1928, p. 601). The Hawasina Series was originally defined as a very thick sequence of shales, sandstones, detrital limestones, and red and green chert or radiolarite. It is an incompetent group between two rigid members, the Musandam Limestone below and a massive igneous group above. Owing to the violent minor folding, no measurement of thickness for this group can be obtained, but it is estimated to be about 5000 ft thick. The Semail Igneous Series consists of serpentine, gabbro and diorite according to LEES (1928). In Lees' opinion the Hawasina Series and Semail Igneous Series are probably of about the same age, i.e. Upper Jurassic to Lower Cretaceous. The whole Hawasina zone was considered by the same author as a thrust-sheet or nappe, which in turn is overlain by the nappe of Semail Igneous.

HUDSON, MCGUGAN & MORTON (1953) described contorted Jurassic and Lower Cretaceous tuffs and radiolarian cherts from the Jebel Hagab area in northern Oman. The cherts are considered to be of shallow-water origin in an area of igneous activity marginal to an offshore detrital facies.

MORTON (1959) produces good evidence for the following views:

1. Hawasina and Semail Igneous are both Upper Cretaceous. The Semail Igneous series are usually younger than the Hawasina Group, but interfingering of the two units can also be observed.
2. The contact between the Hawasina Group and the Middle Cretaceous (Cenomanian-Turonian) is conformable, and no important thrusting occurs.
3. Correlation of displaced Hawasina beds is difficult because the evidence of their radiolaria has been found to be unreliable and they often contain derived faunas ranging from Permian to Cretaceous.

MORTON (1959) also mentions the existence of numerous massive slumped blocks of the sub-strata (the klippen of LEES), and remarks that the Semail itself has entrained blocks of underlying sediments.

Fig. 2. Contorted, thinly-bedded radiolarian cherts alternating with thick-bedded, oolitic lime grainstones showing graded-bedding. Wadi Miaidin, south flank of Jebel Akhdar, Oman. Cherts and lime grainstones are part of the Hawasina Group which is of Upper Cretaceous age.

Fig. 3. Thick bed of oolitic lime grainstone with lithoclasts, showing graded-bedding. The overlying and underlying layers are thinly-bedded radiolarian cherts. Wadi Miaidin, south flank of Jebel Akhdar, Oman. Line grainstone and cherts are part of the Upper Cretaceous Hawasina Group.

In 1962, the author of this paper had an opportunity to visit some of the contorted chert outcrops east of Ibri together with C. PERIAM and J. HOHLER, and two years later he also examined Hawasina and Semail rocks in the area south and north of Jebel Akhdar and in the Sumail gap under the guidance of P. LLEWELLYN and H. KAPP. The following observations appear to be worthy of note:

1. In Wadi Miaidin on the south flank of Jebel Akhdar the lower part of the Hawasina Group contains chert beds with interlayers of lime-grainstone with distinctive graded bedding (Figs. 2 and 3).
2. Contorted chert beds over- and underlain by isoclinally dipping strata could be observed at the southern end of Wadi Miaidin gorge. This could be interpreted either as slumping or incompetent folding (Fig. 2).
3. Layered gabbros (H. KAPP) frequently occur in the Semail Ophiolites.
4. In the Ibri-Nizwa area a «Coloured Melange» type ophiolite-olistostrome mixture (Fig. 4) is found, which merits further investigation.

Although it appears premature at this stage to draw any far-reaching conclusions on the Hawasina-Semail rocks, this association could be said to be a perfect example for illustration of KÜNDIG's (1959) views on the slope-eugeosynclinal environment. In this context, it should also be mentioned that the Hawasina facies

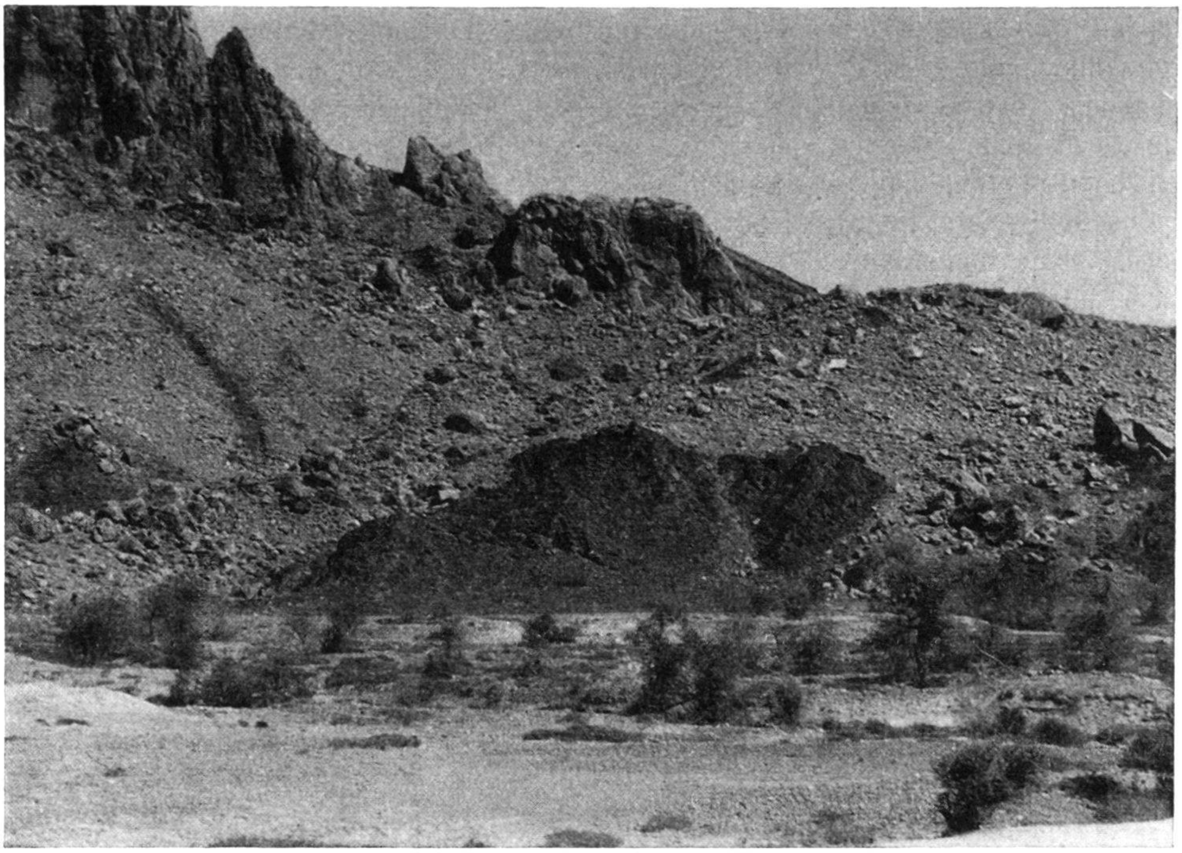

Fig. 4. Limestone blocks (olistoliths) on top of Semail serpentinites. Nizwa, southern flank of Jebel Akhdar, Oman. This is part of a typical Coloured Melange association (ophio-olisto-silite according to nomenclature suggested on p. 189).

tongues westward into normal marine globigerinal marls of the foreland (M. CHATTON in MORTON, 1959).

INDIA-TIBET

In the Kiogar Mountains in the Central Himalayas (borderland between India and Tibet), a complex mass of ophiolites associated with sandy-siliceous flysch and blocks of limestones ranging from Permian, Triassic, Jurassic to Cretaceous, Cretaceous shales and radiolarian cherts, are found (HEIM & GANSSER, 1939, GANSSER, 1959). The whole sequence is thrust on Cretaceous flysch.

This exotic ophiolite-sediment block complex can easily be compared with the «Coloured Melange» of Turkey, Cyprus, Iran, and Oman.

ANDAMANS AND BURMA

The Andaman-Nicobar group of islands in the Bay of Bengal consists of two arcs: the outer non-volcanic arc comprising the major islands of the Andamans and the Nicobars, almost entirely made up of Tertiary sediments, and the inner volcanic arc (JACOB, 1954). These two arcs are easily traceable northwards into Burma and southwards into the islands of Indonesia. It is in the outer arc that ultramafics with associated radiolarian cherts occur in the Andamans and «jaspers» (possibly radiolarian cherts) in the Burmese region.

TIPPER (1911) observed the occurrence of pre-Tertiary red and yellow «jaspers», quartzites, and pink and white porcellaneous limestones, sometimes as isolated exposures in the Eocene, but occasionally in association with serpentines. It is quite probable that the «jaspers» in association with the ultra-mafics are fairly widespread along the eastern parts of the Andaman and Nicobar Islands. Red and greenish «jaspers» are also reported by GEE (1926) from Porlob Island and several localities in the interior of the Middle Andaman. JACOB (1954) describes specimens of radiolarian chert composed of Spumellaria and Nassellaria, which were collected by M. C. PODDAR in the South Andaman Island. The age of the cherts is considered to be Upper Cretaceous or early Eocene. The basic and ultra-basic rocks of the «Saddle Hill Phase» consist of peridotites, often serpentinised, diorite and gabbroic rocks with dolerite dykes, which are of the same age as the cherts.

In Burma «jaspers» associated with ultra-mafics are found in the Negrais series on the flanks of the Arakan-Yoma belt, and further north in Manipur (CHHIBBER, 1934, pp. 206–208; JACOB, 1954, p. 402). The Burmese occurrences which lie in the northward extension of the Andaman-Nicobar belt, are believed to be Upper Cretaceous or early Eocene.

MALAY PENINSULA

SCRIVENOR (1929, 1931) has carefully described the radiolarian cherts and associated shales which occur in numerous localities on the Malay Peninsula. The cherts are usually grey, but also black due to the abundance of carbon, and the alternating shales have the same colours. Radiolaria are often present together with bryozoa, sponge spicules and foraminifera. Owing to the high degree of folding and faulting in the bedded rocks of the Malay Peninsula it is not possible to be certain of the exact position in the geological sequence of the chert and associated shale. The evidence available points to the bulk of the radiolarian rocks lying at the base of the Triassic series of quartzites and shales, and immediately above the Carboniferous limestone, but some chert horizons may be higher in the series. The age of the radiolaria-bearing chert and shale is assumed to be Triassic, but may be older.

According to SCRIVENOR (1929, p. 239) radiolarian chert in Johore is found near volcanic rocks, and in Singapore is associated with fine grained acid tuff. ALEXANDER (1963, p. 83), however, states that in the absence of conclusive information to the contrary it is now considered that many of the present undated arenaceous formations are more likely to be Carboniferous than older Palaeozoic or Triassic in age.

In the Indonesian archipelago radiolarian cherts ascribed to the Triassic are found in Ceram only.

SUMATRA

Gabbro, serpentine, red siliceous shales and radiolarites are reported from Tangse-Geumpang in northern Sumatra (SCHÜRMANN, 1929).

BORNEO

The radiolarian cherts of Borneo were discussed by MOLENGRAAFF (1900, 1902, 1910), REINHARD & WENK (1951), LIECHTI (1960), WILSON (1961), and BRONDIJK

(1964) and many other authors. The cherts are part of the Danau Formation which strikes approximately east–west from West and Central Borneo to near the east coast. The area it occupies has a length of at least 650 km and an average width of 60 km. It also occurs in south-eastern Borneo and has a wide distribution in North Borneo.

MOLENGRAAFF (1900 – Dutch version of his report, 1902 – English version) grouped under the name of Danau Formation a system of deposits, which he saw typically developed in the area of the great lakes and in the hilly district bordering the north side of these lakes. The constituent rocks are diabase-tuff, diabase, diabase-porphyrite, quartzite, chert, jasper, hornstone, clay-slate, and sandstone. The most characteristic rocks in this formation are a silicified and partly serpentinized diabase-tuff and jasper. The examination of the abundant radiolaria in the cherts and also in the diabase-tuff has revealed that these deposits have a pre-Cretaceous, probably Jurassic age. The strata of this formation are almost everywhere folded and tilted.

The jasper and hornstone consist in many places almost exclusively of closely packed tests of radiolaria, between which a few sponge spicules may be seen. MOLENGRAAFF (1900, 1902, 1910) felt justified in maintaining that the cherts were deep-sea deposits, formed most probably at a considerable distance from the mainland.

The Danau Formation of North Borneo is carefully described by REINHARD & WENK (1951). The guide rocks of the Danau Formation, ophiolites and radiolarian cherts, occur in a sedimentary sequence which consists of alternating layers of more or less sandy shales and sandstones. The cherts are usually brown to red, but yellow, green, white and occasionally variegated hues also occur, and often speckled throughout with radiolaria. Together with the radiolarites there are occurrences of limestones and marls, which are partly Paleocene to Lower Eocene, partly Mesozoic, Cretaceous or Tertiary, and partly Tertiary, possibly post-Eocene. Ophiolites occur in the sediments of the Danau Formation, where they consist of serpentine and related rocks, peridotite, pyroxenite, gabbro, diabase, basalts, and spilites. Ophicalcites, calcified breccias and tuffs are also present. The genesis of the Danau Formation is discussed at length by REINHARD & WENK (1951, pp. 91–97). The chaotic, strongly disturbed aspect is not only due to strong diastrophism, but might also be connected with the intrusion of the ophiolites. Moreover, subaquatic landslides might have occurred. In contrast to MOLENGRAAFF (1900, 1902, 1910), REINHARD & WENK see no reason for regarding the radiolarian cherts as deep-sea deposits, as they consider the ophiolite-chert relationship a petrogenetical rather than a depth problem. The age of the Danau Formation in the north-western part of Borneo is pre-Middle Eocene, probably Mesozoic to Paleocene.

The following views on cherts in British Borneo are expressed in LIECHTI's (1960) comprehensive compilation:

The oldest known occurrence of chert is the Sebangan Hornstone Formation (HAILE, 1954), which is composed of chert-like, typically light greenish-grey, rarely white hornstone, silicified volcanic rocks and amphibolite. It is probably Carboniferous or older.

Chert is also found in the Seijngkat Formation of uncertain, probably mainly Mesozoic age, and in the Bau Formation, which is of Upper Jurassic and Cretaceous age and represents a litoral to neritic shelf deposit.

The Lupar Formation (MILROY, 1953) consists of an *Orbitolina*-bearing shale-sandstone alternation overlain by volcanic breccias, conglomerates, spilitic extrusive rocks, chert layers and lenses, and a well-developed shale succession with subordinate sandstones. Its thickness is not less than 5000–8000 ft. On foraminiferal evidence the Lupar Formation ranges from Cenomanian to Maestrichtian, but it is not excluded that part of the heterogeneous formation is older than indicated by the Upper Cretaceous foraminifera.

The Lupar Formation is a typical eugeosynclinal chert-spilite association and appears to mark a development characteristic of the southern hinge zone of the north-west Borneo geosyncline. An essentially bathyal environment is suggested. The Lupar Formation is more or less synonymous with MOLENGRAAFF's (1900, 1902) Danau Formation.

WILSON (1961) deduces a late Cretaceous to possibly Eocene age for the chert-ophiolite association in Sabah.

BRONDIJK (1964) reintroduces the term Danau Formation in Sarawak and Sabah and states that terms like Lupar Formation and Chert-Spilite Formation have become obsolete. In Sarawak the age of the formation is late Cretaceous to possibly Eocene based on pelagic foraminifera.

CELEBES

The eastern part of the island of Celebes contains what is probably one of the largest aggregations of ophiolites known in the world (KÜNDIG, 1956). Associated with the ophiolites are Jurassic and Cretaceous sediments, which consist of crystalline to aphanitic, grey to reddish limestones with brown nodules and layers of radiolarian cherts (probably Jurassic), grey marly limestones and marls with belemnites, red marly limestones and marls, a flysch-like sequence of well-bedded, sandy, occasionally slaty shales alternating with limestones and bituminous paper shales (probably Jurassic).

The ophiolites (KÜNDIG, 1956) consist of peridotites, serpentinites, gabbro, diabase, and spilite. Their age is assumed to be Upper Cretaceous; it is, however, probable that the whole phase of initial magmatism may have lasted from early Cretaceous deep into Paleogene.

The eastern arm of Celebes belongs to a zone of strong tectonical deformation with a structural trend coinciding with the morphological orientation of the peninsula. An imbricated structure, with a regional homoclinal dip towards the north coast of the peninsula, is the outstanding feature. In KÜNDIG's (1956) opinion some of the so-called sedimentary imbrication slices represent slumped masses.

From a regional comparison with Timor, Ceram and Borneo, the author would be inclined to attribute an Upper Cretaceous age to the radiolarian cherts of eastern Celebes.

CERAM

GERMERAAD (1946), who studied material collected by RUTTEN & HOTZ (1918–1920) in the years 1917 to 1919, gives the following description of the Upper Cretaceous Cherty Limestone Formation of Central Ceram:

The Upper Cretaceous (-Lower Eocene, author) is widely distributed in Central Ceram. Wherever it contains fossils it is always characterised by small *Globigerinas* (*G. cretacea*), *Globotruncana*, *Globorotalia velascoensis* (*aragonensis*) and *Guembelina*. Two members can be distinguished: a lower member consisting of grey limestones with or without chert, marls and shales, and an upper member consisting of red limestones with or without chert, marls and shales. The fossil content is the same in both members. The cherts contain silicified micro-organisms (very probably radiolaria). – The same formation is also described by v. D. SLUIS (1950) from East Ceram.

The Upper Cretaceous-Lower Eocene of Central and East Ceram has strong affinities to the ?Upper Cretaceous-Lower Tertiary Bibiliu Group of Portuguese Timor (GRUNAU, 1953, 1956, 1957).

RUTTEN & HOTZ (1918–1920) and RUTTEN (1927, p. 728) mention silicified shales, rocks which resemble cherts (? probably claystones), and true, mainly red, radiolarian cherts which are interbedded with Triassic rocks in flysch-facies of Western Ceram (see also VALK, 1945, p. 46).

BROUWER (1919) describes Triassic rocks from East Ceram: sandstones, limestones, cherty limestones, hornstones, radiolarites, shales and marls. The radiolarites are though to be of abyssal origin.

Unfortunately, field relationships in Ceram are far from clear. The island was investigated mainly before World War II but no field work has been done since as far as the author knows. Thus no up-to-date environmental interpretation of cherts and associated rocks is available.

TIMOR

Radiolarian cherts and radiolaria-bearing claystones are known from western and eastern Timor in structurally complex areas. Their age is Cretaceous, partly Upper Cretaceous, and probably even Lower Tertiary.

In western Timor the cherts of the Sonnebait Series in the south-western Moetis region have been described by DE ROEVER (1940). Grey and dark red cherts are of widespread occurrence as layers and concretions in *Globotruncana*- and *Globigerina*-limestones, and their Upper Cretaceous age is established for certain. Furthermore, variegated brown, yellow, white, green, blue or black cherts, sometimes finely stratified with an alternation of layers of various colours, have been found, mostly as detached blocks. The cherts are usually badly crumpled and crushed.

VAN WEST (1941) mentions red-brown, banded radiolarian cherts associated with Globotruncana-limestones from the Sonnebait Series of the Miomaffo region. *Globotruncana*-limestone, cherty limestones and cherts were found in the upper part of the Palelo Series at Noil Noni.

In eastern Timor, GRUNAU (1953) grouped under the name of Bibiliu Series, (correctly Bibiliu Group) a variety of rocks ranging from red clays and marls, coarse sandstones and block clays to claystones and red-brown radiolarian cherts, often with manganese impregnations. The Bibiliu Group is heavily folded and crushed and no original rock sequence could be established. Its age is believed to range from Upper Cretaceous to Pliocene by GRUNAU (1957), but GAGEONNET and LEMOINE (1958) doubt whether such a wide range can be proven. They attribute an Eocene age to part of the Bibiliu «Series». – The predominance of block clays in the Bibiliu Group has always been emphasised by ESCHER (see GRUNAU, 1956). Recently, DE AZEREDO LEME (1963), inspired by FREYTAG and AUDLEY-CHARLES, presented some views on the Bibiliu Group, which he calls «Clay Complex» (Complexo argiloso). DE AZAREDO LEME describes the «Clay Complex» as consisting of badly consolidated, plastic clays with a great amount of angular to subangular fragments and large boulders of rocks of different ages and origins, presenting a heterogeneous mixture. The «Clay Complex» is believed to be of Middle to Upper Miocene age. Although the genesis of the «Clay Complex» is still in the dark, it might be related to turbidity currents (DE AZAREDO LEME, 1963, p. 387). The author considers that the publication of AUDLEY-CHARLES' investigations in Portuguese Timor, backed up by thorough laboratory studies, should be awaited before any further conclusions on the origin of the Bibiliu Group can be drawn. At present, the interpretation of the Bibiliu Group as a gigantic slope breccia, interfingering with a basinal chert facies, appears to have some merit.

NEW GUINEA

The North New Guinea province (VISSER & HERMES, 1962, p. 125) is characterised by:

a. the occurrence of widespread ultra-basic rocks associated locally with greenschists;

b. a sequence of several thousand metres of late Cretaceous to early Oligo-Miocene basaltic to andesitic extrusives with intercalated radiolarites, pelagic limestones and, higher in the section, shoal limestones;

c. a late Oligo-Miocene to Plio-Pleistocene sequence, 7000–8000 m thick, in the area of the Geelvink Bay, predominantly clastic, and characterised in its lower part by a flysch-like aspect and graded bedding (possibly turbidites).

In the Radja Ampat area (VISSER and HERMES, 1962, p. 114) the radiolarites are mainly associated with Paleocene-Eocene pelagic limestones, which themselves often carry radiolaria.

Apparently the radiolarite complex of northern New Guinea has never been studied in detail, but the above short description gives a clear picture of a eugeosynclinal-continental slope environment which can easily be compared with similar associations in the Far East (Philippines, Borneo, Timor, and Celebes) and the Middle East (especially Turkey and southern Iran). In this case the eugeosynclinal phase, during which perennial sediments such as pelagic limestones and cherts were deposited, seems to be followed by a slope-phase, characterised by turbidites. This indicates shifting of the basin axis.

JAPAN

The radiolarian cherts of Japan have been reviewed by KOBAYASHI & KIMURA (1944), KOBAYASHI (1956), and TAKAI, MATSUMOTO & TORIYAMA (1963) in their «Geology of Japan». Additional references are found in the literature list of these authors.

The chert occurrences of Japan range from Carboniferous to Jurassic (TAKAI, MATSUMOTO & TORIYAMA, 1963). Carboniferous sandstones and shales associated with chert and thin lenses of limestone are developed in the inner zone of southwest Japan. The most striking feature in the Permian is a remarkable contrast between calcareous and non-calcareous facies. The latter consists of sandstone, shale, and chert. Cherts are also found in the Triassic. The so-called Torinosu Series in Hokkaido and north Kitakami are characterised predominantly by chert, pillow lava and associated rocks.

KOBAYASHI (1956) states that the radiolarian cherts of Japan are mostly interbedded with fine terrigenous rocks either together with or without pyroclastic rocks. He emphasises that the chert-bearing facies was shifted from the continental to the oceanic side from time to time in accordance with the cycles of orogeny.

In 1944, KOBAYASHI and KIMURA studied the radiolarian fauna of radiolarian-bearing rocks in Japan and came to the conclusion that from Silurian to Tertiary the *Sphaeroidea*, which developed earlier, were later replaced by the *Cyrtoidea*. Apart from some general remarks on radiolarian rocks, the bearing of such rocks (mainly cherts) on the geotectonics of Nippon is stressed by the authors, as outlined above.

PHILIPPINES

Radiolarian cherts associated with basic rocks, serpentines and peridotites are reported from some of the Philippine islands such as Luzon (VAN BEMMELEN, 1949, p. 371), Mindoro (CORBY, 1951, p. 83) and Iloilo (CORBY, 1951, p. 88). Cherts, ophiolites and other rocks are grouped together by VAN BEMMELEN (1949) and CORBY (1951) in the basement complex, a name which does not conform to modern nomenclature concepts. This basement complex, according to VAN BEMMELEN (1949), consists of granitic rocks, basic and ultra-basic igneous, the Baruyen Cherts, the Kaal Formation (shales, sandstones and rarely limestones) and batholitic intrusions.

Basic and ultra-basic igneous rocks (gabbros, peridotites, pyroxenites, serpentines, etc.) form the bulk of the basement complex, and they are widely exposed in the cores of the mountain ranges. These ophiolitic rocks are related to the Baruyen Cherts, and it is thought that both the igneous and the sediments are of pre-Tertiary age. Deposition in deep sea is suggested by VAN BEMMELEN (1949, p. 372) and IRVING (1952).

The chert-ophiolite association of the Philippines, which is only very superficially known, can easily be compared with the Danau Formation of Borneo and similar rocks in eastern Celebes. From a regional viewpoint the inclination is to attribute an Upper Cretaceous age to the cherts and ophiolites of the Philippines, but no convincing age evidence can be given.

AUSTRALIA

Cambrian, Silurian, and Devonian radiolarian cherts were deposited in the Tasman geosyncline, a major tectonic depression, which covered at various times much of Queensland, New South Wales, Victoria and Tasmania (DAVID, 1950). As early as 1913, BENSON (1913) focused attention on spilite lavas and radiolarian rocks from New South Wales.

In New South Wales, the name of Wagonga Series has been given to a rock sequence which occupies a strip of the south coast from the Victorian border to Clyde River. The rocks consist of black, banded cherts and beds of volcanic tuff, with greywackes, phyllites and mica-schists. The cherts contain veins of turquoise, but except for radiolaria have yielded no fossils. The series is much folded and the cherts are intensely crumpled. At Narooma some of the weathered rocks resemble amygdaloidal pillow-lavas (DAVID, 1950, p. 124). A Cambrian age is assigned tentatively to the Wagonga Series, but it might range into the Lower Ordovician.

The Brisbane Schist Formation is a sequence of more or less altered rocks consisting of serpentines, cherts, jaspers, greywackes, slates, grits, quartzites and altered basic to intermediate rocks which might be partly of Cambrian age. The Brisbane Schist Formation is exposed in parts of Queensland and New South Wales.

Upper Ordovician radiolarian cherty shales, and radiolarian cherts are known from New South Wales.

Silurian radiolarian cherts seem to be rare in New South Wales. In Queensland, the Middle to Upper Silurian Chillagoe Series consists of coral-reef limestones with sandstones and quartzites, shales, calcareous mudstones, slates, greywackes or tuffs and radiolarian cherts and jaspers. The Chillagoe Series may ascend to the Lower Devonian.

The Lower to Middle Devonian Tamworth Series of western New England in New South Wales consists of radiolarian cherts, limestones, tuffs and a spilite flow. The cherts forming an important part of the Tamworth Series have yielded a rich radiolarian fauna described by HINDE (1899). The radiolaria are extremely abundant and sometimes form up to 50 % of the rock. The thickness and extent of the radiolarian rocks of the Tamworth Series make them unique among such deposits. The cherts in part may be of the nature of exceedingly fine volcanic dust cemented by silica chemically precipitated on the sea-floor, and they are regularly banded with thin layers of fine crystal-tuff, which is locally transgressive towards the cherty material.

In Queensland the Lower to Middle Devonian Etna Series is made up of rhyolite flows and tuffs with interbedded shales, radiolarian cherts, greywackes and lenticular coral limestones. In the Mt. Etna area the series is invaded by serpentine.

The Upper Devonian Barraba Series in the Great Serpentine Belt lies immediately to the west of the Tamworth Series, with which its structural relations are not quite clear. The lower part of the series consists of agglomerates, breccias and keratophyric tuff with lenses of banded radiolarian chert and flows of spilite.

The radiolarian cherts of the Silverwood Series grade upwards through shales with chert bands into intensely crumpled and contorted shales. These may perhaps ascend to the Upper Devonian, but they have yielded no significant fossils.

NEW ZEALAND

The Waipapa Group in northern New Zealand (Kawau Island, Tawharanui Peninsula) consists of argillites, greywacke sandstones, red, brown and grey banded cherts and jaspilites, and also spilitic lavas with limestone lenses commonly associated with deposits of manganese oxide (HOPGOOD, 1961). A thickness of approximately 8500 ft is estimated for the group in this area.

Cherts and jaspilites occur in bands 1–3 in. in thickness making up composite bodies as much as 200 ft thick.

The rocks of the Waipapa Group may be classified as typical eugeosynclinal deposits. It would seem that the bulk of the Waipapa Group of sediments was formed in the moderately deep waters of a late Paleozoic or early Mesozoic mobile geosynclinal belt, the axis of which ran parallel to the present east coast of the North Auckland peninsula.

In the northern part of the South Island opposite Wellington a sequence consisting of spilites, altered dolerites and camptonites associated with unfossiliferous ?Upper Jurassic greywacke-argillite-chert, is found in the Cape Palliser area (CHALLIS, 1960). The spilitic laves, which show well-developed pillow structures, occur as several flows separated by thin bands of greyish-green or red chert.

NORTH AMERICA

Ordovician cherts (State of New York)

Ordovician cherts occur in the eastern part of the State of New York (RUEDEMANN & WILSON, 1936). They are found at many places within the slate belt that extends from Washington County to the Highlands of the Hudson, on both sides of the river, and are commonly associated with shales, and not with the arenaceous or arkosic members of the formation in which they occur.

The lowermost zones of cherts are of Deepkill age, as shown by the occurrence of *Didymograptus nitidus* and several beds of *Phyllograptus* in the chert, or associated with it. The graptolites indicate that the Deepkill chert is in the upper part of the formation. The Normanskill beds, younger than the Deepkill, consist of shale, grit, sandstone, chert, arkose, and conglomerate, ranking in the order named. Their thickness is probably 2000 ft. The extremely complicated structures of normal and reverse faults, pinched and overturned folds, obliterate everywhere the original sequence of beds over any considerable vertical range.

The cherts are of various colours. The Deepkill chert is grey-green, and the Normanskill chert is found in associations of black and green, red and green, as well as black alone and green alone.

The Ordovician chert beds have no fossils except radiolarians, graptolites, sponge spicules, and some problematica. The radiolarians are found in great abundance and often completely compose some of the beds.

RUEDEMANN & WILSON (1936, p. 1563) conclude that the presence of small amounts of clastic material in the chert, the occurrence of the chert only with pure graptolite shales, the presence of fossil radiolarian genera, today characterised by deep-water habitat, and the presence of zones of radiolarite are indicative of a deep-sea origin of some of the cherts. The bottom of the Appalachian geosyncline, where the cherts were deposited, is considered to be at abyssal depth.

Carboniferous cherts (Independence Range, Nevada)

Rocks of eugeosynclinal origin in the northern Independence Range, Elko County, Nevada (FAGAN, 1962) compose the Schoonover Formation, which is, in part, Mississippian. The rocks, allochthonous with respect to a Carboniferous and Cambrian terrain of miogeosynclinal facies, have been folded and thrust from the north-west during the late Mississippian or post-Mississippian. Principal rock types include argillaceous lutites, bedded cherts, arenites and conglomerates, and andesite lavas.

The bedded cherts appear to have been pelagic accumulations of siliceous organic debris, mostly radiolarian fragments, on the sea floor. Bedded cherts grade from those clearly composed of solid organic debris to those in which the finer radiolarian fragments have merged into a featureless silica continuum. Partial solution and interstitial crystallisation during diagenesis and accompanying compaction are considered the essential mechanisms of lithification.

The arenites show graded bedding and flute casts and consist mainly of poorly sorted, poorly rounded quartz grains and once-argillaceous, finer material. They are turbidites intermittently deposited by currents from the west. The cherts are products of flourishings and settlings of siliceous plankton. Layers of pebbly mudstone record chaotic submarine slides into the relatively deep-water site of sedimentation. The source of the turbidites and slide deposits was a tectonic land not far to the west, composed of rocks formed in the eugeosyncline.

Upper Jurassic-Cretaceous cherts (California and Oregon)

Radiolarian cherts belonging to the Franciscan Group are widely distributed and attain a great thickness in the Coast Ranges of California and south-western Oregon (TALIAFERRO, 1943). The geosyncline in which they were deposited was more than 700 miles in length and probably more than 100 miles in width. The name Franciscan implies a lithologic assemblage characterised by arkosic sandstones, radiolarian cherts, pillow lavas, basic and ultrabasic intrusives, and pneumatolytic metamorphics (glaucophane and related schists).

Genesis, age and field relationships of the Franciscan Group were discussed by a great number of authors. DAVIS (1918) has given a complete and comprehensive account on the radiolarian cherts of the Franciscan Group. His paper became classical not only because of his meticulous analysis of known facts, but also by the originality of his experiments (chert stratification in vitro) and his lucid theoretical considerations on chert genesis. Taliaferro produced a number of excellent papers on the same subject. Attention is drawn to his well-known publication on the Franciscan-Knoxville problem (TALIAFERRO, 1943), which gives a full list of bibliographic references. IRWIN (1957) and DURHAM & JONES (1959) contributed to the age problem of the Franciscan Group, and HSU (1958, p. 320), in contrast to DAVIS (1918) and TALIAFERRO (1943), considers the rocks in the Coast Range of California to be of deep-water origin.

Cherts occur here and there in the lower part of the Franciscan Group, interbedded with sandstones and associated with the few volcanics, but it may be stated categorically that the maximum development of the cherts coincided with maximum volcanism. In many places the cherts are directly associated with pillow basalts, although they may occur with any type of volcanics; they are more commonly associated with flows and tuffs than with volcanic breccias and agglomerates (TALIAFERRO, 1943, p. 147). DAVIS (1918) concluded that the silica of the cherts was introduced to the sea floor by siliceous springs accompanying volcanism. TALIAFERRO (1933) pointed out that, in addition to the silica from submarine springs, a considerable amount might have resulted from the interaction of hot lava and sea water. Whatever the mode of introduction of the silica, the volcanics appear to have been its original source.

The cherts are rhythmically banded with shales which usually have the same colour as the cherts; red cherts are interbedded with red shales and green cherts with green shales. The colours of the cherts vary from white through various shades of pink and red to deep red, red-brown, and chocolate-brown, and from white through shades of pale green to dark green; sometimes they are yellow, yellow-brown, or buff, and very rarely they are black (TALIAFERRO & HUDSON, 1943, p. 227). No regularity was observed in colour variation in the lenses of rhythmically bedded cherts and shales. Radiolaria occur in cherts of all colours, but they stand out most clearly in those in which iron and manganese oxide are most abundant.

Volcanics appear to be the original source not only of the silica, but also of the iron and manganese so commonly associated with the chert.

There are numerous intrusions in the Franciscan Group almost throughout its extent. Several different petrographic types are represented, but the most common is serpentinised peridotite. The peridotites are accompanied by gabbros and diabase.

TALIAFERRO (1943, p. 186) believes that an estimated thickness of 25,000 ft for the Franciscan Group is not excessive.

Both DAVIS (1918) and TALIAFERRO (1943) produce many arguments in favour of a shallow water origin for the radiolarian cherts.

The age of the Franciscan-Knoxville rocks, including associated igneous, is assumed to be late Jurassic by TALIAFERRO (1943, p. 219). IRWIN (1957), however, states that fossils ranging from late Jurassic to early Cretaceous have been found in the Franciscan Group. DURHAM & JONES (1959) discovered fossils in rocks previously assigned to the Franciscan, which are indicative of late Jurassic (*Buchia piochii*), Turonian (*Inoceramus labiatus*) and Campanian (*Inoceramus schmidti*), but they emphasise that the relationship to Franciscan rocks in San Francisco, generally regarded as the type locality, is unknown.

The author, accompanied by D. SEARS and W. V. MILROY, visited a few outcrops of Franciscan rocks in the San Rafael Mountains (Coast Range). A chaotic mixture of serpentine, fractured diabase or spilite with obliterated pillow-structure, dark grey shales, dirty brown sandstones and a chert-breccia was observed along road-cuts. The writer was inclined to interpret these rocks as an ophiolite-sedimentary flow association, and is now very doubtful with respect to the validity of the arguments in favour of the shallow-water origin of the Franciscan cherts and associated rocks. From literature study and his own experience, the author thinks that the slope-eugeosyncline concept of KÜNDIG (1959) seems to be compatible with many observed facts, and could probably be applied to part if not all of the Franciscan rocks.

GUATEMALA

Green radiolarian cherts of ? Albian age associated with ophiolites are reported from the Jalapa area north of Pedro Pinula. This information is drawn from unpublished reports by H. H. WILSON and H. F. JANSEN.

COLOMBIA

Eocene and Lower Oligocene rocks of the Costal Cordilleras in Colombia (GANSSER, 1959), which were deposited during periods of ophiolitic extrusions, are characterised by a high silica content. A connection between silicification and basic igneous rocks can be assumed.

Diabase with small intercalated chert beds occurs in the mountain range of the Central Cordillera (NELSON, 1956, p. 41). A Middle and Upper Cretaceous age is ascribed to the diabase.

Paleocene black cherts and greenish sandstones in the Rio Tulua area are associated with greywacke (NELSON, 1956, p. 43). The cherts often have a fine sandy appearance and probably cannot be regarded as true radiolarian cherts.

U.S.S.R.

Siliceous shales, cherts and radiolarian cherts, which range from Ordovician to Devonian, are found in the Ural Mountains.

Upper Ordovician siliceous shales passing into radiolarites (part of the Bardym Group) attain a thickness of 350 m. Graptolites such as *Climacograptus* sp. are present in this sequence (OVECHKIN, 1959, p. 257).

Silurian and Devonian cherts and siliceous shales occur on the eastern slopes of the Ural. They are hundreds of metres thick, often show a red to pink colour and occasionally contain a high manganese concentration. Graptolite-bearing siliceous rocks are often found associated with diabase-albitophyres (OVECHKIN, 1959, p. 294). The silica concentration is ascribed to the accumulation of tests of radiolaria and to volcanic activity (NALIVKIN, 1962).

In the Altai-Saian province (Kalba) the Upper Silurian is represented by argillites, siliceous rocks and red cherts (OVECHKIN, 1959, p. 308).

3. Remarks on the chert problem

A comprehensive and exhaustive discussion of the chert-associated sediment-ophiolite problem is beyond the scope of the present article. A few remarks will be made only on time-stratigraphic, paleogeographic, petrogenetical, sedimentological and structural aspects of these rocks, which follow from a review of their world-wide occurrences, and which are more intended to stimulate interest rather than to present solutions to the problem.

A. THE STEINMANN TRINITY

In 1905, STEINMANN emphasised the association of deep-sea deposits such as radiolarian chert, deep-sea clay and cherty limestone («Radiolaritkalk») with ophiolites. Twenty-two years later, STEINMANN (1927, p. 640) pointed out that three ophiolite members, serpentinite (peridotite), gabbro and diabase-spilite (including variolite), usually occur together with radiolarian cherts and deep-sea clays, tintinnid-bearing limestones, and shales (argille scagliose) and argillaceous limestones. Although STEINMANN did not introduce a name to describe the three ophiolitic and the three sedimentary members, it would be logical to call them the «Steinmann Ophiolitic Trinity» and the «Steinmann Sedimentary Trinity». In the literature the term «Steinmann Trinity» is not always used in this sense. KÜNDIG (1956, p. 109), for example, called serpentine, pillow lavas and radiolarites the «Steinmann Trinity», which was a rather liberal interpretation of STEINMANN's original thinking. In the light of present knowledge, it would appear that a new nomenclature should be introduced to incorporate the variety of rock-types found in a slope-eugeosynclinal environment. Terms such as Ankara Melange (BAILEY & McCALLIEN, 1953) and Coloured Melange (GANSSER, 1955, p. 286), although useful and concise, cover one aspect only of ophiolitic-sedimentary associations and, moreover, are not precise enough in their meaning to anyone not thoroughly familiar with the subject.

In order to group together different lithologies and other characteristic phenomena, the following nomenclature scheme is proposed:

	Prefix	End of word
a. Radiolarian cherts, cherts, interbedded shales		-silite
b. Limestones, marly limestones, marls, and shales	carbo-	
c. Breccias, greywackes, sandstones, shales	clasti-	
d. Ophiolites	ophio-	
e. Turbidity phenomena	turbi-	
f. Slumping, sliding	slumpi-	
g. Olistostromes, olistoliths	olisto-	

Ophio should always be used at the beginning of a composed word, silite at the end. Turbi, slumpi, and olisto should be inserted between ophio and carbo or clasti and silite where necessary. Composed words should only be used to designate associations which are more or less synchronous.

Examples:

	Suggested name
Radiolarite-carbonate association in southern Switzerland and northern Italy	Carbo-silite
Ophiolite-chert association in France	Ophio-silite
Ophiolite-olistostrome-chert association in southern Iran	Ophio-olisto-silite
Ophiolite-radiolarite-greywacke-shale association in eastern Australia	Ophio-clasti-silite

B. TIME-STRATIGRAPHIC RELATIONSHIPS AND RELATED PROBLEMS

Geological age-dating of radiolarian cherts and ophiolites is a challenging problem, which in many cases may never be solved satisfactorily. This is especially true in tectonically complex areas and in Coloured Melange-type (ophio-olistosilite) outcrops. Even in undisturbed and easily accessible sequences, a subdivision into stages or sub-stages is hardly possible. Age assignments in literature, therefore, are usually rather generalised (e.g. Jurassic, Upper Cretaceous, possibly younger), or, if more evidence is available, indicate a lower and an upper time limit (such as post-Bajocian and pre-Upper Tithonian).

a. Age-dating of radiolarian cherts. Radiolarian cherts usually contain no fossils except radiolarians, sponge spicules and some problematica. Since HAECKAL's (1887) classical monograph on the radiolarians collected by the Challenger Expedition and RÜST's (1885, 1888, 1891–92) papers on fossil Mesozoic radiolarians, a number of contributions to the radiolarian problem have been made, among which the following should be mentioned: HINDE & FOX (1895), HINDE (1899), RUEDEMANN & WILSON (1936), ABERDEEN (1940), KOBAYASHI & KIMURI (1944), DAVIS (1950), CAMPBELL (1954), and ELLIOTT (1959). ELLIOTT's (1959) work on various Triassic, Jurassic and Cretaceous radiolarian faunas from sections in Iraq and elsewhere in the Middle East, confirms the existing view that as indicators of age, without associated evidence, these fossils as commonly preserved are of little use, but that in local and regional problems where they are associated with other evidence, they may be of considerable stratigraphic value. These remarks summarise clearly the stage of our present knowledge on radiolarians as time indicators. RIEDEL and FUNNELL (1964), who examined Tertiary sediment cores and microfossils from the Pacific Ocean floor, state that age assignments based on calcareous nannoplankton and radiolarians cannot at present be so precise as those based on the planktonic foraminifera. This appears to be principally a function of the amount of research into stratigraphical distributions that has been carried out and published on the various microfossil groups, rather than of any fundamental differences in the rates of evolution and geographical dispersal of the members of the three groups. Fossil radiolarians as contained in radiolarian cherts are usually poorly preserved, and it is doubtful whether intensified research would shed much new light on the stratigraphic value of these fossils without taking into account additional evidence.

Radiolarian cherts are often interbedded with shales, marls and limestones, which contain diagnostic fossils such as graptolites, belemnites, aptychi and foraminifera. Graptolites usually enable an accurate age determination to be made. The time-range of belemnites and aptychi is somewhat wider, but provides such age assignments as Kimmeridgian-Tithonian. Foraminifera, if not re-worked, are often excellent age indicators, especially for Upper Cretaceous chert formations.– Type-fossils, however, are normally found only in parts of a chert sequence, and therefore do not indicate the time range of the complete sequence.

Chert sequences, which are conformably overlain and underlain by type-fossil-bearing strata, can be fairly well dated, although some minor uncertainties still remain to be solved. Well-dated chert formations in this sense are, for example, those occurring in Morocco, southern Switzerland, northern Italy and Poland. One of the difficulties, however, is to assess whether the transition of the top and bottom layers of a chert formation into fossil-bearing strata, which often consist of limestones and marls with chert nodules, is continuous or discontinuous. A clear-cut answer to this problem cannot be given, as sedimentary conditions in a eugeosynclinal environment are not fully understood.

Radiolarian cherts in Mediterranean areas are usually overlain by tintinnid-limestones, which are generally of Upper Tithonian-Berriasian age. Thus the upper time-limit of the cherts can be fixed as lowermost Upper Tithonian or Lower Tithonian. If a more refined tintinnid stratigraphy were available, a more accurate age assignment of the uppermost part of the Mediterranean chert sequence could be made. A comparison of recent work on tintinnids by DOBEN (1962), BOLLER (1963) and REMANE (1964) shows slightly divergent interpretations of their time range. Further research on a regional basis could probably straighten out these differences.

Isolated chert lenses, which are often found as part of an ophio-olisto-silite, cannot be dated without proper regard to their complex field relationship. In a chaotic block mixture, the age of the blocks is not indicative of the age of the cherts. The Mammonia Formation of Cyprus is a striking example of an erroneous age-dating of the cherts on fossil evidence in an olistolith.

b. Age-dating of ophiolites. Dating the ophiolites in relation to cherts and associated sediments still remains a difficult task. Literature evidence on this subject is usually vague, and age assignments such as «pre-Tertiary, probably Mesozoic», or «Jurassic, possibly younger», are often made. KÜNDIG (1956) does not

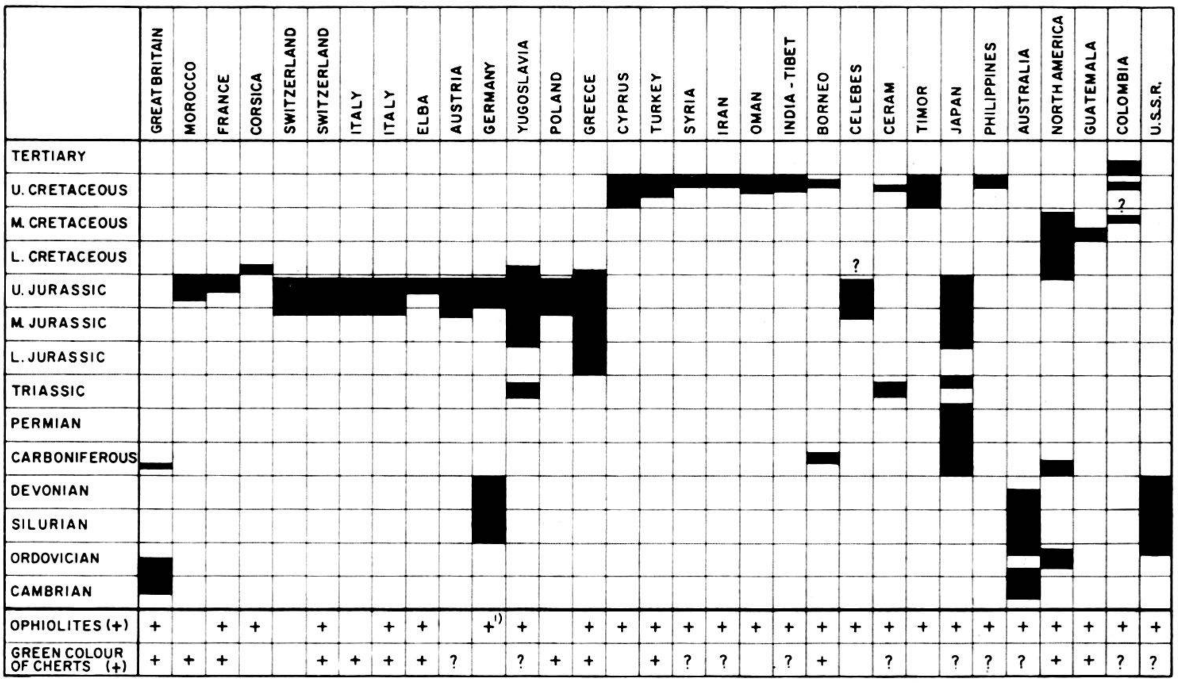

Fig. 5. Geological age of radiolarian cherts, association with ophiolites, and green colour of cherts. This is a simplified version of Plate I.

[1]) Palaeozoic cherts only are associated with ophiolites.

believe that an ophiolitic catastrophe is repeated in an orogenic cycle and therefore considers it improbable that a wide variance in age could exist in the ophiolitic belt of the alpine orogenic system. STILLE (1940b) relates intrusions and extrusions of ophiolites to an initial, simic, geosynclinal phase of magmatism. From a regional comparison of the eugeosynclinal parts of the Tethys geosyncline, an Upper Jurassic and Upper Cretaceous emplacement of the ophiolites could be postulated (see Table 1). It seems, however, that factual evidence is still more convincing than any speculation. What then are the facts?

The upper age-limit of an ophiolite emplacement can be fixed by normal superposition of well-dated sediments or by ophiolite detritus found in associated, younger sediments, which contain diagnostic fossils or which can be compared with sediments of known age. Overlap of Maestrichtian sediments on ophiolites can, for example, be observed in Turkey (KÜNDIG, 1959) and Oman (MORTON, 1959). Sediments containing ophiolitic detritus are reported from Switzerland (GRUNAU & HÜGI, 1957; GEES, 1955), Italy (GÖRLER & REUTTER, 1963; V. D. WAALS, 1946), and other places. GRUNAU (1957 a, b) produces evidence that the green colouration of radiolarian cherts in the south-eastern part of Switzerland (Arosa area) is partly due to fine serpentine detritus. Trace element investigations (GRUNAU & HÜGI, 1957) corroborate this point of view. The world-wide, frequent association of ophiolites with green cherts (Fig. 5), as far as is known to the author, has not been studied in detail. Although it is premature to advance a theory which is not based on a number of reliable observations, it would seem to the writer that the green colour of chert occurrences in California, France, Elba, Italy, Yugoslavia, Greece, Turkey, and Borneo might be caused partly or wholly by ophiolitic particles. This would provide means of dating the upper time-limit of ophiolitic emplacement. The identification of the nature of these particles could help in determining the relative age of different rock types of the ophiolitic suite. It would, of course, be tempting to interpret the absence of green colouration in a chert sequence as evidence that the ophiolites are younger than the cherts. In Oman, for example, this argument might be used to prove that the Semail Ophiolites are younger than the Hawasina Cherts. The author, however, is not inclined to believe that such negative reasoning is really convincing.

The lower age-limit of ophiolites could be established, in theory, from low-grade thermo-contacts with well-dated sediments (GRUNAU, 1947b). Such contacts, where observed, cannot always be interpreted unambiguously. Undisturbed superposition of ophiolite flows on sediments usually gives some indication of the lower time-limit of the ophiolite emplacement. Good examples are known from Syria (DUBERTRET, 1955) and Oman (MORTON, 1959).

The stratigraphic range of radiolarian cherts, associated sediments and ophiolite emplacement, as shown in Table 1 has to be regarded in the light of the aforementioned critical remarks. Time relationships of these occurrences in Europe, the Middle East, Australia and North America seem to be fairly well, although not yet entirely satisfactorily, established. Much work still remains to be done in the Far East, South and Central America in order to eliminate the existing gaps of knowledge and the uncertainties.

C. PETROGENETICAL RELATIONSHIPS

The association of basic and ultra-basic igneous rocks with radiolarian cherts is so common (see Fig. 5), that the few chert occurrences not related to ophiolites, as observed in the western part of the Mediterranean Tethys geosyncline, can be considered exceptions of a general rule. It is, therefore, not surprising that views and hypotheses on petrogenetical relationships between cherts and ophiolites have been expressed by a great number of authors. As early as 1880 Pantanelli concluded that pillow lavas extruded at the sea-bottom during the deposition of chert and thereby created conditions which destroyed the natural animal enemies of the radiolarians, so that only the latter survived. This is probably the first, albeit somewhat fantastic attempt towards an interpretation of the chert-pillow lava association. LOTTI (1886) believed that during the final phase of ophiolitic extrusions silica- and soda-rich sources originated, which silicified already deposited, originally clayey sediments and at the same time stimulated enormously the development of radiolarians. STEINMANN (1905), one of the first geologists to emphasise the frequent association of ophiolites and cherts, thought that the abyssal sediments such as chert, deep-sea clay and pelagic limestones, were older than the basic and ultra-basic igneous rocks. The magmatic intrusion took place during a phase of uplift of the abyssal sedimentary trough. These early views by PANTANELLI, LOTTI & STEINMANN stressed two fundamental relationships of a chert-ophiolite association, namely the supply of silica and other elements to the sea-water as characteristic for differentiation processes of ophiolitic magmas, and the tectonic history of the basin. The many authors who have contributed to an explanation of the chert-ophiolite association, have produced additional evidence for these fundamental aspects.

The petrogenetical relationships of cherts and ophiolites, especially the problem of material supply, are treated by DEWEY & FLETT (1911), TALIAFERRO (1933), TALIAFERRO & HUDSON (1943), BURRI & NIGGLI (1945), BRAMLETTE (1946), ROUTHIER (1946), GRUNAU (1947 a, b), GEIGER (1948), WENK (1949), CORNELIUS (1951), GRUNAU (1957 a, b), GRUNAU & HÜGI (1957), CONTI (1958), IRELAND (1959), KRAUSKOPF (1959), and NEBERT (1959), apart from remarks and further contributions to the subject contained in papers of more regional interest.

Ophiolite emplacement in relation to eugeosynclinal basin history was discussed especially by STEINMANN (1927), STILLE (1940b), KÜNDIG (1956, 1959), and TRÜMPY (1958b, 1960).

The following remarks on chert-ophiolite associations resulting from the present world-wide review and the author's own experience are not intended to present an exhaustive discussion of the problem.

It would seem appropriate to tackle the chert-ophiolitic problem by attempting to establish mutual time-relationships before any further conclusions are drawn. In structurally complex areas, as for example in eastern Timor, ophiolites and cherts occur in close vicinity. The ophiolites, however, are of Permian or even pre-Permian age, and the cherts, belonging to the Bibiliu Group, are considered to range from ?Upper Cretaceous to Tertiary. No mutual relationship therefore exists, unless it could be proved that Tertiary magmatism took place. In many parts of the world, as for example in Ceram, Celebes, the Philippines, Borneo, and Colombia, no entirely satisfactory age assignment can be given to the ophiolites. Any assumption of silica supply in connection with ophiolitic extrusions in these areas would, therefore, seem highly speculative. In Syria, Turkey, Iran and Oman, good arguments can be advanced to prove that cherts and ophiolites are at least partly synchronous, and the silica could, in this case, have originated from a magmatic source. Ophiolite extrusions and intrusions probably took place in more than one phase in parts of Italy and Switzerland. Upper Jurassic cherts are associated with Jurassic serpentine, and the spilitic pillow-lavas are probably Middle to Upper Cretaceous. Serpentine particles are found in cherts and produce the green colouration of some of them. To what extent silica was supplied, still remains an enigma.

Observations made in Elba, Germany (Devonian and Silurian cherts) and other places, point to a direct relationship between ophiolite and chert thicknesses, which can best be explained by silica exhalations in connection with ophiolite extrusion. In Oman and Iran, the chert facies is restricted to ophiolite occurrences. Synchronous marls and shales are found more distant from any ophiolite influence.

Differentiation of a spilitic magma rich in carbon dioxide, water, other volatiles and soda, may lead to the formation of an end-member rich in silica and soda and other differentiation products rich in iron and manganese (DEWEY & FLETT, 1911; WENK, 1949). These hydrothermal silica-rich and soda-rich solutions and vapours emanate into sea-water, where they trigger off the inorganic precipitation of silica, and create favourable conditions for the development of siliceous organisms. According to NEBERT (1959, p. 14) silica-rich emanations originating also from arrested ultra-basic intrusives could rise along fissures and extrude into sea-water. This differentiation theory would account for the association of synchronous pillow lavas and serpentines on the one hand and siliceous sediments on the other. Inorganic precipitation of silica and silicification of bottom sediments would be the result of silica-rich emanations into sea-water, irrespective of bathymetry. Stimulation of the growth of radiolarians, however, seems only conceivable if the majority of them are forms which live close to the sea-bottom. Silica-rich emanations in deep water, for example, may hardly have any influence on radiolarians living at shallow depths. Determination of the depth range of radiolarians found in cherts, therefore, would be important in proving whether the silica supply theory, in connection with differentiation processes in ophiolitic magmas, can be applied to certain cases. As, however, the depth range of fossil radiolarians can only be established by comparison with recent species, any depth range assigned to fossil radiolarians is of restricted validity, since the depth ranges of fossil and recent radiolarians may not necessarily be identical.

The theory of decomposition of silicate minerals originating from eroded ophiolite bodies as a source of silica would be applicable in many cases, although its mechanism is not yet understood.

Carbon dioxide exhalations in connection with magmatic differentiation could explain the absence of carbonate in many chert sequences.

Hydrothermal solutions rich in iron and manganese may account for hematite and manganese concentrations in cherts. The majority of the hematite found in cherts, however, is probably derived from ferritic products of weathering in the source area, which were possibly altered at the place of deposition.

The pre-orogenic relationship between cherts and ophiolites as outlined by KÜNDIG (1956, 1959) and TRÜMPY (1960) seems to have a world-wide application. In the Tethys geosyncline, which extends from western Europe to the Indonesian archipelago, for example, ophiolites usually occur on continental slopes and continental edges. The prevalence of tensional stresses in the areas between the continental shelf and the deeper, eugeosynclinal parts may have led to the development of fissures, along which the rise, intrusion and outflow of ophiolitic magma took place. This could have happened during an initial, intermediate or final phase of a eugeosynclinal stage, which in itself may have extended through geological periods or may have been as short-lived as an epoch (for example: Upper Cretaceous in Oman), preceded and succeeded by miogeosynclinal stages. The mechanism of ophiolite intrusion and its relationship to extrusive phenomena is still somewhat controversial, and will not be discussed here. The author would not deny that ophiolites may also occur in areas not related to continental slopes.

From the foregoing the impression is gained that the chert-ophiolite petrogenetical relationship is one of the most challenging, but still imperfectly understood problems of geology and petrology.

D. SEDIMENTOLOGICAL ASPECTS

The colour of radiolarian cherts, the carbonate proportion in a chert sequence, and the association of turbidites with radiolarites merit special attention in a regional context. Problems of a more specific nature such as diagenetic processes

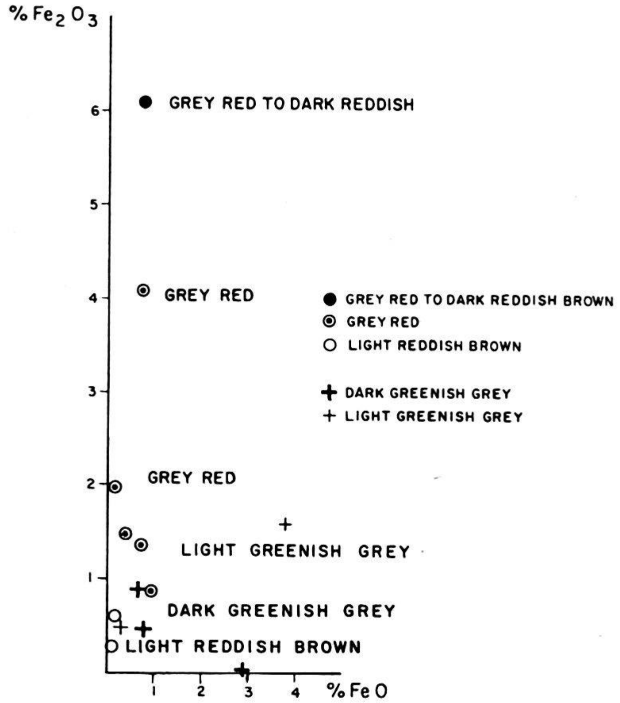

Fig. 6. Ferric-ferrous iron content in relation to colour of chert. Analyses by Grunau, Hügi and Rüfenacht (GRUNAU, 1959).

(IRELAND, 1959; GIANNINI, PIERUCCINI & TREVISAN, 1950) are not within the scope of this paper.

Colour. One of the most characteristic features of a chert sequence is its wide variety of colours, ranging from all shades of grey-red, red and reddish brown over dark green, light green, greenish grey to white-grey, dark grey and black, apart from the brown, orange and purple hues which occasionally occur. The relationship between colour on the one hand, and mineralogical and chemical composition on the other hand is not yet fully understood. Chemical analyses or partial analyses, especially of the ferric and ferrous iron content, are rather scarce (DAVIES, 1918; NIGGLI, DE QUERVAIN, & WINTERHALTER, 1930; GRUNAU, 1959) and do not provide a comprehensive answer to the colour problem. Mineralogical analyses of cherts are found sporadically in literature, but accurate colour descriptions of cherts in relation to chemical analyses and mineral content are practically non-existent. Fig. 6, which is based on analyses by GRUNAU, HÜGI and RÜFENACHT (GRUNAU, 1959, p. 126), clearly shows that light red hues become gradually darker with increasing ferric iron (hematite) content. Green colours are due to ferrous minerals such as chlorite. A comparatively high ferrous and low ferric iron content produces dark green colours. A rather astonishing fact is that cherts having almost the same ferric-ferrous iron content can be either red or green. The red or green rock colour is in such cases determined by the relative size and the density of the colour pigment.

The possible derivation of pigment in red beds is fully discussed by VAN HOUTEN (in NAIRN, 1961). Four main possibilities are considered:

1. Erosion of red soil containing anhydrous ferric oxide pigment.
2. Erosion of red bedrock containing anhydrous ferric oxide pigment.
3. Dehydration of goethite, aging of hydrohaematite, alteration of ilmenite-magnetite or biotite.
4. Precipitation of anhydrous ferric oxide or of hydrated ferric oxide later dehydrated.

VAN HOUTEN's review refers to continental and shallow marine red beds. The author would like to add a few remarks on eugeosynclinal red beds, although he is not in a position to make any straightforward nor yet definite statements:

Chert sequences deposited in the Tethys geosyncline are predominantly red. Their age is usually Upper Jurassic in the Mediterranean area and Upper Cretaceous in the Near and Middle East and south-eastern Asia. Upper Jurassic and Upper Cretaceous in the Tethys belt were periods of moist tropical or subtropical climate. Ferric oxide probably originated in red upland soils, and was subsequently washed into the Tethys geosyncline. Oxidising conditions at the bottom of eugeosynclinal basins preserved the red colour.

Red colours are reported from Palaeozoic chert sequences in Great Britain, Germany, the Urals, Eastern Australia, and North America. From literature evidence it is not clear to what extent the red colour is present, but it appears that the same palaeoclimatic reasoning as above could be applied for Ordovician, Silurian and Devonian red cherts.

Hydrothermal solutions connected with ophiolite extrusions might be an additional source of ferric iron. The author, however, is inclined to believe that the original source of hematite is from lateritic weathering on a mainland, since cherts which are not associated with ophiolites also show red colours.

The possible origin of green colour minerals is an even more delicate problem than the derivation of red pigment. In a few cases (see p. 42) it can be shown that ophiolitic particles cause the green colour of cherts. This, however, is not a general rule, and considerably more investigation is required before a more precise explanation can be given.

Carbonate proportion in a chert sequence. Only a few chert sections are accurately described in literature, so that little reliable data is available with regard to the carbonate-silica proportion of chert sequences in general, especially if they occur together with ophiolites. The hypothesis of carbon dioxide exhalations in connection with basic magma extrusion, which would have kept calcium carbonate in solution, undoubtedly appears attractive in order to account for the lack of, or small percentage of, carbonates in a number of chert sections all over the world. Some cherts which are not associated with ophiolites, however, such as Upper Jurassic radiolarites in the Bavarian Alps, are practically carbonate-free, but probably due to different reasons. In this context, the results of modern deep-sea research in the Pacific Ocean are of special interest. In considering the general lithology of two middle Tertiary cores from the western tropical Pacific, OLAUSSON (cited in RIEDEL & FUNNELL, 1964, p. 308) tentatively concluded that the release of magmatic volatiles into the bottom-water might have been responsible for a decrease in the calcareous content in the upper part of one of these Tertiary sequences. RIEDEL & FUNNELL (1964) conclude that the absence of contemporaneous calcareous microfossils from pre-Quaternary sediments containing apparently indigenous siliceous microfossils can be interpreted in two ways: (i) either decalcification took place by submarine leaching, or (ii) it may be reasonable to assume that the sediment accumulated below the calcium carbonate compensation depth at the time of deposition.

For fossil radiolarian chert sequences free or almost free from carbonates, it could by analogy be argued that they were deposited below the compensation depth, which at present in the Pacific lies between 4000 and 5000 m. Carbo-silites on the other hand were in most cases deposited above the compensation depth of that time. Compensation depth in this context refers to the depth below which the rate of solution of calcium carbonate exceeds the rate of its supply to the sea floor.

The author is not inclined to attribute a minor value to the carbon dioxide exhalation theory in favour of the depth theory or vice versa. Both theories are applicable, have a high degree of probability and do not exclude each other.

The association of turbidites with radiolarites. Radiolarian cherts interbedded with coarse clastics and sandstones are known from many parts of the world (for example, from California, Switzerland, Austria, Cyprus, and Australia). Graded beds in breccias were also observed (GRUNAU, 1959, p. 90). Tectonic activity, followed by slumping and slow mass-gliding movements down the continental slope into the deeper parts of a eugeosynclinal basin, provides a most satisfactory explanation to account for the clasti-silite association, which is in line with modern thoughts on turbidites (BOUMA & BROUWER, 1964). These views were held by KÜNDIG (1959) and TRÜMPY (1960) in full appreciation of the meaning of turbidites. The writer can only corroborate this interpretation as a general principle of world-wide significance.

In 1964, the author observed graded-bedding in oolitic lime grainstone (Fig. 3) alternating with chert at the base of the Upper Cretaceous Hawasina Cherts in Wadi Miaidin on the south flank of Jebel Akhdar (Oman). The oolitic grainstone, which was deposited originally in very shallow water, must have been reworked and slid as a turbidite down the slope into the chert basin. A similar oolitic lime grainstone intercalated in red cherts was noticed by the author in the Kevan area in south-eastern Turkey, north-west of Diyarbakir, on an excursion with M. RIGO DE RIGHI and M. SHEPHERD.

KÜNDIG's (1959) schematic cross-section through a geosyncline at an early stage is a most valuable contribution to illustrate the relationship between shelf, slope and eugeosynclinal sediments, which in KÜNDIG's scheme are presented as being more or less syntemporaneous. In many cases, the isochronous slope equivalents of the radiolarian cherts are nowhere exposed or may even be non-existent. A turbi-slumpi-clasti-phase often precedes or succeeds the perennial eugeosynclinal phase, which is usually characterised by chert deposition. In southern Switzerland, for example, Liassic, Lower Dogger and lowermost Biancone Limestone show turbidity or slump phenomena, whereas no turbidity or slump characteristics can be observed in the Upper Jurassic radiolarian cherts. In southern Iran, the Upper Cretaceous ophio-olisto-silites of Makran are succeeded by an Eocene-Oligocene flysch sedimentation. Similar observations are known from many other parts of the world, e.g. Japan and New Guinea. A careful and detailed analysis of the chert-turbidite associations would provide valuable palaeogeographic indications of the shifting of major sedimentary basins in space and time.

E. BASIN CONFIGURATION AND BATHYMETRY

The present world-wide review of radiolarian cherts and associated rocks clearly demonstrates that radiolarian cherts were deposited in huge eugeosynclinal basins, flanked by continental slope and shelf regions. In the Tethys geosyncline, two major basins existed at different times: the Upper Jurassic Mediterranean basin and the Upper Cretaceous Middle East-Far East basin, which can be traced over a distance of thousands of kilometres. The extent of Palaeozoic eugeosynclinal basins was probably much less.

The two Tethys eugeosynclinal basins were differentiated into deeper zones and submarine swells which controlled sedimentation to a certain extent. The existence of systems of island arcs in the eugeosynclinal basins no longer seems convincing.

The absolute depth of eugeosynclinal basins is still a matter of speculation. The author would consider deposition in 1000–5000 m-deep water highly probable. In any case, all faunistic and sedimentological evidence points to an environment much deeper than neritic.

F. POST-OROGENIC TECTONIC POSITION AND STRUCTURAL STYLE

Radiolarian cherts and associated rocks usually occur in the internal zones of mountain systems. They are often part of structurally complex units, characterised by faulting, thrusting, gravity-sliding and large-scale overthrusting. Epi-metamorphism is also observed.

Vertical tectonics and gravity-sliding play a major role not only during the eugeosynclinal stage of a basin but also characterise the orogenic history. Major basinal downwarps in tectonically active zones are followed by major uplifts, and the extreme difference in relief is compensated by tectonics.

The chaotic puzzle presented by an ophio-olisto-silite is difficult to untangle, as basinal and orogenic history are closely interwoven. The incompetent structural style of a chert sequence can be interpreted as resulting from slumping in the basin, disharmonic folding due to compression or post-upheaval gravity-sliding. In most cases no really convincing argument can be produced in favour of any particular one of these interpretations.

Radiolarian chert-ophiolite belts have a structural style of their own representing a complex, comparatively short-lived eugeosynclinal phase of a long miogeosynclinal basin history. Where chert-ophiolites are exposed, the impression of major diastrophic events is created. It should not be overlooked that the structural style of older and younger sediments in the vicinity of ophio-silites is usually completely different. In some areas a simple anticlinal belt can hide a complex ophiolite-chert body, which itself can be underlain by large, competent folds. Ophiolite-chert associations can be considered therefore as crustal layers distinguished by a difference in their behaviour as a result of basinal and orogenic deformation as compared to the overlying and underlying strata of different lithologic composition.

4. Conclusions

From a world-wide literature review of radiolarian cherts and associated rocks and the author's personal experience, the following conclusions may be drawn:

1. The impression is gained that radiolarian cherts and associated rocks, in comparison with continental and shallow marine sediments, have been inadequately investigated and are not fully understood. Many uncertainties regarding their petrographic characteristics, geological age, field relationship and genesis still exist, so that an attempt at even a partial synthesis of the chert problem seems premature. In this context the following remarks have to be considered.

2. Radiolarian cherts and associated sediments such as pelagic limestones, siliceous shales, graded lime-grainstones, sandstones, greywackes and coarse clastics, which occasionally show graded bedding, were deposited in the eugeosynclinal part of major geosynclines. In accordance with KÜNDIG's views, the eugeosynclinal sedimentary fill can be subdivided into perennial cherts, pelagic limestones and siliceous shales, and catastrophic olistostrome-turbidite rocks. Sedimentological and faunistic evidence points to deposition in rather deep water, thus confirming concepts held by MOLENGRAAFF (1900), the STEINMANN school, and more recently by COLOM (1955), KÜNDIG (1959), TRÜMPY (1960) and others.

3. Ophiolites are found together with radiolarian cherts on a world-wide scale (see Table 1). Chert occurrences not associated with ophiolites are rather the exception to a general rule. In many cases it can be shown that ophiolites and cherts are syntemporaneous. A direct relationship between ophiolite thickness and chert thickness can often be observed and seems to confirm the long held view that silica was supplied in connection with the intrusion and extrusion of ultra-basic and basic magma. Other ophiolite-chert relationships are less obvious. KÜNDIG's view that ophiolites usually occur along hinge zones can be corroborated.

4. Radiolarian chert-ophiolite associations are known throughout the geological column from Cambrian up to Eocene-Lower Oligocene. Chert deposition is especially characteristic of the Upper Jurassic and Upper Cretaceous, and to a minor extent of the Ordovician, Silurian and Devonian. The predominantly red colour of Upper Jurassic and Upper Cretaceous cherts can be ascribed to hematite, which originated in red upland soils under a moist tropical and subtropical climate, and was subsequently washed into the geosynclinal basin. As the main periods of chert genesis, i.e. Ordovician, Silurian and Devonian, Upper Jurassic and Upper Cretaceous, were characterised by a tropical to subtropical, moist climate, the theory is advanced that there is probably a close relationship between tropical palaeoclimate, abundant growth of radiolarians in surface water and red colour of cherts.

5. Radiolarian cherts occur mainly in the eugeosynclinal parts of the Tethys geosyncline, which extends from south-western Europe to the Malayan archipelago. In the Mediterranean part of the Tethys, the radiolarian cherts are Upper Jurassic; in the Middle-East–Far-East part they are predominantly Upper Cretaceous. Mesozoic radiolarian cherts are also found in the Circumpacific Belt (California, Latin America, Japan, Philippines and New Zealand).

Palaeozoic radiolarian cherts occur in the Caledonian trough, the Ural geosyncline, the Tasman geosyncline, and sporadically in a few other Palaeozoic basins.

6. Radiolarian chert-ophiolite belts have a structural style of their own, which is due to differences in their behaviour as a result of basinal and orogenic deformation as compared to overlying and underlying layers of different lithologic composition. Vertical tectonics and gravity-sliding play a major role not only during the eugeosynclinal stage of a basin but also characterise the orogenic history.

7. Radiolarian cherts and associated rocks belong to a sedimentary-magmatic unit which is characteristic for the slope-eugeosynclinal phase of a major geosynclinal basin.

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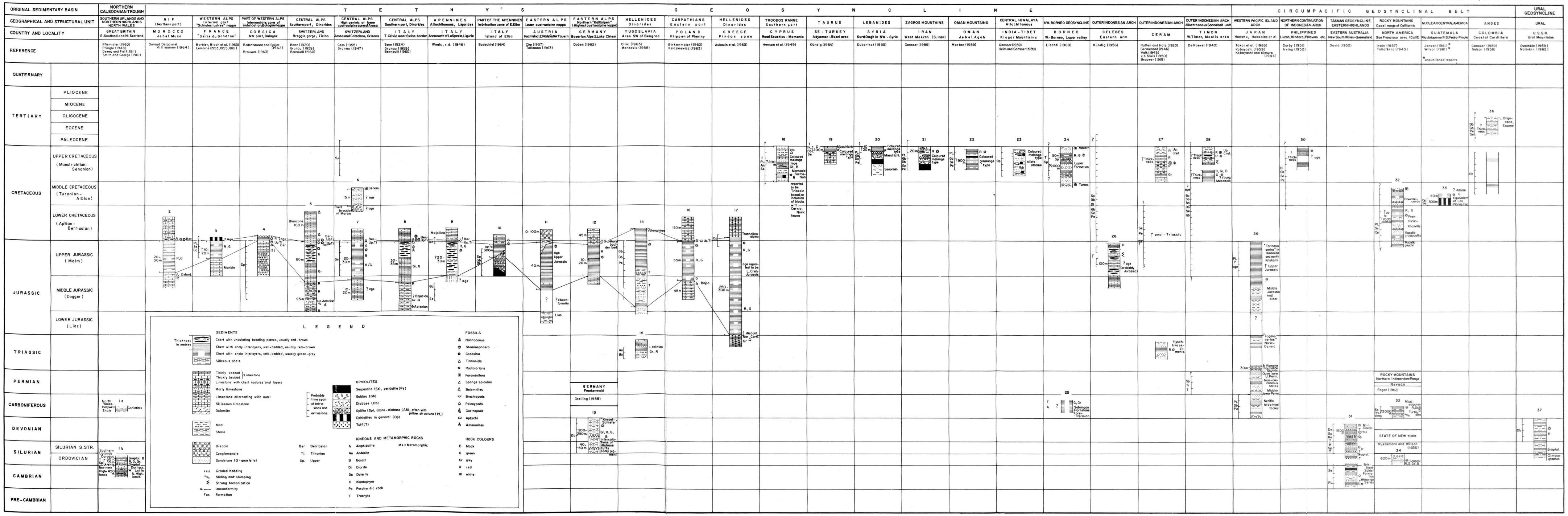

Stratigraphic and geographic distribution of selected radiolarian chert-ophiolite sections. — Not to scale