SEDIMENTOLOGY OF THE WEST
SICILIAN JURASSIC

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THESIS

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Rocca Busambra with Rocca Argenteria in the foreground. Western Sicily.

'Ammonitico rosso'. Upper Jurassic of Monte Bonifato, western Sicily.
IN PRAISE OF LIMESTONE

If it form the one landscape that we the inconstant ones
   Are consistently homesick for, this is chiefly
Because it dissolves in water. Mark these rounded slopes
   With their surface fragrance of thyme and beneath
A secret system of caves and conduits; hear these springs
   That spurt out everywhere with a chuckle
Each filling a private pool for its fish and carving
   Its own little ravine whose cliffs entertain
The butterfly and the lizard; examine this region
   Of short distances and definite places;
What could be more like Mother or a fitter background
   For her son, the flirtatious male who lounges
Against a rock in the sunlight, never doubting
   That for all his faults he is loved; whose works are but
Extensions of his power to charm? From weathered outcrop
   To hill-top temple, from appearing waters to
Conspicuous fountains, from a wild to a formal vineyard,
   Are ingenious but short steps that a child's wish
To receive more attention than his brothers, whether
   By pleasing or teasing, can easily take.

W. H. Auden
What means Sicilia?

Shakespeare: The Winter's Tale
SUMMARY

This thesis examines the petrology, geochemistry, and palaeoecology of the west Sicilian Jurassic deposits and, where possible, compares them to similar facies elsewhere in the Alpine-Mediterranean region.

The Liassic platform carbonates form the greatest part of the west Sicilian Jurassic in terms of thickness; these are a series of white limestones and dolomites whose shallow-water origin is suggested by the presence of such structures as Stromatactis, birdseyes, and shrinkage cracks - and the component lithologies which include pelletal, oolitic and stromatolitic facies. The modern Bahamian pattern of sedimentation compares well with the reconstructed depositional environment of these rocks.

Crinoidal limestones, which cap the Liassic platform carbonates, usually occur as discontinuous lenses, and these are interpreted as sand-waves deposited on oceanic seamounts - seamounts which were formed after the carbonate platform had disintegrated during the Lias. The Toarcian iron pisolites, which may also cap the white
Liassic limestones, are considered to result from volcanic emanations that accompanied this disintegration.

Fossil manganese nodules, which occur in condensed sequences of Middle Jurassic age, have been subject to detailed investigation, and these ancient concretions are comparable in their structure, mineralogy and geochemistry to Recent oceanic iron-manganese accumulations. The condensed sequences themselves - like the crinoidal calcarenites and the iron pisolites - are interpreted as seamount deposits formed as the presence of stromatolites, boring algae and herbivorous gastropods suggests, in shallow photic zones.

Seamount evolution in the Upper Jurassic followed two patterns: the seamounts either sank with the consequent formation of more basinal deposits such as red nodular limestones and radiolarites, or with possible uplift, were the site of more massive carbonate production, with the formation of oolitic and pelletal deposits. Finally, in the Tithonian and extending into the Neocomian, a more uniformly basinal coccolith ooze covered much of the area.
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INTRODUCTION
INTRODUCTION

The Tethyan Ocean lay between the ancient continents of Gondwana and Laurasia. During the Mesozoic this ancestral Mediterranean was the site of deposition of a variety of carbonate facies; dominated during the Trias by shallow-water white limestones, comparable to those now being formed in the Bahamas; by pelagic red, yellow and grey limestones during the Jurassic; and finally by oceanic oozes, like those of recent oceans, in the Cretaceous.

The Jurassic was a time of marked palaeogeographic evolution over the whole of the Tethyan region and rocks of this age exhibit a variety of facies; this is particularly true of western Sicily, which seems to have occupied as central a position in the ancient
FIG. 1. DISTRIBUTION OF MAJOR JURASSIC OUTCROPS IN WESTERN SICILY
(Modified from Wendt, 1969)
Mediterranean as it does today. The Jurassic of western Sicily shows negligible continental influence; nevertheless, these deposits are perhaps not 'oceanic' in the sense we use today.

The series of papers in this thesis aim to reconstruct the various sedimentary environments that characterised the different stages of evolution of the Mesozoic Tethyan geosyncline particularly over the area which is now western Sicily and also elsewhere in the Alpine-Mediterranean realm — and to compare these environments, wherever possible, to similar situations in recent oceans. Detailed palaeogeographic reconstructions of the west Sicilian Jurassic can only be made with reservations, however, since the present distribution of Jurassic outcrops (Figure 1) which occur on isolated mountains separated by Miocene clays, may not reflect their original depositional position — and many of the Mesozoic massifs may have suffered lateral transport. Some of the small outcrops are undoubtedly 'rootless'. Nevertheless, a general picture of the sedimentary history of the area can be obtained.

Chapter 1 deals with the white limestones (Trias to Lias) that compose most of the west Sicilian Mesozoic mountains, and the succeeding chapters describe
and interpret the various facies that overlie this deposit. Crinoidal calcarenites and the Toarcian iron pisolites are dealt with in Chapters 2 and 3, respectively. Detailed studies of the Middle Jurassic ferromanganese nodules are presented in Chapter 4, notes on Tethyan stratified manganese deposits in Chapter 5, and the sedimentology and palaeoecology of the west-Sicilian condensed sequences, in which the ferromanganese nodules occur, are outlined in Chapter 6. Chapter 7 deals with the various Upper Jurassic facies of western Sicily, and the 'conclusions', summarising the previous chapters, with some additional palaeontological information supplied by Dr. H. S. Torrens, have been written as a joint paper.
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CHAPTER 1

The Liassic Platform Carbonates of western Sicily
CHAPTER 1  

THE LIASSIC PLATFORM CARBONATES  
OF WESTERN SICILY

INTRODUCTION

During the course of work on the red pelagic limestones and associated deposits of western Sicily, certain observations were made on the underlying beds, and these are set out below. These rocks are of some interest since similar lithologies, of roughly the same age, have recently been described from a variety of places within the Tethyan region.

In western Sicily these deposits belong to the "Dolomia Principale" formation. This is composed of a thick sequence (greater than 2,000 metres) of light-coloured massive platform carbonates with no true reef structure. Their age is Triassic-Liassic and the lower part of the series is dolomitic. It is of this facies
that most of the west Sicilian Mesozoic mountains are built.

Megalodont bivalves occur commonly near the top of the succession in southern exposures, whilst these are absent at the same horizon in the north. Fossils of any sure biostratigraphic significance are, in fact, lacking in most outcrops, though some localities have yielded molluscan faunas of undoubted Liassic age.

Study of these limestones has been concentrated (Rocce Maranfusa) on a locality/where new investigations have shown the presence at one level of a Hettangian–Sinemurian ammonite fauna; similar facies, however, occur throughout western Sicily.

NOMENCLATURE AND PREVIOUS WORK

The name "Dolomia Principale" was applied by Di-Stephano (1912) to these massive carbonate sequences as they resembled similar formations in the Alpine region, particularly in Lombardy. This name is not entirely applicable since dolomite is entirely absent in the topmost part of the succession; however, it has historical precedent and emphasises the genetic relationship of these rocks to those elsewhere in Italy and in many other parts of the Tethyan realm.
All of the previous studies of these Sicilian limestones have been primarily palaeontological, pioneered by G. G. Gemellaro, during the latter half of the last century; the general shallow-water nature of these sediments has, however, been commented upon by many workers. Warman (Warman and Arkell, 1954) has given some data on the white limestones (Trias to Lias) of Monte Inici; Giannotti (1958) briefly described the succession on Monte Bonifato, considering it representative of western Sicily as a whole, and suggested an origin in a biostromal-lagoonal milieu. Tamajo (1960) carried out a microfacies study of the Jurassic of Rocca Busambra, and again noted the 'recifale' character of the Lias; and Christ (1960) in his palaeogeographic reconstruction of the Sicilian Mesozoic attributed the Trias and Lias of north-western Sicily to a 'pararecifal' environment, whereas Wendt (1965) referred simply to 'reef limestone'. Caflisch (1966) interpreted the Liassic 'Formazione Inici' of Monte Kumeta again as a result of the continuation of Triassic reefoid sedimentation.

Some studies of Rocce Maranfusa itself have been made by De Stefani (1954) but these have dealt primarily with geomorphological aspects.
Figure 1: Rocce Maranfusa, western Sicily, showing quarries on right. Arrow indicates the position where the section (Figure 3) was measured.

Figure 2: Fossil karst, with an arch of white limestone projecting into higher beds. Length of hammer handle, 28cm. Isola di Favignana, western Sicily.
The observations and interpretations of Fischer (1964) from the Alps and D'Argenio (1966a) from the Appennines (dealing exhaustively with open-space structures) are closely relevant to the present study. Wendt (1969) has recently outlined the palaeogeographic evolution of the west Sicilian Jurassic.

LOCALITY

Observations have been concentrated on the limestones exposed in a series of abandoned quarries on the eastern flank of Rocce Maranfusa, visible from and immediately to the west of Roccamena village (Figure 1). (Foglio 258 della Carta d'Italia. IV. S.E. Camporeale; 362893)

GENERAL FEATURES OF THE ROCCE MARANFUSA LIMESTONE

The lithological sequence exposed at Rocce Maranfusa is predominantly white to grey in colour, but some pink bands occur, varying in thickness up to two metres. The boundaries of these pink bands with the more featureless white limestone may be sharp and marked by a thin brown stain, or gradational. These coloured bands do not invariably correspond with distinct
lithologies; and some must owe their origin to post-depositional staining.

The limestones are capped in different positions along the quarry with but little obvious discordance by crinoidal iron pisolites, red stromatolitic limestones, both of Jurassic age, and transgressive Miocene glauconitic sandstone.

The sequence is cut by a series of Neptunian dykes and sills; some of these fissures are parallel or sub-parallel to the bedding and contain deposits which may or may not be matchable in the succession above. Several vertical faults cut the sequence, some breccia- and sediment-filled; in some cases these faults have affected the deposition of the younger beds.

**FAUNA AND AGE OF THE FORMATION**

The faunal contents of the Dolomia Principale in general have been listed by Wendt (1969); they comprise dominantly gastropods, sporadic ammonites and rare brachiopods, lamellibranchs, chitons (see Fucini 1912), ostracods, foraminifera, echinoderm debris, and calcareous algae.

The Rocce Maranfusa limestone has at one level, however, yielded a new ammonite fauna of Hettangian-
Figure 3: Section at Rocce Maranfusa, showing top of the "Dolomia Principale".
SECTION AT ROCCE-MARANFUSA
SHOWING TOP OF THE DOLOMIA PRINCIPALE

Red stromatolitic limestones of pelagic facies

Finely oolitic white limestone

Finely oolitic saccharoidal white limestone, with small-scale current bedding

Moderately oolitic white limestone with oncolites, and sparse gastropod fauna concentrated in bands

Grey in basal 30 cms.

Pale grey limestone with birdseye structure

Pale grey limestone with Stromatolites, pink stained in parts. Darker pink-grey in basal 60 cms.

White saccharoidal oolitic limestone with some coarser oncolitic bands

White featureless to slightly oolitic limestone, small oncolites in bands

Base of quarry
Sinemurian age, with one questionable Pliensbachian form higher in the succession (H. S. Torrens, personal communication). This sequence is thus the same age as that of Casale at Rocca Busambra (Gugenberger, 1936; Arkell, 1956). Faunas from two other localities, Rocca che Parla and Monte Erice, show that at least in some places the formation extends into the Upper Pliensbachian (Wendt, 1969).

**LITHOLOGY OF THE ROCCE MARANFUSA SEQUENCE**

The sequence is purely calcareous with no dolomite. Terrigenous clastics are lacking.

The distribution of rock types within the succession is roughly cyclical with an irregular repetition of sharply bounded facies; the sedimentation pattern is thus of an incomplete cyclothem type, similar to that described from the Dolomites by Bosellini (1967) and from the southern Appennines by D'Argenio and Vallario (1967). For interpretations of this cyclicity in terms of various tectonic, eustatic, and sedimentary factors, see Fischer (1964) and Bosellini (1967).

An attempt has been made below to distinguish the dominant lithological characteristics of the sequence and to describe them.
STROMATACTIS

Three-dimensional open-space structures of centimetre scale are concentrated at one level in the succession (Fig. 3); they are similar to the Stromatactis cavities as described by several authors. They tend to have the characteristic flat-bottomed form and compose a network which on a weathered surface can be seen to consist of an anastomosing complex of tubes and irregularly shaped tunnels, whose outer walls are smooth. Some of the cavities show in two dimensions a spiral structure (Figure 4) and it is evident that these have resulted from early solution of aragonitic gastropod shells (see Friedman, 1964).

The limestone in which the Stromatactis occurs is conspicuously darker than most of the limestone at Rocce Maranfusa and the structures themselves are almost invariably outlined by a thin red or brown haematitic stain.

The infills of the Stromatactis are various; some consist of concentric rings of radial fibrous calcite with, in some cases, a centre of later granular carbonate crystals (Tamajo (1960) has recorded similar phenomena from the Lias of Rocca Busambra); others contain red, grey or green argillaceous limestones which may be
Figure 4: *Stromatactis*. Note the concentric structure of some of these cavities, probably produced by solution of a gastropod shell. Polished block. Rocce Maranfusa, western Sicily.
interlaminated with one another and with spar. The fibrous calcite usually has a length of about 0.2 mm, and is light brown in thin section due to the presence of inclusions (see Hudson, 1962); it possesses the same optical properties as that examined by Bathurst (1959). The granular spar, with diameter commonly around 0.1 mm, is clear.

The coloured lutite patches (or Scherben of German authors) also occur as small masses outside the Stromatactis, apparently 'floating' in the sediment with sharp but irregular boundaries - presumably also cavity infills. They are present at other horizons than that of the Stromatactis and may occupy the interior of gastropods. Such phenomena are common in reefoid limestones (e.g. Flügel and Flügel-Kahler, 1962; Fischer, 1964; D'Argenio, 1966a).

As haematitic stains occur associated with the Stromatactis, it is sometimes difficult to assess whether the coloured patches are due to diagenetic ferruginous staining and replacement or to the introduction of an originally iron-rich sediment (Wolf, 1965). Red and green patches may cross the boundaries of the Stromatactis and sometimes occur beneath it, suggesting that the lower calcite wall of the cavity must have formed after the
original space had been partially filled by an influx of sediment (Bathurst, 1959); see Figure 8.

Various origins have been suggested for the Stromatactis structures in reefoid sediments and several different agencies may be responsible for their formation (Bathurst, 1959; Lees, 1964; Wolf, 1965). Possible origins are: decay of soft-bodied organisms within the lime mud; solution of aragonitic shells; and formation of shrinkage structures due to desiccation – and these may well have been modified by water circulation joining the various spaces together to form a labyrinthine network. However, Shinn (1968a) from a study of the recent lime sediments of Florida and the Bahamas, has shown that some Stromatactis cavities may result from the activities of burrowing organisms, with possible later modification by leaching.

BIRDSEYES

Small blebs of calcite, a few millimetres in size, occur throughout the succession, but in certain levels they are concentrated; these patches of spar are often referred to as 'birdseyes' (Ham, 1952). The birdseyes are ovoid to irregular in shape and, in general, tend to be elongated parallel to the bedding (Figure 5).
Like those described by other authors (e.g. Fischer, 1964; Wolf, 1965; D'Argenio, 1966a) these structures may possess two well-defined generations of carbonate, an earlier thin lining of radial calcite (length about 0.2mm) and a later infilling of coarser spar (diameter around 0.5mm). Only rarely do they contain internal sediments. The boundaries of the birdseyes are usually sharp.

The host rock is often pelletal - a typical association (Wolf, 1965).

Some of the birdseye horizons are associated with intraformational conglomerates, with well-rounded pebbles up to 4cm across. This association is significant and relates to the environment. The formation of birdseyes is probably due to more than one mechanism; Fischer (1964) in his work on the Dachstein suggested that they were shrinkage phenomena, and that such an origin is possible has been confirmed by Shinn (1968b) in a study of recent carbonates.

SHRINKAGE CRACKS

Cracks, sharply bounded, and filled with the usual two generations of fibrous and granular calcite, sometimes feebly ferroan, occur commonly. These can be either parallel or roughly normal to the bedding and
internal sediments may be found within them (Figure 9). Their diameter is usually in the 1-10 mm range.

These structures have been interpreted by Fischer (1964) as due to dessication, and this view is accepted here.

**NEPTUNIAN DYKES AND ARGILLACEOUS HORIZONS**

Neptunian dykes and sills are common phenomena in many reefoid limestones and are well displayed throughout the Jurassic of western Sicily (Wendt, 1965); the origin of these structures has recently been discussed by Castellarin (1966) and Sturani (1967) (see Figure 6).

Some of the argillaceous limestones at Rocce Maranfusa may have infilled contemporaneous desiccation cracks as suggested by Fischer (1964). Many of the fissures, however, are undoubtedly of a tectonic origin since the dyke form is often highly irregular, varying from horizontal to vertical, and the infills may contain breccia. Many of the dykes contain sediments recognisable in the succession above, intruded along obvious faults.

Coloured argillaceous matter can occur within the succession in thin filmy layers, although it cannot be assigned to a definite position within a well-developed cyclothem (cf. Fischer, 1964). These horizons constitute
lines of weakness and it is possible that some have been utilised by intruding sediment to form Neptunian sills.

The argillaceous limestone is best interpreted as modified and redeposited lateritic matter which has found its way down cavities, *Stromatactis*, and along cracks, and which was derived from the weathered surface of the exposed carbonate platform (Fischer, 1964). Small molluscs may sometime be found incorporated in this material.

The sill complex of coloured argillaceous limestones (Figure 3) gave insoluble residues of illite and kaolinite, which is consistent with the origin outlined above, since kaolinite is a common clay mineral in laterites and bauxites (e.g. Bracewell, 1962). Residues of the onkolitic facies, however, yielded only tiny pyrite cubes and illite. Kaolinite was barely detectable.

Although some of the argillaceous sills may be Miocene and primarily green — there is some lithological similarity with superincumbent beds of this age — those contemporary with the platform carbonates were probably intruded as red sediment and then later bleached by reducing solutions working along fissures.
Figure 5: Birdseyes in pelletal facies, with calcareous algae. Note the two generations of sparite in the birdseyes. Thin section; negative print. Rocce Maranfusa, western Sicily.

Figure 6: Pelletal limestone showing ?true bedding overlain discordantly by crinoidal iron pisolite. Note the thin Neptunian sill of argillaceous material in the pelletal facies. Thin section. Rocce Maranfusa, western Sicily.
This colour change probably took place before the final consolidation of the argillaceous material, allowing some to further penetrate the cavity system and become interlayered with red sediment.

LITHOLOGICAL FACIES

Pelletal limestone

Pelletal limestones are common within the succession and the allochems usually occur, with small foraminifera, close-packed in a matrix that grades through the microspar range of Folk (1965). The pellets are irregular in shape, but generally tend to vary between spherical and ellipsoidal forms; their size is usually of the order of 0.1 mm, though a few are larger. They are well sorted (see Figures 5 and 6).

It is difficult to ascertain whether the sparite matrix is a cavity fill or a micrite replacement (Beales, 1965); certain void growths occur, with pellet linings, in the birdseyes, but the very diffuse boundaries of some pellets suggest that some recrystallisation of micrite has taken place.

Oolithic limestone

Ooliths and pellets with oolithic overgrowths
Figure 7: Pellets and microfossils with oolithic envelopes. Thin section. Rocce Maranzusa, western Sicily.
occur at many levels, giving the rock a saccharoidal appearance and gritty feel. The dimensions of the ooids are in the 0.15-0.55mm range; anything smaller is an uncoated pellet. They are only moderately well sorted, but the different size ranges tend to be concentrated in bands; they occur associated with algal fragments, small gastropods and foraminifera, often also with oolitic envelopes (Figure 7). The matrix is dominantly sparite, commonly of a 40μ scale.

Definite carbonate rims, continuous round perhaps a third of an ooid, can be seen in some cases, attesting to original cavities; others show the more usual radiating drusy growth.

Current-bedded oolites occur near the top of Rocce Maranfusa section.

Limestone with stromatolites

Onkolites (SS-type of Logan, Rezak and Ginsburg, 1964) are concentrated at certain levels and may be associated with ooliths. The onkolites vary considerably in size, their diameter ranging from a few millimetres up to a centimetre; some show completely concentric structure, whereas others may be only unilateral coatings (Figure 10). Many of them are very obviously broken
Figure 8: Facies rich in recrystallised gastropods, with some calcareous algae. Stromatactis cavity on right, with basal fill of red argillaceous limestone capped by spar. Thin section. Rocce Maranfusa, western Sicily.
Figure 9: Stromatolitic (algal-mat) facies with dessication pores and sheet cracks - note sediment infill (white) in the largest crack. Stromatolites with desiccation structures may provide unequivocal evidence of inter- to supratidal conditions. Peel; negative print. Rocce Maranfusa, western Sicily.
Figure 10: Onkolitic facies. Note that many of the stromatolites are broken. Peel. Rocce Maranfusa, western Sicily.

Figure 11: Detail of a single onkolite showing finely concentric structure. Thin section. Rocce Maranfusa, western Sicily.
and a few show regeneration layers. Some onkolites have incorporated smaller brethren to produce composite bodies; other nuclei include algal-bound micrite and fragments of calcareous algae. Well-developed drusy textures with granular centres occur between the onkolites, the size of spar varying between 0.1 and 0.3 mm.

Similar onkoltic beds have been described by Elliot (1966) and Farinacci (1967), among others, from Jurassic reefoid sequences.

Lamination within the Rocce Maranfusa onkolites is produced by an alternation of microsparite and micrite layers of variable thickness (Figure 11). The micrite layers are of the order of 30 μ across; the sparite layers around 100 μ. The lime mud is presumably that originally trapped by the algal filaments, whereas the microspar may be the replacement of what was the dominantly mucilaginous layer (Ginsburg, 1960); the spar is unlikely to be a desiccation void filling since these onkolites are probably subtidal.

The onkoltic beds are often rich in gastropods and may occur in distinct pink bands (see above); this colouring, presumably related to the presence of trivalent iron, may be due to an admixture of lateritic material and/or algal influence in precipitating colloidal ferric
hydroxide in a marine environment - deposition of this substance on aquatic plants is a common modern phenomenon (Harvey, 1949).

Other stromatolites and algal-mat structures, composed of horizontal or undulose laminae (LLH-type of Logan, Rezak and Ginsburg, 1964), occur commonly, often giving the rock a rich creamy appearance. Petrographically, this lamination when best developed can be seen to consist of alternate layers of pellets in a microspar matrix and vaguely pelletal micrite - presumably both acquisitions of the algal mat. The laminae are usually about 1mm across, and are often interrupted by small-scale desiccation voids. Larger-sized cracks also occur commonly (Figure 9).

Algal structures very similar to these have recently been described by D'Argenio (1966b) from the Trias of Calabria.

OTHER LOCALITIES

The lithological types and structures described above occur throughout the upper part of the Dolomia Principale of western Sicily; the most commonly noted facies, however, is the oölitic (e.g. Wendt, 1963 for Monte Kumeta; Giannotti, 1958; Caflisch, 1966).
Figure 12: Limestone conglomerate with grey and white pebbles in a white limestone matrix. Pebbles have been outlined. Polished block. Contrada Casale, western Sicily.
One of the more interesting localities is at Contrada Casale at the top of a small quarry near Rocca Busambra (Foglio 258 della Carta d'Italia. I. S.E. Godrano; 549908). Here a well-developed intraformational conglomerate occurs, with grey and white pebbles in a white 'birdseye' limestone (Figure 12). The pebbles vary in diameter from 0.5 to 6cm and are all well-rounded, presumably due to wave action. Broquet (1964) has also recorded 'calcaires graveleux' from the Lias of the Sicani Mountains.

CONTACT WITH THE BEDS ABOVE

At Rocce Maranfusa the upper contact is generally very sharp; however, in some places ferromanganese-encrusted pinnacles of white limestone, up to 30cm high, project into the overlying beds. At other localities and in some parts of the Rocce Maranfusa quarry, the contact can be irregular with basins and narrow troughs, up to a metre in depth, infilled with later sediments; such structures are well displayed in one exposure on the island of Favignana, off Trapani (Figure 2) at a locality described by Wendt (1963).

These irregularities are interpreted, in contrast to some recent authors (e.g. Wendt, 1965; Jurgan, 1967),
as generally originating in a sub-aerial karstic environment and not being the results of deep submarine solution (as envisaged by Hollmann, 1964); they occur elsewhere in the Tethyan region at similar stratigraphic positions (e.g. Fabricius, 1961). Cloud (1957) has demonstrated that some solution and abrasion occurs in the intertidal areas of limestone shoals, where a topography much smoother than supratidal regions is produced — and this effect may have been significant in some areas.

At Rocce Maranfusa the deposits immediately overlying the white limestones, although probably of open-sea origin, are of obvious shallow-water nature and there is thus no indication of a vast submergence of the platform. Significant dissolution of calcium carbonate in the present oceans takes place at some 4000 metres (Peterson, 1966) and even bearing in mind the argument of Hudson (1967), a formidable depth would be required to chemically dissolve a consolidated limestone surface even under conditions of negligible sedimentary rate.

ENVIRONMENT AND PALAEOGEOGRAPHIC EVOLUTION

ENVIRONMENT

The Triassic-Liassic platform carbonates that occur throughout the Alpine-Mediterranean region can, in
a general way, be compared with the present day Bahaman sediments (e.g. Wiedenmayer, 1963; D'Argenio, 1966a; Fabricius, 1967) and the lithologies described here are no exception. The depositional environment of the white Rocce Maranfusa limestone and of similar facies in western Sicily is thus interpreted as a vast semi-emergent platform embracing milieux of island (cay) lagoon, and submerged shoal that varied through time and space. Less specifically these were supratidal, intertidal, and subtidal regimes. This platform was subject to considerable subsidence, thus accounting for the massive thickness of the deposits.

Although Bathurst (1966) has reported oolithically coated carbonate sand grains from low-energy environments in the Bahamas, there is little doubt that the ooliths and pellets with oolitic envelopes from the Rocce Maranfusa section were laid down in current-swept regimes; the cross-bedding in this facies (Figure 3) confirms this. These ooids were probably formed in warm shallow agitated water and swept up into submarine banks and shoals; modern parallels of the superficial ooliths occur in the peripheral areas of true oolitic sand belts in the Bahamas (Ball, 1967). The pellets were probably deposited in more sheltered lagoonal areas (Purdy, 1963). Onkolites
have been reported from the Bahamas and Florida Bay by Ginsburg (1960) in intertidal and subtidal environments, in one locality associated with ooliths. Other algal-mat structures of the attached type are also present in inter- and subtidal zones of this area (e.g. Black, 1933; Monty, 1965). The abundance of gastropods and calcareous algae and the presence of chitons in these Sicilian limestones also finds some parallel in Bahaman bottom communities (Newell, Imbrie, Purdy, Thurber, 1959).

Birdseye and Stromatactis structures are usually considered strong evidence for a littoral environment (Wolf, 1965) and the association of rounded pebbles with birdseyes is consistent with this. Fischer (1964) placed his loferites - carbonate rocks with shrinkage pores - in an intertidal regime; but the recent work of Shinn (1968b) on modern birdseys from Florida and the Bahamas suggests that a supratidal environment is more favourable for the preservation of these structures. If Shinn's (1968a) interpretation of Stromatactis is accepted, then these structures may originate in environments ranging from sub- to supratidal, since burrowers are effective in all these regimes.

Emergent areas may have undergone some laterisation to produce the coloured argillaceous 'soils';
Ball (1967) has reported red weathered zones on Bahaman islands. The karst topography of the upper surface of the Dolomia Principale is also reminiscent of the Bahamas (e.g. Purdy, 1963) and indicates areas uplifted above sea level where solutional cavities could form.

**PALAEOGEOGRAPHIC EVOLUTION**

Fabricius (1961), dealing with the upper facies boundary of the shallow-water carbonates of the north-central Limestone Alps, suggested that cessation of reef growth in the Lower Lias was due to a deterioration of climate; and indeed palaeotemperatures do show a decline during the Sinemurian-Pliensbachian (Fritz, 1965). However, at least some Sicilian platform sediments were still being deposited at this time (Wendt, 1969) and a similar type of sedimentation, with corals and calcareous algae, continued throughout the Jurassic in the eastern Madonie, north-central Sicily (Schmidt di Friedburg, Barbieri, Giannini, 1960). Platform carbonates were also deposited in parts of the Alpine region during the Middle and Upper Jurassic (Aubouin, Bosellini, Cousin, 1965; Fenninger, 1967). Thus, although climatic decline may well have adversely influenced true reefs, it is not enough to account for the cessation of Bahaman-type
sedimentation in western Sicily or in any other part of the Tethyan realm; and indeed this halt in large-scale carbonate production took place at different times in different areas.

Some of the deposits immediately overlying the Dolomia Principale — crinoidal biosparites, iron pisolites, pelsparites, stromatolitic limestones — must have been laid down in at least moderately shallow water. Thus an outpacing of carbonate accretion by sudden depression of the west Sicilian carbonate platform is unlikely. Moreover, as the top surface of the succession is sometimes karstified, uplift or fall in sea level may have been influential in at least some areas, and this would have eliminated lime-secreting organisms; although admittedly this may have been purely a local effect and part of the environmental pattern associated with cyclic platform deposition.

In western Sicily tectonic movements, illustrated by Neptunian dykes, syn-sedimentary faults, and the occasional discordance between the Dolomia Principale and the overlying beds, took place during the Middle Lias (Wendt, 1969). I consider, with Wendt (1969), that this tectonism was the agent that caused the cessation of reefoid sedimentation by dissecting and destroying the
corporate identity of the carbonate platform (see Scandone and Bonardi, 1968, for a comparison with the southern Appennines). The subsidence that had been continuing throughout the Trias and Lias must have ceased at this point and raising above sea level of some parts of the shattered platform may well have taken place. The subsidence that occurred after this was non-uniform over the area and differentiation of environment occurred; thus the diverse sediments that overlie the Dolomia Principale were able to accumulate.

A modern parallel of this final condition might be the Blake Plateau to the north of the Bahama Banks; this, according to Pratt (1968), may in fact be a sunken Bahaman platform, and it is now accumulating essentially oceanic sediments. These include ferromanganese crusts and nodules, and fossil concretions of this type occur in condensed sequences above the Dolomia Principale (Wendt, 1963; Jenkyns, 1967). The origin of the non-magnetic seamounts off the Iberian coast (Black, Hill, Laughton, Matthews, 1964) may also be relevant in this connection since the sedimentary record of one of these features shows an environmental change-over from that of shallow-water carbonates to pelagic oozes within the limits of
Thus the picture that is revealed of western Sicily during the Middle Lias is that of a carbonate platform that was breaking up into a series of fault-delineated blocks which eventually foundered; these major tectonic events finally resulted in essentially pelagic conditions being established over the whole area.

CONCLUSIONS

The Liassic platform carbonates of western Sicily are similar in facies to many coeval deposits in the Tethyan realm and can, in a general way, be compared with modern Bahaman sediments.

The cessation of this type of large-scale limestone production is attributed to tectonic disintegration of the carbonate platform.
CHAPTER 2

Crinoidal Limestones

from the Tethyan Jurassic
CHAPTER II
CRINOIDAL LIMESTONES
FROM THE TETHYAN JURASSIC

INTRODUCTION
This paper will deal specifically with crinoidal limestones from the west Sicilian Jurassic, and then discuss the significance of this widespread Tethyan lithofacies in more general terms.

In western Sicily crinoidal limestones usually occur immediately above the Liassic platform carbonates, but below the Middle Jurassic condensed sequences. This bioclastic facies is very discontinuous in outcrop and is absent from the succession in many places; it may, however, be sometimes preserved in tectonic fissures. Macrofaunally the crinoidal calcarenites are sparse, and thus usually cannot be directly dated. To some extent these crinoidal deposits have an intermediate character
Figure 1: Iron-rich Toarcian deposits infilling karstic solution hollow in crinoidal limestone. Monte Kumeta, western Sicily. Length of hammer head = 12cm.

Figure 2: Karstic pinnacle of crinoidal limestone capped by ferromanganese crust. Polished block. Monte Kumeta, western Sicily.
between the carbonate-platform sediments that preceded them and the red pelagic limestones which followed.

**OCCURRENCE AND DESCRIPTION OF CRINOIDAL CALCARENITES FROM THE WEST SICILIAN JURASSIC**

Occurrence in stratigraphical succession:

Crinoidal calcarenites occur as well-developed sequences in stratigraphical succession at Monte Kumeta, Rocca Nadore and Rocca che Parla; and in somewhat ambiguous field occurrence in the Balata di Baida gorge. They are also feebly developed at some localities on Monte Erice (Wendt, 1963).

At Monte Kumeta the crinoidal bed is developed as an extensively fissured, pink to yellow calcarenite of surprisingly variable thickness, but with a maximum of about three metres (see appendix for section and locality details). The top surface is highly irregular and iron-rich Toarcian deposits may infill solution hollows (Figure 1); or ferro-manganese crusts may coat upstanding spines (Figure 2). This deposit contains a brachiopod macrofauna; its age, judging from the succession, is probably Domerian.

Microscopically the rock is an intraclastic crinoidal biosparite (using Folk's 1962 classification)
Figure 3: Crinoidal limestone: Monte Kumeta, western Sicily. Thin section, negative print. Scale bar = 2mm.

Figure 4: Lens of crinoidal limestone (dark) capping the Trias—Lias white limestones. Rocca Nadore, south-west Sicily.
containing a little micrite; ill-sorted with a large proportion of micritic, algal-bored intraclasts (diameter 0.2—0.4mm) between the grain-supported and pressure-welded ossicles (Figure 3). The size of the crinoid particles varies from 0.2 to 2.5mm, according to whether a complete ossicle or a fragment is present. Rare foraminifera occur. The sparite void fillings are in optical continuity with the crinoid fragments (see Lucia, 1962; Evamy and Shearman, 1965). Clay residues of this rock yielded illite and a little kaolinite.

At Rocca Nadore (see appendix for section and locality details) a well-developed red crinoidal bank occurs showing most spectacular lensing (see Figure 4), with a thickness ranging from nothing to about 3 metres across a horizontal distance of about 25 metres. No macrofauna has been found in this deposit; but its age is possibly Pliensbachian-Toarcian.

Petrographically this is a crinoidal biosparite, with a few micrite patches and a notable admixture of foraminifera and subsidiary echinoid material. The crinoidal debris is moderately well sorted (diameter of ossicles between 0.2—2.5mm), and this material is noticeably more broken up than the Monte Kumeta sample. Many of the ossicles are lightly impregnated with iron oxides.
Large areas of drusy spar, including syntaxial rims, occur (Figure 5). Clay residues of this rock gave illite, kaolinite, and possibly montmorillonite.

At Rocca che Parla (see Wendt, 1963 for section and locality details) a lensoid development of grey-green, red or white crinoidal limestone occurs; here, however, another bed containing pyrite nodules and sometimes reduced to a ferromanganese crust may occur below the calcarenite. Thus, crinoidal limestone can be considered as occurring within the main condensed horizon, and its age, Bathonian, makes it younger than the two similar beds previously described.

In those parts of the crinoidal bank that are grey-green in colour, the ossicles are pink. Much of this locality seems to have been affected by reducing solutions at some stage, as the widespread presence of pyrite suggests, and many of the lithologies are pale green or white. The pink crinoid stems probably record the original colour of the sediment.

The thickness of this crinoidal bed varies from nothing to about 2.5 metres (Wendt, 1963).

Petrographically this is also a biosparite, moderately well-sorted, with numerous crinoid and other echinoderm fragments (diameter around 0.1 mm). These are
and often completely micritized, occur with foraminifera, pyritic intraclasts, and small fish teeth. The matrix is part micritic and the blurred boundaries of much of the spar suggest that some recrystallisation has taken place. Small rhombs of replacement dolomite are scattered through this rock, in both allochems and matrix. Clay residues yielded pyrite, illite and kaolinite.

The Balata di Baida sample (see Warman and Arkell, 1954, for locality details) is a white calcarenite occurring probably in stratigraphic position - field relations are ambiguous - upon the Liassic platform carbonates and just below the red pelagic limestones. It contains rare brachiopods, and is probably Liassic in age. Petrographically, the rock is a crinoidal biosparite with an abundance of ossicles (diameter 0.2-2.5mm) and a considerable amount of other echinoderm material: whole echinoid tests can be seen on a weathered surface of this rock and holothurian fragments also occur. Rare molluscs, chiefly lamellibranchs, a few ferruginous intraclasts, and sparse foraminifera, complete the list of components. The echinoderm fragments are of the order of 0.2 to 2.5mm across and the usual syntaxial rims occur; the matrix is partly micritic but dominantly coarse spar. The allochems
Figure 5: Loose-packed crinoidal biosparite. Thin section. Rocca Madore, south-west Sicily. Scale bar = 1mm.

Figure 6: Crinoidal biomicrite, with replacement dolomite rhombs in micritic matrix. Thin section from Neptunian sill. Monte San Calogero di Sciacca, south-west Sicily. Scale bar = 1mm.
are moderately well-sorted. Clay residues of this rock yielded kaolinite.

Occurrence as Neptunian dykes and sills:
Crinoidal calcarenites are one of the more common fissure fillings and occur at several localities. Crinoidal dykes and sills have been found at Rocce Maranfusa, Monte Erice, Monte Pispisa, Rocca che Parla, and Monte San Calogero di Sciacca, and they doubtless occur elsewhere. Material from Monte Pispisa and Monte San Calogero has been studied petrographically.

The Monte Pispisa quarry (see Wendt, 1963, for locality details) is of some interest since here a large Neptunian dyke of Bathonian age combines both crinoidal and iron-pisolite facies, and probably results from successive intrusion. This lithology is a pink calcarenite speckled with lensoid concentrations of iron pisoliths; it is made up of iron-impregnated crinoid and echinoid debris (diameter about 0.2mm) with the iron pisoliths (diameter about 0.1mm) set in a dominantly sparitic matrix. Foraminifera are very uncommon and lamellibranch shells occur rarely; a few ammonites have been found in this lithology. Clay residues gave goethite and kaolinite.
The pink crinoidal calcarenite from Monte San Calogero (see Wendt, 1965, for locality details) occurs as a sill in the higher regions of the quarry; only fallen blocks are available for study. Petrographically, this rock consists of crinoid and echinoid remains (diameter about 0.2mm) moderately well-rounded, with a few foraminifera and shell fragments set in a dominantly micritic matrix that is sporadically dolomitised (Figure 6). The echinoderm fragments are close-packed and probably grain-supported; thus it is possible that the micrite may be a later sediment infill that has filtered down between the intergranular spaces; this seems likely to happen to fissures that are open on the sea floor.

DEPOSITIONAL ENVIRONMENT

Some of the west Sicilian crinoidal calcarenites are of Liassic age and this time was one of widespread formation of similar beds in the Alpine region. Bearing this in mind, the depositional environment of these Sicilian limestones will be discussed with reference to similar Tethyan facies elsewhere.

Tethyan crinoidal limestones are often developed immediately above reef or carbonate-platform deposits such as the Dachsteinkalk or Dolomia Principale (e.g. Hlauschek,
1922; Geczy, 1961; Kotanski, 1961; Fabricius, 1966; Jurgan, 1967) and this stratigraphic location is significant since it means that these crinoidal accumulations characterise the environment immediately following that of reef or platform. This explains their widespread development during the Lias since this was a time when many carbonate platforms and reefs broke up (Jenkyns, 1969). It also incidentally explains the common occurrence of this lithology as Neptunian dykes and sills, since these fissures must have been produced as a by-product of the tectonic disintegration of the reefs and platforms—the resulting openings being filled by the succeeding sediments.

All of the stratigraphic occurrences of the west Sicilian crinoidal limestones exhibit a lensoid form, most spectacularly demonstrated at Rocca Nador (Figure 4), and this mound-like shape has been commented upon by other authors when describing Tethyan crinoidal banks (e.g. Andrusov, 1965, p.161; Geczy, 1961; Fabricius, 1966, p.44) for Carpathian, Hungarian and Alpine occurrences. This characteristic form is significant and relates to the depositional regime.

At Monte Kumeta, the upper surface of the crinoidal bed is extremely irregular and has obviously been subjected to solution of some kind; it is most
unlikely that this effect was produced in a submarine environment (cf. Hollmann, 1964), since by reference to modern analogues, significant dissolution of calcite does not take place until a depth of some 4000 metres is reached (Peterson, 1966). Although the present model of oceanic calcite solution may not be strictly applicable to the past (Hudson, 1967), I consider that the pitted upper surface of the Monte Kumeta crinoidal bank is best attributed to emergence and subaerial karstic effects. Emergence would also explain the prior lithification (Friedman, 1964) which must have taken place before solution commenced.

If emergence took place, then it seems likely that this crinoidal calcarenite was deposited in very shallow water, unless the emergence was due to sudden tectonic uplift of the depositional area, which cannot be ruled out. In any case, at some time during its lithogenesis, the crinoidal sediment must have been subjected to tidal and even wave influence.

At Rocca Nadore, the crinoidal lens is underlain by fossil Bahaman-type sediments deposited near mean sea level and overlain by pelagic limestones with stromatolites: this also suggests deposition within the reach of tidal currents. In fact, most workers accept
these Tethyan crinoidal calcarenites as essentially shallow-water sediments.

Most of the west Sicilian crinoidal limestones are biosparites and this suggests deposition in at least a moderately high-energy regime (Folk, 1962) which is consistent with the conditions postulated above; obvious cross-bedding structures are, however, absent.

I consider that these crinoidal accumulations both in Sicily and elsewhere in the Tethyan region are best interpreted as sand-waves deposited on open ocean seamounts. Sand-waves (see Cartwright and Stride, 1958; Jordan, 1962; Off, 1963) are essentially giant ripple marks of tidal origin orientated perpendicular to the current direction. These structures occur as deep as 180 metres, but are more commonly found in much shallower water; their crests can be as high as 30 metres (Jordan, 1962) and are commonly in the 3 to 7 metre range (Cartwright, and Stride, 1958).

The size range of the west Sicilian crinoidal beds seems consistent with this. In the Alpine-Carpathian region, however, the Hirlatzkalk can attain thicknesses of up to 50 metres (Andrusov, 1965, p.160), but it must be borne in mind that this is a total thickness and not the height of a wave crest. The Hirlatzkalk is a red to
Figure 7: Hirlatzkalk: crinoidal biosparite, with clastic quartz fragments. Losonec, between Malacky and Trnava, south-western Czecho­
slovakia. Scale bar = 1mm.

Figure 8: Nodular crinoidal limestone. Tata, northern Hungary. Length of hammer handle = 28cm.
violet crinoidal sediment that rests upon the Dachstein reef and platform limestones; besides its greater thickness it differs from the west Sicilian facies in containing clastic quartz fragments (Figure 7), presumably due to the influence of a continental landmass.

The lensoid shape of these crinoidal limestones is thus probably a primary depositional feature; and one would expect to find long linear ridges of this type of sediment. Such a case has been illustrated by Misik (1964) and Misik and Rakus (1964) from the Lias of the Great Fatra mountains of Czechoslovakia; here a strip of crinoidal limestone at least 6 kilometres long and about half a kilometre wide, and between 10-15 metres thick occurs - which seems directly comparable to a sand-wave or at least some kind of tidal-current ridge. Fabricius (1968) has also illustrated some narrow belts of crinoidal sands from the Lias of the western part of the Northern Calcareous Alps.

Although most modern sand-waves have been described from clastic (quartzose) environments, Newell and Rigby (1957) and Ball (1967) have illustrated several characteristic forms of carbonate sand bodies from the Bahamas. Newell and Rigby describe underwater dunes and linear ridges of oolitic sand from current-influenced
environments; these accumulations, notably devoid of benthos, are heaped up and maintained by tidal flow. It is significant that some of these ridges are dry at low tide since this would promote lithification (and permanence) and might, if a fully subaerial environment were achieved, enable karstic solution hollows to form. Such hollows are common in uplifted parts of the Bahamas (e.g. Purdy, 1963).

The recent work of Blyth Cain (1968) on crinoidal limestones is relevant to this argument; he has shown that after death crinoids quickly disarticulate into a mass of arms and cirrus fragments, and, when subjected to a current competent to move them, this mass moves downstream eventually to form a small dune. Only a moderate degree of sorting is attained because the smaller particles filter down between the grain-supported ossicles (see also Folk, 1962, on textural inversion). This is in agreement with the petrographic observations on the west Sicilian crinoidal calcarenites and shows that a lack of sorting is not inconsistent with deposition in a high-energy regime.

Seamount deposition for the west Sicilian crinoidal limestones seems likely as even the oldest deposits probably accumulated when the Bahaman-type
carbonate platform that had dominated deposition during the Trias and Lias (Jenkyns, 1969) began to break up into a series of differentially subsiding blocks. The close association of crinoidal limestones with stratigraphically condensed sequences - which must have formed on topographic highs - is notable throughout the Tethyan region (e.g. Aubouin, 1964; Aubouin, Cadet, Rampnoux, Dubar, et Marie, 1964; Jakobshagen, 1964). Such bioclastic accumulations may, however, underlie more expanded basinal sediments (e.g. Balata di Baida for western Sicily) which shows they were deposited on rapidly subsiding blocks during an early evolutionary phase as well as on the more stable ones.

Crinoidal limestones may also occur as alldapic lenses in more basinal sediments, which shows they must have originated "upslope" from a submarine swell. An example of this has been quoted by Misik (1966, p.150), and a crinoidal lens of probable turbidite origin occurs in the Tithonian 'ammonitico rosso' of La Stua in the Dolomites (personal observations, 1968; see Cita, 1965, p.28 for stratigraphical section).

Calcareous sands, often rippled, have been reported from several seamounts including the Blake Plateau (Pratt, 1963, 1967, 1968), but the constituents
are usually pelagic foraminifera and pteropods. However, modern crinoids do occur in relative profusion on some seamounts as bottom photographs show (Black, Hill, Laughton, Matthews, 1964) and they favour hard bottoms and well-aerated water (Clark, 1957). During the Mesozoic, crinoid populations were probably much more extensive than they are now; significant accumulations of their ossicles, forming more or less in situ, might thus be expected.

Seamounts are areas of relatively slow deposition and in environments of low sedimentary rate today crinoids are sparse unless suspended organic matter is abundant (Sokolova, 1959), although currents may supply the maximum food available (Driscoll, 1967). As Bordovskiy (1965) has shown, in modern oceans there is a seaward depletion of organic matter in sea water; and there is no indication that any of the west Sicilian Jurassic crinoidal limestones were deposited in the proximity of any continental landmass, although this objection may not apply to deposits like the Hirlatzkalk that contain detritus of continental origin. However, most of the clay residues from the Sicilian crinoidal sediments show the presence of kaolinite, whereas this clay mineral is generally absent in limestones elsewhere.
in the succession; and in present marine environments kaolinite is generally spatially related to tropical landmasses (Griffin, Windom, Goldberg, 1968). It is difficult to know how much importance to place on this, but it is possible that some seamounts may have been emergent at this time with the consequent formation of a lateritic or bauxitic cover. Such residual soils often contain kaolinite (Van Houten, 1964). Moreover, if these oceanic islands were vegetated and colonised, then a potential source of organic matter would be available for the crinoid population.

This postulate is not unreasonable since De D'Argenio and Cunzo (1963) and Crescenti (1966) have described fresh-water molluscs, crocodile teeth, insect remains and pollen from the Cretaceous bauxites of the Appennines which are developed on shallow-water limestones of an 'intraoceanic platform'.

The origin of the red colour in the Sicilian crinoidal limestones is interesting in this respect; it could simply be due to an influx of lateritic material from an emergent area, and this idea has been suggested for the origin of many marine red beds (e.g. Termier and Termier, 1962; Kovacs, 1960; Trevisan, 1934; Grunau, 1959). The previously mentioned evidence suggests that
such emergent areas were likely. However, as Hallam (1967) has pointed out, red colour can probably be produced simply by deposition in a fully oxidizing environment, and a seamount with little net deposition is likely to fulfil this requirement. Thus for the crinoidal calcarenites both origins, 'oceanic' and 'land-derived', seem possible for the red colouration.

**NODULAR CRINOIDAL LIMESTONES**

Some Tethyan crinoidal limestones have a nodular structure reminiscent of the 'Adneterkalk' or 'Ammonitico rosso' calcilutites. The nodularity is, understandably enough, best developed in the more muddy crinoidal deposits, and the nodules are composed of relatively fossil-poor micrite, whilst the more marly matrix has a greater abundance of skeletal material.

This nodularity is spectacularly demonstrated in the Pliensbachian crinoidal limestones of Tata, near Budapest, Hungary (Figure 8), and has also been observed in the crinoidal limestones on Monte Misone, North Italy (see Aubouin, 1964, for stratigraphical section). Such nodularity in red calcilutites has been ascribed to submarine solution (Hollmann, 1962, 1964), but this hardly seems applicable to what must be a shallow-water sediment.
Rather, this structure is best interpreted as due to early diagenetic segregation of calcium carbonate (cf. Lucas, 1955; Hallam, 1967).

CONCLUSIONS

Crinoidal lenses, both in Sicily and elsewhere in the Tethyan region, are probably sand-waves produced by tidal currents in water tens of metres deep; such structures were particularly well developed during the Lias, when open platform and seamount deposition was initiated. Tectonic fissures were often filled by such migrating sand bodies. Emergent areas, vegetated and probably lateritized, may have provided a source of food for the crinoid gardens and may also account for the red colour and the presence of kaolinite in the resulting sediments.

Large-scale crinoidal accumulations may be depth-controlled if tidal currents are necessary to form them, and thus characterise phases of tectonic uplift like the *Bositra buchi* biosparites described by Sturani (1967). The sequence illustrated by Geczy (1961) from the Bakony Mountains of Hungary, with a return to crinoidal deposition in the Lower Cretaceous after its inception in the Lias, may be a function of tectonic control on a...
pelagic seamount. The crinoidal components in most condensed sequences probably never reached significant proportions because currents were not powerful enough to concentrate the debris into sand-waves. Crinoids may have been equally abundant at this time, though the paucity of kaolinite in the sediments from condensed sequences precludes the presence of large emergent areas which might be necessary for abundant food supply.

During early diagenesis the more muddy crinoidal sediments sometimes underwent segregation to produce a nodular limestone.
CHAPTER 3

Submarine volcanism
and the Toarcian iron pisolites
of western Sicily
CHAPTER III

SUBMARINE VOLCANISM AND
THE TOARCIAN IRON PISOLITES
OF WESTERN SICILY

INTRODUCTION

Oolitic iron deposits are well developed throughout the north European Jurassic (Hallam, 1967) and also occur as very minor constituents of the Jurassic of North Africa (Lucas, 1942); in both cases the depositional site may be related to the proximity of a large landmass. However, in the Toarcian of western Sicily thin iron-pisolite beds occur associated with red limestones of pelagic facies, and an origin other than continental must be sought for the limonitic material. These deposits, previously undescribed, are most spectacularly developed at Monte and Rocce Maranfusa and can also be traced, usually as centimetre-thick remanie horizons, at other
localities. Such pisolite horizons are not confined entirely to the Toarcian, occurring also as minor developments within the main ferromanganiferous condensed sequences of the Middle Jurassic. The Toarcian, however, seems to have been their optimum period of formation.

**OCCURRENCE AND DESCRIPTION OF IRON–PISOLITE HORIZONS**

Iron pisolites occur in well-developed but discontinuous sequences throughout the group of mountains known as Rocce and Monte Maranfusa, west-central Sicily (see appendix for sections and locality details). This group of mountains has recently been interpreted as a sedimentary klippe (Broquet, Caire, Mascle, 1966). In these localities the pisolite bed is richly crinoidal and varies in colour from chocolate brown through shades of red and yellow to, in rare circumstances, green. It is capped by a ferromanganese crust. The bed directly overlies the Liassic platform carbonates (see Jenkyns, 1969) and its thickness, varying from nothing up to about 20cms, is considerably affected by syn-sedimentary faults and the surface topography of the underlying formation, lensing out where the Lias bulges upwards, or infilling karstic cavities within it. The pisoliths themselves vary in colour from yellow-brown to green and tend to
Figure 1: White Liassic limestone with Stromatoptaxis cavities, overlain by liming Tertiary iron pisolithite which is, in turn, capped by ferromanganese crust. Monte Galillo, western Sicily.
occur in bundles within the crinoidal sediment. At Monte Maranfusa larger (2-3cms) calcareous ferromanganese nodules, associated with the pisoliths, are particularly conspicuous.

At Rocca Busambra, and its off-faulted blocks Rocca Argenteria and at Contrada Drago, the iron pisoliths occur as small lenses in the same stratigraphic position, and are intimately associated with the ferromanganese crust which usually directly overlies the white Liassic limestones (see appendix for sections and locality details). Although the pisoliths are concentrated at the contact, a few range as high as 30cms into the bed above, presumably a result of continual reworking. At Monte Galiello (see appendix for section and locality details) the exposure is similar with pisoliths occurring sporadically in a lensing red limestone (Figure 1) that generally underlies the ferromanganese crust.

At Monte Arancio (see Wendt, 1963, for section and locality details) iron pisoliths have been found forming the core of a ferromanganese nodule (Figure 2), demonstrating that the pisoliths were formed earlier in time. A few pisoliths also occur scattered through the basal horizons of the red limestone at this locality.
Figure 2: Iron pisolite forming the core of a ferromanganese nodule. Polished block. Monte Arancio, south-west Sicily.
At Monte Monaco, north-western Sicily (see Wendt, 1969, for locality details), pisoliths are amply distributed through the condensed horizon and are intimately intermixed with the later ferromanganese crust; the pisoliths, however, are notably associated with yellow-stained fossils and matrix, in contrast to the red limestone and its black mineral crust. The same is also true at Monte Kumeta (see appendix, section and locality details) where a yellow ferruginous deposit, with some large pisoliths, infills solution hollows in the crinoidal limestone beneath. Only at this locality does the pisolitic horizon not rest directly on the Liassic platform carbonates.

At some of these localities the iron pisoliths occur as fissure infillings.

**FAUNA AND AGE OF THE IRON-PISOLITE HORIZONS**

The iron-pisolite horizons at Rocce and Monte Maranfusa have yielded a number of ammonites (see Jenkyns and Torrens, 1969) that indicate an age at the Lower/Toarcian boundary (Erbaense Zone, Bayani subzone). Bearing in mind the diminutive thickness of the deposit, it is apparent that this bed is considerably condensed. At Monte Galiello some badly preserved ammonites of
probable Liassic age have also been obtained from this horizon (H. S. Torrens, personal communication). Ammonites of Upper Toarcian age have also been found at Monte Kumeta (Wendt, 1963) and Monte Monaco (Wendt, 1965).

Apart from ammonites, other macrofauna in these beds include belemnites, gastropods, rare brachiopods, and fish teeth—which weather out conspicuously.

**PETROLOGY**

The most obvious feature of the Toarcian iron pisolites is that they all contain igneous material, and this will be discussed later. Petrographically, the rocks are highly ferruginous biomicrites, containing considerable echinoderm debris, chiefly crinoidal, and foraminifera, broken lamellibranch shells, and ostracods. Fish teeth are as noticeable in thin section as they are in the field. Subsolved aragonitic fossils are common (Hollmann, 1964).

The pisoliths are usually 0.2–0.5 mm in diameter but may range as large as 4 mm across; they are sporadically distributed in the ground-mass. The pisoliths usually consist of a concentric limonitic rind (20–150 μ thick) round a variety of nuclei; these include
Figure 3: Trachyte with flow structure forming the core of an iron pisolith. Thin section. Rocca Busambra, western Sicily. Scale bar = 1mm.
dolomitised micrite, calcitised igneous material, felspar crystals (Figure 3), crinoid ossicles and spines, foraminifera, fish teeth, chamosite flakes, often highly distorted, and micrite intraclasts which may or may not be limonitised. Compound nuclei occur; and some pisoliths have been broken and show regeneration coatings.

The yellow-brown pisolith material, although giving a goethite X-ray powder pattern, can probably be best described as limonite; the optical identification of the yellow-green mineral as chamosite, confirmed by its X-ray powder pattern, is further borne out by the electron-probe analysis (Figure 12). X-ray patterns of all pisoliths gave goethite and calcite; some contained haematite; chamosite has only been identified at a few localities. The large nodules that occur at Monte Maranfusa have only yielded patterns of goethite and calcite.

Insoluble residues

Insoluble residues of these Toarcian facies varied from 5-30% depending on the amount of limonitic material present. Clay minerals present included illite and kaolinite in varying amounts, with montmorillonite.
Illite and montmorillonite are common constituents of modern oceanic sediments (Griffin, Windom, and Goldberg, 1968), whereas kaolinite tends to be localised around continental margins, being derived from weathering products on land. Illite is probably detrital. Montmorillonite is commonly regarded as being a breakdown product of volcanic material, and its presence is not surprising since the iron pisolites contain considerable amounts of igneous fragments. The presence of kaolinite, even in the non-chamositic sediments, is a little more puzzling; according to Van Houten (1964), the occurrence of this mineral in a red sediment presupposes the proximity of lateritic soils, but there is certainly no evidence of a continental landmass in this area during Toarcian times. However, the iron pisolite beds are very close to the top of the Liassic platform carbonates and parts of this surface may have been lateritised with the production of kaolinite (Jenkyns, 1969) — and this weathered mantle could have been later incorporated into the Toarcian sediments. Nevertheless, it is not by any means inconceivable that there were some oceanic limestone islands providing kaolinite from exposed weathered surfaces at this time (see Jenkyns, 1969).
Chamosite

Chamosite has only been identified from Rocce and Monte Maranfusa. In thin section it exhibits typical properties: good spherulitic structure with an extinction cross shown under cross-nicols, and it commonly occurs as bent flakes or spastoliths (see Rastall and Hemingway, 1939), and may alternate in layers with limonite. Almost invariably it is outlined by a 'protective' limonite coating. The origin of chamosite presents something of a problem since it is a divalent iron compound, presumably only stable at negative values of Eh, and yet it occurs in rocks that must have been laid down in oxidising conditions. Two main possibilities seem feasible for the origin of chamosite ooliths: either they formed below the sediment-water interface by some concretionary mechanism producing a 'pseudo-oölitic' structure, or they were formed, in the same way as aragonite ooliths, but were originally composed of some substance, stable at positive Eh values, that crystallised diagenetically to chamosite. Hallam (1967), Curtis and Spears (1968) and Schellmann (1969) deal with these problems. Porrenga (1965, 1966) has recorded modern chamosite replacing faecal pellets, and in the tests of organisms, in some tropical shallow-water shelf regions;
here the close association with organic matter suggests that reducing environments have been influential in the genesis of this mineral. However, the origin of the oolitic structure in fossil chamosite remains a mystery.

The Toarcian iron pisoliths are condensed, and thus in this environment of minimal sedimentation any organic matter is liable to be oxidised before it becomes buried. The concentration of manganese in this bed (see Figures 12 to 15) and its prevailing chocolate-brown colour all suggest a realm of positive Eh. Nevertheless, rare patches of green do occur in this ferruginous limestone and if these are primary, it is conceivable that small areas of reducing conditions did exist below the sediment-water interface. However, although chamositic pisoliths are more prominent in these green patches, they occur with equal frequency in the chocolate-brown matrix. The pisolith from Rocce Maranfusa contains considerably more silica than those from Monte Galiello and Monte Monaco, and these latter may be primary limonite precipitates rather than oxidation products of chamosite.

The formation of chamosite does not seem to be restricted to any depths or temperatures of water (Rohrlich, Price, and Calvert, 1969; cf. Porrenga, 1967),
Figure 4: Slightly limonitised micritic pisolith, with traces of algal tubules towards the centre. Thin section. Monte Monaco, north-west Sicily. Scale bar = 0.25mm.

Figure 5: Moderately limonitised micritic pisolith. Thin section. Monte Monaco, north-west Sicily. Scale bar = 0.25mm.
Figure 6: Skeletal calcite or calcitised igneous fragment showing partial limonitisation. Thin section. Monte Monaco, north-west Sicily. Scale bar = 0.25mm.

Figure 7: Iron pisolith showing virtually complete limonitisation. Thin section. Monte Monaco, north-west Sicily. Scale bar = 0.25mm.
although it does not seem to have been recorded deeper than 150 metres.

Boring algae and limonitisation

It is apparent that although a few of the pisolith nuclei are composed of grey micrite or sparite, many of them are limonitised to a considerable degree. The formation of this limonitic material can be best interpreted as due to the activities of boring algae or boring fungae. Thus the limonitisation process is an absolute parallel to the micritisation described by Bathurst (1966) only in this case the algal (or fungal) bores are filled with precipitated limonite or at least limonitic micrite. Various stages can be observed in this process, as illustrated by Figures 4 to 7. The first stage is the invasion of filaments (diameter commonly 5-10μ) round the periphery of the particle, then further advance, until a uniformly dense limonitic area is eventually produced. In most cases this limonitisation process took place before the formation of the pisolithic coating, as this outer limonitic ring is not usually bored (cf. Hessland, 1949, for comparable observations).

The boring organisms choose various hosts to invade, including calcitised igneous material, skeletal
Figure 8: Limonitic 'cauliflower' structures showing massive columnal development. Thin section. Contrada Drago, western Sicily. Scale bar = 0.25mm.

Figure 9: Single limonitic segregations. Thin section. Contrada Drago, western Sicily. Scale bar = 0.25mm.
calcite, fish teeth, crinoid ossicles, and micrite intraclasts. The most frequently chosen hosts are those composed of sparry calcite; unaltered felspars are not attacked to any great extent.

If these boring organisms are algal, then their activities will be limited to environments where sufficient light is present for them to photosynthesise. As Holmes (1957) has remarked, it is impossible to set a depth limit to the photic zone, but in low latitudes a maximum figure around 150-200 metres is perhaps reasonable, although Nadson (1927) found no boring algae living deeper than 50 metres.

Limonitic 'cauliflower' structures

Small limonitic 'cauliflower' structures occur 'growing' in limestone at many ferruginous horizons in the west Sicilian Jurassic, but they are particularly well developed in the Toarcian facies (Figures 8 and 9). Such structures, commonly of a millimetre scale, have been interpreted as either organic or inorganic. Farinnicci (1967) considered similar ferruginous segregations as stromatolites, and indeed such dendritic patterns have been recorded by Radwanski and Szulczewski (1965) / Szulczewski (1963, 1967, 1968), from undoubted algal-mat structures.
Figure 10: Toarcian igneous localities, western Sicily. The infilled circles indicate localities where trachytic fragments have been found associated with iron pisolites, immediately above the top of the white Liassic limestones. The black oblong indicates the position of Monte Bonifato where a large-scale trachytic extrusion is present.
In these examples the dendrites are tentatively interpreted as being formed after blue-green algal colonies.

Similar structures occur within ancient and modern ferromanganese nodules (Wendt, 1963; Cronan and Tooms, 1968); and the latter authors interpret them as being due to early diagenetic re-arrangements, since the segregations may also occur in the volcanic cores of some nodules (Bonatti and Mayudu, 1965).

In some cases these segregations may cross-cut calcite skeletons and veins which proves their non-syngenetic origin, and they are probably best interpreted as products of the diagenetic mobility of iron (and manganese).

**VOLCANISM**

Fragments of porphyritic trachyte have been identified in the iron pisolite horizon, immediately above the Liassic platform carbonates, at Monte Maranfusa, Rocce Maranfusa, Rocca Busambra and its off-faulted blocks, Rocca Argenteria and at Contrada Drago; Monte Galiello, Monte Arancio, Monte Kumeta, Monte Monaco, and Bolognetta. The spatial distribution of this igneous material is plotted in Figure 10, and it is evident that the effects
Figure 11: Phenocrysts of sanidine and fragments of trachytic groundmass with flow structure set in ferruginous limestone. Crossed nicols. Monte Monaco, north-west Sicily. Scale bar = 1mm.
of this volcanic episode were felt over a considerable area. This extrusion is presumably pre-Erbaense Zone, since the ammonite fauna at Rocce Maranfusa is of this age.

The lava type is an alkali trachyte with phenocrysts of sanidine set in a felspathic groundmass showing well-developed flow structure (Figure 11). In general, the felspars are not greatly altered, but some show varying degrees of replacement by sericite and carbonate, usually with preservation of the original structure. Ferromagnesian minerals are usually completely altered and only biotite has been positively identified. In some cases the felspathic matrix is completely glassy, and various stages of crystallisation can be seen.

This type of alkali volcanism is very rare in the Jurassic of western Sicily - most extrusions are described as basaltic - and it is probable that these trachytic fragments provide a good marker horizon. However, a thick extrusion of biotite-hornblende trachyte has also been described from Monte Bonifato by Wendt (1963) who considered it to be Bajocian; however, there is a possibility that this may also be of Toarcian age (Jenkyns and Torrens, 1969) and the similarity in texture
between this lava and the igneous fragments described here is consistent with a genetic relationship.

Rounded quartz fragments (up to 1mm diameter) have been found at Rocce che Parla just above the top of the Liassic platform carbonates in a bed dated as Lower Bathonian by Wendt (1963). These fragments are probably also of volcanic origin, but it is impossible to assign them to a known phase of volcanism, since they may have been extensively reworked, and preserved, whilst zonal ammonites have been dissolved. Their age must lie between Pliensbachian and Bathonian, as delimited by the succession (Wendt, 1963, 1969); no quartz phenocrysts have been found associated with the trachytes, so this Rocca che Parla example may record a separate period of acidic volcanism.

Comparison with modern submarine volcanism

Although Sicily must have occupied a fairly central position in Tethys, it is not particularly surprising to find traces of alkali volcanism in what may have been an oceanic region. The Tethyan region as a whole was the site of the basic ophiolitic suite, and although these rocks are absent in western Sicily, the alkali volcanism is here quantitatively insignificant
when compared to the basic.

In fact, trachytes are a common associate of alkali basalts on modern oceanic islands (e.g. Baker, Gass, Harris, Le Maitre, 1964); and a region of submarine acid and intermediate volcanism has been recorded from the East Pacific Rise (Arrhenius and Bonatti, 1965). In this area the alkali felspars are relatively little altered (Peterson and Goldberg, 1962), which is consistent with the observations on the Sicilian examples. In other respects, the various secondary products - carbonate, limonite, chlorite - are in agreement with descriptions of altered submarine flows (Matthews, 1961, 1962; Nayudu, 1964; Cronan and Tooms, 1968).

**GEOCHEMISTRY**

Electron-microprobe analyses have been undertaken on some of the Toarcian iron pisoliths, and the data is presented in Figures 12 to 14. One of the larger ferromanganese nodules from the pisolite horizon at Monte Maranfusa has also been analysed (Figure 15), as well as an iron oolith from the Bathonian Twinhoe Beds of Somerset, England (Figure 16).
Methods

The analyses were obtained by taking 125-second scans across 375μ traverses in selected parts of the specimen. Errors were minimised by using composite oxide standards for the analyses, but the results have been presented as weight percentages of the elements, except for calcium which has only been analysed semi-quantitatively using a pure limestone standard.

With the graphs presented in Figures 12 to 16, the zero percentage has been calculated for the iron-rich area and since the background is lower for the calcareous phase, this accounts for the scan-line falling below zero in this part of the traverse.

Accuracy for the major element analyses should lie in the range ±5%. Errors increase as the amount detected decreases, and for the minor elements an uncertainty value of ±20% is probably suitable. The detection limits of the various elements are set out below:

<table>
<thead>
<tr>
<th>Element</th>
<th>Detection Limit</th>
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<tr>
<td>P</td>
<td>0.012</td>
</tr>
<tr>
<td>V</td>
<td>0.012</td>
</tr>
<tr>
<td>Co</td>
<td>0.038</td>
</tr>
<tr>
<td>Ba</td>
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</tr>
<tr>
<td>Si</td>
<td>0.027</td>
</tr>
<tr>
<td>Cr</td>
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<tr>
<td>Ni</td>
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<tr>
<td>CaCO₃</td>
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<tr>
<td>Al</td>
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<tr>
<td>Mn</td>
<td>0.016</td>
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<tr>
<td>Cu</td>
<td>0.038</td>
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<td>(Ca)</td>
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<td>Ti</td>
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<tr>
<td>Fe</td>
<td>0.023</td>
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<tr>
<td>Zn</td>
<td>0.034</td>
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Figure 12: Electron-probe microanalysis of an iron (chamosite-goethite-haematite) pisolith from the Toarcian of Rocce Maranfusa, western Sicily. Length of scan line = 375μ.
Figure 13: Electron-probe microanalysis of an iron (goethite-haematite) pisolith from the Toarcian of Monte Galiello, western Sicily. Length of scan line = 375 μ.
Figure 14: Electron-probe microanalysis of an iron (goethite) pisolith from the Toarcian of Monte Monaco, north-west Sicily. Length of scan line = 375μ.
Figure 15: Electron-probe microanalysis of calcareous ferromanganese nodule from the Toarcian of Monte Maranfusa, western Sicily. Length of scan line = 375 μ.
Figure 16: Electron-probe microanalysis of an iron oölith from the Bathonian Twinhoe Beds of Somerset, England. Length of scan line = 375μ.
Results

It is apparent that the Toarcian iron pisoliths are considerably enriched in trace elements. Perhaps the most striking feature is that all show thin bands (10-15μ) considerably enriched in manganese. With the samples from Monte Monaco and Monte Galiello, cobalt and nickel are obviously sympathetic with manganese, whereas chromium, titanium and vanadium are covariant with iron. Zinc and copper seem also to be sorbed in the iron-rich phase. These selective sorption phases are less obvious with the Rocce Maranfusa pisolith, where all of the ferromanganiferous material is concentrated in a central band. In all cases the ferromanganese phase is antipathetic to the calcareous matrix.

These results may be compared with electron-probe investigations on modern ferromanganese nodules: Burns and Puerstenau (1966), Cronan and Tooms (1968), and Aumento, Lawrence and Plant (1968) have reported differing inter-element relationships in the material investigated and it is apparent that sorption phases can be highly variable. All authors are agreed on the association of nickel with manganese, and Aumento, Lawrence and Plant found cobalt also sorbed in this phase. Burns and Fuerstenau recorded an association of titanium with iron,
whereas their other data is not in agreement with that presented here. In modern ferromanganese nodules, there are variations in the relative amounts of iron and manganese, but this variation is not as spectacular as with the Toarcian iron pisoliths.

The concretion from Monte Maranfusa is rather calcareous, with interlayered ferromanganese bands; in most parts of the nodule analysed manganese is present in greater quantities than iron. As with the pisoliths, titanium is obviously covariant with the ferruginous phase.

Hallam (1966, 1967a, 1969) has proposed a model of Jurassic palaeogeography where a northern area dominated by river drainage was the depositional site of a variety of facies, including ironstones; whereas in a southern domain, in at least some areas, more manganiferous red limestones were laid down. The Sicilian iron pisoliths are associated with the red limestone facies; so, bearing in mind these two depositional provinces, one epicontinental, one oceanic, it is instructive to compare the chemical composition of a 'northern' iron oolith with the more pelagic Sicilian specimens. The Twinhoe oolith was chosen because it comes from a calcareous facies in which ooliths are,
as with the Sicilian examples, only sporadically distributed.

From an examination of the chemistry of other sedimentary iron deposits (Taylor, 1949; Hegemann and Albrecht, 1954; Krejci-Graf, 1964; Schellmann, 1969), it is clear that the Twinhoe iron oolith is typical of a Minette ore, although local sources can greatly affect elemental abundances. Comparing the analysis of this oolith (Figure 16) with the Sicilian iron pisoliths (Figures 12 to 15), a considerable difference in trace-element abundance can be seen. This bears out the idea that the Sicilian pisoliths were deposited in a more oceanic regime, since, by comparison with modern ferromanganese nodules, the pelagic concretions are notably more enriched in minor elements than their epicontinental counterparts (Price, 1967). The presence of manganese, also essentially a 'pelagic' element, in these pisoliths, and in the nodule from Monte Maranfusa, reinforces this interpretation.

**ORIGIN OF IRON**

With the ferromanganese nodules of the present oceans, two primary elemental sources are postulated (see Mero, 1965): 1) from continental run-off; 2) from
leaching of volcanic rock on the sea floor, and direct supply from volcanic effusions. A secondary remobilisation of manganese from the reduced zone below the sediment-water interface has also been suggested (Lynn and Bonatti, 1965). These mechanisms have all been proposed for the origin of the iron in oölitic iron deposits. Taylor (1949) suggested that a continental source would be sufficient to account for all of the iron in the Northampton Sand Ironstone, and Hallam (1966), in a useful review of British Liassic ironstones, accepted this view, as does Bubenicek (1968). Hümmerl (1922) in a classic paper dealing with the origin of iron-rich rocks through halmyrolysis (submarine leaching) suggested that the iron in iron oöliths could come from oceanic sources; it is essentially this idea, that iron is remobilised from the oceans, albeit in a more sophisticated form, that has been adopted by Borchert (1960, 1965). Aldinger (1955) has suggested that as some iron oöliths are deposited at great distances from land (more than 100 kilometres) a continental source is by no means obvious; and that (1957) iron must be remobilised from a reduced zone to the sediment-water interface to form oöliths.
Reviews on the origin of iron ooliths have been given by Dunham (1960), Kreji-Graf (1967), and Hallam (1966).

It is obvious that the Toarcian iron pisoliths constitute a special case. Krauskopf (1956, 1957) has shown that, relative to manganese, iron is much less mobile and will thus tend to precipitate near its source; this is in agreement with the continental derivation proposed for the iron in most iron-oolith deposits, but makes a large-scale continental supply of this element less likely as a source for the Sicilian pisoliths. Their high iron content (relative to manganese) is still indicative of a local origin, however, and the association of the rocks with submarine effusives suggests an obvious source.

The iron may have been derived from leaching of the lava or from hydrothermal effusions accompanying the extrusion, and both sources seem likely. The fact that some of the lava, particularly the mafic minerals, has been replaced by carbonate shows that some of the ferromagnesian material must have gone rapidly into solution. The high content of chromium and titanium in the pisoliths may also be indicative of volcanic influences (Goldberg and Arrhenius, 1958); however, chromium is
usually very low in ferromanganese nodules (but may be present in greater amounts in some iron ooliths; see Schellmann, 1969), since this element tends to remain locked up in spinels and end up among the resistates (Arrhenius and Bonatti, 1965). High chromium does occur, however, in the hydrothermal precipitates on the East Pacific Rise (Bostrom and Peterson, 1966) and in this region Bonatti and Joensuu (1966) have also recorded pelagic high-iron deposits associated with manganiferous material — and assume a local source for this poorly crystalline and rapidly precipitated goethitic matter. This suggests that direct hydrothermal supply has played a major part in the formation of the Toarcian iron pisoliths.

If the iron was deposited relatively quickly, then it is clear that the manganese-rich bands in the pisoliths and the Monte Maranfusa ferromanganese nodule — representing the normal pelagic 'input' — must have been formed more slowly (Goldberg and Arrhenius, 1958), allowing, in some cases, a greater uptake of some minor elements, possibly by the scavenging mechanism of Goldberg (1954). Rona, Hood, Muse and Buglio (1963) have demonstrated that the amount of manganese co-precipitated with iron is inversely proportional to the
rate of precipitation, which is consistent with this. Arrhenius, Mero and Korkisch (1964) have suggested a criterion for distinguishing ferromanganese material deposited by submarine volcanism from that formed from dilute solutions of continental origin: they propose that a manganese to cobalt ratio of less than 300 is probably indicative of volcanic origin. From a study of the cobalt and manganese concentrations in the manganese-rich regions of the iron pisoliths (Figures 12 to 14), it is clear that a ratio considerably less than 300 is obtained, which is further evidence for a volcanic origin - although this type of numerical exercise must clearly be treated with some caution.

Thus a local volcanic source, leading to relatively early precipitation of iron, seems the best explanation of the origin of the west Sicilian iron pisolites.

DEPOSITIONAL ENVIRONMENT

As the Toarcian iron pisolites occur only as remanie beds, and are considerably condensed, it is obvious that currents have been instrument in their formation, and it is likely that deposition took place on open ocean seamounts after the Liassic carbonate
platform had broken up (Jenkyns, 1969). The association of iron oölites with high-energy environments has been remarked upon by numerous authors and it is evident that an essentially non-depositional environment is required for the concentration of iron (Hallam, 1967); and indeed Black, Hill, Laughton and Matthews (1964) have recorded a ferruginous limestone from Vigo Seamount, off the Iberian Coast.

Thus the depositional environment of the Toarcian iron pisolites is thought to be very similar to that of the main ferromanganeseferous condensed sequences which overlie them (see Jenkyns, 1967), but in the former case with submarine effusives and exhalations playing a more immediate role. The environment was probably strongly oxidising in most places, although small reduction zones may have enabled chamosite to form: Palmer (1964) has recorded a comparable association of glauconite and ferromanganese crusts from Rodriguez Seamount.

The presence of probable traces of boring algae in the Toarcian iron pisolites, plus the fact that they are underlain and overlain by stromatolitic sediments, suggests that the tops of the seamounts probably reached to within tens of metres of the surface.
FURTHER EXAMPLES OF PELAGIC IRON OOLITHS

During the Jurassic there was large-scale formation of oolitic iron deposits in northern epicontinental regions (Hallam, 1967) and this realm extended south to the Alps (Lucas, 1942, p. 79) and Carpathians (Misik, 1964) where chamositic and haematitic ooliths were also formed, particularly during the Lias. Epicontinental conditions also existed over parts of southern Spain and iron oolites also occur there (Geyer, 1967). In north Africa, also, small-scale oolitic iron bodies are not uncommon (Lucas, 1942), and in this case deposition may be related to a southern epicontinental influence. However, in the pelagic red limestones of Tethyan facies such oolitic iron deposits are certainly very rare.

Geyer (1967) has, however, recorded the presence of sparse iron ooliths associated with a limonite crust in the Subbetic zone of Spain; this horizon is developed in red limestone facies and contains a fauna of Toarcian-Bajocian age. Since this is a pelagic facies, it is likely that the 'limonite' crust contains considerable quantities of manganese. It is also interesting to note that southern Spain was, like
Sicily, a region of submarine volcanism during the Jurassic.

CONCLUSIONS

The Toarcian iron pisoliths of western Sicily, which occur as remanent horizons at several Jurassic localities, are made up of limonite (goethite), haematite, and, in rare cases, chamosite. Since these iron pisoliths are developed in pelagic red limestones, a continental origin for the limonitic material seems unlikely; however, to produce high iron (relative to manganese) deposits in an oceanic realm it is still necessary to postulate a local supply, since iron will tend to precipitate near its source (Krauskopf, 1958).

The iron pisoliths contain igneous material - sanidine trachyte - and it is probable that much of the iron and trace elements that compose the pisoliths were derived from hydrothermal effusions that accompanied the submarine extrusion.

The presence of chamosite, probable traces of boring algae, in the iron pisoliths and the stratigraphic position of the bed between two shallow-water sediments suggests that deposition took place in water tens of metres deep, probably on oceanic limestone seamounts.
CHAPTER 4

Fossil manganese nodules
from the west Sicilian Jurassic
CHAPTER 4

FOSSIL MANGANESE NODULES
FROM THE WEST-SICILIAN JURASSIC

INTRODUCTION

Since the discovery of manganese nodules during the course of the 'Challenger' expedition (1873-76), these concretions have constantly held a place in the pages of oceanographic literature. Fossil nodules, however, although recognised soon after the publication of the 'Challenger's' results have received little attention, and although such concretions are by no means uncommon in the geological succession, and are often recorded, their true nature and significance has not always been realised. A brief review of documented occurrences of fossil nodules will therefore be given.
Jukes Browne and Harrison (1892) in describing the Tertiary Barbados Earth referred, rather cryptically, to "hollow spaces ....... which appear to be the casts of small manganese nodules". This seems to be the first reference to fossil concretions of this type. Sokolow (1901) described some irregular pyrolusite concretions, some of which had knobbly surfaces and concentric shells, from the Tertiary of Russia; they were associated with clays, sands, and shallow-water fossils, and were compared by Sokolow to the recent nodules from the Black Sea and particularly to those of Loch Fyne, Scotland, where similar molluscan faunas and sediments occur (Buchanan, 1891; Murray and Irvine, 1894).

Molengraaf (1916, 1922) described what is probably the best-known occurrence of fossil nodules: those from the Cretaceous red clays of western Timor. Audley-Charles (1965) has recently described and analysed similar concretions from the eastern part of this island. Heim (1924), in a brilliant paper applying modern oceanographic evidence to the interpretation of Alpine geology, compared the manganese nodules from the Lower Jurassic limestones at Gossau, Austria, to those found in the deep sea. Grunwald (1964) interpreted some manganese carbonate concretions from the Pierre Shale of South
Dakota as fossil manganese (oxide-hydroxide) nodules that had undergone diagenetic alteration. Sorem and Gunn (1967) related some features of parts of the Tertiary manganese deposits of the Olympic Peninsular, Washington, to modern nodules.

Jenkyns (1967) briefly described and interpreted the nodules from western Sicily; Jurgan (1967, p.46-47, 1969) compared the ferromanganese concretions from the Berchtesgadaner Alps, Germany, with those from the Baltic, Atlantic and Pacific, and considered that the fossil nodules signified slow sedimentation rates in oxidising environments. Hurley (1966) and Fischer and Garrison (1967) have recorded some pancakes of ferromanganese partly embedded in hard Cenozoic limestones dredged from off Barbados; these may perhaps qualify as fossil nodules. Fabricius (1968) has figured a manganese nodule from the Sonnwend Mountains, Tirol, Austria, and Wendt (1969a) has further described the nodules from this area and related some of their structural features to those in modern concretions.

In the present study fossil nodules from the west Sicilian Jurassic will be described further and details of their geochemistry will be presented; these concretions occur in comparable facies to those described
Figure 1: Approximate zone of distribution of Jurassic red limestone containing ferromanganese crusts and nodules in western Sicily. Modified from Wendt, 1969b.
APPROXIMATE ZONE OF DISTRIBUTION OF LIMESTONE CONTAINING FERROMANGANESE NODULES AND CRUSTS.

**OCCURRENCE IN WESTERN SICILY AND STRATIGRAPHIC RELATIONS**

Ferromanganese nodules occur throughout western Sicily associated with the red limestone facies typical of the Tethyan Jurassic, and are invariably localised in extremely condensed sequences (Wendt, 1963; Jenkyns, 1967). The distribution of the nodule bearing red limestones is shown in Figure 1 as adapted from Wendt (1969b).

The ferromanganiferous condensed sequences can overlie a variety of facies, most commonly a shallow-water white limestone, but other deposits such as crinoidal limestones and iron pisolites may intervene between this white limestone and the beds containing ferromanganese nodules (see Appendix for sections). The condensed sequences are generally of Middle Jurassic age (for more precise data, see Wendt, 1963), and may be overlain by red nodular limestones and cherts, or by oolitic and pelletal deposits.
**Figure 2:** Discrete, concentrically laminated ferromanganese nodules concentrated in one main horizon. Vertical section. Rocca Argenteria, western Sicily. Length of hammer handle = 36 cm.

**Figure 3:** Thin ferromanganese pavements formed by lateral accretion and fusion of nodules. Bedding surface. Rocca Argenteria, western Sicily. Approximate length of pencil = 15 cm.
Figure 4: Concentrically laminated ferromanganese nodules. Vertical section. Contrada Drago, western Sicily. Length of hammer head = 18 cm.

Figure 5: Thick ferromanganese crust with limestone interstices. Bedding surface. Monte Kumeta, western Sicily. Length of hammer handle = 28 cm.
DESCRIPTION OF THE NODULES

A brief description of the nodules and crusts was given by Jenkyns (1967). Different characteristic forms occur at different localities: for example, at Rocca Busambra, Rocca Argenteria, and at Contrada Drago beds of concentric nodules and thin ferromanganese pavements are well developed (Figures 2, 3 and 4); here distinct populations of nodules with particular size ranges are characteristic of each ferromanganese horizon and are usually separated by barren sediments. The concentration of nodules in certain horizons has been observed by Strakov (1961) in present ocean sediments. The aforementioned localities also compare well with the Blake Plateau where both nodules and continuous pavements occur (Mero, 1965; Pratt and McFarlin, 1966). At Rocche San Felice and Monte Kumeta thick fused crusts occur (Figure 5) and the Monte Kumeta deposit bears a quite striking resemblance to that on San Pablo seamount (Aumento, Lawrence and Plant, 1968).

The variation in form of modern ferromanganese concretions from locality to locality has also been remarked upon by Murray and Renard (1891, p.366), Murray and Irvine (1894), Mero (1965, p.132) and Grant (1967). Murray, in fact, claimed that he could identify the source
Figure 6: Karstic pinnacle of white limestone coated by ferromanganese crust. Vertical section. Rocca Argenteria, western Sicily. Length of hammer handle = 36cm.
Figure 7: Fossil ferromanganese nodules from various localities of Middle Jurassic age in western Sicily.
area of a manganese nodule by its characteristic shape, and to some extent this is also possible with the Sicilian deposits.

Ferromanganese crusts may also coat upstanding parts of the shallow-water white limestones that underlie the condensed sequences (Figure 6; cf. Fabričius, 1968); these are probably karstic pinnacles that have acted as non-depositional points on the sea floor and have thus accreted mineral matter around themselves.

A few fossil nodules, extracted from their matrix, are shown in Figure 7; their outer morphology varies from crenulate, or mammillated to completely smooth. Concentric lamination is particularly well developed in the roughly spherical nodules found on Rocca Busambra and adjacent localities; with the crusts the lamination may only be developed as a lustrous outer skin with a more homogeneous earthy texture towards the centre. Some nodules show alternate light and dark bands. All this is in accord with the observations of Murray and Reynard (1891, p. 344-346; 351-366), Pettersson (1943) and Riley and Sinhaseni (1958) on modern iron-manganese concretions.

Jurgan (1967, 1969), when describing fossil Jurassic manganese nodules from the Berchtesgadener Alps, related the typical crinkled onion-skin structure of the
Figure 8: Nodule textures. Iron-manganese segregations in calcareous matrix. Polished sections from the ferromanganese crust on Monte Kumeta, western Sicily. Scale bar = 0.1 mm.
Figure 2: Iron-manganese 'cauliflower' structures in limestone. Vertical section. Ferromanganese horizon, Monte Irini, western Sicily.
fossil concretions to the dehydration of goethite to haematite during diagenesis as this would cause volume reduction. However, in the photograph of a modern nodule given by Mero (1965, p.138), this structure is already apparent, so the crenulate arrangement of laminae is probably primary.

A series of photographs of polished sections from the Monte Kumeta crust is illustrated in Figure 8; these should be compared with those presented by Sorem (1967) and Cronan and Tooms (1968) for modern nodules. With the Sicilian concretions, however, the interstitial areas between the ferromanganese segregations are made up of carbonate as opposed to the aluminosilicate matrix of the recent concretions described by Cronan and Tooms (1968). These authors suggest that the 'cauliflower' structures are due to early post-depositional migration and precipitation of the ferromanganese, and that they are of certain diagenetic origin in the fossil nodules is shown by the fact that they occur also in the limestone in which the concretions are embedded (Figure 9) (see also Jenkyns, 1969, for a further discussion of these structures). To some extent these migrating segregations may replace the limestone in the immediate vicinity of the nodules' periphery.
Figure 10: Large discoid ferromanganese nodule. Bedding surface. Monte Inici, western Sicily. Length of hammer handle = 28cm.
Calcite veins, both concordant and discordant with the lamination, occur in some crusts and nodules; some of these are probably of tectonic origin, but since aragonitic vein fillings have been recorded from modern manganese nodules (Manheim, 1965; McFarlin, 1967), a primary origin of some of these is possible. Micritic calcite is also often bound into the fossil nodules, as is the case with modern concretions formed in areas of carbonate accumulation; organic remains may also be found within the Sicilian nodules.

The fossil nodules are commonly around 0.5-5cms in diameter but may range up to 30cms across (Figure 10); the colour of the concretions varies from black through brown to reddish purple: this variation is probably a function of the degree of hydration of the component iron oxides and is not a reliable indication of the amount of manganese present. In fact, the opposite of that observed by Mero (1965, p.132) is often true; that is, brown or purple nodules are often higher in manganese than those of jet-black colour. The hardness of the fossil nodules is commonly around 3 Mohs scale, and increases with greater carbonate content (cf. Mero, 1965, p.132). The density of one nodule tested was 2.3gms/cc.
Figure 11: Ferromanganese-encrusted ammonites from various localities of Middle Jurassic age in western Sicily.
which is also comparable with the figure given by Mero (1965, p.135).

Some fossil nodules have no obvious nucleus, but most are formed either around a limestone intraclast or an ammonite (Figure 11) which may or may not have been partially dissolved. In some cases the encrustation of ferromanganese has preserved the outer shell, showing that precipitation of the mineral matter proceeded faster than the solution of aragonite. Kovacs (1956) has described a similar mode of preservation for ferromanganese-coated ammonites from the Hungarian Jurassic; furthermore, seizing upon the association of the black oxide material with fossil shells, he assumed that the decay of the original organic body had caused precipitation of the mineral matter. This, as Hollmann (1964) has pointed out, seems unlikely; more probably the shells just acted as nuclei. Manganese coatings on both dead and living molluscs from the Clyde estuary have been recorded by Murray and Irvine (1894) and Allen (1960).

At Monte Bonifato the ferromanganese horizon overlies a submarine extrusion of hornblende-biotite trachyte, and the nuclei of some of the nodules above are formed of reworked volcanic material. Igneous
MINERALOGY OF FOSSIL FERROMANGANESE NODULES

Although polished sections of the ferromanganese material are dominantly isotropic, X-ray powder patterns of virtually all crusts and nodules show the presence of goethite. Haematite is also detectable in some samples, usually those that are more reddish in colour. The only manganese mineral that has been identified with reasonable certainty is todorkorite and this is a common component of modern nodules (Sorem, 1967; Meyland and Goodell, 1967; Grill, Murray and Macdonald, 1968). The todorkorite lines, when present, are broad, so the mineral must be fine-grained. However, it must be stressed that in general the fossil nodules are not particularly crystalline, even after diagenesis, and presumably reflect an original dominantly colloidal nature. Mero (1965, p.152) notes the ill-crystallinity of modern nodules and Aumento, Lawrence and Plant (1968) found identifiable mineral phases only with difficulty. Smith, Gassaway and Giles (1968) have recorded entirely X-ray amorphous manganese oxides from some modern nodules; only secondary goethite was detectable - and this iron mineral is not uncommon.
in deep-sea concretions (e.g. Buser and Grütter, 1957). Thus it seems as if the fossil nodules must also bear a very strong mineralogical resemblance to their modern counterparts. The only difference is the presence of haematite; however, as Berner (1969) has recently pointed out, goethite is unstable relative to haematite in almost all geological conditions, so this latter mineral is of obvious diagenetic origin (see also Jurgan, 1967, p.46; 1969).

GEOCHEMISTRY

Several analyses of the black crusts and nodules associated with Jurassic red limestones have been carried out by various authors and these are summarised below. It is apparent that no detailed quantitative data, apart from the determination of iron and manganese has been produced; the analyses of Sigal and Truillet (1966) are the most comprehensive. The disparity between the major element composition must be due to a carbonate dilution factor as it is impossible to exclude some calcareous matter when analysing by standard geochemical methods. To overcome this, the present determinations have been performed using the electron-probe microanalyser.
<table>
<thead>
<tr>
<th>Authors</th>
<th>Date</th>
<th>Locality</th>
<th>Age</th>
<th>Chemistry of nodules of crusts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two authors</td>
<td>1956</td>
<td>Aultusse/Steiermark region, Austria</td>
<td>Jurassic</td>
<td>Mn 18.6%, Fe 25.2% MnFe, Fe—major components, lower Jurassic</td>
</tr>
<tr>
<td>Wiedenmayer</td>
<td>1963</td>
<td>Saltrio/Tremona region, Italian-Swiss border</td>
<td></td>
<td>Mg, Sr, Ti, Al, B, Pb, K, Alkali, Cu, Zn, Co, Ni, Cr—traces</td>
</tr>
<tr>
<td>Hollmann</td>
<td>1964</td>
<td>Monte Baldo region, north Italy</td>
<td>Middle Jurassic</td>
<td>Pyroclastic (1-2%) Fémére (35-55%) Calcite (45-55%) Illite (30-35%)</td>
</tr>
<tr>
<td>Sigal and Frulli</td>
<td>1966</td>
<td>Taormina region, eastern Sicily</td>
<td>Middle-Upper Jurassic</td>
<td>Mn 0.80, Fe 0.64, Ti 0.70, Al 2.30, Mg 3.75, P 1.95, Ca 10.90, Sr 13.00</td>
</tr>
<tr>
<td>Hallam</td>
<td>1967</td>
<td>Lower Jurassic region, Austria</td>
<td></td>
<td>MnO 3.29%, Fe2O3 4.68%</td>
</tr>
</tbody>
</table>
Fossil ferromanganese nodules have been analysed from a variety of localities in western Sicily; the sample locations are shown in Figure 1. Polished blocks were used for the determinations with 125-second scans across selected parts of the sample. The traverse distance, in all samples but one, was 375μ. Errors were minimised by using a composite-oxide standard for most of the analyses (comparable in composition to a nodule); but the results have been presented as weight percentages of the elements except for calcium which has only been determined semi-quantitatively, using a pure limestone standard.

With the graphs shown in Figures 13-24, the zero percentage has been calculated for the ferromanganeseferous area and the background is higher here than for the calcareous phase; this accounts for the scan-line falling below zero in the lime-rich part of the traverse.

Accuracy for the major elements (Fe, Mn) should lie in the range ±5%. Errors increase as the amounts of trace-metal decrease and, for the minor elements, the uncertainty value is probably ±20%. The detection limits of the various elements are set out below:
Figure 12: Electron-probe microanalysis of Recent ferromanganese nodule from the central Pacific. Length of scan-line = 375μ.
Figure 13: Electron-probe microanalysis of ferromanganese crust from Rocche San Felice, western Sicily. Length of scan-line = $375\mu$. 
Figure 14: Electron-probe microanalysis of ferromanganese crust from Monte Marafusa, western Sicily. Length of scan-line = 375μ.
Figure 15: Electron-probe microanalysis of ferromanganese nodule from Rocca Argenteria, western Sicily. Length of scan-line = 375μ.
Figure 16: Electron-probe microanalysis of ferromanganese crust (containing foraminifera) from Monte Bonifato, western Sicily. Length of scan-line = 375μ.
Figure 17: Electron-probe microanalysis of ferromanganese crust from Rocce Maranfusa, western Sicily. Length of scan-line = 37μ.
Electron-probe microanalysis of ferromanganese crust from Rocce Maranfusa, western Sicily. This sample comes from a stratigraphically higher position than that analysed in Figure 17. Length of scan-line = 375μ.
Electron-probe microanalysis of ferromanganese crust from Monte San Calogero di Sciacca, south-west Sicily. Length of scan-line = 375μ.
Figure 20: Electron-probe microanalysis of ferromanganese nodule from Acque Calde, southwestern Sicily. Length of scan-line = 375.
Al

Si

CaCO₃

P

Ti

V

Cr

Mn

Fe

Co

Ni

Cu

Zn

Ba

NOT DETECTABLE

NOT DETECTABLE
Figure 21: Electron-probe microanalysis of high-iron nodule from Monte Inici, western Sicily. Length of scan-line = 375μ.
Al

Si

CaCO₃

Ti

P

Cr

Mn

Fe

Co

Ni

Cu

Zn

Ba

NOT DETECTABLE
Figure 22: Electron-probe microanalysis of ferromanganese-coated limestone intraclast from Monte Inici, western Sicily. Length of scan-line $= 188\mu$. 
Figure 23: Electron-probe microanalysis of ferromanganese crust from Monte Monaco, northwest Sicily. Length of scan-line = 375 µ.
Figure 2: Electron-probe microanalysis of ferromanganese crust from Monte Kumeta, western Sicily. Length of scan-line = 375µ.
Major Elements

It is evident that the concretions show a tremendous variation in elemental composition, notwithstanding the disparity in carbonate content; and since the publication of Jenkyns (1967), several nodules with manganese higher than iron have been discovered (Figures 13, 14, 15 and 16). Figure 12 shows a microprobe analysis of a modern ferromanganese nodule from the central Pacific, and it is apparent that as far as the abundances of major (and minor) elements are concerned, many of the fossil concretions are comparable to this. Two nodules, those from Monte Bonifato (Figure 16) and Rocca Argenteria (Figure 15) assay particularly high in manganese, are rather low in iron, and impoverished in trace elements. Modern equivalents of these have been recorded by Niino (1955), Goldberg (1961), and Mero (1965, p.207, 227-228); the nodules described by Niino are in the Fuji volcanic zone and their formation may be due to manganese-rich springs (geothermal brines?) entering the ocean at this
point. Alternatively, the formation of iron-poor manganese nodules may result from diagenetic migration of manganese (Cheney and Vredenburgh, 1968).

Two crusts have been analysed from Rocce Maranfusa, coming from different parts of the succession and understandably the Fe/Mn ratios are somewhat different. However, at Monte Inici two concretions coming from the same bed, and separated by only a few millimetres, have vastly different amounts of manganese present, although the iron content is comparable (Figures 21 and 22). The iron-rich nodule (diameter 44mm) is not dissimilar in composition to the Toarcian iron pisoliths that occur in parts of western Sicily (Jenkyns, 1969).

A possible modern parallel to this situation has been recorded by Bonatti and Joensuu (1968) from the East Pacific Rise; they describe high-iron deposits in intimate association with manganese crusts, and postulate a local source for the differentially fractionated material. Ahrens, Willis, and Oosthuizen (1967) have also recorded marine limonitic nodules, which contain 0-15% manganese. Bonatti and Joensuu assume rapid precipitation for the more iron-rich phases; and Rona, Hood, Muse, and Buglio (1963) have shown in a laboratory
Figure 25. Electron-scanning beam photographs of ferromanganese-coated intraclast from Monte Inici, western Sicily. Area scanned = 375 x 375 µ². (Light portions of photograph indicate presence of element.)
study that, if manganese and iron are co-precipitated, the amount of manganese thrown down is inversely proportional to the rate of precipitation. Goldberg and Arrhenius (1958) found inshore limonitic nodules that had formed around shell fragments, probably not more than fifty years old. For the samples from the East Pacific Rise, hydrothermal solutions of volcanic origin and leaching of basic lavas are suggested as source materials, and Cronan and Tooms (1967) also explained the presence of two morphologically and chemically different nodule populations as due to hydrothermal and volcanic agencies. Thus the close juxtaposition of the manganese-high and manganese-low concretions from Monte Inici may be important in understanding the genesis of the Jurassic ferromanganese nodules.

Electron-scanning beam photographs of a thin ferromanganese-coated intraclast from Monte Inici are shown in Figure 25. It is evident from these that manganese is essentially confined to the mineral crust and is very much enriched in certain bands where iron is correspondingly poor. Iron, on the other hand, is also present to considerable extent in the calcareous centre of the nodule, where it may be bound in clay minerals or as limonite in algal or fungal borings. A calcareous
band is also present in the crust, presumably formed by trapping of local sediment when ferromanganese precipitation waned. The manganese- and calcite-rich bands both suggest that conditions during the formation of this concretion were subject to change; this may again be interpreted as due to intermittent local supply. In other crusts and nodules, the amounts of iron and manganese may also vary considerably across a traverse.

Many of the Sicilian Jurassic nodules show relatively high iron content and this would seem atypical when compared with Mero's (1965) analyses of modern Pacific concretions, though not perhaps with those of samples from other oceans. This relatively high iron concentration could be primary or may on the other hand reflect the diagenetic mobility of manganese. Murray and Irvine (1891), Wangersky (1963), Lynn and Bonatti (1965) and others have suggested that manganese can be remobilised upwards towards the sediment-water interface during early diagenesis, especially under reducing conditions. Thus, in this situation, any buried nodules would end up with a higher Fe/Mn ratio than originally; Lepp (1963) has also pointed this out with reference to iron-manganese deposits. The limestones in which the nodules are found are generally red, which suggests
that oxidising conditions persisted after deposition; but nevertheless bleached reduction zones, with pyrite, can be seen in some condensed sequences. Dendrites occur commonly in the limestone around which the nodules are buried (Figure 9) and this confirms that such migration of manganese can indeed take place. Some nodules from Rocca Argenteria are virtually hollow and perhaps this loss of material could be attributed to mobility of the constituents at some stage during diagenesis, as well as to the dehydration of goethite to haematite.

Minor Elements

The trace-metal composition of the modern nodule (Figure 12) is, in general, comparable to the Sicilian examples, though some of these are more enriched than others (compare Figure 16 with Figure 24). Those samples that contain very high iron or very high manganese are usually relatively depleted in minor elements; and the same phenomenon is apparent in the Cretaceous nodules from Timor (Audley-Charles, 1965). Barium and chromium, however, not detected by the microprobe in the modern nodule, are present in some of the Jurassic samples, occasionally in relatively high but local amounts (Figures 14, 22, 24). Some of the modern nodules analysed by
Mero (1965, p.182) have high barium but chromium is very low since, according to Arrhenius and Bonatti (1965), this element cannot easily be removed from igneous rocks and hydrolysed. Where both barium and chromium occur in significant amounts in modern oceans is in the region of the East Pacific Rise (Bostrom and Peterson, 1966); here hydrothermal exhalations are assumed to reach the surface and chromium attains values up to 0.02%, and barium up to 3.5%. The presence of these elements in some of the Jurassic nodules may thus have a bearing on the interpretation of their genesis.

Cobalt, nickel, titanium and vanadium are detectable in all of the west Sicilian Jurassic samples; zinc and copper only in a few.

Using the direct reading spectrometer some semi-quantitative determinations were carried out for elements not attempted on the probe; samples from Rocche San Felice, Monte Bonifato, Monte Inici, and Monte Kumeta were analysed. Of the elements sought Ag, Li, Sn, and W were not detected, while Pb, K, Zr, Cd, Sr, Mo, Bi, Be, Ga and Ge were found. Of these, lead was the most abundant and could, in fact, be picked up by the probe; no detailed analyses were attempted, however, since the
specimens were polished on a lead lap with the consequent likelihood of contamination.

Inter-element Relationships

Using microprobe techniques on modern nodules and crusts, inter-element relationships have been established by Burns and Fuerstenau (1966), Cronan and Tooms (1968) and Aumento, Lawrence and Plant (1968). From a study of their data, it is evident that such phase relationships differ from sample to sample; and such a situation can be seen with the fossil nodules analysed here. The only association found by all these authors is the covariance of nickel with manganese; yet in the Jurassic nodule analysed in Figure 14 this relationship is not fully established. Generally, however, (see Figure 24 for most obvious example) nickel does seem to be sorbed in the manganese-rich phase. Titanium is usually sorbed with iron (Figures 14, 15, 22), a relationship found by Burns and Fuerstenau (1966), but is sympathetic with manganese in Figure 24. Cobalt is sympathetic with manganese in Figures 22 and 24 (cf. Aumento, Lawrence and Plant, 1968) and ambiguous with many of the others. Barium is spectacularly sorbed with manganese in Figures 14 and 24. Figure 24 showing the
Figure 26: Electron-scanning beam photographs of ferromanganese crust from Monte Maranfusa, western Sicily. Area scanned = 375 x 375μ². (Light portions of photograph indicate presence of element.)
analysis of a crust from Monte Kumeta, gives by far the clearest display of inter-element relationships; apart from the elements previously referred to, zinc, copper, vanadium, chromium and possibly aluminium all appear to be sympathetic with iron, while silicon shows some covariance with manganese.

Electron-beam scanning photographs of a crust from Monte Maranfusa (same sample as Figure 14) are shown in Figure 26. These show titanium is strongly sorbed with iron and barium with manganese. Nickel and cobalt are more ambiguous. The ferromanganese phase is always antipathetic to the calcite matrix.

DISTRIBUTION OF FERROMANGANESSE CRUSTS AND NODULES IN THE TETHYAN REGION

The red pelagic limestone that is characteristic of the Mediterranean Jurassic is known by various local names such as "Ammonitico Rosso" and "Adneterkalk": this is a red nodular calcilutite. In its condensed facies, however, the limestone is never nodular - and it is only in these stratigraphically reduced horizons that ferromanganese deposits occur (see Aubouin, 1964, for data on the distribution of red limestones in time and space in the Tethyan region.
The approximate limits of this red limestone zone, which can be taken as reflecting oceanic conditions (Hallam, 1967), are shown in Figure 27 and it is only in this area that Jurassic ferromanganese nodules occur. It must be stressed, however, that red limestones are not by any means the only facies found within this area as neritic and even continental deposits are developed in some places (Arkell, 1956).

Occasionally ferromanganese enrichment may be found associated with hard-grounds in oölitic and pelletal deposits rather than the red biomicrites (e.g. Sturani, 1964, for the Venetian Alps; Accordi and Bosellini, 1965, for the Dolomites), though these localities still fall within the oceanic realm.

**ORIGIN OF "FERROMANGANESE"**

The origin of modern ferromanganese concretions is still in dispute; thus the genesis of the Jurassic nodules is also somewhat problematical. Two primary sources of manganese are postulated for modern iron-manganese accumulation: hydrothermal or volcanic effusions within the ocean basin and continental run-off (Murray and Reynard, 1891, p.372-378; Arrhenius, Merò and Korkisch, 1964; Arrhenius and Bonatti, 1965; Bonatti
and Nayudu, 1965; Manheim, 1965). Wangersky and Gordon (1965) have stressed the importance of organic aggregates as carriers of manganese. Currently, the volcanic theory seems to be the most fashionable; certainly its importance in the genesis of oceanic nodules cannot be disputed.

Terrigenous clastics are lacking both in the ferromanganiferous condensed sequences of the west Sicilian Jurassic and in coeval basinal sediments; the clay content, illite and montmorillonite is a typical oceanic association (Griffin, Windom and Goldberg, 1968), so any major ancient land-mass must have been at some distance. Minor exposed areas may, however, have existed in Sardinia and over parts of eastern Sicily and Calabria (Arkell, 1956), and river drainage may have supplied small amounts of iron and manganese to the Tethyan ocean. Moreover, the Jurassic was a time of widespread ironstone formation, particularly in northern Europe (Hallam, 1967), and also in a very minor way, in North Africa (Lucas, 1942). This iron is generally assumed to be derived from continental sources (e.g. Taylor, 1948; Hallam, 1967) and if this is so, one would also expect some manganese to be leached into the ocean. These epicontinental iron ores are not
rich in manganese (Taylor, 1948; Hegemann and Albrecht, 1954; Schellmann, 1969), so presumably this element must have become separated from iron and transported oceanwards in the manner outlined by Krauskopf (1957). Thus some continental contribution is to be expected for the Jurassic ferromanganese nodules associated with Tethyan red limestones.

However, submarine volcanism has already been appealed to as an explanation of the high iron contents of some of the west Sicilian ferromanganese concretions, and this source was the one that Wendt (1963) favoured as most likely for the origin of the mineral accumulations. Volcanic activity in the Middle Jurassic, particularly the Bajocian of western Sicily, is well documented (e.g. Fabiani, 1926; Trevisan, 1927; Schmidt di Friedberg, Barbieri, e Giannini, 1960; Broquet, Caire et Mascle, 1966; Caflisch, 1966; Montanari, 1966). The extrusions are generally described as basaltic and are often considerably altered; they may be extensively limonitised, chloritised, and replaced by carbonate in a comparable manner to that described by Matthews (1961), Naidu (1964) and Bonatti and Nayudu (1965) when dealing with modern altered volcanics and their association with ferromanganese enrichment. Reworked fragments of the altered
Figure 28: Altered trachytic lava fragment from ferromanganeseiferous horizon on Monte Bonifato, western Sicily. Note ferromanganese segregations; the matrix is largely replaced by calcite. Thin section. Scale bar = 1mm.
trachytic tuffs and lavas from the condensed sequence on Monte Bonifato (Figure 28) match the descriptions of these authors very closely.

At Montagna Grande, below the main ferromanganiferous condensed bed, there is a small pocket of green and purple clay-rich limestone (see appendix for section). This contains altered igneous minerals, and the clay is virtually all montmorillonite; ammonites from this horizon indicated a Bajocian age (H. S. Torrens, personal communication). Thus this locality is further evidence of a Bajocian volcanic phase, the montmorillonite being the alteration product of basic igneous material.

Thus, for the Middle Jurassic ferromanganese crusts and nodules of western Sicily, volcanism, which must have been widespread, was probably the most immediate source of material.

Although normal submarine volcanics are spatially related to ferromanganese deposits in western Sicily, and a similar relationship may perhaps be found in southern Spain (Geyer, 1965), elsewhere in the Tethyan region this association may not seem so obvious. However, some of the ophiolites (greenstones) which occur throughout the Tethyan region are of Jurassic age (Aubouin, 1965, p. 61; Grunau, 1965) and extrusion of
this basic material on to the ocean floor would have supplied considerable quantities of iron and manganese to the sea water. Some of this appears to have been precipitated locally, since iron and manganese are often intimately associated with radiolarites and ophiolitic rocks – the so-called Steinmann Trinity (e.g. Gäger, 1948, for Switzerland; Tromp, 1948, for Turkey; Debenetti, 1964, for Italy).

Thus, generalising for the whole of the Jurassic Tethyan ocean, primary source materials for the formation of ferromanganese crusts and nodules probably came from oceanic sources – submarine volcanism and exhalations – and from continental run-off.

**ENVIRONMENT OF DEPOSITION**

The depositional environment of the Sicilian ferromanganese crusts and nodules has been outlined elsewhere (Jenkyns, 1967): they are considered to have formed on ancient seamounts. These topographic highs probably reached to within a hundred or so metres of the surface, since the mineral concretions are often associated with algal stromatolites – and thus a depth limit must be imposed by the extent of the photic zone (see McMaster and Connover, 1966, for maximum depth
recorded for "live" algal-mat structures). Attempts have been made to correlate mineralogy and elemental composition of recent ferromanganese nodules with depth (e.g. Barnes, 1967), high cobalt, according to this author, being indicative of relatively shallow-water environments. Mero (1963, p.229-230), too, noted an association of cobalt enriched nodules with topographic highs. However, although some of the west Sicilian Jurassic nodules contain high cobalt (Figure 13 and 14), most of them do not, and I am inclined to the view of Nicholls (1967) and Price (1967) who were sceptical about the direct use of geochemistry as a depth indicator.

**CONCLUSIONS**

The Jurassic ferromanganese nodules from western Sicily are comparable in their shape, internal structure, mineralogy, and geochemistry to recent oceanic iron-manganese concretions. The high-iron content of some of the fossil nodules, and the occasional presence of chromium suggests that hydrothermal effusions may have strongly influenced the genesis of some of the mineral accumulations, and there is a spatial and temporal relationship with submarine volcanism. Elsewhere in the Tethyan Ocean, the ophiolites may have supplied iron
and manganese to the sea water; however, the Jurassic was a time of widespread ironstone formation in epi-continental northern Europe and river drainage must have supplied some manganese to the ocean, whilst the iron was deposited nearer the shore.

Formation of the Tethyan ferromanganese crusts and nodules is thought to have taken place on seamounts whose tops probably reached to within some tens of metres of the surface; this shallow-water environment seems to have had no effect on the geochemistry of the mineral accumulations.
CHAPTER 5

Notes on some Tethyan
stratified manganese deposits
CHAPTER 5

NOTES ON SOME TETHYAN STRATIFIED MANGANESE DEPOSITS

INTRODUCTION

Modern ferromanganese crusts and nodules accumulate in essentially non-depositional environments, particularly on topographic highs. The association of condensed sequences and hardgrounds with Jurassic ferromanganese concretions is thus to be expected (Jenkyns, 1967, 1969). It is therefore instructive to examine Tethyan stratiform ferromanganese-oxide deposits of economic importance and to determine whether or not they are associated with stratigraphic lacunae; if they are, then a genesis related to modern ferromanganese nodules might be assumed.
DESCRIPTION AND INTERPRETATION OF MOROCCAN AND HUNGARIAN DEPOSITS

Two major manganese deposits occurring within the Alpine-Mediterranean region are of importance in this connection: one in Morocco, and one in Hungary. Both are of Liassic age (Hewett, 1966). The Moroccan deposits are not associated with the typical Tethyan red limestone facies but are nevertheless relevant to the problem. Much of the manganese occurs as stratiform oxides - generally considered to be syngenetic (Pouit, 1964a) and it is perhaps worth noting that todokorite is among the mineral constituents of some of these deposits (Pouit, 1964b), since todokorite is a common constituent of recent ferromanganese nodules (e.g. Manheim, 1965). Time and again, Pouit (1964a) has stressed the association of ferromanganese mineralisation with evidence of submarine erosion and sedimentary discontinuities. Thus, in this case, rather than a basin of deposition, perhaps the opposite topographic feature, a shoal or swell, was the site of ore formation; such an uplifted area would inevitably be the site of considerable current activity and reworking. Pouit (1964a) himself suggested that modern ferromanganese nodules might be related in genesis to the Moroccan deposits; and certainly the Blake Plateau
can be cited as the site of a striking example of a recent stratiform ore, since this seamount is capped by a ferromanganese (and phosphate) pavement continuous for thousands of square kilometres (Pratt and McFarlin, 1966). These authors consider that accretion of the pavement is primarily the result of its special environmental situation - it is swept by the Gulf Stream - and a palaeogeographic condition similar to this could account for some of the Moroccan deposits. Otherwise, Hewett's (1966) suggestion of thermal waters as an ultimate source of the manganese in many stratiform ores seems most reasonable.

With the manganese deposits of Hungary, the associated limestone facies are typically Tethyan in aspect. The most spectacular deposits are in the region of Epleny and Urkut in the Bakony Mountains where stratified deposits of both oxides and carbonates occur (Szabo-Drubina, 1959, 1961), though the position is somewhat complicated by the fact that many of the carbonate ores are secondarily oxidised.

Primary manganese oxides, sometimes in the form of nodules, occur at Epleny, however, where they directly overlie white Dachstein limestone or a crinoidal calcarenite (Szabo-Drubina, 1959) and this stratigraphic
situation is directly comparable to that of the ferromanganiferous condensed sequences in western Sicily (Jenkyns, 1969). At Urkut, on the other hand, the ore, which is of a primary carbonate type, overlies a grey radiolarian marl or a red nodular chert-bearing limestone (Szabo-Drubina, 1959; Cseh Nemeth, 1967).

Both crinoidal limestones and chert-bearing marls are considered to have a certain palaeogeographic significance during the Tethyan Jurassic; crinoidal calcarenites are generally related to submarine highs (Jacobshagen, 1964; Jenkyns, 1969), whereas marls and cherty limestones may be indicators of more basinal environments (Bernoulli, 1967; Flügel, 1967). Thus at the onset of manganese deposition it is probable that a differential sea-bottom morphology was present over the area, with a swell or seamount over part of the Epleny region and basin towards Urkut; this submarine topography presumably originated by faulting of the Dachstein limestone into a horst and graben structures. To bear this hypothesis out, Cseh Nemeth (1967) has noted that at Epleny there is a stratigraphic gap at the Middle-Upper Lias boundary and the manganese oxide is discordant on the beds below, whereas at Urkut the
manganese carbonate succession is unbroken and lies concordantly above the radiolarian marls.

It therefore seems likely that where primary manganese oxide was deposited the depositional site can again be related to that of topographic high, whereas the carbonates accumulated in a more basinal environment. The obvious modern analogue to this is the Baltic Sea. Here, on topographic highs and on the rims of basins, nodules, crusts and pavements of ferromanganese oxide occur (Manheim, 1965); in the stagnant troughs, however, where the bottom sediments are rich in organic material and hydrogen sulphide, finely banded ferromanganese carbonates accumulate, since this is the stable phase under reducing conditions (Manheim, 1961; Hartmann, 1965).

Small-scale Jurassic ferromanganese carbonate deposits, some of which may have suffered secondary oxidation, occur throughout the Alpine region associated with the basinal bituminous shale facies, posidonienschiefer and the fleckenmergel (e.g. Lechner and Plochinger, 1956; Huckriede, 1959; Jacobshagen, 1964, 1965; Andrusov, 1965, p.145-147, 238). It is perhaps not fortuitous that the Urkut manganese-carbonate is of Lower Toarcian age – which
Figure 1: Electron-probe microanalysis of primary manganese-oxide ore from Epleny, Hungary. Length of scan-line = $375\mu$. 
corresponds to the most spectacular horizon of bituminous shales in northwest Europe (Hallam, 1967).

A sample of the primary oxide ore from Epleny has been analysed and the results are shown in Figure 1. It is interesting to compare this with the composition of the west Sicilian Jurassic ferromanganese concretions (Jenkyns, 1969). Two of the nodules (Figure 15 and Figure 16 in Jenkyns, 1969, Chapter 4) approach the Epleny ore in composition: both of these have high manganese relative to iron and are depleted in trace elements. Modern equivalents of this situation can also be found (e.g. Niino, 1955; Goldberg, 1961; Mero, 1965, p. 207, 227-228). The Epleny sample does, however, contain high barium (surprisingly antipathetic to manganese in its sorption phase - possibly due to crystallisation of discrete manganese minerals?). Nevertheless, this sample of ore seems comparable with some modern and some fossil nodules; and other analyses of material from Epleny (Vadasz, 1952; Szabo-Drubina, 1961) show higher iron contents, which allow a more ready comparison.

In this case, also, the origin of the ferromanganese is a problem; from a study of the heavy mineral assemblage in the Upper Liassic sediments,
Szabo-Drubina (1959, 1961) was of the opinion that a basic igneous or metamorphic complex or submarine volcanic extrusion might be the source. Certainly the economic quantity of the ore-body, when compared to most Tethyan manganese occurrences, necessitates that some specialised source must be envisaged. However, the Blake Plateau model may still be in part applicable; and it is worth remembering that deposition of ferromanganese is here taking place no more than 200km from the shoreline of a continental landmass.

CONCLUSIONS

Those ferromanganese-oxide deposits that are associated with stratigraphic lacunae and condensed sequences may have an origin related to recent ferromanganese crusts and nodules. Stratified oxides of iron and manganese thus may indicate areas of former topographic high on the sea or ocean floor, whereas ferromanganese carbonates probably accumulated in stagnant basinal environments.
CHAPTER 6

The Genesis of Condensed Sequences in the Tethyan Jurassic
CHAPTER 6

THE GENESIS OF CONDENSED SEQUENCES
IN THE TETHYAN JURASSIC

INTRODUCTION

Many Mesozoic sequences in the Alpine-Mediterranean region are referred to as condensed when characterised by diminutive stratal thickness with concomitant faunal enrichment. It is the purpose here to describe the lithological features of such horizons and to examine the processes involved in their formation. This paper will deal particularly with the red Middle Jurassic limestones of western Sicily, with some reference to other Tethyan carbonates, particularly those of similar facies.

The west Sicilian condensed sequences usually overlie the "Bahaman" Liassic platform carbonates; but other deposits such as crinoidal calcarenites and iron
pisolites may intervene between the shallow-water white limestones and the stratigraphically reduced horizons. These condensed sequences contain ferromanganese nodules and crusts (Wendt, 1963; Jenkyns, 1967), and are generally red in colour, but may be locally bleached to grey or pale green. They may be overlain by red nodular 'ammonitico rosso' limestones (see Aubouin, 1964) or by grey pel- and oosparites.

In parts of western Sicily expanded basinal deposits coeval with the condensed sequences are developed, i.e. at Balata di Baida (Warman and Arkell, 1954) and at Piana degli Albanesi (Caflisch, 1966). Basinal deposits also seem to be widespread throughout the Jurassic in northern Sicily and in parts of the Sicani Mountains in the south (Wendt, 1969a).

**STRATIGRAPHIC CONDENSATION AND REWORKING**

From a study of the literature on condensed sequences, it is evident that two separate processes are envisaged in the formation of such horizons: both stratigraphic condensation itself and reworking. Much of the classic work on the causes and effects of these processes was carried out by Arnold Heim (1934, 1958), Heim and Seitz (1934), and by Rod (1946) and Schaub (1948).
Rod (1946) defined stratigraphic condensation as a process that results in extremely slow or 'stagnant' sedimentation being continued over a long period of time to produce a bed characterised by the following features:

1. Enrichment of well-preserved fossils and fossil fragments.
2. Faunal mixing, fossils from different palaeontological zones being mixed up together within the bed.
3. Widespread distribution and negligible thickness.

Reworking, on the other hand, was envisaged as a process acting on a normal sedimentary series, either consolidated or unconsolidated, in such a way as to remove the fine particles by submarine denudation and leave the coarser more or less in situ.

Heim's idea of stratigraphic condensation was not so clear-cut as this; he included small-scale reworkings to fall within the process he termed condensation, thus blurring the distinction between the two definitions. Rod admitted that reworking effects could occur with condensation, but excluded it from his definition. The presence of this slight confusion over terminology has been pointed out by Mensink (1960) when referring to condensed sequences in the Spanish Jurassic.
It seems to me that the process of stratigraphic condensation — reflecting a minimal sediment input in an environment of negligible current action — is most likely to be realised in the hypothetical barred basin of Woolnough (1942). Some radiolarite and red limestone sequences in the Alps have been interpreted as starved basin deposits (e.g. Fischer, 1964; Mutch and Garrison, 1967), but in western Sicily the basinal cherty marl sequences are nevertheless considerably thicker than some coeval successions. These latter successions are the condensed sequences that I wish to discuss.

The red (or brown) deep-sea clay that forms in the present-day oceans is the nearest to a purely condensed deposit and even the abyssal regions where this material accumulates are not immune from quite strong currents (Heezen and Hollister, 1964). And where there are currents one would, on Rod's definition, expect some reworking. Thus, if 'reworking' is to include the transport of unconsolidated sediment, it is probable that in practice stratigraphic condensation cannot be separated as a distinct process; it is hypothetical end-member. Certainly, if current activity is precluded altogether as instrument in the formation of condensed sequences, faunal mixing, listed by Rod as one of its
characteristics, is a little difficult to understand. Shaub (1948), recapitulating Rod's ideas on the origin of condensed sequences, referred to a bed whose deposition extended throughout many palaeontological zones, so that fossil accumulations remained loose and sometimes 'de-sedimented' but not transported over any great distance. It is clear that currents were considered as the agents of the 'de-sedimentation'.

Hollmann (1964), dealing with condensed sequences in the Jurassic red limestones of North Italy, presented a more balanced view: he suggested that although extensive mechanical reworking had not taken place, the role of currents had been considerable; Flügel (1967) expressed similar opinions on the genesis of the Austrian Steinmühl-Kalke. Lucas (1966) considered that violent submarine erosion, engendered by the 'tsunami', could explain, particularly in former regions of tectonic instability, the formation of condensed sequences and sedimentary lacunae; however, although removal of sediment by sudden powerful currents may have taken place, continuous water agitation of lesser extent seems more ably to explain the authigenic mineralisation that accompanies many such horizons (see below).
Jenkyns (1967) suggested that the condensed sequences of the west Sicilian Jurassic were deposited on transient topographic highs; this idea was put forward because the condensed beds are of different inclusive ages at different localities. The same is true of the condensed sequences described by Heim and Seitz (1934) from the Cretaceous of Switzerland, which suggests that they, too, may have been deposited on separate seamounts. As submarine topographic features tend to be current-swept (Heezen and Hollister, 1964), some reworking is to be expected on the deposits that form on them. Also, authigenic oxide minerals will obviously develop more favourably in a current-influenced environment than in a stagnant one, albeit of low sedimentary rate.

One of the arguments adduced against reworking by both Heim (1934) for the Cretaceous of Switzerland and Wendt (1963) for the west Sicilian Jurassic is that the older faunal elements in a 'condensed' assemblage are often as well and sometimes better preserved than the younger; however, burial and subsequent uncovering could account for this - burial giving protection against erosional and solutional influences on the exposed sea floor.
Both Rod (1946) and Heim (1958) proposed faunal mixing as a criterion of stratigraphic condensation, but as the degree of condensation can vary from place to place, clearly some sequences will have microstratigraphically separable zonal fossils whilst still being considerably condensed when compared with other beds of the same age. Thus, this criterion cannot be considered as an integral part of an inclusive definition of condensation. Apart from this, the definitions of the processes of condensation and reworking, as outlined by Rod (1946), seem perfectly satisfactory.

In an environment where most of the sediment is swept away before it has the chance to settle, the term 'reworking' is hardly applicable; nor is this an environment of stagnant sedimentation, yet the final deposit will obviously be condensed. This case suggests that it is better to consider the characteristics of a sequence, and apply a label to it, without necessarily implying a particular genesis in the name used.

A condensed sequence will therefore be defined as a bed that is considerably reduced in thickness relative to another of equal age and whose origin is a product of minimal net sedimentation.
Figure 1: Idealised diagram of a condensed sequence (*sensu lato*) showing hardground interrupting two condensed sequences (*sensu stricto*).
condensed sequence (s.s.)
with mineral nodules

hard-ground with
mineral crust

condensed sequence (s.s.)
with mineral nodules

net sedimentation increasing

sink in deposition

net sedimentation decreasing
HARDGROUNDS

There is an obvious genetic connection between condensed sequences and hardgrounds; condensed sequences are produced by minimal net sedimentation, hardgrounds by nil or negative sedimentation. Aubouin (1964) described a condensed bed as a 'hardground avorte' or 'failed hardground'. Hardgrounds are often referred to in German literature as 'omission surfaces', omission being a period of shorter or longer cessation of sedimentation (Heim, 1958). It is obvious that current activity is a prerequisite for the development of hardgrounds; and in the west Sicilian Jurassic some of the condensed sequences are interrupted by these stratigraphic breaks (see appendix). In fact, ideally, we may distinguish a condensed sequence (sensu lato) consisting of a series of hardgrounds from a condensed sequence (sensu stricto) which intervenes between the hardgrounds (Figure 1). These condensed sequences (s.s.) may contain discrete mineral nodules, whereas a continuous crust or pavement may be developed over a hardground. In the Tethyan Jurassic ferromanganese mineralisation is most prominent (Jenkyns, 1969), although phosphorite, glauconite, limonite and other iron minerals, and possibly leptochlorite (see Misik, 1964; 1966, p.132) can occur
associated with other condensed sequences (e.g. Heim, 1924; Lindstrom, 1963; Lucas, 1966).

Carraro (1964) has illustrated, in colour, a hardground from the Jurassic of the Venetian Alps.

**EVIDENCE OF CURRENT ACTION IN THE WEST SICILIAN CONDENSED SEQUENCES**

Wendt (1963) came to the conclusion that the red west Sicilian limestones of Middle Jurassic age were formed predominantly by the condensation as opposed to the reworking process. Similar pronouncements have been made for red Tethyan limestones in the Alps (Hirschberg and Jacobshagen, 1965), although the process they described was, in fact, reworking. Evidence will be presented below to show that current activity has played a very considerably role in the formation of the condensed red limestones of western Sicily, and it is likely that such effects will also have contributed to the genesis of similar rocks elsewhere.

1. Removal of sediments from the stratigraphical succession; sediments which occur only in Neptunian dykes. At several localities in western Sicily sediments may be preserved in tectonic fissures when they are absent
from the stratigraphic succession (Wendt, 1965). Although some reduction in thickness may be due to removal into the dykes themselves, this process could not conceivably remove a whole bed. Thus there is evidence here of sedimentation and later erosion – i.e. reworking.

2. Thickness differences in beds (cf. Hollmann, 1964, for North Italy). This is most spectacularly shown at Monte Pispisa (see Wendt, 1963, for section and locality details) where, in places, Cretaceous marls rest directly on white Liassic limestones, whereas elsewhere along the succession thin representatives of the Oxfordian and Kimmeridgian fill this stratigraphic gap (Wendt, 1963); this hardly corresponds to widespread lateral extent (see Rod's definition of condensation).

3. Presence of volcanic fragments. At Monte Bonifato (see Wendt, 1963, for section and locality details) a thick bed of volcanic tuff occurs below the main condensed horizon, and fragments from this, some very large (up to 45cm diameter) and often rounded, are contained in higher beds. Continual reworking is the only explanation for this.
Figure 2: Thin section from the condensed sequence on Monte San Calogero di Sciacca, south-west Sicily. Note the difference in microfacies between the ammonite and matrix. Scale bar = 2.5 mm.
4. Difference in lithology between fossil infill and surrounding sediment. Although Wendt (1963) expressly stated that the lithology within and without ammonite shells is the same, this is not always the case as Figure 2 illustrates. This attests to reworking.

5. Presence of ferromanganese pisoliths and nodules; these occur in virtually all the west Sicilian condensed sequences. Many of these concretions have limestone cores, so the nucleus must have been more consolidated than the surrounding sediment to enable ferromanganese to accrete around it. This suggests reworking as Wendt (1963) admitted; and the formation of a continuous mineral coating would be favoured in conditions of water agitation.

Thus the condensed limestone sequences that occur in the Tethyan Jurassic, particularly those that are associated with authigenic mineralisation, cannot have accumulated in purely stagnant environments of minimal sedimentary rate. These condensed sequences are considered to have arisen by both the condensation and reworking processes as defined by Rod (1946); their genesis, and those of other Tethyan facies, are
Figure 3: Diagram showing relationship of stratigraphic condensation and reworking to the genesis of various Tethyan facies.
represented diagrammatically in Figure 3. Similar conclusions were reached by Andree as long ago as 1908.

The role of 'subsolution' (Hollmann, 1962, 1964) in the genesis of condensed sequences will be discussed later.

**SOURCE OF PELAGIC LIMESTONES IN THE TETHYAN JURASSIC**

The red limestones that characterise parts of the Tethyan Jurassic have been interpreted as being deposited a considerable distance from a major continental landmass (Hallam, 1967) and this is a view I hold myself. In such an environment the sediment input from terriginous sources will be minimal; and this will hence lead to stratigraphic condensation (*sensu* Rod). This, in turn, raises the problem of the origin of the limestone composing the condensed sequences.

Photomicrographs of some thin sections taken from condensed sequences are shown in Figures 2 and 17; it is evident that these rocks are rich in microfauna and that skeletal calcite occupies a significant proportion of the rock. The limestone matrix, however, is not resolvable under the ordinary microscope, although it may in some cases show faint pelletal texture - and only under the electron microscope can any structure be
Figure 4: Coccolith ghost. Condensed sequence, Monte Kumeta, western Sicily. Electron micrograph of polished and etched surface. Scale bar = 5μ.
seen. Figure 4 shows the remains of a coccolith from the condensed sequence on Monte Kumeta; nevertheless these planktonic forms are very rare in these rocks.

Other workers (Fischer, Honjo and Garrison, 1967; Mutch and Garrison, 1967; Flugel, 1967; Farinacci, 1967) have found remains of coccoliths in Jurassic red limestones in other parts of the Tethyan realm. Fischer, Honjo and Garrison (1967, p.25,28) give the impression that coccoliths are plentiful in the Austrian Adnet limestones of Middle Jurassic age, noting that they occur in rock-forming numbers. Farinacci (1967) also assumed a biogenic origin for some red micrites of Upper Jurassic age, assuming that the non-organic grains were diagenetic. Thus it seems that the Middle Jurassic limestones of western Sicily can also be best interpreted as essentially organic in origin; the scarcity of planktonic algae before the coccolith 'explosion' in the upper part of the Jurassic may account, to some extent, for the extremely condensed nature of these deposits.

Assuming that the west Sicilian condensed limestones are biogenic, one must then explain why coccoliths are so scarce within them. Several possibilities suggest themselves.
The coccoliths may have been largely destroyed by recrystallisation; in support of this idea is the fact that Bramlette (1958) recorded coccoliths in an undeformed Maestrichtian chalk from south-central Tunisia - whilst only interlocking calcite crystals could be found in a highly folded limestone equivalent to the north. Thus tectonism - or diagenesis - might have destroyed the coccolith tests; although this does not explain the presence and excellent mode of preservation of these bodies in the Tithonian-Neocomian 'Lattimusa' limestone (see Jenkyns, 1969) that occurs above the condensed sequences.

Another possibility is that in an environment of considerable current action where the bottom sediments are being continually stirred, mechanical and solutional influences may have caused coccolith tests to disintegrate. Any organic matter binding the plates together would also be quickly oxidised in an environment of slow deposition.

A third possibility is that during the Middle and perhaps during the parts of the Upper Jurassic the majority of coccoliths were not completely calcified; some living coccolith-bearing algae are constructed of minute prisms of calcite, each enclosed in an organic membrane and would presumably break down into their
component crystals soon after falling to the sea floor (Black, 1968). A predominance of such forms during much of the Jurassic would account for their lack of geological record - but they would nevertheless contribute significantly to sediment accumulation.

Of these three possibilities, I am inclined to favour the last two as being most likely; nevertheless, some diagenetic recrystallisation is to be expected in the post-depositional history of these Middle Jurassic limestones.

**LITHOLOGICAL AND FAUNAL CHARACTERISTICS OF WEST SICILIAN CONDENSED SEQUENCES**

General lithological features

The west Sicilian condensed limestones, unlike the 'ammonitico rosso' facies which usually overlies them, are never nodular and marly and are hence very pure (Hollmann, 1962); the insoluble component is generally in the region of 1-5% (see appendix) and terrigenous detritus is virtually absent. After digestion with acid the colour of the residue is far more intense than in the original limestone and it is apparent that the red coloration is bound up with the clay minerals: these consist predominantly of illite with traces of
montmorillonite and possibly chlorite and kaolinite (cf. Hallam, 1967). These limestones are presumably red for the same reason that the present deep-sea clay is red (or brown) — that is, slow sedimentation under fully oxidising conditions. As Hallam (1967) has pointed out, the red colour is probably secondary and on deposition these sediments were probably brown — diagenesis having converted the goethitic pigment to a 'haematitic' one (Berner, 1969). There is certainly no need to invoke the proximity of a laterised landmass and the influx of terra rossa, as has been so popular in the past (e.g. Kovacs, 1960; Termier and Termier, 1962). In fact, although not depth dependent (cf. Heim, 1924; Brinkmann, 1936), this colouration is probably a function of distance from a major landmass being also dependent on low organic productivity. The origin of the iron may still ultimately be sought in continental run-off, with the addition of submarine volcanic sources.

General palaeontological features
Many detailed observations on Tethyan condensed sequences and the state of their contained fauna have been made by Wendt (1963) for western Sicily and Hollmann (1964) for north Italy. Ammonites are by far the most
Figure 5: Part of serpulid colony preserved in limestone. Condensed sequence, Monte Bonifato, western Sicily. Thin section. Scale bar = 1mm.

Figure 6: Close-up of serpulid tubes in section. Condensed sequence, Monte Bonifato, western Sicily. Thin section. Scale bar = 1mm.
Figure 7: Encrusting foraminifera in ferromanganese nodule. Condensed sequence, Monte Bonifato, western Sicily. Polished section. Scale bar = 0.25 mm.

Figure 8: Traces of boring algae in ferromanganese nodule. Condensed sequence, Rocca Argenteria, western Sicily. Electron micrograph of ground and etched surface. Scale bar = 100 μm.
Figure 9: Detail of Figure 8, showing moulds of boring algae. Scale bar = 10μ.
common macrofaunal element in the west Sicilian condensed sequences and occur in various stages of preservation; the larger shells in general lie parallel to the bedding, whereas the smaller may rest at higher angles (cf. Hallam, 1960). Apart from ammonites and aptychi, the condensed sequences may contain a few brachiopods and gastropods, belemnites and fish teeth. Rare single corals occur on Monte Kumeta and part of a reptile bone has been found at Montagna Grande. In thin section lamellibranchs, chiefly Bositra, are very common and may be accompanied by ostracods, crinoid debris, calcitised râlolaria, globochaetes, globerigerines and other foraminifera. The rocks are dominantly biomicrites - thus constituting a typical Tethyan microfacies (Colom, 1955; Cita, 1965; Fabricius, 1966; Misik, 1966).

Serpulid tubes (cf. Sarcinella sp.) are common in the west Sicilian condensed beds, often encrusting ammonite shells and ferromanganese nodules - or as discrete masses within the sediment (Figures 5 and 6) (cf. Wiedenmayer, 1963; Hollmann, 1964; Fabricius, 1968; Wendt, 1969b, for other Tethyan regions). Encrusting foraminifera also occur very abundantly in some ferromanganese concretions (Figure 7), though they may be completely absent in others; these mineral accumulations
Figure 10: Stromatolitic horizon on weathered rock surface. Note the intimate association with ferromanganese nodules. Monte Maranfusa, western Sicily. Diameter of 5 lire piece = 2 cm.
Figure 11: Faint undulose stromatolitic laminae from condensed sequence on Rocca Nadore, southwest Sicily. Peel, negative print.
may also harbour traces of boring algae and fungi (cf. Wendt, 1969b for the Sonnwend Mountains of Austria) which have penetrated the carbonate layers of the concretions and whose tunnels (diameter $2-4\mu$) have later been infilled by limonite (Figures 8 and 9). Large vertical borings (diameter 1-2cm), whose walls may be coated with ferromanganese oxides, occur in many hardgrounds.

Stromatolites

Stromatolites have been found in many of the west Sicilian condensed sequences: at Rocce and Monte Maranfusa, Monte Bonifato, Contrada Drago, Rocca Argenteria, Montagna Grande, Monte Inici, and at Monte San Calogero di Sciacca (see Wendt, 1963, and appendix for sections and locality details) - and it is probable that such structures occur at other localities and indeed throughout the Tethyan region. Stromatolites are, in fact, very difficult to recognise in the field unless they weather out (Figure 10); on fracture surfaces they are often indistinguishable. Polished surfaces show up the algal laminae to advantage, and negative prints from acetate peels may also be rewarding (Figure 11).
Figure 12: Onkolithic overgrowth on ammonite. Condensed sequence from Rocce Maranzasa, western Sicily. Polished block.
The stromatolites are usually of the LLH-type of Logan, Rezak and Ginsburg (1964) and generally consist of rounded or flattened domes, but sometimes the laminae are virtually horizontal [compare the recent algal-mat structures illustrated by Black (1933), Monty (1967) and others]; these stromatolites are never associated with desiccation cracks. At most localities the algal-mats are concentrated in a single horizon, although some structures may be developed elsewhere in the succession, particularly as onkolitic overgrowths on ammonites (Figure 12). Small ammonites may also occur within the algal-mat structures. Generally, the stromatolitic layers overlie a ferromanganese hardground - although they may in turn be overlain by another non-sequence.

Microscopically the lamination, where best developed, consists of alternate layers of dense micrite (thickness 5-10μ) and skeletal detritus set in a pelletal micrite and microspar matrix (thickness 200-300μ). This skeletal detritus is generally of a small size, and includes globochaetes, foraminifera, crinoid and fine shell debris. Presumably, the dense micrite is that originally trapped by the algal mat while some of the skeletal detritus may have filtered in after the decay of the organic hyaline layer, with some micrite
Figure 13: Large stromatolitic clumps built of fine sediments with accumulations of crinoid ossicles in the interstices. Condensed sequence on Rocce Maranfusa, western Sicily. Polished blocks.
precipitated within the mudflats to form pelletal or 'clayey' texture (Monty, 1967).

Thus the stromatolitic clumps are built of essentially fine-grained sediment, which the dyes have selectively trapped, whilst the coarser sedimentary particles such as aragonite crystals have collected between the laminae. This suggests that the sedimentation and diagenesis reflect a variety of conditions, including possible reworking of the clays by water flows and deep-water environments. Szurowski (1963, 1966) and Szurowski and Szurowska (1966) have described a variety of stromatolites with stromatolites, with reworked feldspars, and sedimentary iron enrichment, and suggests a depositional environment of 'intrusional ridges'. All of this indicates

Figure 14: Stromatolitic laminae picked out by ferromanganese staining. Note halo of dendrites from the ferromanganese nodule. Condensed sequence on Rocce Maranfusa, western Sicily. Polished block.
precipitated within the mucilage to form pelletal or 'clotty' texture (Monty, 1967).

Thus the stromatolitic clumps are built of essentially fine-grained sediment, which the mats have selectively trapped, whilst the coarser sedimentary particles such as crinoid ossicles, have collected between the algal domes (Figure 13); this is perfectly in accord with the observations of Black (1933) on recent stromatolites.

The stromatolitic laminae are sometimes outlined by ferromanganese staining (Figure 14) - and whether this is a primary depositional feature or a result of the diagenetic movement of manganese cannot be determined. Nevertheless, this figure and Figure 10 illustrate the intimate association of ferromanganese nodules with stromatolites, thus demolishing the idea that these mineral concretions indicate deep-water environments.

Szulczewski (1963, 1968) and Radwanski and Szulczewski (1966) have described a variety of stromatolites in Jurassic red limestones from both Hungary and Poland; and Szulczewski (1968) notes their invariable association with reworked faunas, stratigraphic lacunae, and sedimentary iron enrichment, and suggests a depositional environment on 'intrageanticlinal ridges'. All of his detailed
Figure 15: Diagram illustrating hypothetical relationship between stromatolites and sediment supply.
ammonites with stromatolitic overgrowths
stromatolitic laminae
mineral crust

30 cm
net sedimentation increasing
observations are applicable to the stromatolites described here; although the west Sicilian Jurassic contains negligible terrigenous detritus (c.f. Szulczewski, 1968).

The association of stromatolites with condensed sequences is undoubtedly significant and its significance is probably twofold. Condensed sequences will tend to form on topographic highs and thus the amount of light reaching these areas will be greater than for the neighbouring deeps. If the light is sufficient for photosynthesis, then algal colonies might develop. Secondly, Monty (1967) has pointed out that in environments of sediment movement algal mats form preferentially on hard substrates - and such substrates must have existed after a 'hardground' had been developed. When sediment again began to build up, ammonite shells and belemnite guards provided hard surfaces on which the algal mats could anchor (Figure 15).

The association of stromatolites with mineralised condensed sequences and hardgrounds is also notable outside the Tethyan region (e.g. Bromley, 1967, for the Irish Chalk; Gatrall and Jenkyns, in preparation, for the Inferior Oolite of Dorset, England).
Figure 16: Hardground, studded with *Bositra buchi* and dwarfed fauna. Condensed sequence from Rocche San Felice, west-central Sicily.
Figure 17: Thin section of *Bositra buchi* lumachelle, part biosparite, part biomicrite. Condensed sequence from Monte Kumeta, western Sicily. Scale bar = 1mm.
It is worth considering that although the condensed sequences represent vast periods of time, the stromatolitic laminae may be at most an annual or even a nocturnal phenomenon (Monty, 1965, 1967) and hence the growth of an algal clump could take place very fast. Some factor must hence control the growth (or preservation) of the stromatolites, since these horizons are of such limited vertical extent. This may be a function of sediment supply, current velocity, and the subsidence of the depositional area, which could all be critical for the formation and maintenance of preservable algal mats (cf. Monty, 1967; Gebelein, 1969). It may be that favourable conditions for algal growth were only realised for short periods of time; or that erosion continually stripped the stromatolitic cover until sediment began to accumulate in sufficient quantities to allow its preservation.

Other evidence of algal growth is provided by the herbivorous gastropods that Sturani (1967) has described from the *Posidonia alpina* (= *Bositra buchi* (Römer)) lumachelles that occur in the Middle Jurassic of western Sicily and elsewhere in the Tethyan region (Figures 16 and 17). Sturani favoured a very shallow environment (wave-influenced) for these lumachelles.
since the matrix was frequently sparitic, and this indicated a high-energy regime with winnowing of fine material. However, the energy regime during the deposition of these lumachelles may have been no different than for the condensed sequences, which, as we have seen, must have been subject to considerable current influence. Nevertheless, these rocks are micrites; thus micrites per se are not necessarily indicators of a low-energy environment (cf. Folk, 1962); and for sparites to develop it is necessary to have sufficient bioclastic material to pack together to produce primary pore space. Throughout much of condensed-bed deposition these pore spaces were probably not available, and only in local micrite-free shell accumulations was sparite eventually able to form.

**SUBMARINE SOLUTION AND LITHIFICATION**

Much of the Tethyan Jurassic shows evidence of submarine solution - and also of submarine lithification; and it may be that these processes are inextricably linked. Hollmann (1962, 1964) has graphically described and illustrated the various stages of solution that have affected ammonite shells from the Jurassic red limestones of north Italy; and it seems
Figure 18: Lithological sample of the condensed sequence from Monte San Calogero, Sicily. Note the subsolved ammonites including the spar-filled example in centre.
likely that solution of aragonite took place both at the sediment-water interface and below it. The upper sides of particularly the larger shells are always preferentially dissolved away (see also Wendt, 1963, for west Sicilian examples) and the sediment infills may be coated with ferromanganese material which must have formed on the sea floor. Partial dissolution on the sea floor probably accounts for the fact that the internal sediment of the ammonites is usually the same as the matrix in which they are set; yet this is not invariably the case, as we have seen (Figure 2), and the sparry calcite fillings in some ammonite casts (Figure 18) show that original voids existed in some shells below the sediment-water interface. Thus this case seems parallel to the modern situation described by Friedman (1965) from the Red Sea where pteropod shells in various degrees of corrosion, and casts produced by diagenetic sub-surface solution, can be found together. Significantly, perhaps, this is an environment also of submarine lithification (Gevirtz and Friedman, 1966).

With calcitic fossils, obvious evidence of solution is more scarce: aptychi are usually unaffected, as are the outer layers of *Bositra* shells. Belemnite
Figure 19: Belemnite showing effects of boring organisms and ?corrosion. Condensed sequence from Montagna Grands, western Sicily. Thin section. Scale bar = 1mm.

Figure 20: Solution-(or erosion-)plane in condensed limestone from Monte Bonifato, western Sicily. Thin section, negative print. Scale bar = 2mm.
guards are usually well preserved, but in rare cases may show traces of irregular corrosion (Figure 19) (see also Radwanski and Szulczewski, 1966; Misik, 1966, p.133; Fabricius, 1968), although some of this could be attributed to boring. If coarse skeletal calcite has been chemically dissolved on the sea floor, then it is evident that fine-grained lime-mud, with its greater surface reaction area, will be dissolved also and in some cases this seems to have happened (see Figure 20). It is probably impossible here to distinguish between erosion - physical abrasion - and submarine solution, as both processes may have been active. Currents may be very important in promoting solutional effects, as continuous water movements would ensure that an influx of carbonate-undersaturated water was sweeping over the sea bottom. Prokopovich (1955), when dealing with corrosion zones in the Middle Ordovician limestones of Minnesota, stressed the fact that bottom currents could cause solutional as well as erosional effects.

Nevertheless I am not inclined to place so much importance on the role of 'subsolution' in the genesis of Tethyan condensed sequences as Hollmann (1964); and it is worth bearing in mind that evidence of calcite (as opposed to aragonite) solution is relatively scarce.
Many sea-bottom irregularities / might be due to irregular cementation rather than solution; and large reductions in sediment thickness are better attributed to current action. However, Flugel's (1967) argument against subsolution for some Austrian condensed limestones on the grounds that the amounts of clay solution residues were so small, is invalid, since currents would sweep away any released clay particles.

The general preservation of calcite at the expense of aragonite has been taken to signify deep-sea conditions (e.g. Garrison, 1967, and older references), and Hollmann (1962, 1964) gives the impression that he holds this view.

The present oceans are saturated with calcium carbonate to a depth of a hundred to two hundred metres (Pytkowicz, 1965); thus at any depth below this some solution of aragonite (and calcite) can be expected - and such effects will clearly be most important in environments of slow deposition where the carbonates are exposed on the sea floor for a great length of time. This was clearly the case with the condensed sequences here described; so no certain depth imputation can be made from the evidence of dissolved fossils and sediments. Indeed, Fischer and Garrison (1967) have described
calcereous sediments off Barbados from depths of between 280-440 metres that show evidence of both aragonite and calcite solution; these sediments are associated with ferromanganese nodules and were presumably also exposed to environments of minimal sedimentary rate.

Furthermore, Hudson (1967) has argued that in equable climates of the past, such as the Jurassic, the rate of aragonite (and calcite) solution in warm oceans would be higher than it is today - and would hence take place in shallower water. Possible confirmation of this is provided by Chen (1968) who found that aragonitic pteropods dissolved at greater depths during the last glacial period than they do now.

Within Tethyan condensed sequences there is also ample evidence of submarine lithification; in fact, the formation of hardgrounds necessitates the consolidation of the sea bottom to some extent before deposition recommenced. In the past this phenomenon (in other areas) has been attributed to emersion (e.g. Weiss, 1958; Jaanusson, 1961; see also Voigt, 1959, for a discussion of this problem); however, in the Middle Jurassic of western Sicily and elsewhere in the Tethyan region there are no facies changes that might be attributed to a shallowing sequence. Lindström (1963) taking up this
issue with respect to some Ordovician limestones from Scandinavia presented ample geological evidence for establishing submarine lithification, as well as solution; and there are, in fact, many recent examples of this (Fischer and Garrison, 1967, and references therein; Ginsberg, Shinn and Schroeder, 1967; Thompson, Bowen, Melson, and Cifelli, 1968). With Tethyan red limestones, however, the formation of hardgrounds may be aided somewhat by cementation with ferromanganese minerals, much as described by Morgenstein (1967) for some recent deep-sea sediments.

Other evidence of submarine lithification is provided by the vertical borings that occur in many of the west Sicilian condensed sequences; and Hollmann (1962, 1964) has described the impressions that occur on the undersides of ammonite casts and which must ultimately owe their origin to irregularities on the sea floor, which presupposes a certain degree of consolidation in the bottom sediments.

It is interesting that most examples of submarine lithification under conditions of normal salinity quoted by Fischer and Garrison come from the tops and flanks of seamounts, as this is essentially the environment in which the condensed sequences must have
been formed. Both Milliman (1966) and Fischer and Garrison (1967) suggest that very slow sedimentation may be a prerequisite for lithification on the sea floor. Thus in environments of little net deposition in recent oceans and seas, submarine lithification seems to be associated with submarine solution—this is the case with the previously mentioned Barbados sample described by Fischer and Garrison—with, in general, removal of aragonite and deposition of high-magnesian calcite. Thus sub-surface dissolution of aragonitic shells may supply carbonate that is precipitated as a high-magnesian calcite cement at the sediment-water interface. A process such as this would explain much of the observed data on condensed sequences from the Tethyan Jurassic (see also Wolfe, 1968, for a comparable discussion on the Irish Chalk).

**ENVIRONMENT AND PALAEOBATHYMETRY**

The condensed sequences of the west Sicilian Jurassic encompass different ages from locality to locality. This suggests that they were laid down on separate topographic features affecting sedimentation at different times (Jenkyns, 1967), and a similar situation must have existed throughout the Tethyan Ocean. The ferromanganese
crusts, pavements, and nodules that are so characteristic of these condensed sequences may all be matched on modern seamounts (Jenkyns, 1969). Griffin, Windom and Goldberg (1968) have remarked on the high illite content in sediment samples recovered from topographic highs in today's oceans, which is also consistent with the clay mineral composition of the condensed sequences; and indeed, many of their other features can be related to recent submarine mountains.

The mixed ammonite faunas of the Tethyan condensed sequences have a parallel in the Palaeocene, Eocene, and Recent foraminifera that occur together on some Pacific guyots (Hamilton, 1956, p.34). Coquinas, comparable in origin to the *Bositra buchi* lenses, also occur, current-rippled, on some seamounts (Pratt, 1967, 1968, p.32).

As already pointed out, submarine solution and lithification can occur on modern seamounts; and the limestone in these environments may be heavily bored (Milliman, 1966). Pratt (1967) has illustrated a well-cemented, solution-pitted limestone surface from the Upper Terrace of Great Meteor Seamount which is indistinguishable from some Tethyan Jurassic hardgrounds.
From a study of the fauna of the west Sicilian Jurassic, Arkell (Warman and Arkell, 1954) considered that these beds were laid down in shallow water; and this opinion was shared by Wendt (1963). This interpretation would seem to be borne out by the presence of herbivorous gastropods, stromatolites, and the probable traces of boring algae, all reliably suggesting deposition within the photic zone. Nadson (1927) in a world-wide survey of boring algae found none ranging deeper than 50 metres, but nevertheless the depth beyond which photosynthesis is generally assumed to cease is around 100-150 metres in clear oceanic water (Ryther, 1956). However, a rather disquieting occurrence of the blue-green alga *Schizothrix calcicola* at a depth of 390 metres in the Red Sea has been mentioned by Drouet (1963). Bearing this in mind, one should perhaps exercise caution in imputing very shallow depths from the presence of stromatolites and other algal remains.

Attached algal-mat structures have been found down to 8 metres off Bermuda (Gebelein, 1969), and onkolites with some signs of anchorage to the substrate have been recorded in situ as deep as 125 metres off the Canary Islands (McMaster and Connover, 1966). There seems no
reason why attached stromatolites should not be found at comparable depths.

Thus for the Jurassic condensed sequences of western Sicily and elsewhere in the Alpine-Mediterranean region, I am inclined to favour a depositional depth of at most 200 metres; and many of the ancient seamount terraces were probably considerably shallower. Modern topographic equivalents of this situation are not hard to find: examples are Cobb Seamount, a Pacific volcanic feature that rises to within 34 metres of the surface (Budinger, 1967) with a summit platform 183 metres deep; Plantaganet Bank, an Atlantic seamount lying about 50 metres below sea level (Pratt, 1967, p.146, 148, 305); and Vema Seamount, to the west of South Africa, whose plateau is some 120 metres deep (Simson and Heydorn, 1965). The upper terrace of this latter seamount is covered with onkolites which range up to 7 cm. in diameter and may be encrusted with serpulae. Such structures, according to Olson (1964) are, in fact, common on seamounts: thus this attests to the feasibility of postulating widespread algal mats on the Jurassic topographic highs. Pratt (1963) has also recorded "sea biscuits" from Great Meteor Seamount, whose minimum depth is 269 metres: this is beyond the region where
one would expect abundant algal growth to take place. Hence, with recent parallels it is obviously very important to distinguish between 'live' onkolites, and 'dead' ones - algal biscuits which were formed when the seamount was at a shallow depth and which have now ceased carbonate accretion. Pratt does not indicate the condition of his "sea biscuits", so the maximum depth of formation of 'live' onkolites must for the present remain the 125 metres recorded by McMaster and Connover (1966).

Sturani (1967), who postulated very shallow water for the deposition of the *Bositra buchi* lenses, admitted that the scarcity of reef corals was a problem, and tentatively related it to lack of subsidence. Two other contributory possibilities suggest themselves. Wells (1967) has mentioned that by depths of 100 metres significant reef construction has ceased; however, seamounts at this level would be able to maintain significant algal growth, and, as we have seen, such a palaeobathymetry may have existed. Secondly, according to Wells (1957, p.1688), corals can rarely survive where large amounts of sediment are shifted over the bottom by waves or currents, and this may have been happening when the condensed sequences were formed. The same
restriction would presumably apply to algal mats; but these could probably become established much quicker than a coral colony and could immediately take advantage of a halt in sediment movement; furthermore, unlike a coral, a few days successful growth might be recorded.

Tethyan condensed sequences are always very pure calcareous deposits, whilst the coeval basinal sediments are more marly and siliceous; this is probably a result of sediment fractionation with clay minerals and siliceous tests being swept into troughs, rather than enhanced solution in the greater depths. Nevertheless, it is tempting to compare this with some modern oceanic environments where *Globigerina* ooze accumulates on ridges and red clay in neighbouring basins (Schott, 1955). The Jurassic basinal sequences must have been formed in primary morphological depressions, since they may contain allodapic carbonates displaced from 'upslope' (Bernoulli, 1967); hence deposition must have taken place deeper than with the condensed facies. However, the abyssal depths in which the recent red clay accumulates are probably not comparable to those that existed in the Jurassic Tethyan basins - some of which may only have been several hundred metres deep.
CONCLUSIONS

1. A condensed sequence is defined as a bed that is considerably reduced in thickness relative to another of equal age, and whose origin is a product of minimal net sedimentation.

2. Both stratigraphic condensation (minimal sediment input) and reworking (fine sediment removal) were involved in the genesis of Jurassic Tethyan condensed sequences.

3. These condensed limestones probably owe their origin to planktonic organisms; the paucity of such organisms before the Upper Jurassic may account, in part, for their condensed nature.

4. Both submarine solution and lithification have affected these condensed sequences.

5. The presence of boring algae, herbivorous gastropods, and algal stromatolites suggests deposition in shallow photic zones.

6. Most of the lithological and faunal characteristics of these condensed sequences can be matched on modern
seamounts, and it is clear that the genesis of these beds was related to transient topographic highs in the Jurassic Tethyan ocean.
CHAPTER 7

Seamount Evolution and Facies Differentiation
in the Upper Jurassic of western Sicily
CHAPTER 7

SEAMOUNT EVOLUTION AND FACIES DIFFERENTIATION
IN THE UPPER JURASSIC OF WESTERN SICILY

INTRODUCTION

In western Sicily during the Middle Jurassic, extending into the Callovian, there was a period of minimal deposition in many areas, which gave rise to a series of condensed sequences containing stromatolites and ferromanganese nodules and crusts (Wendt, 1963; Jenkyns, 1967, 1969). Deposition probably took place on separate limestone seamounts, since the condensed sequences are of differing temporal extent (due to topographic irregularities affecting sedimentation at different times) and coeval expanded basinal deposits, containing allodapic carbonates, can be found (e.g. Caflisch, 1966). The environment envisaged is pelagic, with negligible continental influence (e.g. Hallam, 1967).
After this, although each seamount had a separate history, two main evolutionary patterns were followed. The seamounts either sank with the consequent formation of basinal deposits, or, with possible uplift, were the site of more massive shallow-water carbonate production.

In this paper the different facies that characterise the Upper Jurassic of western Sicily will be described and interpreted.

**CARBONATE PLATFORM FACIES**

Well-developed oolitic (or micro-onkolithic) and pelletal limestones, of obvious shallow-water nature, have been found in the Upper Jurassic of the group of mountains known as Rocce and Monte Maranfusa (see appendix for sections and locality details). This group of mountains has recently been interpreted as a sedimentary klippe (Broquet, Caire and Masce, 1966) and it is probable that they were originally part of the same block. The limestone is dominantly grey in colour, but occasionally pink, and contains ammonites, brachiopods and gastropods; the fossils are exceedingly difficult to extract, however, and no accurate dating has been possible. A microfauna, typical of the Tethyan Upper Jurassic, such as *Globochaete* and *Saccocoma*, is plentiful,
Figure 1: Ooliths or micro-onkolites in sparite matrix. Note variety of nuclei. Thin section. Upper Jurassic of Rocce Maranfusa, western Sicily. Scale bar = 1mm.

Figure 2: Detail of Figure 1. Note the globigerines forming the cores of some of the ooliths. Thin section. Scale bar = 0.25mm.
Figure 3: Stromatolitic laminae in pelletial facies. Upper Jurassic of Rocce Maranfusa, western Sicily. Thin section. Scale bar = 1mm.
as are globigerines, crinoid ossicles and calcitised radiolaria. Continental detritus is absent.

The best developed oolites have been found at Rocce Maranfusa: here lenses of oo- and pelsparite (Figures 1 and 2) occur interleaved with a more micritic pelletal facies. The oöds are generally around 0.25mm in diameter and many show a well-developed concentric structure; composite bodies (diameter up to 2.5mm), which could be termed onkolites, occur rarely. The most frequent nuclei are globigerines, but other foraminifera, shell and crinoid (Saccocoma) fragments, as well as micritic intraclasts, can be found. Stromatolitic laminae occur at some levels (Figure 3); they consist of alternate layers of dense micrite, (thickness 0.5mm), presumably a direct acquisition of the algal mat, and biomicrite (thickness about 1mm), which may have filtered in after the decay of the mucilaginous layer (cf. Monty, 1967). An insoluble residue of this limestone facies yielded less than 1% illitic clay.

At Monte Maranfusa the grey limestone is particularly rich in large (diameter 0.5 - 2.0cm) micritic intraclasts, which give the rock a faintly nodular appearance. This sequence, at the localities examined, is considerably more micritic than at Rocce Maranfusa
Figure 4: Pelmicrite. Upper Jurassic of Monte Maranfusa, western Sicily. Thin section. Scale bar = 1mm.

Figure 5: Part of broken onkolite, showing well-developed lamination. Note the calcitised radiolaria. Upper Jurassic of Massa Patria, western Sicily. Thin section. Scale bar = 1mm.
and true ooliths are more scarce. Pellets (diameter 0.15mm) are well developed, however, (Figure 4) and some composite 'onkolites' (diameter around 2mm) may be found. This facies may represent a less-turbulent environment.

Rocca Busambra, its faulted offshoots Rocca Argenteria and Contrada Drago, and Monte Galiello (see appendix for sections and locality details) have a grey sparry limestone development in the Upper Jurassic which is reminiscent of the facies at the nearby Rocce and Monte Maranfusa - and quite unlike the 'ammonitico rosso' (see below). Rocca Busambra has been the object of an extensive study by Wendt (unpublished), and thus no detailed investigations have been carried out at this locality. However, a few thin-sections have been studied and although no true ooliths have been found, the facies can sometimes be pellletal and is always richly fossiliferous - and may also represent a shallow-water deposit. A grey Upper Jurassic limestone has been sampled from Massa Patria (see appendix for locality details) which is also in the Rocce/Monte Maranfusa - Rocca Busambra area; a thin-section of this limestone showed a broken onkolite (Figure 5), which again might indicate a shallow-water platform environment.
Figure 6: Stromatolitic head (overgrowth on ammonite) in pelletal facies. Upper Jurassic of Monte San Calogero di Sciacca, south-west Sicily. Thin section, negative print. Scale bar = 0.5cm.

Figure 7: Pelmicrite, showing partial dolomitisation. Upper Jurassic of Monte San Calogero di Sciacca, south-west Sicily. Thin section. Scale bar = 1mm.
Hence, it is tempting to conclude that the Upper Jurassic in the Rocce/Monte Maranfusa - Rocca Busambra area is essentially of the same facies development and may have been formed on a single seamount.

Oolitic (or micro-onkolitic) and pelletal textures, directly comparable to those from Rocce and Monte Maranfusa, are also developed in the Upper Jurassic of Monte San Calogero di Sciacca (see Wendt, 1963, for locality details). Well-developed stromatolites may also occur (Figure 6). The limestone here is pale pink and nodular - but quite unlike 'ammonitico rosso' - and the nodularity is due to irregular dolomitisation of the matrix (Figure 7). Wendt (1965) recorded dolomitic calcarenites from this locality and indeed replacement dolomites are well developed both throughout the normal succession and in Neptunian dykes; and there is no doubt that this is a late-stage alteration. Accurate sampling from this locality is difficult, however, because of the state of the quarry face (1966-1967), and the succession has not been studied in detail.

**Palaeogeographic Significance**

The shallow-water carbonates here described are of some interest because they indicate a facies change
Figure 8: Coccolith fragment from Upper Jurassic pelletal limestones of Monte Maranfusa, western Sicily. Electron micrograph of ground and etched surface. Scale bar = 5μ.

Figure 9: Red nodular limestone. Upper Jurassic of Monte Kumeta, western Sicily. Hammer handle = 28cm.
from pelagic and condensed in the Middle Jurassic to "reefoid" in the Upper Jurassic; i.e. a change from a ride de type Briançonnois to a ride de type Gavrovo of Aubouin (1966). This must presumably involve uplift into a zone where massive carbonate production can take place, and subsequent subsidence, but with continuance of shallow-water deposition. However, the large amounts of planktonic fossils in these rocks suggest that there may have been considerable carbonate input from pelagic organisms, and the presence of coccoliths (Figure 8) in some of the micrite confirms this.

There is no true reef structure developed in these sequences, so they cannot be compared to coral atolls; but nevertheless they can perhaps be envisaged as submerged or semi-submerged oceanic islands. The presence of stromatolitic laminae suggests shallow, but not necessarily intertidal depths (Monty, 1965; Gebelein, 1969); and the ooliths in a sparite matrix again indicate a moderately high-energy régime in little depth of water.

The obvious analogy lies with the Bahamas, with its large-scale formation of true and superficial ooliths in some of its sand-belts (Ball, 1967). The fact that ooliths are common at Rocce Maranfusa but less
so at Monte Maranfusa suggests that they may have an irregular spatial distribution. In the Bahamas, oölitic sand belts are often concentrated at breaks in slope (Ball, 1967), and to speculate, we may imagine that similar accumulations may have built up round the terrace-edges of the ancient seamounts, while the more micritic pelletal low-energy facies might have been a more 'internal' development.

The successions at Rocce and Monte Maranfusa and Monte San calogero di Sciacca bear a striking resemblance to some Polish and Hungarian Jurassic sequences, where Middle Jurassic condensed stromatolitic limestones containing reworked faunas (Radwanski and Szulczewski, 1966) are also overlain by grey Upper Jurassic oölitic or micro-onkolitic facies (Kotanski, 1961, for the High Tatras; Kaszas, 1963, for the Villany Mountains). Thus the change from pelagic to reefoid sedimentation was perhaps a not uncommon event during the history of Jurassic seamounts in the Tethyan ocean.

**BASINAL FACIES**

In most areas of western Sicily more basinal red limestones and marly facies are developed above the Middle Jurassic condensed sequences. Several facies
Figure 10: Stromatolitic (onkolitic) overgrowth on partially dissolved ammonite. Upper Jurassic nodular limestone from Monte Inici, western Sicily.

Figure 11: Sparsely fossiliferous limestone nodules in richly fossiliferous marly matrix. Upper Jurassic of Montagna Grande, western Sicily. Scale bar = 1 mm.
types may be distinguished; the typical Tethyan nodular red limestone (knollenkalk, fausse breche = 'ammonitico rosso calcaire' of Aubouin, 1964) or a more marly chert-bearing facies ('ammonitico rosso marneux' of Aubouin, 1964); or a virtually continuous succession of bedded cherts (= radiolarite). As well as being laterally equivalent, such facies may succeed one another vertically at the same locality. These rocks contain ammonites, preserved as casts, belemnites, and the brachiopod *Pygope* in the upper part of some successions; the microfauna is dominated by *Saccocoma* and *Globochaete* with radiolaria, aptychi, rare crinoid fragments, a little shell debris, sponge spicules, and foraminifera.

Red nodular limestone facies

The limestone above the condensed sequences usually becomes progressively more marly and nodular, until the typical 'ammonitico rosso' marble is developed. This facies is well seen, for example, on Monte Inici, Montagna Grande, Monte Bonifato, and parts of Monte Kumeta (Figure 9), but its age at these localities is variable. The Monte Inici section (MI 1 of Wendt, 1963) is particularly instructive, for stromatolitic overgrowths on the upper side of corroded ammonites (Figure 10)
can be seen extending from the condensed sequence up into the more nodular limestone. About 1 metre above the main condensed horizon, although ammonite shells are present, they are not coated with algal structures. This is important, as it gives a clue to the palaeo-bathymetric situation at the time of development of at least some 'ammonitico rosso' limestones – and presumably in this case indicates a deepening sequence that passes beyond the limit where active photosynthesis can occur.

The problem of the origin of these nodular limestones has a great deal of literature to its credit, which has recently been reviewed by Jurgan (1967, 1969) and Farinacci (1967) and will not be repeated here. Perhaps the most influential papers on this topic have been those of Hollmann (1962, 1964), who suggested that 'subsolution' or submarine solution was the prime cause of the nodularity; Hollmann envisaged irregular limestone corrosion on the sea floor acting in such a way that isolated 'solution remnants' were left as nodules in the insoluble marly residue. However, although there is ample evidence of aragonite solution in these rocks, traces of calcite corrosion are more scarce; moreover, as significant dissolution of calcite does not take place until a depth of some 4,000 metres in the present oceans
(Peterson, 1966) and the presence of stromatolites in some nodular limestones indicates depths within the photic zone (0-200 metres at most), I am not inclined to place much importance on this process even though submarine solution may have taken place at shallower depths in the past (Hudson, 1967). Instead, I am inclined to the view of Lucas (1955) and Hallam (1967), who suggested that the nodular structure was due to early diagenetic segregation or 'unmixing'. With the west Sicilian nodular limestones one can see every gradation between a fully segregated nodule (diameter usually 1-5cm) and the more marly and darker matrix, and a 'micronodular' texture may sometimes be developed within the nodules themselves. Similar diagenetic origins have been postulated for many limestone nodules in shale (e.g. Hallam, 1964; Voigt, 1968) and indeed such a process can be found happening in some recent sediments (Pantin, 1958; Ho and Coleman, 1969).

The nodular appearance of the rock is further enhanced by stylolites, particularly in the less marly lithologies: these pressure-solution phenomena, which may truncate fossils, must have formed during diagenetic compaction of the differentially segregated (and lithified?) sediment (see Park and Schot, 1968). With
the more marly lithologies the stylolites seem to be 'absorbed' by the clay layers that wrap around the nodules in a sort of pseudo-flow structure that must be simply a compaction effect.

However, as 'ammonitico rosso' limestones are characteristically related to submarine slopes (Aubouin, 1964), some slumping might be expected in the original sediments, with possible differential movement between the segregated nodules and marly matrix. And, indeed, Jurgan (1967, p.77-84; 1969) has stressed the role of sliding in the formation of some nodular limestones (see also Bernoulli, 1964, p.52-53). In some cases, also, the nodules may be washed free of their matrix (Lucas, 1955) and transported (Hudson and Jenkyns, 1969).

With the west Sicilian limestones, however, there is usually no positive evidence that such movement has taken place, and, in general, the nodules lie parallel to and elongated along the bedding (cf. Szulchewski, 1965), interleaved with more marly layers. Ammonite casts always act as nodules and are invariably covered with a glistening clay patina.

The marly interstices of these rocks are always richer in fossil material than the nodules (Figure 11), presumably due to removal of fine-grained
Figure 12: Electron-probe microanalysis across nodule matrix boundary; matrix on left, nodule on right. Upper Jurassic nodular limestone, from Montagna Grande, western Sicily. Length of scan-line = 375 μ.
carbonate from this area and subsequent differential compaction. Several authors (e.g. Lucas, 1955; Szulczewski, 1965; Jurgan, 1969) have commented on the relatively greater frequency of skeletal calcite in the clay matrix of Jurassic nodular limestones. One apparent exception to this rule is sponge spicules, which according to Misik (1965) and Jurgan (1967, 1969) occur only in the nodules; their non-preservation in the matrix must be due, however, to their originally siliceous nature, the silica being dissolved rather than replaced during early diagenesis. The marl matrix of the west Sicilian nodular limestones is crossed by thin red strands of ferruginous clay material (cf. Jurgan, 1969) which is roughly parallel to the bedding. Sometimes these bands, which are particularly rich in Fe, Al, and Si, may wrap round the periphery of a nodule (see Figure 12 for analysis).

Insoluble residues of these rocks vary between 5-15% (see appendix); their clay content consists of illite, montmorillonite, with quartz and possible traces of haematite. The quartz content can be traced back to a few uncalcitised (i.e. siliceous) radiolaria, sponge spicules, and also to small angular shards (10-30u diameter) that are particularly common in the marly
matrix but occur also in the nodules. These angular quartz fragments do not necessarily imply the immediate proximity of a landmass; shards of a similar size range have been recorded by Rex and Goldberg (1958) from pelagic clays — and are of aeolian origin. The clay mineral assemblage of the west Sicilian nodular limestone is also consistent with an oceanic environment with volcanic influences (Griffin, Windom and Goldberg, 1968).

Coccolith ghosts may occur in these nodular limestones, becoming more frequent towards the top of the Jurassic.

**Palaeogeographic Significance**

Aubouin (1964) related the depositional site of the 'ammonitico rosso' to the tops and flanks of ridges; however, since more condensed facies occur (which Aubouin does not distinguish), it is clear that the nodular limestones should be considered a more basinal deposit than the highly condensed ferromanganiferous stromatolitic sequences that underlie them (see Jenkyns, 1969, for western Sicily; Hollmann, 1962, for North Italy). The presence of unreplaced siliceous organisms in some of these nodular limestones suggests that there is a tendency here towards the nodular chert and
radiolarite facies that are generally assumed to characterise the deepest parts of the basin (e.g. Geczy, 1961; Aubouin, 1966). The fact that stromatolites occur in the basal regions of some nodular limestone sequences and disappear higher up perhaps suggests that the photic zone has been crossed; this might imply a depth around 150 metres and below for the deposition of these limestones. In these deeper environments high solution rates of calcium carbonate were probably offset by greater sedimentation.

The red colour of these rocks and their general lack of terrigenous detritus must reflect relatively slow deposition, under fully oxidising conditions, a considerable distance from a major continental landmass (see Jenkyns, 1969), although similar facies elsewhere may contain considerable quantities of sandy material (Szulczewski, 1965).

**Red Marl and Cherty Facies**

The marl and cherty facies (= 'ammonitico rosso marneux' of Aubouin, 1964, and 'scisti silicei') may overlie the 'ammonitico rosso calcaire' at some localities (e.g. Monte Kumeta, Monte Inici, Bolognetta) or may persist for much of the Jurassic (e.g. Balata di Baida).
Figure 13: Nodular and lensoid chert in marly limestone. Jurassic of Balata di Baida, western Sicily. Length of hammer handle = 28cm.
Figure 14: Electron-probe microanalysis of chert from Balata di Baida, western Sicily. Electron-scanning beam photograph for iron shows the irregular distribution of the haematitic pigment. Length of scan-line = 375μ.
Figure 15: Semi-obliterated radiolarian spheres in siliceous limestone; note the incipient chert lenses. Upper Jurassic of Monte Kumeta, western Sicily. Thin section. Scale bar = 1 mm.

Figure 16: More or less infilled radiolarian spheres. Upper Jurassic cherty and nodular limestone from Bolognetta, western Sicily. Electron micrograph of ground and etched surface. Scale bar = 100 μm.
These rocks are generally red to brown, due to colouration by an irregular haematitic pigment, and may contain chert as nodules and lenses (Figure 13) or give way to massive bedded radiolarite (see Figure 14 for analysis of chert nodule; note the virtual elimination of calcium). With the chert nodules, the marl may bed round them producing a similar pseudo-flow structure to that in the 'ammonitico rosso calcaire' nodular limestones (Figure 9); in this case also this "streaky" structure must be due to differential compaction around the early diagenetic chert nodules.

These cherts are dominated by the presence of radiolaria (Figure 15) and also contain minute shards of quartz similar to those in the red nodular limestones. The most instructive section for studying the relationship of cherts and limestones is at Bolognetta (see appendix for sections and locality details); here every gradation between bedded cherts, incipient lenses, and siliceous radiolaria in carbonate matrices can be seen.

The general problems associated with the origin of Tethyan radiolarite sequences have been dealt with by Grunau (1959, 1965), Ulrich (1960), and most recently by Flügel (1967), and will not be reviewed here. Suffice it to say, that there is no obvious connection with
Figure 17: Partially filled radiolarian test, showing remnants of the original architecture in the centre. Upper Jurassic cherty and nodular limestone from Bolognetta, western Sicily. Electron micrograph of ground and etched surface. Scale bar = 50μ.
submarine volcanism and the silica is probably entirely of biogenic origin.

The radiolaria, if not carbonate-replaced, are always partially overgrown and obliterated by silica; and it is evident that they have acted as nuclei for incoming solutions. Figure 16 shows some completely silicified radiolarian spheres, and Figure 17 a partially filled test. With a greater influx of silica, the carbonate matrix may be replaced — and a chert nodule produced. It is evident that radiolaria (and sponge spicules) supply some of the silica for the cherts, but the problem then reduces to the origin of the opaline matrix in which the fossils are set.

There will tend to be a primary concentration of radiolaria in basins rather than on highs, since there will be a greater head of water over the former, and radiolaria living between 0-400 metres will thus be preferentially accumulated there after death (Flügel, 1967); also, since highs tend to be current-swept (Heezen and Hollister, 1964), radiolaria will tend to be moved into quieter basinal environments. Lisitsyn (1967) has recorded that modern siliceous sediments are never found on submarine high ground, whereas recent
basinal accumulations of siliceous material are well documented (e.g. Calvert, 1966).

Berger (1968) has recently shown that radiolarians dissolve quickly in the shallow silica-undersaturated parts of today's oceans, whereas the rate of solution is less at greater depth of water. Thus, in basins rich in primary silica, one would not expect much solution of siliceous organisms to take place whereas upslope in the more carbonate-rich (and silica-undersaturated) sediments the opaline tests would presumably dissolve. This dissolution might take place at the sediment-water interface, or below it (see Siever, 1966; Bernoulli, 1964, p.95); the occurrence of this latter situation is proved by calcite mosaic casts that occur in the Upper Jurassic carbonate platform sediments (Figure 5) and red nodular limestones. Thus, some of the opaline silica of the cherts may result from migration of dissolved siliceous material originally deposited on the flanks of the basins; these silica-rich solutions would presumably precipitate when they reached an area of silica saturation. Some diagenetic adjustment into chert-rich and chert-poor layers might occur later.

The high marl content of these beds is presumably also related to current action sweeping clay particles off
neighbouring highs into the adjoining basins.

**Palaeogeographic Significance**

The radiolarite facies is generally accepted as the deepest of the Tethyan lithologies (e.g. Geczy, 1961; Aubouin, 1966; Flügel, 1967), although estimates as to its actual depth of accumulation vary widely. Evidence of aragonite and calcite dissolution can be found but, bearing in mind the argument of Hudson (1967), there seems no need to envisage depths greater than several hundred metres.

**LATTIMUSA**

The 'ammonitico rosso' and radiolarite sequences grade upwards into the so-called 'Lattimusa' (Tithonian-Neocomian) which is similar in facies to the 'Maicolica' and 'Biancone' of the Alpine region. This time of transition is non-uniform over the area, however (Wendt, 1969), showing that some topographic features still controlled deposition, even though an infilling of the basins and a sinking of the pelagic seamounts must have considerably evened out the sea-bottom topography. Nowhere has a transition or contact between the carbonate-platform facies and 'Lattimusa' been seen, so the oceanic
Figure 18: Coccolith-rock with calpionellid test. Upper Jurassic 'Lattimusa' facies from Balata di Baida, western Sicily. Electron-micrograph of polished and etched surface. Scale bar = 10μ.
'islands' may have continued into the Cretaceous.

The Lattimusa is a white fine-grained limestone containing blue-black chert nodules. It can contain rare ammonites and the brachiopod Pygope. The microfauna consists of some skeletal debris and radiolarias, but is dominated by calpionellids (cf. Catalano, 1965). The micrite consists dominantly of coccoliths (e.g. Nannoconus). (Figure 18) and is thus comparable, in some respects, to a modern pelagic ooze (see also Grunau, 1959; Farinacci, 1964; Fischer, Honjo and Garrison, 1967, for electron micrographs of similar facies elsewhere).

Palaeogeographic Significance

This facies can best be interpreted as a uniformly basinal sediment deposited when most bottom irregularities had been evened out; the input of silica was now more evenly distributed, instead of being fractionated into limited basins. Depth estimates for the deposition of this facies also vary widely, but again there seems no need to invoke vast figures, and accumulation in hundreds of metres of water could well account for the observed sedimentary and fauna1 features of this lithology.
Figure 19: Schematic diagram illustrating hypothetical evolution of the west Sicilian seamounts during the Jurassic.
MIDDLE JURASSIC

TRIAS - LIAS

WHITE LIMESTONE

Fe-Mn crust

uplift + later subsidence

nodular limestones
marls & cherts

UPPER JURASSIC

Gypsumic

marls & chert
CONCLUSIONS

Following a variable period of condensation and non-deposition during the Middle Jurassic, the west Sicilian seamounts either sank, with the consequent formation of more basinal sediments such as red nodular limestones, marls and radiolarites, or they were uplifted into the zone where shallow-water oolites and stromatolites could develop (Figure 19).

Thus the bottom topography of the Tethyan Ocean over the area which is now western Sicily must still have been differentiated into seamounts and basins during the Upper Jurassic. The summit platforms of these topographic highs probably came to within a few tens of metres of the surface, whilst the cherty basinal deposits must have been laid down at least as deep as 200-300 metres.

During the Tithonian and continuing into the Cretaceous, a more uniformly basinal coccolith ooze covered much of the area; its depth of deposition may have been similar to that of the radiolarite facies.
CHAPTER 8

Conclusions
INTRODUCTION

The stratigraphy of the west Sicilian Jurassic is now well known, thanks to the published works of Warman and Arkell (1954), Arkell (1956), Christ (1958, 1960, 1963), Caflisch (1966) and Wendt (1963, 1965, 1969) and the unpublished observations of Wendt and Torrens. It is of typically Tethyan character, being analogous to similar facies in the Alps and elsewhere in the Mediterranean region. Limestones are present throughout, and clastics are notably absent.

Most of the Jurassic outcrops occur on isolated mountains surrounded by low-lying incompetent Miocene clays. The relationship between the massifs and clays
has often been disputed; some mountains are undoubtedly best interpreted as horsts (Ruggieri, 1966), whereas a few are sedimentary klippes or olistoliths - and thus allochthonous (Broquet, Caire, Mascle, 1966). Hence it is difficult to know whether the present spatial relationship of these mountains reflects their original depositional position, and broad palaeogeographic reconstructions must be made with certain reservations.

It does not seem to us that this problem will be finally solved merely by general studies of the region, and the relationship of the present-day massifs to the surrounding sediments. We have conducted sedimentological investigations, under as strict stratigraphical control as possible, on the Jurassic of many of these mountains, and it is clear that each major massif differs in the details of its stratigraphical succession. This is important since it means that during the Jurassic, western Sicily was not simply a 'schwellen area' but the site of considerably topographic and environmental variation.

Although the west Sicilian Jurassic mountains exhibit varied and diachronous facies developments, there is a general similarity between them. We will thus
describe the palaeogeographic evolution of these massifs in ascending stratigraphic order.

"DOLOMIA PRINCIPALE"

The basal formation of the Jurassic, together with the underlying Triassic of similar facies, comprises the major part of the west Sicilian mountains in terms of thickness. This deposit, called the 'Dolomia Principale' by Di-Stefano (1912), has subsequently been divided into various units by other authors; these divisions, however, seem unusable without better stratigraphic control. The lowest part of the 'Dolomia Principale' is composed of well-bedded white crystalline dolomites or dolomitic limestones. Floridia (1931) estimated a thickness of about 700 metres for those exposed at Monte Inici. Upwards these pass gradationally into about 300 metres of purely calcareous deposits. The total thickness at this locality is thus at least 1,000 metres, and elsewhere may extend to over twice this figure (Christ, 1963).

Dating this formation is difficult because macrofossils of stratigraphic significance are so rare. Gemellaro, however, discovered an extensive fauna of gastropods, bivalves, and ammonites near the top of the
'Dolomia Principale' at Rocca Busambra; these fossils indicated an age somewhere in the Lower Sinemurian Bucklandi or Semicostatum zones. Recent work by us has shown that a similar faunal assemblage, in an identical matrix, occurs at the nearby Rocce Maranfusa; this is also of Hettangian-Sinemurian age and has been found in situ 56 metres below the top of the 'Dolomia Principale'. These fossils comprise ammonites, abundant gastropods, and numerous aulacoceratid cephalopod fragments; a similar aulacoceratid fauna has been described by Jelletsky and Zapfe (1967) from the Rhaetian of Austria.

At other localities rare ammonites from nearer the top of the 'Dolomia Principale' suggest that this formation may extend into the Upper Pliensbachian. It is important to stress, however, that there is no certainty that the top of the 'Dolomia Principale' is a constant time horizon, and in south-west Sicily, where megalodont bivalves occur in the upper part of the formation, the age is in dispute. It has been claimed as Triassic (Cox in Warman and Arkell, 1954; Ruggieri, 1963) and Liassic (Zapfe in Wendt, 1965).

The sedimentology of the upper part of the 'Dolomia Principale' has been studied in detail by one of us (Jenkyns, 1969). Observations have been mainly
confined to the Rocce Maranfusa massif where the succession consists of a roughly cyclic sequence of sharply bounded lithologies, including onkolitic, oölitic and pelletal facies. Birdseye and Stromatactis structures are common, as are algal laminae. Deposition is considered to have varied between sub- and supratidal regimes, and the cyclicity is reminiscent of similar deposits elsewhere in the Tethyan region (e.g. Fischer, 1964; Bosellini, 1967; D'Argenio and Vallario, 1967).

The environmental pattern may, in a general way, be compared with the present-day Bahaman type of sedimentation, with massive deposition of carbonate on a shallow extended platform that was undergoing considerable subsidence. The widespread occurrence of the 'Dolomia Principale' attests to the extension of the platform throughout western Sicily as far south as the Sicani mountains.

**TRANSITIONAL PHASE AND ASSOCIATED DEPOSITS**

Above the 'Dolomia Principale' a variety of sediments occur, and some of these record a transitional phase between the cessation of shallow-water limestone deposition and the onset of pelagic conditions.
Crinoidal calcarenites

Deposition of the 'Dolomia Principale' apparently continued no later than the Pliensbachian. This facies may be overlain by a white, pink or red crinoidal calcarenite, with brachiopods constituting the only major macrofaunal element, which is well developed at Monte Kumeta, Rocca Nadore, and in somewhat ambiguous field occurrence in the Balata di Baida gorge. This deposit is often notably lenticular in form and commonly attains a thickness of several metres. At Monte Kumeta its age must lie within the range Pliensbachian - topmost Lower Toarcian, as delimited by the dated stratigraphic succession above and below, and is thus probably Domerian. Nowhere has it been possible to date this lithology with complete accuracy, but a similar age elsewhere seems possible. Crinoidal limestones capping reef/platform successions occur in other parts of the Tethyan region (e.g. Hlauschek, 1922; Fabricius, 1961; Jurgan, 1967; Sturani, 1967) and this characteristic super-position is probably significant (Jenkyns, 1969).

Microscopically most west-Sicilian examples of these rocks are crinoidal biosparites, and the sparite void filling suggests deposition in at least a moderately high-energy regime (Folk, 1962). The critical factors
for the formation of such banks of crinoidal debris are uncertain, but the bioclastic material, derived from local crinoid forests, was probably concentrated into submarine dunes (see Blyth Cain, 1968) or sand-waves by current action, possibly tidal. Obvious cross-bedding is, however, absent. Some of these sand banks must have risen above sea level since at Monte Kumeta solution hollows (interpreted as subaerial karstic phenomena and not the subsolution effects of Hollmann, 1964) occur in the top of this deposit.

These sediments reflect considerable environmental change from the 'Dolomia Principale', and whether this is due to a world-wide eustatic change in sea level, postulated at this time (Hallam, 1963, 1967), or initial disintegration of the carbonate platform, cannot be determined. It is, however, interesting to note that carbonate sands, albeit composed of planktonic organisms, occur on some modern seamounts (Pratt, 1968).

Variable Deposits

Apart from the crinoidal limestones, the 'Dolomia Principale' may be overlain abruptly by a series of remanie beds of very contrasting lithology. These are of extremely local occurrence; in many places they
occur only in centimetre-thick horizons, and are often absent from the succession altogether. In this case, however, they may be occasionally preserved as Neptunian dykes and sills.

The following lithologies, dated on ammonite evidence, have been recognised in the normal stratigraphic succession:

a. Grey pelsparites of Lower Toarcian age; these have only been recorded from Monte Bonifato (Wendt, 1963). This facies contains a varied fauna of ammonites, bivalves (Pectenids), gastropods, and belemnites. Being so limited in distribution it is difficult to generalise about its significance or say whether it was once of wider distribution, but it may represent a local prolongation of a platform type of deposition.

b. Red fine-grained limestones, probably also of Lower Toarcian age; this facies has been tentatively identified in the stratigraphic sequence at Monte Kumeta, but occurs with certainty in Neptunian dykes below (Wendt, 1965). This facies records pelagic deposition.

c. The third Toarcian lithology is the most interesting and one hitherto unrecognised. It is best developed
at Rocce and Monte Maranfusa where it directly overlies the 'Dolomia Principale'. This facies is a blood-red to chocolate-brown crinoidal iron pisolite, containing numerous well-preserved and normal-sized ammonites of truly Tethyan character. Gastropods are also abundant with less frequent sharks teeth and rare brachiopods. The following ammonite genera have been kindly identified by Dr. M. K. Howarth: _Phymatoceras_, _Hammatoceras_, _Polyplectus_, _Paroniceras_, and _Catacoeloceras_, which date the bed at the Middle-Upper Toarcian boundary, Erbaense Zone, Bayani Subzone (Donovan, 1958; Fischer, 1966).

This lithology is rich in iron pisoliths and crinoidal debris; the latter may be reworked from an earlier deposit. The pisoliths themselves are of particular interest and are being studies in detail by one of us (H.C.J.). Their most significant feature is that a few contain cores of igneous material (sanidine trachyte) and similar pisoliths, with similar cores, have been traced, in identical stratigraphical position, as very thin horizons at Rocca Busambra and its off-faulted blocks, and Monte Galiello, Monte Arancio and Bolognetta. Thus the basal horizon above the 'Dolomia Principale' at these localities must also be of Toarcian age. Similar igneous material has also been found at Monte Kumeta and
at Monte Monaco, in horizons dated as Upper Toarcian (Wendt, 1969, and our own observations).

**Platform disintegration and Volcanism**

The crinoidal deposits described above may have heralded the initial disintegration of the carbonate platform, but more positive evidence is supplied by the occurrence of several of the variable Toarcian deposits as the first infillings of tectonic fissures. By early Toarcian times the identity of the carbonate platform had been destroyed and pelagic conditions, reflected in facies and fauna, may have been widespread. The area was now split into a series of fault-delineated blocks undergoing differential subsidence. The Toarcian volcanism can be seen as an accompaniment of this tectonic disintegration.

The igneous episode can be dated as being between Upper Pliensbachian and Erbaense Zone, since the ammonites contemporary with pisolith formation are of this latter age. The extent of this volcanism is unknown, but the occurrence of lava fragments in the Toarcian at Monte Monaco, north-west Sicily, as well as in the west-central regions of the island, suggests that it may have been more than a local event. In mineral composition
and texture these Toarcian volcanic fragments resemble the lavas interbedded in the succession at Monte Bonifato, where igneous material attains a thickness of 15 metres (Wendt, 1963). This extrusion is demonstrably older than Bathonian (Wendt, 1963) and the lower contact was dated by him, on rather dubious ammonite evidence, as Upper Bajocian. Bajocian volcanic episodes have been recognised elsewhere in western Sicily (e.g. Fabiani, 1926; Trevisan, 1937), but these are generally described as basaltic and if the lower contact of the Monte Bonifato trachyte cannot be confirmed as this age, it might well be Toarcian. There is now, in any case, evidence for at least Toarcian and Bajocian volcanic phases during the deposition of the west Sicilian Jurassic.

The crinoidal iron pisolite is a condensed or remanie deposit and sedimentation probably took place in an oceanic environment, subject to considerable submarine reworking and erosion. The preceding volcanism is an obvious source for the iron and high concentrations of trace elements that compose the pisoliths, and it is interesting that Bonatti and Joensuu (1966) have recorded high-iron deposits associated with basaltic rocks from a seamount in the South Pacific and assume a local volcanic source for this material.
Toarcian sediments were probably once more widespread than their stratigraphic record suggests; submarine erosion, a common phenomena on modern seamounts, has probably removed many of the original deposits, leaving only isolated remnants. All of the Toarcian beds described above are exceptional; more usually the upper surface of the 'Dolomia Principale' is directly overlain by condensed red ferromanganiferous limestones of Middle Jurassic age.

**CONDENSED SEQUENCES**

Above the crinoidal and variable deposits, or resting directly on the 'Dolomia Principale', a thin series of very striking beds is developed. These are fine-grained red limestones, often containing ferromanganese nodules and crusts (Jenkyns, 1967); and this association of extremely condensed sequences with ferromanganese deposits is notable throughout western Sicily and indeed the whole of the Tethyan region. However, although this may be a universal association, almost every other feature of the west Sicilian condensed beds - lithology, fauna, age, thickness - is variable.

The abundant ammonites that are contained within these condensed sequences, though often reworked
and eroded, usually allow an accurate age determination to be made. However, unless all the faunal elements, which may extend over considerable temporal range and be homeomorphic, can be collected and distinguished, the full extent of condensation may not be recognised.

**Dating**

The earliest ferromanganese horizon that we have been able to date conclusively is Bajocian (Humphriesianum Zone); this is well developed on Monte Kumeta, overlying yellow ferruginous limestones of Toarcian age. Wendt (1965) considered the condensation here may extend as low as the Aalenian (Opalinum Zone). The stratigraphic record between the Aalenian and Middle Callovian on each massif is in general somewhat similar but often differs in detail, and usually there is a period of non-deposition between the Upper Toarcian and Bajocian. At Rocce Maranfusa the ferromanganiferous condensed bed can be shown to be as old as Upper Bajocian; more commonly, however, condensation appears to have commenced in Lower Bathonian times (e.g. Monte Inici, etc., Wendt, 1969) or later. The upper limits of condensed-bed deposition must lie below the Upper Callovian.
The most extreme case of condensation is at Monte Pispisa where Lower Cretaceous marls may directly overlie the 'Dolomia Principale' (Christ, 1960); even in the fullest sequence seen here only thin representatives of the Oxfordian and Kimmeridgian fill this stratigraphic gap (Wendt, 1969). Dated Middle Jurassic occurs only in Neptunian dykes.

Associated features

The significance of fossil ferromanganese nodules, crusts and pavements has been outlined elsewhere (Jenkyns, 1967). These concretions indicate areas of very slow sedimentary rate and are essentially confined, in modern oceans, to the central deeps and the tops and flanks of seamounts. The fact that the west Sicilian condensed sequences are of different temporal extent shows that the areas of non-deposition varied through time and space - due to the topographic irregularities affecting sedimentation at different times. The closest analogues of these fossil ferromanganese deposits are thus with those being formed on modern seamounts (e.g. Pratt and McFarlin, 1966; Aumento, Lawrence and Plant, 1968).
On modern seamounts deposition is usually hindered by currents and this must have been the case with the Jurassic sequences here described - thus accounting for the extreme condensation, formation of hardgrounds, and submarine solution effects. A period of minimal deposition existed throughout much of the Middle Jurassic, including most of the Callovian (Table 1), on these ancient topographic highs.

Lithologically most condensed limestones are red biomicrites, with broken bivalve shells, ostracods, crinoid debris, calcitised radiolaria, globochaetes, globigerines and other foraminifera. Macrofaunally they contain rare brachiopods, belemnites and abundant ammonites, the latter often eroded and subsolved (Hollmann, 1964).

There are two other important features commonly associated with these deposits; one, of particular palaeotopographic significance, is the presence of stromatolites immediately above many of these condensed sequences. The algal structures (LLH - type of Logan, Rezak and Ginsburg, 1964) are intimately associated with ferromanganese crusts and nodules. Very similar stromatolites have been described from Jurassic pelagic limestones in Hungary and Poland by Radwanski and
Szulczewski (1965) and Szulczewski (1968) who also noted their association with stratigraphic lacunae, reworked faunas, and sedimentary iron enrichment. The depth significance of stromatolites is uncertain although Logan, Rezak and Ginsburg (1964) claimed the LLH-structures as intertidal; but a lower limit must be imposed by the extent of the photic zone, which may range down to at least 150 metres at low latitudes.

Monty (1965) has reported attached stromatolites in permanently subtidal depths of two metres; algal mats have been found at 20 metres by Ginsburg (1960), and unattached onkolites have been discovered in situ as deep as 125 metres (McMaster and Connover, 1966). Thus for the condensed west Sicilian sequences, deposition on a seamount tens of metres below sea level is most likely. Modern topographic equivalents might be Cobb Seamount, a Pacific volcanic feature that reaches to within 34 metres of the surface and on whose summit bottom fauna abounds (Budinger, 1967); or Plantagenet Bank, an Atlantic seamount also within the photic zone (less than 50 metres deep) which supports algae and corals (Pratt, 1967).

The second feature of presumed palaeotopographic significance associated with condensed sequences is the
presence of thin bands or lenses of red micrite or white sparite packed with *Bositra buchi* (Roemer) = (*Posidonia alpina* auctt.). These bivalves, presumably nektoplanktonic (Jeffries and Minton, 1965) can occur associated with broken or more commonly "stunted" ammonites, gastropods, more rarely brachiopods, and with crinoid debris. The origin proposed for such deposits by Sturani (1967) in wave-swept algal meadows on shallow ocean platforms is given strong support by the definite presence of algal growth as indicated by the stromatolites that occur in intimate association — at least in western Sicily.

The diminutive size of gastropods and some benthonic bivalves living in the algal meadows of shallow lagoons in the Bahamas seems to have been first recorded by Dall (1894). A better documented study of a similar situation in Puerto Rico (Warmke and Almodovar, 1963) has shown that here 99% of the molluscan faunas living on algae were gastropods, most of them under 2mm. in size. Not There seems no reason why such "stunting" should have occurred in similar algal meadows on seamounts.
The condensed ferromanganese deposits usually grade upwards into massive limestones with only rare ferromanganese concretions, and then pass by degrees into a more nodular, marly red (or reduced green) facies of typical Mediterranean type - the 'ammonitico rosso calcaire' of Aubouin (1964) or 'knollenkalk' of German authors. The massive limestones can encompass the topmost Callovian to the Upper Oxfordian, and the 'ammonitico rosso' can range in age from the Upper Oxfordian as high as the Upper Tithonian. Again these facies are not restricted to particular time horizons and may be absent altogether. Faunally, they are impoverished; ammonites, whose aragonitic shell has invariably been dissolved, are still locally abundant as casts, but otherwise only calcitic aptychi and belemnite guards can generally be found. Microfauna is correspondingly sparse. In the upper part of this succession the Tethyan brachiopod Pygope appears and can be quite frequent, but the absence of benthonic mollusca is conspicuous.

The 'ammonitico rosso calcaire' is another facies characteristically related to topographic highs - deposited on the tops and flanks of ridges according
to Aubouin (1964). Its depth significance is probably variable but in general deposition must have taken place deeper than with the condensed sequences since although these beds are considerably reduced in thickness relative to coeval epicontinental deposits, they are expanded relative to the ferromanganiferous horizons that underlie them. This nodular limestone marks a progressive phase in the slow stable evolution from deposition on topographic highs (Upper Bajocian - Middle Callovian) to deposition in a more uniform basin (Tithonian - Neocomian).

_Pygocelis_ seems to have been morphologically adapted to a benthonic mode of life on quiet sea floors with very little water movement (Vogel, 1966). This fossil first appears in the upper parts of 'ammonitico rosso' sequences, which suggests that such an environment, pelagic but not necessarily at great depth, had been evolved at this time (Ager, 1965). The nature of the sediments, marly and sometimes with chert, also indicates that an essentially basinal sea-bottom morphology, subject to minimal current action, had been achieved.

However, in some areas during the Upper Jurassic two other facies are developed above the ferromanganese condensed sequences. One is a cream- to rose-coloured pel- or oosparite, and occurs at Rocce Maranfusa, Monte
Maranfusa, and Monte San Calogero. This facies, which can attain a thickness of 20 metres, suggests a return to a platform type of deposition, but still in a pelagic realm – and has parallels in the Villany Mountains of Hungary (Kaszap, 1963) and the High Tatras of Poland (Kotanski, 1961).

The second, which may be developed as intercalations in the 'ammonitico rosso marneux' type of Aubouin (1964), is a thin-bedded radiolarian chert, which again indicates a basinal environment. This facies can be well seen on Monte Kumeta (Wendt, 1965).

We have so far described only seamount deposits and indicated that more basinal facies are sometimes developed towards the top of the Jurassic. However, basinal sediments, in relatively expanded sequences, occur throughout much of the Jurassic in some areas: e.g. Balata di Baida (Warman and Arkell, 1954) and Piana degli Albanesi (Caflisch, 1966) and these can be interpreted as inter-seamount deposits. Such facies are usually red nodular and marly limestones with interbedded cherts (scisti silicei); they may also contain intercalations of allodapic carbonate deposits (cf. Bernoulli, 1967; Garrison, 1967). The association of cherts with basinal facies has been commented upon
by several authors (e.g. Bernoulli, 1967).
It is due, as Flügel (1967) has pointed out, to a two-
fold mechanism:
a) a primary process whereby most siliceous organisms,
   chiefly radiolaria, are concentrated preferentially
   in basins and,
b) a secondary enrichment of diagenetic silica.
Lisitsyn (1967) in a study of recent sediments reported
that siliceous deposits are never concentrated on
submarine highs, whereas modern basins of siliceous
material are well documented (e.g. Calvert, 1966).

Upwards the Upper Jurassic facies usually grade
into the so-called Lattimusa (comparable in lithology
to the Biancone and Maiolica), a lithified coccolith
ooze which may contain chert. This is a widespread
basinal facies deposited when most topographic
irregularities had been evened out; however, the onset
of Lattimusa deposition is slightly diachronous (Wendt,
1969) showing that a few residual seamounts still
exercised control on sedimentation at this time. The
Lattimusa contains pelagic tintinnids, Pygopex, rare
ammonites and aptychi; and tintinnids associated with
similar facies are of remarkable Tethyan extent (Colom,
1965; Garrison, 1967). Colom (1967) estimates a
depositional depth of around 3,000 metres for the Maiolica of the Subbetic-Balearic zone, whilst Ziegler (1967) has taken the scarcity of macrofossils apart from ammonites in this facies to indicate a depth greater than 500 metres. Vogel (1966) was also of the opinion that the presence of Pygope was dependent on considerable depth of water. However, the rarity of macrofossils could well reflect distance from land, and lack of hard substrates, than depth alone, and these figures may be much overestimated.

**INTERPRETATION OF PALAEOGEOGRAPHIC EVOLUTION**

The first stage in the evolution of the west Sicilian Jurassic was already well established in Triassic times when a rapidly subsiding carbonate platform of Bahaman type allowed thick accumulations of shallow-water limestones and dolomites to develop.

Platform-carbonate deposition ceased, in at least some areas, during the Pliensbachian; the crinoid banks and 'variable deposits' are the first signs of facies differentiation, and attest to considerable change in environment. Tectonism may have commenced in the Upper Pliensbachian (Wendt, 1969) but certainly became widespread during the Lower Toarcian, with abundant fissure
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| VERY SPORADIC | COMMON | FREQUENT | INFREQUENT | AMMONITES |
| ??STUNTED     | COMMON | FREQUENT | INFREQUENT | AMMONITES |
| COMMON ??STUNTED | COMMON | FREQUENT | INFREQUENT | AMMONITES |
| MEGALODONTS | COMMON | FREQUENT | INFREQUENT | AMMONITES |
| LOKALLY ABUNDANT | COMMON | FREQUENT | INFREQUENT | AMMONITES |
| FREQEANT     | OCCASIONAL | OCCASIONAL | RARE | CRINOID DEBRIS |
| FEW          |          |          |          | CRINOID DEBRIS |
| RARE         |          |          |          | CRINOID DEBRIS |
| PLATFORM     |          |          |          | CRINOID DEBRIS |
| DISINTEGRATION |          |          |          | CRINOID DEBRIS |
| NEPTUNIAN    |          |          |          | CRINOID DEBRIS |
| DYE FORMATION |          |          |          | CRINOID DEBRIS |
| WIDESPREAD   |          |          |          | CRINOID DEBRIS |
| VOLCANISM    |          |          |          | CRINOID DEBRIS |

| NONE        | NONE | NONE | VERY RARE QUARTZ FRAGMENTS | CONTINENTAL DETRITUS |
| NONE        | NONE | VERY COMMON | WIDESPREAD | IGNEOUS DETRITUS |

| FAR          | FAR | FAR | FAR | FAR | FAR | FAR | INFERRRED DISTANCE FROM MAJOR LANDMASS |
| VARIABLE     | HIGH | HIGH | LOW | ENERGY REGIME |
| HIGH         | NIL | NIL | SLIGHT | RATE OF SUBSIDENCE |
| MINIMAL      | CONSIDERABLE | EXTREME | MINIMAL | DEGREE OF CONDENSATION |

| SUBSIDING PLATFORM | EMBRYO | SEAMOUNT | UNIFORM BASIN | SUBMARINE TOPOGRAPHY |
| SUBTIDAL TO SHALLOW SUBTIDAL | SUBTIDAL | DEEPENING | SUBTIDAL | INFERRRED DEPTH |

| SUPRATIDAL | SHALLOW SUBTIDAL | TIDAL INFLUENCED | DEEPENING | INFERRRED DEPTH |
| SUPRATIDAL TO SHALLOW SUBTIDAL | SHALLOW SUBTIDAL | TIDAL INFLUENCED | DEEPENING | INFERRRED DEPTH |

| ? FAR | FAR | FAR | FAR | FAR | FAR | FAR | INFERRRED DISTANCE FROM MAJOR LANDMASS |
| VARIABLE | HIGH | HIGH | LOW | ENERGY REGIME |
| HIGH | NIL | NIL | SLIGHT | RATE OF SUBSIDENCE |
| MINIMAL | CONSIDERABLE | EXTREME | MINIMAL | DEGREE OF CONDENSATION |

| SUBSIDING PLATFORM | EMBRYO | SEAMOUNT | UNIFORM BASIN | SUBMARINE TOPOGRAPHY |
| SUBTIDAL TO SHALLOW SUBTIDAL | SUBTIDAL | DEEPENING | SUBTIDAL | INFERRRED DEPTH |

| SUPRATIDAL | SHALLOW SUBTIDAL | TIDAL INFLUENCED | DEEPENING | INFERRRED DEPTH |
| SUPRATIDAL TO SHALLOW SUBTIDAL | SHALLOW SUBTIDAL | TIDAL INFLUENCED | DEEPENING | INFERRRED DEPTH |
fillings of this age, as the carbonate platform split into a series of fault-bounded blocks that underwent differential subsidence to produce features of high and low relief. Thus the characteristic seamount topography originated, each topographic high being formed of a considerable thickness of lithified and competent shallow-water carbonates, like the present non-magnetic seamounts off the Iberian coast (Black, Hill, Laughton, and Matthews, 1964). The accompanying volcanism may have supplied the iron for the formation of the limonite pisoliths preserved in patches on the embryo seamounts, which were now subject to considerable submarine erosion.

Further volcanic activity occurred in the Bajocian, and more material for the formation of ferromanganese concretions was supplied. A period of some stability followed in the Bathonian and Callovian, and the absence of any major tectonism during this time is confirmed by the rarity of Neptunian dykes containing faunas of this age (Wendt, 1965), whereas in the normal sedimentary sequence ammonites of this age are the most widespread in distribution. Only minimal amounts of sediment were now being deposited on the seamounts, probably due to strong current action, whilst considerably more must have been laid down in the basins. Most of
the seamount tops developed stromatolites at this time, showing that they reached the photic zone.

By the beginning of the Upper Jurassic (Oxfordian), due to a slow sinking of the seamounts and/or an infilling of the basins, the topographic influence was lessening in most areas, and the more marly red nodular limestones were deposited; a few seamounts, however, were the site of more massive shallow-water carbonate deposition. Some tectonism took place during the Upper Jurassic, producing more fissures that were filled by unconsolidated sediment and "stunted" ammonite faunas conceivably also derived from algal meadows.

At the end of the Jurassic much of the irregular bottom topography had been obliterated; by the early Cretaceous the process may have been complete and widespread coccolith ooze now covered the area. Following this, there were pronounced periods of tectonism during the Upper Cretaceous and Tertiary. These have consorted together to produce the chaotic present-day distribution of Mesozoic mountains isolated by Miocene clays. There is an essentially orderly pattern in this distribution which suggests that many
of the mountains are not far travelled. But the debate as to the proportion completely untravelled must remain.
APPENDIX
APPENDIX

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APPENDIX

SECTIONS IN MESOZOIC ROCKS FROM WESTERN SICILY

Much of the recent stratigraphic and palaeontological information on the west Sicilian Jurassic has been accumulated by Christ (1960) and Wendt (1963, 1965). The sections presented here are either new or modified from previous work. Where possible, the nomenclature employed by Wendt has been retained.

Most of the material set out below is a product of joint work with Dr. H. S. Torrens, and the age determinations of the ammonite faunas are entirely due to him.

GENERAL SECTIONS

Bolognetta

This locality has never been described in detail, but is briefly mentioned by Wendt (1969). The outcrop occurs about two kilometres south of Bolognetta village,
Figure 1: Cliff exposure of Upper Jurassic limestones and cherts. Bolognetta, western Sicily.
BOLOGNETTA

~ 8 metres

5 Metres

The southern flank of the site contains, down-sloping, the same series of clays and marls as the general area, but the best exposure is that of a cliff-section shown in Figure 7 (Negril 1957). The 17th. of September 1952 (Negril 1953).

3b. Clayey to sandy marls with blue-grey and green, nodular limestone, with bed bottom, rare dolines, and doline-Negrochelites. Coarsely crystalline, with blocky limestone, some red and green, with red and green horizons, towards the base. (Probably all Devonian).

Red and green shale-like material, regular in the lower part, with three small intercalations, towards the lower part. (Rogue 1952).

Ammonites of Lower Jurassic formation.

Red-grey, very green lime-grained sandy lime-stone, interbedded with red nodules, nodular in central part.

Red blocky, slightly calcareous lime-grained limestones, has blocky fine-grained limestone with occasional fine yellow intercalations for ammonite fragments.
on the southern flank of Monte Balatelle; down-faulted blocks occur on the mountain slope, but the best exposure is a cliff-section towards the top (Figure 1) (Foglio 259. IV. N. O. Ventimiglia di Sicilia: 643012).

Section:
7 Thin-bedded white compact limestone with blue-grey chert nodules. Gradational contact with bed below. Rare calpionellids. Age: Tithonian-Neocomian.
6 Coarsely crystalline whitish limestone; more red and green, with red and brown cherts, towards the base. (Probably allodapic in origin).
5 Red and green fine-grained limestone, nodular in the lower part, with many belemnites and aptychi. Ammonites of Lower Kimmeridgian age.
4 Red, grey, and green fine-grained marly limestones interbedded with red cherts; very nodular in central part.
3 Red blocky, slightly nodular fine-grained limestone.
2b Red blocky fine-grained limestone with occasional red-to-yellow concentrically laminated ferromanganese nodules.
2a Red to grey compact limestone very ferromanganese-stained in parts, with numerous crusts and nodules. Frequent belemnites and many unidentifiable ammonites. 

Age: ? Bathonian - Callovian, by comparison with other condensed sequences.

1 Massive white limestone with irregular upper surface.

Age: Trias - Lias.

Isola di Favignana

This section has been briefly described by Wendt (1963), who gives full details of the location, but a more detailed profile is included here. The bed numbers used do not correspond to those of Wendt.

Section:

8 Grey crystalline limestone, more or less nodular, split by numerous irregular, sometimes iron-encrusted surfaces. Ammonites of Lower Callovian age (Wendt, 1963).


6 Lensing bed of brown-to-pink crystalline limestone with upper surface bored and iron-stained.
Figure 2: Large-scale nodular structure in limestone. Jurassic of Isola di Favignana, western Sicily. Length of hammer handle = 28 cm.
5 Grey, pink to brown crystalline limestone with large-scale nodular structure (Figure 2), more obvious on weathered surface; the more marly bands wrap around the nodules. The top of this bed is an extensively bored iron-stained surface; the borings are vertical with solid cores coated with iron-rich crusts.

4 Grey-brown to pink crystalline limestone, with some discontinuous lenses showing nodular structure and marl bands. The basal 20cm are well laminated and gritty; this was described as a lime sand by Wendt (1963); in fact, it is an extensively recrystallised limestone, possibly tuffaceous. Trace fossils occur on bedding planes.

3 Grey, red to brown crystalline limestone slightly dolomitised with flecks of glauconite; laminated, with the laminations following round incipient nodules. Sponges occur on the upper surface.

2 Dolomite-limestone conglomerate, with red and purple ferruginous crusts; this bed occurs as a thin plaster capping the white limestone. Angularly unconformable on the beds below.

1 White saccharoidal limestone. Age: Trias - Lias.
Monte Bonifato (MBG)

Several profiles have been described by Wendt (1963) from Monte Bonifato; the one given below is new. The section is taken from a small quarry at the top of a dust road on the eastern flank of Monte Bonifato (Foglio 258. IV. N. O. Alcamo: 216033). The bed numbers given correspond to those of Wendt.

Section:

5 Very variable red, green, to cream blocky and nodular fine-grained limestone; some horizons show very well developed nodules with marly coatings, others more incipient nodular structure. Age: Upper Oxfordian (Wendt, 1963).

4b Fine-grained red limestone with many ferromanganese nodules and pieces of reworked volcanic material; a thick ferromanganese crust coats the top of the tuff outcrop. Age: Bathonian (Wendt, 1963).

3 Highly weathered volcanic tuff, with very irregular upper surface.

Monte Kumeta (MKC)

Wendt (1963, 1965) described some fossils from Monte Kumeta, but no section was given. The profile presented below comes from a small disused quarry on the
MONTE KUMETA

1 Metre

...
top of the mountain (Foglio 258. I. N. O. Piana degli Albanesi: 473036).

Section:

8 Thin-bedded red cherts interleaved with fine-grained red marly limestones.

7 Platy yellow-grey calcareous shales with limestone nodules.

6 Fine-grained red nodular limestone with ammonites; ferromanganese-stained in parts.

5 Fine-grained blocky red limestone, slightly nodular in parts, with lenses of *Bositra buchi* biosparite. Single corals, belemnites, and brachiopods; ammonites of Bathonian age in upper part of bed.

4 Fine-grained red limestone with thick undulose ferromanganese crust full of ammonites, with reworked blocks of the bed below. Bajocian age.

3 Ferruginous yellow-stained fine-grained limestones with numerous ammonites, gastropods and sharks teeth. Very irregular in thickness; infilling cavities in the bed below. Age: Upper Toarcian.

2 Yellow to pink coarsely crystalline crinoidal limestone of variable thickness; irregular upper surface forming smooth pinnacles and hollows. Riddled by Neptunian dykes and sills. Age: ?Domerian.
Figure 3: Quarry at Rocca Nadore, western Sicily.
Rocca Nadore

The new section described here is taken from a disused quarry facing on to a private road, immediately to the east of the main Rocca Nadore massif (Figure 3). (Foglio 266. IV. S.E. Sciacca: 348597).

Section:

6 Fine-grained white limestone with ammonites and Pygope at base. Age: ? Tithonian-Neocomian.

5 Fine-grained red to pink limestone, nodular in parts; Sometimes with nodules set in dolomitised matrix. Rare ammonites. Tithonian calpionellids at top.

4 Fine-grained red limestone with many ammonites and concentrically laminated ferromanganese nodules. Underlain by ferruginous hardground.

3 Fine-grained limestone, full of ammonites at the top. Age: Upper Bajocian - Bathonian.

2 Red coarsely crystalline crinoidal limestone of variable thickness; shows very marked lensing across the quarry face. Age: Liassic.

1 Massive white limestone. Age: Trias-Lias.
Figure 4: Limestone gorge at Monte Arancio, south-west Sicily.
Monte Arancio

This locality, where the section is well exposed in a deep limestone gorge (Figure 4), has been briefly described by Wendt (1963) who gives locality details. The numbering system used does not correspond to that of Wendt (1963).

Section:

4 Thin-bedded fine-grained limestone with calpionellids.
   Age: Lower Tithonian (Wendt, 1963).

3 Fine-grained grey limestone, full of aptychi.
   Age: Lower Kimmeridgian (Wendt, 1963).

2 Fine-grained grey limestone, with Middle-Upper Bathonian ammonites at top. Ferromanganese nodules and sparse iron pisoliths at base; Toarcian age.

1 Massive white limestone with irregular upper surface.
   Age: Trias - Lias.
MONTE PISPISA
(Southern end of quarry)

> 10 metres

15 Cms

Fe-Mn

4a

4b
MONTE PISPISA
(Southern end of quarry)

0.5 metres
SECTIONS IN CONDENSED SEQUENCES

The following sections are detailed profiles over condensed sequences; most of the localities are new, but a few have been described previously by Wendt (1963).

With some of the sections an attempt at correlation has been made; however, the great lateral variation in facies and thickness of much of the Middle Jurassic sometimes makes it difficult to correlate profiles from the same massif, let alone between the massifs themselves. Correlation has been attempted, however, between the Maranfusa massifs (Rocce Maranfusa, Monte Maranfusa), Monte Galiello, Rocca Busambra, Rocca Argenteria, and Contrada Drago; these mountains have similar overall facies development throughout the whole of the Jurassic and are spatially related to one another. The correlation has only been attempted for the more persistent beds (designated by a number), but the horizons within them (designated by a letter) are not correlatable and refer only to natural lithological divisions.

Monte Pispisa

This quarry has been described by Wendt (1963) who gives full details of its location.
Section:
5 Soft grey to white marls with belemnites and aptychi.
4 Yellow, red to cream ferromanganese-stained fine-grained limestone with ammonites, aptychi, belemnites, and shell debris; very variable in thickness.
   Interrupted by a discontinuous (c~10 cm) ferromanganese band in the southern section. With small black ferro-manganese beads at base in the northern section.
   Age: ? Tithonian - Neocomian.
3 Orange-black ferromanganese horizon interlaminated with leaves of calcite; very variable in thickness. Upper Kimmeridgian or Lower Tithonian (Wendt, 1963).
2 Pink to white fine-grained limestone with belemnites; encrusted with ferromanganese which fills in topographic irregularities. Age: Oxfordian (Wendt, 1963).
1 Massive white limestone, extensively fissured.
   Age: Trias - Lias.

Monte Bonifato

The sections over condensed sequences from Monte Bonifato are taken from the MB5 (=MBE) of Wendt (1963) and the previously described new locality. Since the two profiles cannot be readily correlated, they are described
MONTE BONIFATO (MBG)
separately and with different numbering systems. The Monte Bonifato condensed sequence is Bathonian in age.

MBE

Section:

4b Fine-grained pink limestone, iron-stained towards the bottom and with discrete ferromanganese nodules up to 30cm from base.

4a Ferromanganese-stained hardground, studded with ferromanganese nodules.

3b Lensing bed of fine-grained pink limestone with ammonites and a few discrete ferromanganese nodules.

3a Black ferromanganese pavement of fused nodules.

2b Fine-grained red limestone with ferromanganese nodules of different sizes.

2a Iron-encrusted hardground.

1 Fine-grained/limestone; top ten centimetres iron-stained.

MBG

Section:

3 Fine-grained pink limestone containing stromatolites, ferromanganese nodules and ferromanganese-encrusted ammonites; angular and rounded tuff fragments (diameter up to 45cm) occur, some forming the nuclei of nodules. Serpulids in growth position.
MONTE INICI.
2 Thick brown ferromanganese crust, very weathered.
1 Volcanic tuff.

Monte Inici

This section is a detailed profile over the Bathonian - Lower Callovian condensed sequence of Wendt's MII (=MIA) locality. For locality details, see Wendt (1963).

Section:

2 Fine-grained pink limestone with discrete black ferromanganese nodules, coated ammonites, and large (up to 1 cm diameter) irregularly shaped brown pisoliths. Stromatolites as laterally continuous laminae and overgrowths on ammonites common. Thin mineral coatings on reworked limestone clasts are frequent. Base of bed is a remarkably continuous smooth black pavement composed partially of fused ferromanganese nodules. This thin crust coats right over minor topographic irregularities in the bed below.
1 Massive white limestone; Trias - Lias.

Bolognetta

This section is an 'enlargement' of the condensed sequence in the previously described profile of Bolognetta.
BOLOGNETTA

15 cms

1

2

3

Fe-Mn
Figure 5: Hillside quarry on Montagna Grande (arrow), photographed from Rocca che Parla, western Sicily.
Figure 6: Burrows in limestone. Montagna Grande, western Sicily.
BELLOLAMPO (BL)

30 Cms

25 metres

1. Hard, pink to yellow, fine-grained limestone, topped with mixed, occasional crinoidal laminae, with some perforate microcrinoid colonies. Parting at top.

2. Red, pink to brown, nodular fine-grained limestone, with occasional crinoidal laminae, topped with mixed, perforate microcrinoid colonies. Parting at top.

3. Fine-grained, grey, carbonaceous, slightly calcareous, with parting at top.

4. Fine-grained, grey, carbonaceous, slightly calcareous, with parting at top.

5. Fine-grained, grey, carbonaceous, slightly calcareous, with parting at top.

6. Fine-grained, grey, carbonaceous, slightly calcareous, with parting at top.

Fe-Mn

upper Dinozogaeus

Dinozogaeus

Allochthone

197a

Notes:

1. See Bell (1960) for a discussion on the stratigraphy of the Dinozogaeus and the well-developed above them. Bell's rock (waste rocks) is shown in the figure.

2. The section is not part of the text, but it is included in the figure. The text indicates a change in the stratigraphic order.

3. The section is not part of the text, but it is included in the figure. The text indicates a change in the stratigraphic order.
2b Alternations of clay (montmorillonite) and beef calcite: purple at top, green at base.

2a Grey-green crystalline limestone with stromatolites; brown-stained in patches. Small pyrite cubes common. Upper Bajocian to Lower Bathonian.

1 Massive white limestone. Age: Trias - Lias.

Bellolampo

This locality is mentioned by Wendt (1969); the outcrop occurs on the summit of Cozzo San Calogero and is well developed along its north-eastern flank (Foglio 249. II. N.0. Torella: 482228). This section is not part of the normal west-Sicilian 'schwellenfacies' but probably indicates a pelagic interlude in a 'reefoid' series.

Section:

6 Grey, slightly sparry limestone, with many compound corals, oysters and much echinoderm debris.

5 Fine-grained grey-pink limestone, slightly crinoidal, with parting at top.

4 Red, pink to brown, more or less nodular fine-grained, occasionally crinoidal limestone, with some ferromanganese crusts. Parting at top.

3 Hard pink to yellow fine-grained limestone, packed with microfossils. Black-blown ferromanganese band at top.
Figure 7: Rocche San Felice group of olistoliths. Arrow indicates block on which section was measured. West-central Sicily.
ROCCHE SAN FELICE

1. Fe-Mn nodules on base of highly-crushed debris.


3. Fine-grained and partly altered fine-grained limestone, 40-50 cm thick.

Sediments:

1. Brown to greyish-brown fine-grained nodular limestone.

2. Fine-grained, finely-crushed limestone with occasional ferruginous patches.

3. Strata with thin intercalation of brown, iron-stained muds of ferruginization debris, with a hardpan at the top.

4. Grey to greyish-brown fine-grained, clastic debris; some with minor Fe-Mn oxide concretions, flasers and pseudomylonite.
2 Yellowish more or less nodular, fine-grained limestone, with many ammonites. Age: Toarcian (Wendt, 1969).
1 Yellowish-pink grading down to grey fine-grained limestone. Age: ? Trias - Lias.

Rocche San Felice

This general locality has been briefly described by Mascle (1966). The detailed section below is taken from one of the Rocche San Felice group of shattered olistoliths (see Figure 7 for exact location) that rest on Miocene clays (Foglio 258. II. N.E. Monte Cardellia: 597796).

Section:
5 Thinly bedded white to grey limestone; seen as fallen blocks. Age: Cretaceous.
4b Grey to pale pink fine-grained nodular limestone.
4a Grey fine-grained limestone with occasional ferromanganese nodules
3e Grey-pink iron-impregnated compact limestone full of ferromanganese nodules. Vertical borings at top.
3d Grey to grey-pink limestone with manganese dendrites; erosion surface at top, with small ammonites, belemnites and pelecypods.
CONTRADA DRAGO

1. Fine-grained grey limestone, weathered erosion surface
2. Fine-grained grey limestone, uppermost Lower Bathonian.
3. Hard, black to brown argillaceous mudstone, uppermost crust
   probably Lower Bathonian.
4. Massive white limestone, uppermost crust.

Sections:

1. Fine-grained grey limestone, weathered erosion surface.
2. Fine-grained grey limestone, uppermost Lower Bathonian.
3. Hard, black to brown argillaceous mudstone, uppermost crust.
4. Massive white limestone, uppermost crust.

Sections:

- 1. Fine-grained grey limestone, weathered erosion surface.
- 2. Fine-grained grey limestone, uppermost Lower Bathonian.
- 3. Hard, black to brown argillaceous mudstone, uppermost crust.
- 4. Massive white limestone, uppermost crust.

---

This section is a geological cross-section of the Contrada Dragó area, showing the stratigraphic sequence from top to bottom. The layers are marked by different colors and compositions, with a focus on the lowermost part of the section, highlighting the transition from argillaceous mudstone to massive white limestone.
3c Fine-grained grey limestone; bored erosion surface at top.
3b Fine-grained nodular red limestone.
3a Fine-grained grey limestone. Age: Lower Bathonian.
2 Hard black to brown undulating ferromanganese crust crossed by calcite veins. Age: Lower Bathonian.
1 Massive white limestone. Age: Trias - Lias.

Contrada Drago

This section is taken from a disused quarry face of a down-faulted block of Rocca Busambra; the locality is immediately to the west of Rocca Argenteria, near the old railway line. Two small houses (Case Scalilli) are nearby (Foglio 258. I. S. O. Rocche di Rao: 507924). By analogy with Rocca Busambra (Wendt, 1965), Bed 3 is Lower Bathonian - Middle Callovian.

Section:
4 Grey to pink slightly sparry limestone with discrete ferromanganese nodules in basal metre. Lens of coquina, with sparry calcite veins above and below it.
3e Dark black to brown ferromanganese crust.
3d Neptunian sill of fine-grained grey marly limestone.
3c Red fine-grained limestone with some ferromanganese staining.
Figure 8: Rocca Argenteria, cliff-section.
Western Sicily.
ROCCA ARGENTERIA

~ 2 metres

2.000

2.00

3.00

2.00

1.00

30 cms

200 b

5b Pink argillite. Fine to coarse powdery mudstone. Small amount of quartz, feldspar, and mica. Thin bedded, often laminated. No visible fossils. Bedded structure.

3a Grey to pale brown, fine-grained, fine to coarse powdery mudstone. Contains occasional plant fragments and small foraminifera. No visible fossils. Bedded structure.

3b Pink argillite. Fine to coarse powdery mudstone. Small amount of quartz, feldspar, and mica. Thin bedded, often laminated. No visible fossils. Bedded structure.

3c Yellow to yellowish brown, fine to coarse powdery mudstone. Contains occasional plant fragments and small foraminifera. No visible fossils. Bedded structure.

4 Grey to pale brown, fine-grained, fine to coarse powdery mudstone. Contains occasional plant fragments and small foraminifera. No visible fossils. Bedded structure.
3b Pink coquina facies capped by vein of sparry calcite.
3a Red fine-grained limestone with some ferromanganese staining. Stromatolithic structures.
2b Purple ferromanganese crust.
2a Pink limestone with sparse iron pisoliths.
   Age: Toarcian
1 Massive white limestone. Age: Trias - Lias.

Rocca Argenteria

From Rocca Argenteria up towards Rocca Busambra the succession is repeated through a series of step faults; this profile is taken from a cliff-section on the south-western flank (Poglio 258. I. S. O. Rocche di Rao: 516922) (Figure 8). By analogy with Rocca Busambra, Bed 3 is Lower Bathonian - Middle Callovian in age.

Section:
4 Grey to pale pink slightly sparry limestone with discrete mineral nodules and ferromanganese crust at base.
3c Red to pink fine-grained limestone with occasional ferromanganese nodules near top.
3b Pink, red to black fine-grained limestone crowded with small ferromanganese nodules.
Figure 9: View of Monte Galiello, western Sicily.
MONTE GALIELLO

~5 metres

30 Cms

1

2a

2b

Fe-Mn

3
3a Pink to red fine-grained limestone, very ferromanganese-stained at base with a few discrete ferromanganese nodules.

2b Red, pink to grey fine-grained limestone with many ferromanganese nodules. Difficult to separate from bed below.

2a Black ferromanganese crust with iron ooliths in a red to pink limestone. Age: Toarcian.

1 Massive white limestone with irregular top.
   Age: Trias - Lias.

Monte Galiello

Wendt (1965) has mentioned this locality, but no section has been described. The outcrop occurs on the north-western spur of the mountain (Figure 9) and is one of a series of shattered blocks (Foglio 258. IV. S.E. Camporeale: 409926).

Section:

3 Red to pink slightly sparry limestone.

2b Black-brown to purple ferromanganese crust.

2a Red to pink fine-grained ferromanganese-stained limestone with disseminated iron pisoliths. Rare ammonites. Age: Toarcian.

1 Massive white limestone with irregular upper surface.
Figure 10: General view of Rocce Maranfusa quarry, western Sicily.

Figure 11: Bed 3 at Rocce Maranfusa. Note the karstic pinnacles of white limestone projecting to this bed; and the transgressive Neptunian dyke. Length of hammer handle = 25 cm.
ROCCE MARANFUSA (RMB)

~ 20 metres

30 cm

4

Fe - Mn

3b

Fe - Mn

3a

2

1
Rocce Maranfusa

These exposures occur in a series of abandoned quarries on the eastern flank of Rocce Maranfusa immediately to the west of Roccamena village (Figure 10) (Foglio 258. IV. S.E. Camporeale;362893). The section RMB is taken from the central part of the quarry; RMD is further south.

RMB

Section:

4  Grey fine-grained limestone with lenses of oolite.
   A few discrete concentrically laminated ferromanganese nodules occur in the basal 15cm. Ammonites rare.

3b Dark red, fine-grained, ferromanganese-stained limestone with a few ferromanganese nodules in the upper part. Some stromatolitic development, especially near base. Ferromanganese crust at top. Sharp contact with bed below.

3a Pink to grey crinoidal limestone (Figure 11), packed with Bositra buchi coquina. Very well developed stromatolites. Rare ammonites. Age: Upper Bajocian.

2 Chocolate brown crinoidal limestone with lenses of green to brown iron pisoliths; ferromanganese crust at top. Numerous gastropods, ammonites, and less
ROCCE MARANFUSA (RMD)

Fe-Mn

~20 metres

30 Cms

1

2

3

4

...
common sharks teeth and brachiopods. Pinnacles of white limestone that protrude into this bed are coated with a dark purple ferromanganese crust.

Age: Toarcian.


Monte Maranfusa

The two sections presented below are taken from the group of mountains in the Monte Maranfusa area - lying to the north of Rocce Maranfusa. The locality MMC is in a little gully on the northern side of Monte Maranfusa itself (Foglio 258. IV. S.E. Camporeale: 357916); MMC is a profile taken from the northern tip of a massif (Figure 12) due south of Monte Maranfusa (Foglio 258. IV. S.E. Camporeale: 352914).
Figure 12: One of the Monte Maranfusa group of mountains due south of Monte Maranfusa proper.
MONTE MARANFUSA (MMG)

~ 20 metres
4 Grey to pink moderately homogeneous limestone, more red at base.

3 Compact red manganese-stained limestone with stromatolitic structures; capped by purple ferromanganese crust.
Age: ? Bajocian by analogy with Rocce Maranfusa.

2 Red limestone full of iron pisoliths and brown calcareous ferromanganese nodules. Black stratified ferromanganese band at top. Irregular contact with bed below.
Age: Toarcian.

1 Massive white limestone. Age: Trias - Lias.

MMC

4 Compact grey limestone, crinoidal at base with fauna of ammonites, gastropods, and brachiopods. Discrete ferromanganese nodules extending up to 1½ metres; rounded intraclasts or 'nodules' occur higher up the succession.

3b Compact red limestone, faintly crinoidal.

3a Compact red to pink limestone with ferromanganese skin at top; contains stromatolites at base. Age: ?Bajocian by analogy with Rocce Maranfusa.
2 Red, brown to grey limestone with iron pisoliths and yellow ferromanganese nodules. Red lensoid ferromanganese crust at top. Ammonites and gastropods common. Irregular contact with bed below. Age: Toarcian.

1 Massive white limestone. Age: Trias - Lias.

OTHER LOCALITIES

Two localities referred to in the text, but for which no section has been given, are: 1) Massa Patria, 2) Monte Monaco.

Massa Patria is an olistolith of grey Upper Jurassic limestone; the outcrops are by the roadside next to and opposite a farmhouse to the south of Contrada Patria. A small quarry is present here (Foglio 258. I. S.O. Rocche di Rao: 463933).

Monte Monaco has been referred to by Wendt (1969) but no section or locality details were given; the outcrop examined occurs in a quarry at the top of a dust road on the western flank of Pizzo di Sella to the south of Monte Monaco proper. (Foglio 248. II. N.O. Castelluzzo: 031246).
INSOLUBLE RESIDUES

The following show the amounts of insoluble residue in certain rock-types; the composition of the residues has been determined on the X-ray powder camera.

Toarcian facies:
Contrada Drago, Bed 2a: 7.1% Kaolinite, montmorillonite, goethite.
Monte Maranfusa (MMC), Bed 2: 15.2% Illite, goethite.
Monte Bonifato (MB4, Bed 2 of Wendt, 1963): 1.1% Illite
Monte Galiello, Bed 2a: 5.4% Kaolinite, trace illite, goethite.
Monte Kumeta, Bed 3: 29.8% Illite, montmorillonite, goethite.
Rocca Argenteria, Bed 2a: 15.5% Kaolinite, trace illite, goethite.
Rocce Maranfusa, Bed 2: 14.3% Illite, kaolinite, goethite.

Condensed Middle Jurassic facies:
Monte Inici (MT1, Bed 2 of Wendt, 1963): 2.1% Illite,

Monte San Calogero, condensed sequence (see Wendt, 1965):
1.6% Illite, trace kaolinite.
Monte Kumeta, Bed 5: 4.6% Illite, possibly haematite.
Monte Kumeta, Bed 6: 2.9% Illite, trace kaolinite, trace haematite.

Montagna Grande (MGL, Bed 3b-3c of Wendt, 1963): 2.3%
   Illite, glauconite, trace kaolinite.

Monte Bonifato (MBE), Bed 4b: 3.6% Illite

Upper Jurassic nodular limestone facies:
Monte Bonifato (MBG), Bed 5: 17.4% Illite, montmorillonite.
Bolognetta, Bed 4: 4.7% Illite, montmorillonite, quartz.
Monte Erice (ME4, Bed 6a of Wendt, 1963): 9.0% Illite, montmorillonite, quartz.

Balata di Baida (Bed 4a of Christ, 1960): 8.4% Illite, quartz.

Montagna Grande (MGL, Bed 5a of Wendt, 1963): 9.4% Illite, montmorillonite, quartz, trace haematite.

Upper Jurassic oolitic limestone facies:

Rocce Maranfusa, Bed 4: 0.6% Illite

Upper Jurassic - Lower Cretaceous 'Lattimusa' facies:
Montagna Grande (MGL, Bed 6a of Wendt, 1963): 3.3% Illite, montmorillonite, quartz.

Monte Arancio (MA, Bed 3 of Wendt, 1963): 1% Illite, montmorillonite, trace quartz.
Balata di Baida (Bed 6 of Christ, 1960): 1.9% Illite, montmorillonite, quartz.

Rocca che Parla (Bed 5 of Wendt, 1963): 6.4% Illite, montmorillonite, quartz.
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CHAPTER 8


APPENDIX - REFERENCES


Published papers by H. C. Jenkyns

Fossil manganese nodules from Sicily.

SEDIMENTOLOGY OF THE WEST SICILIAN JURASSIC

(Ph.D. Thesis, University of Leicester)

by

H. C. JENKYN

This thesis examines the petrology, geochemistry, and palaeoecology of the west Sicilian Jurassic deposits and, where possible, compares them to similar facies elsewhere in the Alpine-Mediterranean region.

The Liassic platform carbonates form the greatest part of the west Sicilian Jurassic in terms of thickness: these are a series of white limestones and dolomites whose shallow-water origin is suggested by the presence of such structures as *Stromatopora*, birdseyes, and shrinkage cracks - and the component lithologies which include pelletal, oolitic and stromatolitic facies. The modern Bahamian pattern of sedimentation compares well with the reconstructed depositional environment of these rocks.

Crinoidal limestones, which cap the Liassic platform carbonates, usually occur as discontinuous lenses, and these are interpreted as sand-waves deposited on oceanic seamounts - seamounts which were formed after the carbonate platform had disintegrated during the Lias.
The Toarcian iron pisolites, which may also cap the white Liassic limestones, are considered to result from volcanic emanations that accompanied this disintegration.

Fossil manganese nodules, which occur in condensed sequences of Middle Jurassic age, have been subject to detailed investigation, and these ancient concretions are comparable in their structure, mineralogy and geochemistry to Recent oceanic iron-manganese accumulations. The condensed sequences themselves - like the crinoidal calcarenites and the iron pisolites - are interpreted as seamount deposits formed as the presence of stromatolites, boring algae and herbivorous gastropods suggests, in shallow photic zones.

Seamount evolution in the Upper Jurassic followed two patterns: the seamounts either sank with the consequent formation of more basinal deposits such as red nodular limestones and radiolarites, or with possible uplift, were the site of more massive carbonate production, with the formation of oolitic and pelletal deposits. Finally, in the Tithonian and extending into the Neocomian, a more uniformly basinal coccolith ooze covered much of the area.
FOSSIL MANGANESE NODULES
FROM SICILY

By
H. G. JENKYNNS

(Reprinted from Nature, Vol. 216, No. 5116, pp. 673-674,
November 18, 1967)
Fossil Manganese Nodules from Sicily

From the stratigraphically condensed limestones of the West Sicilian Jurassic, which overlie a white Trias-Lias reefoid facies, Wendt recorded fossil ferromanganese nodules.

The shape of the fossil nodules varies from place to place and from bed to bed. Some occur as small, roughly spherical, crenulate bodies, showing well developed concentric structure, others are larger, mammillated, potato shaped masses, or the nodules may fuse into an irregular pavement. The nodules and crusts are, in fact, physically indistinguishable from their modern counterparts; and it is interesting that this same geographical variation in nodule form is also found in modern examples. Recent manganese pavements have been reported from the Blake Plateau.

The fossil nodules are also comparable with recent ones in exhibiting lamination, which may disappear inwards, and, in some cases, alternate light and dark bands; at one locality, instead of the usual limestone or organic remnant, pieces of reworked volcanic tuff have formed the nodule nuclei, thus furthering the comparison.

Preliminary microprobe analysis shows that the Sicilian nodules contain most of the trace elements which characterize modern examples; however, in the fossil forms, the quantity of iron is persistently greater than the manganese (compare Mero's analyses). This is possibly a result of post-depositional migration of the more mobile manganese. Calcium also is high, because of the accretion of the nodules in a former limestone environment.

Mineralogically, apart from calcite, only goethite and occasionally haematite are positively identifiable by simple X-ray methods, the conclusion being that all the manganese oxides are colloidal or extremely fine grained—as is the case with many modern nodules. The fossil nodules described from the Cretaceous of Timor, however, contain goethite with pyrolusite, hausmannite and probably cryptomelane.

The association of the fossil ferromanganese nodules with stratigraphically condensed beds is significant. Condensed beds must have been formed in an environment of minimal net sedimentation; in today's oceans the central deeps and current-swept topographic highs qualify as possible milieux, and it is in these two environments
that ferromanganese nodules seem chiefly to occur now. The fossil nodules described by Molengraaf from the East Indies occur in the presumed lithified equivalents of the red deep-sea clay; but there is little evidence for a deep-sea origin of the red condensed limestones of the Sicilian Jurassic. On the contrary, there is some evidence that these deposits were laid down in
shallow water\textsuperscript{1,12}. Ferromanganese nodules themselves are no guide to depth; modern forms occur in a variety of shallow water environments\textsuperscript{12}.

The condensed beds, in similar facies, encompass different time intervals from locality to locality (ref. 1 and personal communication from H. S. Torrens), showing that the conditions for their formation were not realized solely during one period. The evidence therefore suggests that the condensed ferromanganiferous deposits from Sicily were laid down on transient topographic highs composed of the underlying Trias-Lias White Limestone, these topographic highs possibly being comparable with the non-magnetic seamounts now existing off the Iberian coast\textsuperscript{14}.

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