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CHARACTERISTICS OF TRIASSIC CARBONATE BUILDUPS OF THE DOLOMITE ALPS, ITALY: EVIDENCE FROM THE MARGIN-TO-BASIN DEPOSITIONAL SYSTEM.

RICE UNIVERSITY, PH.D., 1979

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CHARACTERISTICS OF TRIASSIC CARBONATE BUILDUPS OF THE DOLOMITE ALPS, ITALY: EVIDENCE FROM THE MARGIN-TO-BASIN DEPOSITIONAL SYSTEM

by

KEVIN T. BIDDLE

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

DOCTOR OF PHILOSOPHY

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May, 1979

ABSTRACT

CHARACTERISTICS OF TRIASSIC CARBONATE BUILDUPS OF THE DOLOMITE ALPS, ITALY: EVIDENCE FROM THE MARGIN-TO-BASIN DEPOSITIONAL SYSTEM

Kevin T. Biddle

The Triassic carbonate buildups of the Dolomite Alps have been the subject of much geologic research and were used for decades as classic examples of ancient coral reefs. Recently, this interpretation has been questioned, and the nature of the buildup margins has remained unclear, the result of Triassic erosion and substantial dolomitization.

During periods of buildup growth, but primarily during times of erosion, numerous limestone blocks were displaced and introduced into the surrounding basinal sediments. These blocks are called Cipit boulders in the literature, and although the record is incomplete, study of them allows conclusions to be drawn concerning the nature of the Triassic buildup-to-basin transition.

The Cipit boulders are integral parts of two basinal sedimentary sequences, the La Valle and San Cassiano formations. These formations document the filling of basins between the Dolomite buildups, and provide a sedimentary record of the development of the region. The two formations consist of a series of small overlapping submarine fans and equivalent slope and basin plain deposits. Beds of

carbonate megabreccia within the upper part of the basinal sedimentary package record the Triassic exposure and destruction of some buildup margins.

Analyses of over 300 Cipit boulders have shown that most are boundstones derived from the buildup margins. Boulders representing buildup interior or foreslope facies are scarce. The most common organic binding agent was sediment-trapping blue-green algae. Foraminifera, calcareous sponges, Tubiphytes, and other organic components assisted in stabilizing the substrate.

Submarine cements, precipitated just below and perhaps at the sediment-water interface, provided additional sediment stability. Two definite morphologic types of submarine cement have been recognized: radial-fibrous and isopachous-fibrous. A third, rarer, cement type, isopachous-bladed, is believed to be submarine in origin also. The amount of submarine cement is substantial, comprising as much as 50% of some samples.

Later diagenesis resulted in conversion of aragonite and high-Mg calcite to more stable carbonate phases, void filling by sparry ferroan calcite, and formation of minor amounts of zoned Fe-rich dolomite. Vadose phenomena are limited and represented primarily by solution cavities formed during Triassic sea level drops.

Bedding geometries preserved at Pale di San Martino show that at least one buildup margin gently rolled over and merged with the steeper foreslope facies. The margins

steepened during the Carnian, as scleractinian corals became more important.

The combined effect of organic binding, submarine cementation, and biologic evolution produced an upward-growing, potentially wave-resistant buildup margin, which steepened with time. In other words, the Triassic buildup margins of the Dolomite consisted of organically-bound and submarine-cemented reefs.

ACKNOWLEDGMENTS

This work would not have been completed without the help of many people, and I am most grateful for their assistance. The members of my committee, Dr. John E. Warme, Dr. James Lee Wilson, Dr. Donald R. Baker, and Dr. Ronald L. Sass, deserve special thanks. The guidance of Drs. Warme and Wilson, both in the field and in the laboratory, was needed and invaluable.

The late Professor Ricardo Assereto provided the necessary introduction to the geology of the area during the summer of 1976. His untimely death during my first field season was both a shock and a tragedy.

My fellow graduate students at Rice University and colleagues at Exxon Production Research Company provided many fruitful discussions and ideas. In particular, the assistance of Katherine Balshaw, Dr. C.V. Campbell, Tony Gorody, Bob Koehler, Rich Reynolds, Dr. John Van Wagoner, Dr. Jack Wendte, and Dr. Don Yurewicz is gratefully acknowledged. Rick Stanley provided many good ideas and able help in the field. Any misinterpretation of data or incorrect conclusions are strictly my responsibility, however. Dr. Pat Parker, University of Texas, Port Aransas, kindly provided the stable isotope data. Dr. Rudy Schwarzer, Rice University and Texas Southern University provided the atomic absorption analyses. Mrs. Becky Lindig typed several drafts of this work.

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INTRODUCTION

Purpose and Scope

The Triassic period was an important time in the evolutionary trend of carbonate margins. The scleractinian corals that dominate many modern shelf-margin reefs were beginning to evolve, and many late Paleozoic "reef" organisms were dying out. The Triassic, in particular the lower to middle Upper Triassic, buildups provide a link between the upper Paleozoic carbonate bodies and the more familiar Jurassic scleractinian coral reefs. An understanding of the composition, texture, and geometry of the Middle and Upper Triassic buildups would further the understanding of carbonate margin development in general.

One of the world's most spectacular and best known Middle and Upper Triassic carbonate terrains occurs in the Dolomite Alps of northern Italy. The Triassic buildups of the Dolomites have been the subject of much geologic research, and for decades were used as classic examples of ancient coral reefs. Recently, critical re-evaluation of the build-ups by French and Italian geologists has replaced the coral reef model with one emphasizing biostromal sedimentation, low-angle depositional slopes, and extensive fresh-water diagenesis and cementation. Coral, as a framework constructor, has been relegated to a minor role.

The actual nature of the Triassic buildup margins has remained unclear, however. The lack of information

results from several periods of Triassic erosion and an extensive Late Triassic episode of dolomitization. In other words, the buildup margins have been largely destroyed. Where they are preserved, lack of bedding-orientation, structural complications, and difficult access have limited the effectiveness of detailed work. As a result, the debate on what factors controlled carbonate buildup growth goes on (Cros, 1967a; Bosellini and Rossi, 1974; Biddle and others, 1978; Leonardi, 1978).

In this study, a different approach was used to gather information on the Triassic buildups. During periods of buildup growth, but primarily during the times of buildup destruction, numerous limestone boulders were produced and introduced into the surrounding basins. These boulders are called Cipit limestone or Cipit boulders in the literature (Richthofen; 1860; Bosellini and Rossi, 1974) and, although the record is incomplete, their study allows conclusions to be drawn concerning the nature of the margin-to-basin transition in the Dolomites.

Using basinal exotic boulders as indicators of buildup composition and morphology may be misleading. The boulders are only erosional remnants of much larger features. Bedding and other large-scale relationships cannot be observed. Information on these aspects of the buildups must come from observation of the buildups themselves. The major advantage of the Cipit boulders stems from their composition. Because of the properties of the host basinal

sediments, the boulders escaped the dolomitization that was so pervasive on the buildups. As a result, the original compositions and textures of the boulders can be observed, and inferences about their environment of deposition can be drawn. This, combined with observations on the shapes and trends of preserved buildup margins, allows a more detailed reconstruction of the Dolomite buildups than those of previous studies.

This study was divided into two parts: analyses of the basinal sedimentary host of the Cipit boulders, and analyses of the Cipit boulders themselves. From this work the following major conclusions have been drawn: 1) the basinal sedimentary rocks represent small-scale, overlapping, submarine-fan bodies and associated deposits formed during growth and destruction of the carbonate buildups; 2) the Cipit boulders were derived from and represent the buildup margins; and 3) the Middle and Upper Triassic buildup margins were not formed by coral construction, but nonetheless were the site of ecologic reefs.

Previous Work

The spectacular scenic and geologic nature of the Dolomite region has attracted the attention of scientists for many years. As a consequence, the geologic literature on the Dolomites is both voluminous and varied.

The first author to describe the geology of the Dolomites was probably Leopold von Buch in 1802

(Ogilvie, 1893). Von Buch's description aroused considerable interest in the geologic community, and numerous theories were put forth to explain the immense masses of dolomite rock. This early work was summarized by Richthofen in 1860.

In addition to summarizing the earlier theories, Richthofen's (1860) work contained two important contributions. First, he provided the first complete and systematic treatment of the stratigraphy of the area, and second he proposed a coral reef theory for the origin of the carbonate rocks in the Dolomites (Richthofen, 1860). He sought to explain the nature and distribution of carbonate rocks by applying Darwin's (1842) theory on the origin of coral reefs. Richthofen suggested that the Dolomite peaks were altered coral reefs formed during subsidence, and that the San Cassiano faunas had developed in lagoons, bays, and channels of a coral sea.

In a classic work on the Dolomites, Mojsisovičs (1879) more fully described the carbonate buildups and their relationships with the surrounding rocks. The interpretations presented by Mojsisovičs strengthened the coral reef theory and led to its general acceptance.

Even though Richthofen's and Mojsisovičs' theories found much support, there were always opponents (Ogilvie, 1893). Gumble (1872) opposed the coral reef idea because he could find little evidence of coral construction in the Sciliar Dolomite. He pointed out the paucity of preserved coral but the relative abundance of dasycladacean algae

with well preserved fine structure. In addition, Ogilvie (1893), Rothpletz (1894), and Diener and Arthaber (1903) questioned the reef origin of the carbonate for one reason or another.

Although there were dissenters, acceptance of the coral reef origin of the buildups prevailed among geologists until quite recently. Leonardi and his co-workers at the University of Ferrara have done extensive work in the Dolomites and their publications have reinforced the coral reef theory (Leonardi, 1955,1961,1962,1963,1967; Leonardi and Rossi, 1975; Rossi, 1957a,1957b,1959a,1959b).

Recently, a new phase of investigation in the Dolomites took place, and the resulting work has again led to the questioning of the importance of coral construction in buildup growth. Cros (1967,1974a,1974b) has questioned the reefal nature of several buildups and has suggested a biostromal origin instead. Bosellini and Rossi (1974) have summarized the recent work and provide an overview of Dolomite geology.

Other aspects of Dolomite geology have attracted nearly as much attention as the nature of the carbonate buildups. For example, the published works on the structural geology of the area and on the stratigraphy and faunas of the San Cassiano formation would number in the hundreds. The previous work concerned with these and other subjects will be reviewed in the appropirate sections below.

Unfortunately for American readers, most of the work on the Dolomites is published in European languages and in

journals that are not readily accessible. However, Bosellini and Rossi (1974) and Wilson (1975) both provide generalized English summaries on the Dolomite Alps.

Methods

Field work for this study was conducted during the summers of 1976 and 1977. The field investigations consisted of reconnaisance work, detailed stratigraphic section measuring and sampling, bed tracing, and examination of other areas of well known Triassic stratigraphy, e.g. Northern Calcareous Alps of Germany and the Triassic platforms of Sicily.

Laboratory work carried out in Houston, Texas included analyses of stratigraphic data, examination of over 300 thin-sections , and limited amounts of electron microprobe, atomic adsorption, and isotope analyses. Individual techniques are discussed in the appropriate following sections.

Terminology

In the literature many different terms have been used to describe various types of carbonate sediments and accumulations. The large number of terms and the lack of consistent usage has led to some confusion, and this has been particularly true in earlier discussions on the Dolomites. In order to avoid further confusion, the terms used in this study are defined below. The terminology used here follows that of Heckel (1974) and Wilson (1975).

Carbonate buildup: a body of locally formed laterally restricted carbonate sediment that possesses topographic relief (Wilson, 1975, p. 20).

Carbonate platform: a very large body of carbonate with a more or less flat top and abrupt margins (Wilson, 1975, p. 21).

Reef: a buildup that displays 1) evidence of potential wave resistance or growth in turbulent water that implies wave resistance, and 2) evidence of control over the surrounding environment (Heckel, 1974, p. 96). The binding that allows growth in turbulent water and influence over surrounding environments can be either organic, inorganic, or a combination of both. Therefore, a descriptive modifier must be used with the term reef, e.g. organic reef or ecologic reef or stratigraphic reef (Dunham, 1970).

Biostrome: a bed of skeletal material that exhibits no (or at least very little) topographic relief (Heckel, 1974, p. 92).

Dunham's (1962) scheme for the classification of carbonate rocks is used to describe the carbonate rock types.

THE DOLOMITE ALPS

Location

The Dolomite Alps are located in the northeast corner of Italy, just south of the Italian-Austrian border (fig. 1). The area is bounded on the west by the valley of the Adige River and on the east by the valley of the Piave River. This study was confined to an area designated as the Western Dolomites, between the cities of Bolzano and Cortina d'Ampezzo (fig. 1).

Regional Geology

The Dolomite Alps are part of the Southern Alps, one of the major physiographic units of the Alpine mountain system. The Insubric-Pusteria lineament, a major fault zone, separates the Southern Alps from the crystalline rocks of the Austroalpine nappes (fig. 2). As part of the Southern Alps, the rocks of the Dolomites are far less deformed than those of the Alps proper.

The region of the Dolomites is presently a large-scale synclinorium about 50 km wide and 100 km long (Bosellini and Rossi, 1974). Metamorphic basement rocks are exposed to the north and south, and a predominately Mesozoic sedimentary section is exposed in between.

In general, the rocks of the Southern Alps are deformed into a series of east-west trending, south-plunging folds, thrusted folds and thrust faults. There is still unresolved controversy over the autocthonous or allochthonous nature of

Figure 1. Location of the Dolomite Alps, Northern Italy, and the names of the most important mountain groups (underlined).

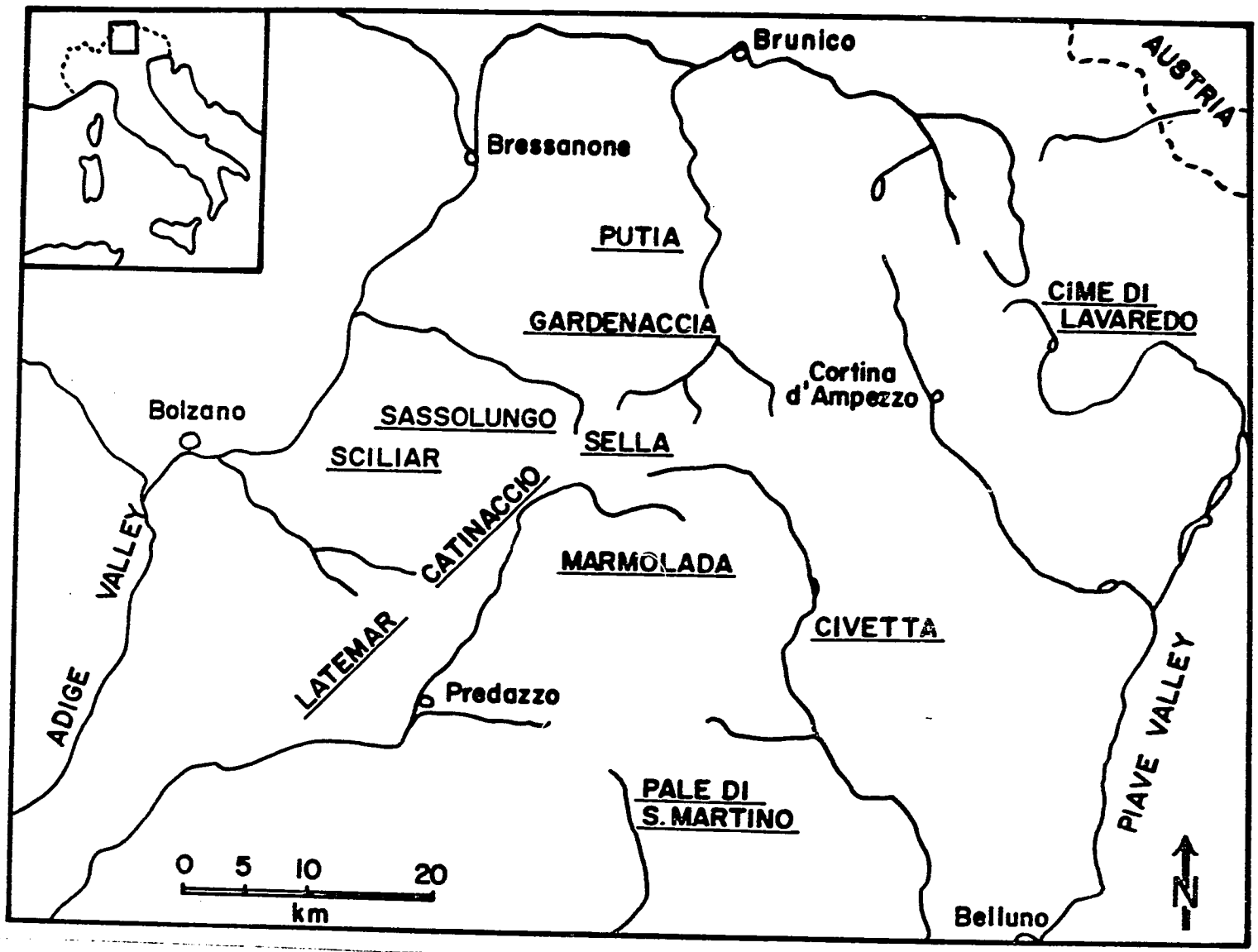
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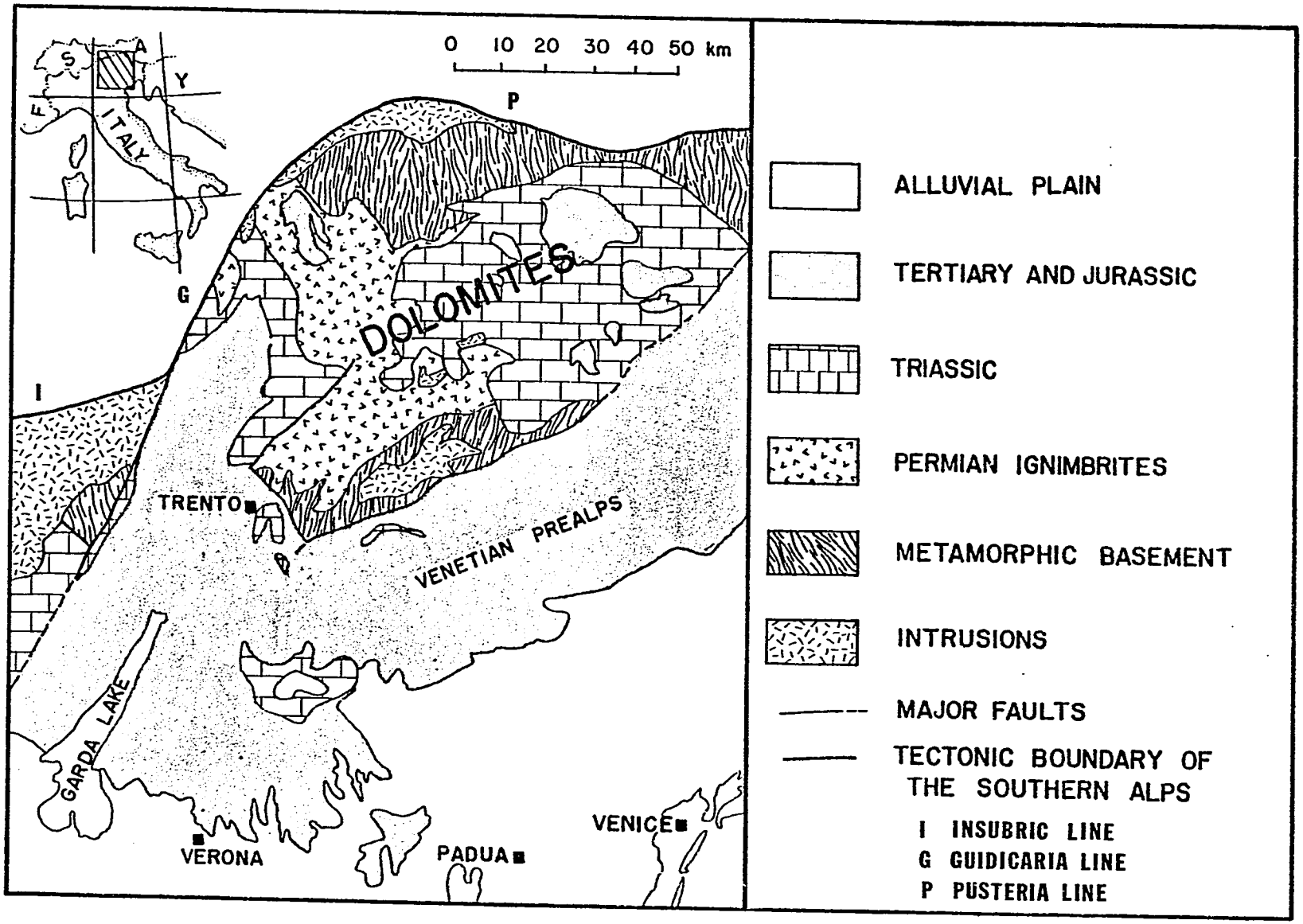
Figure 2. Generalized regional geology of the Dolomites and surrounding area (after Bosellini and Rossi, 1974).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PERMIAN IGNIMBRITES
METAMORPHIC BASEMENT
INTRUSIONS
MAJOR FAULTS
TECTONIC BOUNDARY OF THE SOUTHERN ALPS
I INSUBRIC LINE
G GUIDICARIA LINE
P PUSTERIA LINE

the Southern Alps. Although interesting, the argument is not critical to this study, because even if the Dolomites are not structurally in place they apparently moved more or less as a unit, preserving their internal relationships.

Many schemes and sequences of events have been offered to explain the structures found within the Dolomites. They fall within two broad categories, those that emphasized lateral compression, and those that proposed gravity sliding to be most important. Gravity sliding has been promoted primarily by Dutch geologists led by Englen (1963) and Van Bemmelen (1966), while the Italian school seems to prefer lateral compression as the major cause of deformation, with gravity sliding reduced to a secondary effect (Leondari, 1967, p. 505).

Geologic Evolution of the Dolomite Alps

The geologic evolution of the Dolomites occurred in three major phases: a pre-Hercynian phase, a post-Hercynian to Alpine phase, and an Alpine to present phase. The pre-Hercynian history of the area is complex and not easily deciphered; information on this period of time must await more detailed reconstructions of the Hercynian orogenic belt. The Alpine and post-Alpine history are dominated by vertical uplift and erosion, which have combined to produce the present topography of the Dolomites. The most important evolutionary phase, however, took place between the Hercynian and Alpine orogenies.

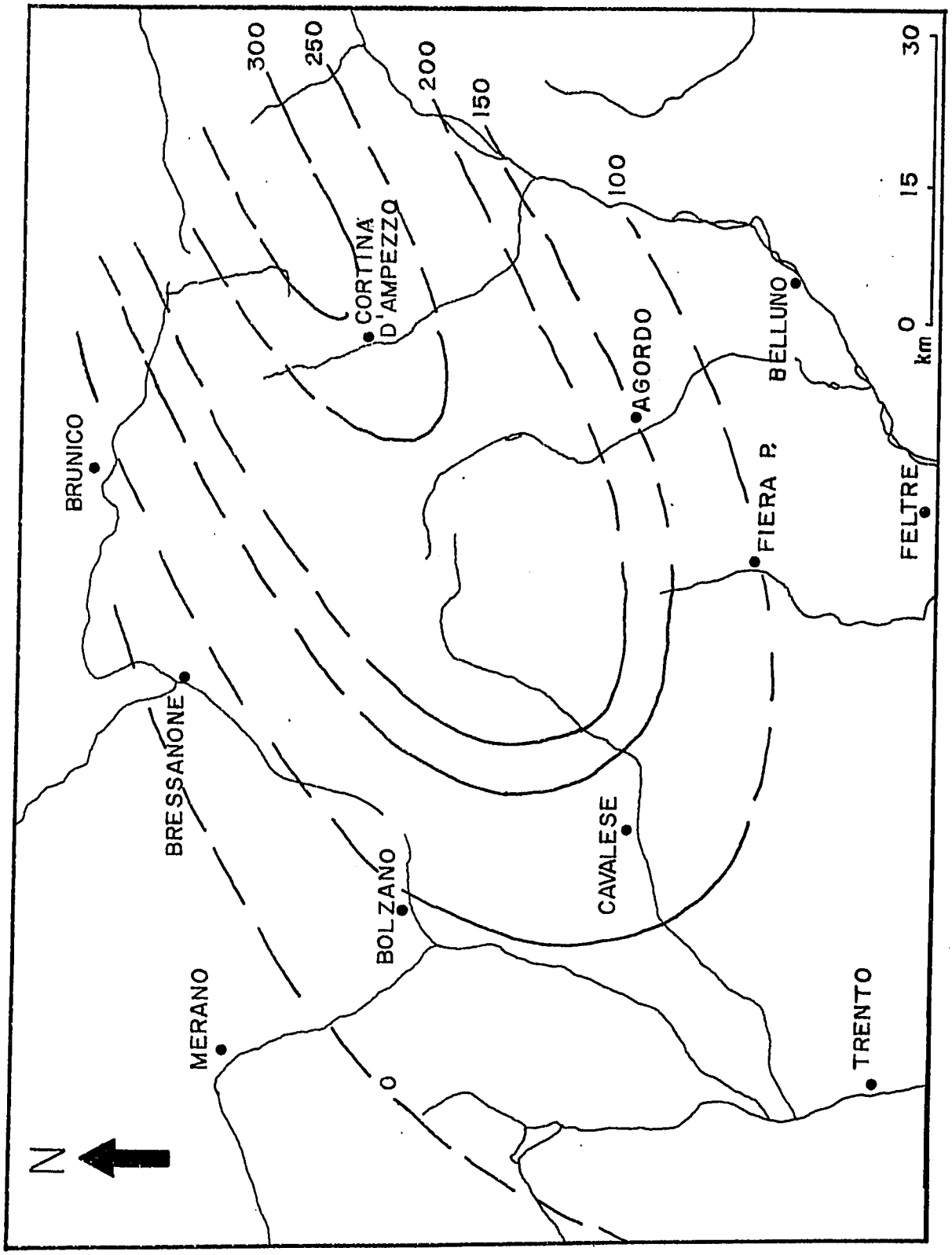
At the close of the Hercynian orogeny a series of roughly north-south trending elongate fault-bounded basins were formed in the area of the present Southern Alps (Bosellini, 1965), and these basins exerted control over the Permian-early Triassic evolution of the area.

In the Dolomites, during the late Permian the axis of sedimentation was roughly northeast-southwest (fig. 3). However, isopach maps of the Lower Triassic rocks show a different pattern (fig. 4). Over the area where the Permian section attains near maximum thicknesses, the lower Triassic section is at its thinnest. This, coupled with the presence of an unconformity above the top of the Lower Triassic (fig. 6) and the development of a lower Anisian conglomerate, suggests that a doming event took place near the Scythian-Anisian boundary. It was the collapse of this domal uplift during Anisian time, I believe, that produced the structures that served as focal points for the development of the Triassic buildups. The causes of the uplift and its subsequent collapse were related to the first stages of the development of the Alpine "geosyncline", and the distensional events that preceded the opening of the Atlantic Ocean (see Dewey and others, 1975).

Paleogeography

Today the Mediterranean area is interpreted as a complex of microplates whose relative motions are controlled by interactions between stable Europe and the African and Arabian plates (Dewey and others, 1975). Information

Figure 3. Isopachous map of the Upper Permian sedimentary units (continental sandstones, evaporites, limestones, and dolomites) in the Dolomites, intervals in meters. Notice the NE-SW trending axis of sedimentation (after Bosellini, in Leonardi 1967, fig. 217).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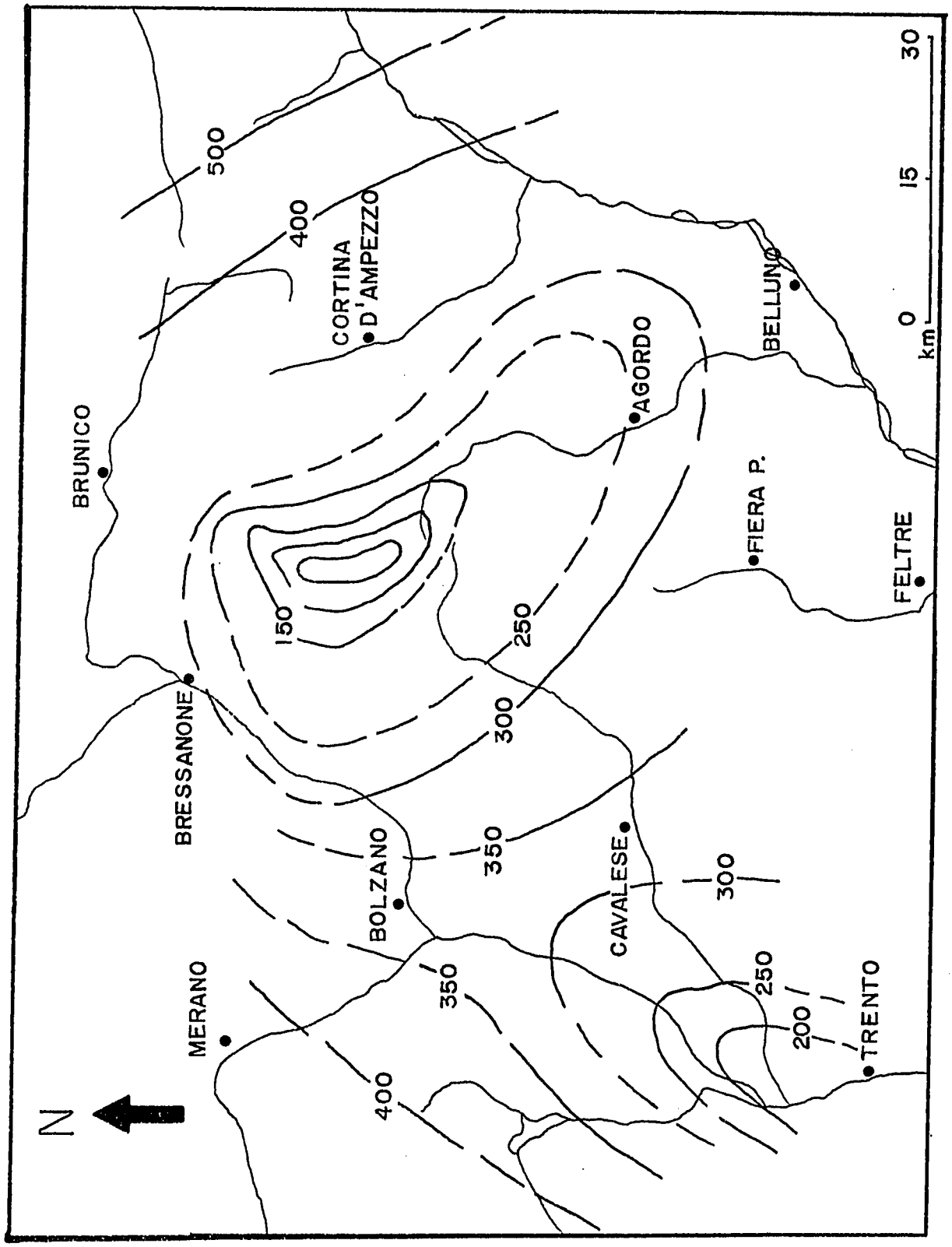
30
km

Figure 4. Isopachous map of the Lower Triassic Werfiano formation (limestones, siltstones, sandstones and rare evaporites), intervals in meters. Thickness trends in the Lower Triassic rocks are quite different from trends in the underlying Upper Permian units (compare with fig. 4), and suggest the formation of a domal uplift at the end of the Early Triassic (after Bosellini, in Leondari, 1967, fig. 218).


BRUNICO
CORTINA D'AMPEZZO
AGORDO
BELLUNO
FIERA P.
FELTRE
BRESSANONE
BOLZANO
CAVALESE
MERANO
TRENTO
500
400
150
250
300
350
300
350
400
250
200
N
0
15
30
km

gathered on ancient plate boundaries (Dewey and others, 1975), coupled with paleomagnetic data (Manzoni, 1970, Zijderveld and Van der Voo, 1973; Klootwijk and Van den Berg, 1975), suggest that this has been the case throughout most, if not all, of Mesozoic and Cenozoic time. These data, combined with facies relationships, allow reconstructions of past plate positions (Bosellini and Hsü, 1973; Dewey and others, 1975).

On these reconstructions, the area that became the Dolomite Alps occupied a position along the continental margin of the Tethys Ocean during late Triassic time (fig. 5). The exact position is debatable and will probably remain so, a result of the subsequent complex tectonic history of the Mediterranean region.

Paleocontinental reconstructions (Smith and Briden, 1977) place the general area of the Dolomites between approximately 10 degrees and 25 degrees north latitude between early and latest Triassic time (200 to 220 m.y.a.).

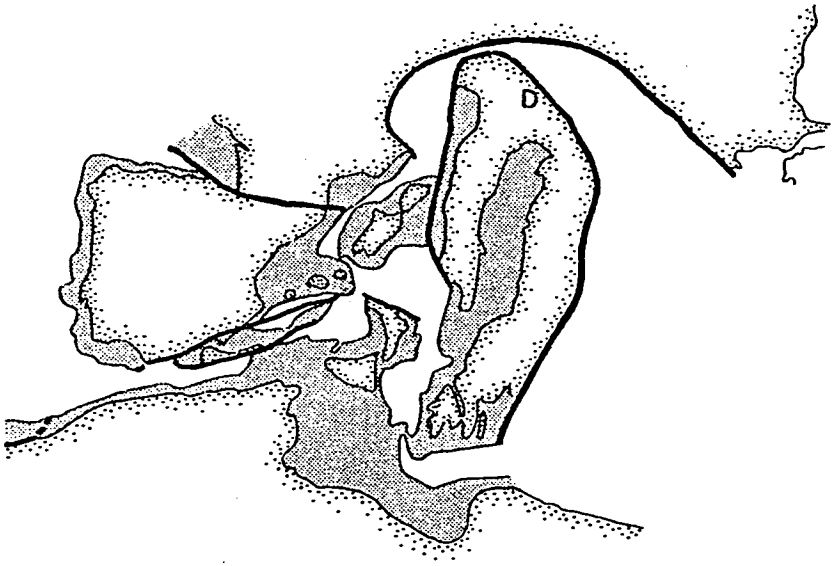
The sedimentary development of the Dolomites began in Permian time, but it is the Triassic section of the area that has drawn worldwide attention. Indeed, the Dolomites are considered one of the classic examples of Triassic stratigraphy.

Deposition began on a peneplaned Hercynian basement, and continental, evaporitic, and near-shore marine depositional environments prevailed from the Late Permian to Early Triassic time. Substantial carbonate deposition started during late Anisian time and continued until the

Figure 5. A) Postulated paleogeographic reconstruction of Mediterranean midcontinents in Late Triassic time.

B) Distribution of Upper Triassic facies, plotted on the Late Triassic paleogeographic map.

(Bosellini and Hsü, 1973)

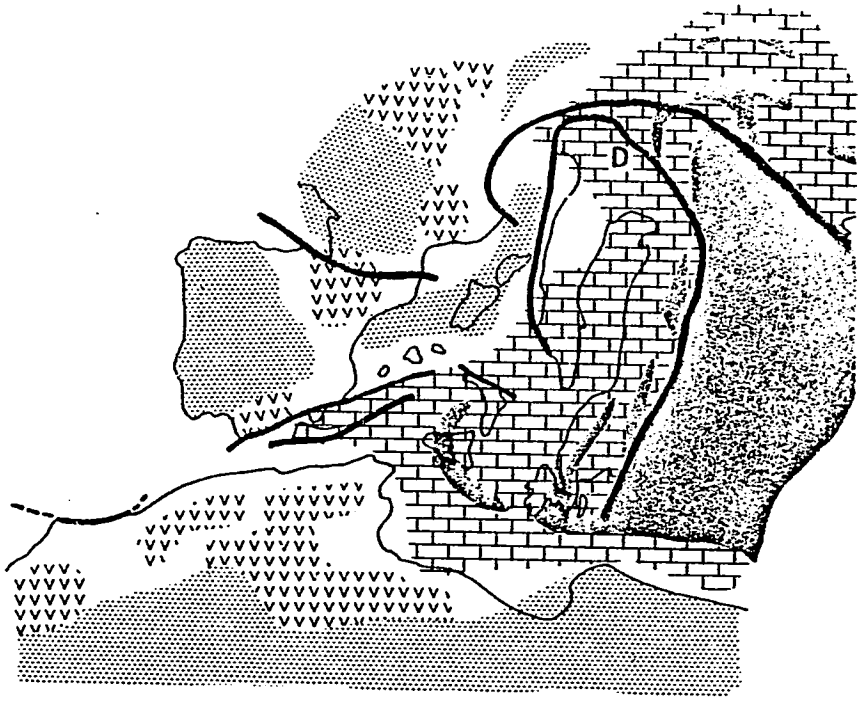


PRESENT LAND

PRESENT SEA DEPTH < 2000 m

SUTURED BOUNDARIES BETWEEN BLOCKS

D APPROX. LOCATION OF DOLOMITE ALPS



CONTINENTAL FACIES

EVAPORITE FACIES

SHALLOW WATER CARBONATE FACIES

DEEPER WATER FACIES

end of the Triassic. It is the tremendous carbonate buildups of the upper Anisian, Ladinian and Carnian that make up the major portion of the Dolomite Alps stratigraphic section.

During the Lias, the shallow-water carbonate environment that had prevailed throughout much of the Triassic was destroyed, and pelagic deposition began. In general, however, rocks of Jurassic and Cretaceous age are scarce in the Western Dolomites.

Almost no Tertiary rocks are preserved within the study area. The Quaternary is represented by alluvial and glacial deposits.

Although the stratigraphy of the Dolomites has been known for about a century, it continues to be refined, resulting in the division of many original time-stratigraphic units into more meaningful lithostratigraphic units.

The major stratigraphic units of the Western Dolomites are briefly described below. For a more thorough treatment see Leonardi, 1967.

The stratigraphic nomenclature adopted here is that compiled by Pisa (1973), and is summarized in figure 6. Italian terminology will be used throughout this report, but the equivalent Germanic terms are presented for comparison in figure 7.

Basement

The basement of the Western Dolomites can be divided into two components: a Carboniferous to Permian age

Figure 6. Stratigraphic column of the Western Dolomites from the Upper Permian to the end of the Triassic (after Pisa, 1974).

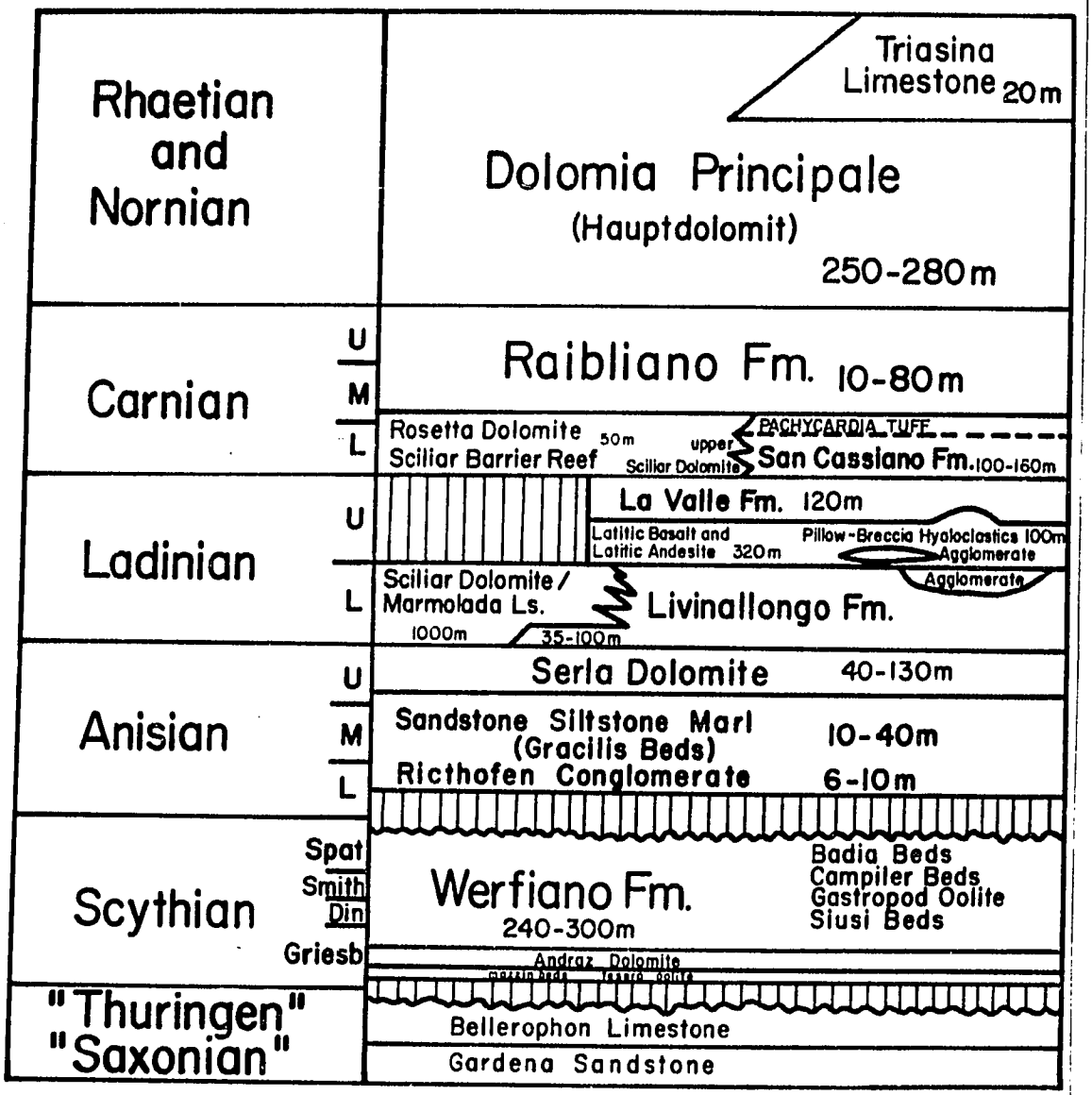

Rhaetian and Nornian
Triasina Limestone 20m
Dolomia Principale
(Hauptdolomit)
250-280m
Carnian
U
M
L
Raibliano Fm. 10-80m
Rosetta Dolomite 50m
Sciliar Barrier Reef
upper Sciliar Dolomite
PACHYCARDIA TUFE
San Cassiano Fm. 100-160m
Ladinian
U
L
La Valle Fm. 120m
Latitic Basalt and Latitic Andesite 320m
Pillow-Breccia Hyaloclastics 100m
Agglomerate
Agglomerate
Sciliar Dolomite / Marmolada Ls.
1000m
35-100m
Livinallongo Fm.
Anisian
U
M
L
Serla Dolomite 40-130m
Sandstone Siltstone Marl (Gracilis Beds) 10-40m
Richthofen Conglomerate 6-10m
Scythian
Spat
Smith
Din
Griesb
Werfiano Fm.
240-300m
Badia Beds
Campiler Beds
Gastropod Oolite
Siusi Beds
Andraz Dolomite
"Thuringen"
"Saxonian"
Bellerophon Limestone
Gardena Sandstone

Figure 7. Germanic equivalents of the Italian stratigraphic nomenclature.

Hauptdolomit	=	Dolomia Principale
Raibl Fm.	=	Raibliano Fm.
Schlern Dolomit	=	Sciliar Dolomite
Sarl Dolomit	=	Serla Dolomite
Werfen Fm.	=	Werfiano Fm.
Grödener Sandstone	=	Gardena Sandstone

ignimbrite sheet and an underlying metamorphic complex.

The metamorphic complex consists of phyllites, schists, and paragneisses. The age of metamorphism is generally assumed to be Hercynian (mid-Paleozoic), although some authors contend that the metamorphism took place during Precambrian time (see Dal Cin and Semenza, 1967, for discussion).

The ignimbrites are rhyolitic, rhyodacitic, and andesitic in composition, and in the Western Dolomites form a slab up to 1500 m thick known as the Bolzano porphyry plateau (Bosellini and Rossi, 1974).

Gardena Sandstone

The Gardena Sandstone is the oldest sedimentary unit in the Western Dolomites, and is assigned a late Early to early Late Permian age (Saxonian to Thuringen stages; Leonardi, 1967, p. 77). The unit consists predominantly of reddish coarse-grained sandstones and conglomerates of continental origin. Tetrapod tracks and plant fossils have been found in the unit, but the Gardena Sandstone is at best poorly fossiliferous. Alluvial, deltaic, and estuarine depositional environments are represented in the unit.

Average thickness of the formation is approximately 150 m (Leonardi, 1967, p. 77).

Bellerophon Limestone

Conformably above, and in gradational contact with, the Gardena Sandstone is the Upper Permian Bellerophon

Limestone. The lower part of the unit is evaporitic and passes upward into dark algal limestone, dolomites, and micritic skeletal limestone. Lithologic variation is great throughout the formation, and facies and thickness changes are quite common.

According to Accordi and Broglio (1967) two major facies can be recognized, a northeastern or Badiota facies and a southwestern or Fiammazza facies. The Badiota facies is suggested to represent a shallow marine to intertidal depositional environment, while the Fiammazza facies represents a coastal evaporitic environment (Accordi and Broglio, 1967). Only the Fiammazza facies is present in the Western Dolomites (Pisa, 1973).

The Bellerophon Limestone varies from 30 to about 300 m in thickness (Accordi and Broglio, 1967).

Werfiano Formation

The Permian-Triassic boundary is not found within the sedimentary package of the Western Dolomites, and the earliest Triassic unit, the Werfiano formation, lies above a slight disconformity (Pisa, 1973).

On the basis of lithology and paleontology the Werfiano formation has been divided into several subunits. Beginning at the base, these subunits are: the Tesoro oolite and the laterally equivalent Mazzin beds, the Andraz dolomite, the Siusu beds, the gastropod oolite, the Campil beds, and the Badia beds. Lithologies represented include oolitic limestones, marly and micritic limestones, marly siltstones,

fine-grained feldspathic sandstones, and rare beds of gypsum (Bosellini and Rossi, 1974).

Coastal and near-shore environments prevailed throughout the Dolomites during deposition of the Werfiano formation.

In the Western Dolomites the unit ranges in thickness from a few meters to nearly 300 m (Leonardi, 1967, p. 120).

Richthofen Conglomerate

The Richthofen Conglomerate, of early Anisian age is a thin unit, attaining thicknesses of only six to ten meters in the Western Dolomites (Pisa, 1973). Where present, the conglomerate overlies an erosional unconformity on the Werfiano formation.

Dadocrinus gracilis Beds

In the Italian literature the early to middle Anisian age sedimentary rocks between the Richothofen Conglomerate and the Serla Dolomite are known as the Dadocrinus gracilis beds. This unit varies in thickness from 10 to 40 m (Pisa, 1973), and is composed of siltstones and thin-bedded micritic limestones with abundant plant fragments and crinoid plates (Bosellini and Rossi, 1974).

Serla Dolomite

The onset of major carbonate deposition began in the Western Dolomites during late Anisian time, and is represented by the wide-spread Serla Dolomite. As the name of the unit implies, the major rock type is a coarsely crystalline dolomite. In a few areas, however, the unit

has not been dolomitized and has remained limestone with a pelletoid texture and abundant dasycladacean algal fragments (Bosellini and Rossi, 1974).

The name Contrin Limestone has been applied to the part of the unit that is still limestone. The differences between the Contrin Limestone and the Serla Dolomite are purely diagenetic, and one name, the Serla formation or Serla Dolomite, is applied to the unit in this report.

A shallow wide-spread lagoonal environment with scattered patch reefs is thought to have prevailed during deposition of the Serla Dolomite (Rossi, 1967), but substantial carbonate buildups were also formed at the same time. The Cernera buildup and the lower part of the Marmolada Group, for example, are both late Anisian in age (Cros, 1974).

Sciliar Dolomite

The Ladinian and Carnian stages of the Dolomites are characterized by tremendous thicknesses of sedimentary rocks and rapid facies changes. The Sciliar Dolomite is the most impressive of the Ladinian-Carnian units, and is responsible for the formation of many of the famous mountain groups of the Dolomite Alps (e.g. Sciliar, Latemar, Catinaccio, Sella, and Pale di San Martino; see fig. 1).

In the literature, several names have been used for the thick Ladinian to Carnian age carbonate bodies. The terms Sciliar Dolomite and Marmolada Limestone describe massive and poorly bedded facies (of appropriate rock type), while Latemar Limestone and Rosetta Dolomite describe

equivalent well-bedded facies. Here, the term Sciliar Dolomite will be used to describe all facies of the Ladinian to earliest middle Carnian carbonate buildups.

The Sciliar Dolomite represents a variety of carbonate environments, such as supratidal, intertidal, subtidal, and foreslope environments. Unfortunately, the most common rock type is a light-colored coarsely crystalline dolomite, in which little or no original texture can be recognized. The relationships between the various facies will be discussed in detail in a later section.

The Sciliar Dolomite did not result from uninterrupted Ladinian to middle Carnian deposition. It appears that carbonate production and platform growth were halted, or at least severely curtailed, during the late Ladinian volcanic episode. Also, Cros (1974 a,b) has recognized several phases of Triassic tectonic activity and karst development, which interrupted, on varying scales, Sciliar deposition.

For convenience, the unit is divided at the Ladinian-Carnian boundary into the Sciliar Dolomite and the upper Sciliar Dolomite (fig. 6). In the field, these two units appear nearly identical, and without additional stratigraphic information, are almost impossible to separate.

Although of limited lateral extent, the Sciliar Dolomite reaches a maximum thickness of about 1000 m (Bosellini and Rossi, 1974).

Livinallongo Formation

The Livinallongo formation is the basinal equivalent of the Ladinian Sciliar Dolomite, and is assigned an early Ladinian age. Lithologic variation within the Livinallongo formation is substantial. Near the margins of the Sciliar Dolomite the formation frequently consists of carbonate breccias and graded limestones, but as distance from the Ladinian carbonate buildups increases the unit becomes a partly nodular, cherty, micritic limestone. On the basis of rock types, three subunits are recognized (Bosellini and Rossi, 1974): a lower dark siliceous laminated limestone, a middle cherty nodular limestone, and an upper micritic limestone with argillaceous interbeds. In the Eastern Dolomites the Livinallongo formation includes rocks known as pietra verde (literally green rock), which are composed primarily of siliceous volcanic debris. This facies is largely absent in the Western Dolomites.

Radiolaria, pelagic bivalves, and rare ammonoids are the most common fossils present. An endemic shelly fauna is almost entirely absent.

Stratigraphic, sedimentologic, and paleoecologic data all point to a basinal depositional environment for the Livinallongo formation. It has been suggested that water depths as great as 1500 m existed during part of Livinallongo deposition (Bosellini and Rossi, 1974).

In the Western Dolomites, unit thicknesses vary from a feather edge of zero beneath the centers of the carbonate

buildups to 300 m in the basin centers (Bosellini and Rossi, 1974).

Ladinian Volcanics

Immediately above the Livinallongo formation and abutting against the Scilian Dolomite are upper Ladinian volcanic rocks. In the Western Dolomites, these volcanics partially fill the basinal areas, and once covered a few of the carbonate buildups (for example, the Latemar Group).

With the exception of a few dikes and sills, the volcanics all represent extrusions under submarine conditions. Pillow lavas, pillow breccias and hyaloclastics are common (Sacerdoti and Sommeville, 1962). Chemical compositions range from basaltic to latitic (Bosellini and Rossi, 1974).

The eruptive episode that produced the Ladinian volcanics was of short duration, covering perhaps a million years (A. Bosellini, pers. comm., 1977).

Maximum thickness of the volcanic pile in the Western Dolomites is several hundred meters. The volcanics thin eastward and are absent in the Eastern Dolomites.

La Valle Formation

The La Valle formation is the first of two units known informally as pseudoflysch, a result of the flysch-like bedding style. Representative rock types include dark laminated mudstones, sandstones, conglomerates and breccias, all of which are commonly graded. The major source of sediment for the La Valle formation is the underlying

Ladinian volcanics. Carbonate boulders derived from the buildups are also present.

The La Valle formation, and the overlying San Cassiano formation, are the result of relatively continuous deposition. Although the character of deposition changed upward with time, the change was in most places gradual. Consequently, the upper contact of the La Valle formation is a gradtional one, and is not easily picked in the field. The contact between the two "pseudoflysch" units is placed at the Ladinian-Carnian boundary, giving the La Valle formation a strictly late Ladinian age.

Formational thicknesses vary and depend on the amount of basin filling accomplished by the underlying volcanics (Bosellini and Rossi, 1974). Maximum thickness in the Western Dolomites is perhaps 120 m (Pisa, 1973).

San Cassiano Formation

The San Cassiano formation documents the continued filling of the basins between the major Triassic carbonate buildups of the Dolomites. This unit is also the major host of the Cipit limestone, or buildup-derived boulders. As such, the San Cassiano formation is of major importance to this study, and will be described in detail in a later section.

In general the unit is similar to the underlying La Valle formation, with the addition of increasing carbonate debris upward.

The maximum thickness of the San Cassiano formation is

difficult to measure; the upper portion of the unit is generally missing due to erosion. The combined La Valle and San Cassiano formations can reach a total thickness of about 1000 m (Bosellini and Rossi, 1974).

The formation is assigned an early Carnian to earliest middle Carnian age (fig. 6).

Raibliano Formation

The Raibliano formation lies disconformably above the older Triassic deposits (Bosellini and Rossi, 1974). Today, the unit is exposed almost exclusively on top of the Sciliar Dolomite, and is generally not present in the basinal areas.

In the Western Dolomites the Raibliano formation includes numerous rock types such as cross-stratified sandstone, marls, calcarenites and skeletal micritic limestones. To the east the section includes some evaporites. Thicknesses range from about 10 to 80 m (Pisa, 1973).

Dolomia Principale

The Norian and perhaps Rhaetian stages in the study area are represented by a rather uniform unit, the Dolomia Principale. The primary rock type is light-colored crystalline dolomite. Relict pelletoid, lithoclastic and fenestrate textures can commonly be recognized. The unit is well bedded and consists of cyclically arranged supratidal, intertidal and subtidal deposits (Bosellini and Rossi, 1974). Fossils are scarce, but include megalodont bivalves,

gastropods, brachiopods, algae, echinoderms, and rarely occurring ammonoids.

The maximum thickness of the Dolomia Principale in the Western Dolomites approaches 300 m (Pisa, 1973).

Jurassic and Cretaceous Rocks

In general, rocks of Jurassic and Cretaceous age are scarce in the Western Dolomites, but can be found in limited outcrops. During the Lias, a change from shallow-water carbonate deposition to predominantly pelagic deposition took place. The changing depositional environment is reflected in the Liassic rock types, which range from oolitic limestones to micritic limestones with pelagic bivalves (Accordi and Bosellini, 1967). The Liassic rocks reach a thickness of about 40 m in the Western Dolomites (Accordi and Bosellini, 1967), and crop out only as small isolated patches.

Rocks of Dogger age are quite rare. Where found they consist of oolitic and crinoidal limestones.

The Upper Jurassic or Malm series is variable, but predominantly represented by red nodular limestone known as Ammonitico Rosso.

The Cretaceous is exposed in the Gardenaccia and Sella Groups in small outcrops, and consists of red to green-gray shales with some chert nodules.

Cenozoic Rocks

According to Cros (1966), a limited amount of Upper Oligocene conglomerate is exposed near Monti Parei, but in general the Cenozoic deposits of the Western Dolomites are limited to alluvial and glacial sediments.

Middle and Upper Triassic Facies Relationships

The facies patterns of the upper Anisian to Norian section of the Western Dolomites are complex, and are characterized by rapid lateral changes (fig. 8). The Ladinian to Carnian carbonate buildups and their basinal equivalents lie between two wide-spread shallow-water Dolomite units, the Serla Dolomite and the Dolomia Principale, creating what has been called the "Dolomite sandwich" (Bosellini and Rossi, 1974).

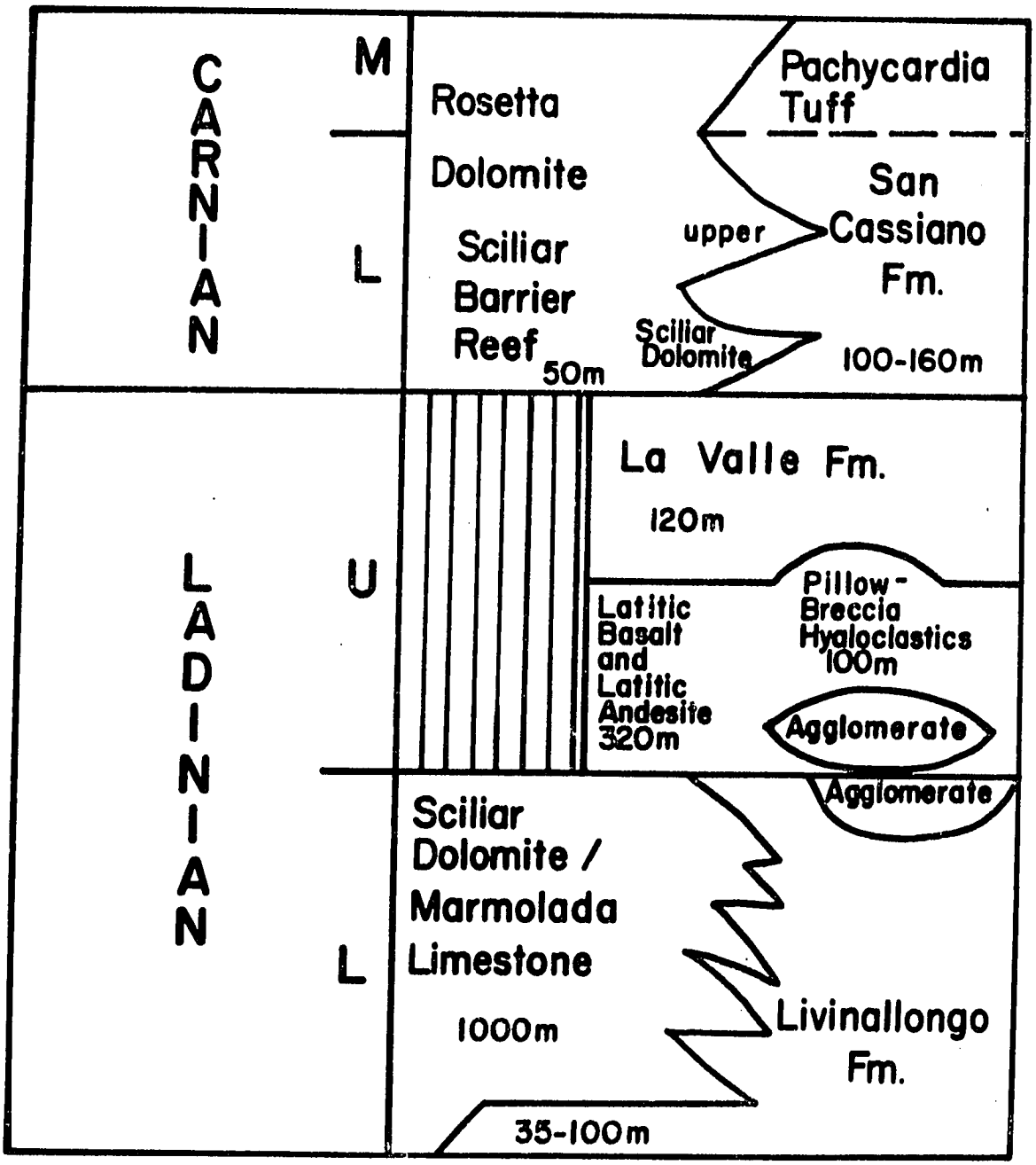
The facies relationships within the carbonate buildups, the relationships between the buildups and the basinal deposits, and the internal relationships of the basinal units are all of primary importance to this study, and are described below.

The Carbonate Buildups

Substantial carbonate buildups are first found in the upper part of the Serla Dolomite, and it appears that many of the Sciliar buildups begin on top of Anisian counterparts (Bosellini and Rossi, 1974).

The Scilian buildups can be divided into two large-scale parts, based primarily on preserved bedding

Figure 8. Detailed stratigraphic column of the Ladinian and Carnian stages of the Western Dolomites (after Pisa, 1974).


CARNIAN
M
L
Rosetta
Dolomite
Sciliar
Barrier
Reef
50m
Pachycardia
Tuff
San
Cassiano
Fm.
upper
Sciliar
Dolomite
100-160m
LADINIAN
U
L
La Valle Fm.
120m
Latitic
Basalt
and
Latitic
Andesite
320m
Pillow-
Breccia
Hyaloclastics
100m
Agglomerate
Agglomerate
Sciliar
Dolomite /
Marmolada
Limestone
1000m
Livinallongo
Fm.
35-100m

styles (fig. 9). These two divisions are an interior horizontally well-bedded facies, and an exterior of flanking crudely bedded facies with steep basinward dips (Leonardi, 1967, p. 254; Bosellini and Rossi, 1974). Frequently, a structureless massive zone of carbonate separates the two.

The Inner Facies

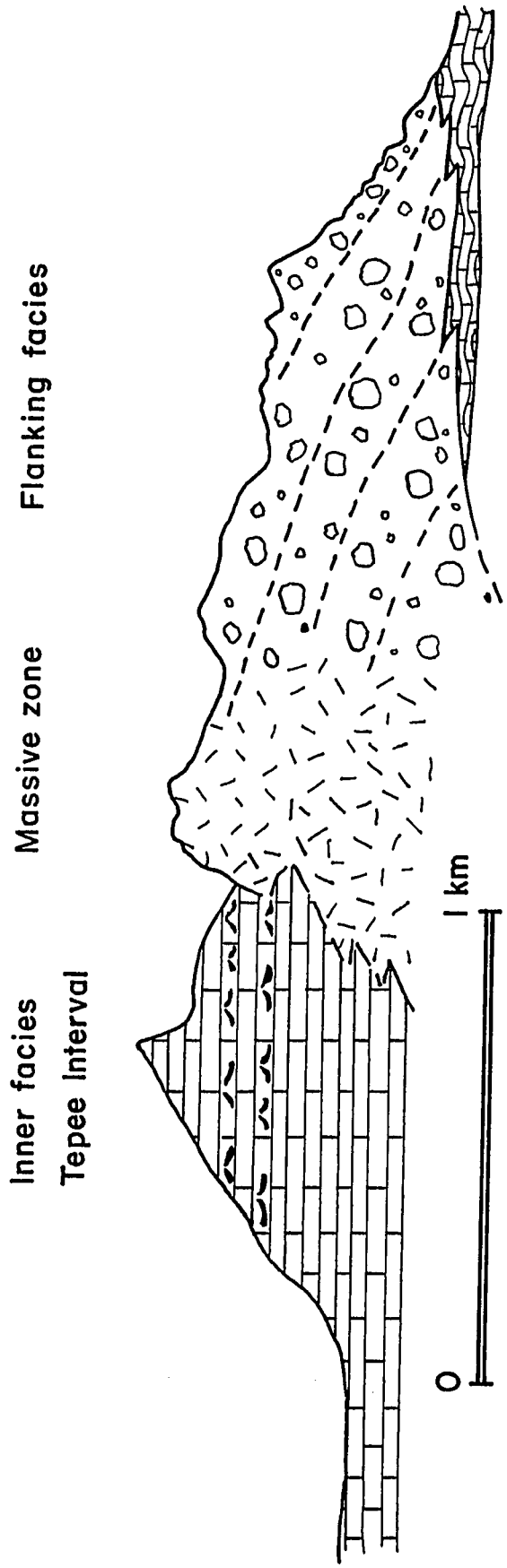
The areas where bedding styles and textures are preserved, several conclusions can be drawn concerning the inner facies of the buildups.

The bedding is arranged in three-part cycles consisting of subtidal, intertidal to supratidal, and subaerial components. The subtidal part of the cycle can be characterized by the following rock types: oncolitic and skeletal grainstones, micritic algal limestones, and micritic pelletal limestones (Bosellini and Rossi, 1974). The sediment is intensely burrowed and fossils are abundant. Dasycladacean algae and gastropods are common (Bosellini and Rossi, 1974). Beds of the subtidal component are on the order of a few meters thick (Bosellini and Rossi, 1974), and are generally the thickest beds of the cycles.

The intertidal cyclic deposits are micritic limestones with abundant stromatolitic structures and fenestral fabric. Intraclastic limestones are also common. Thicknesses of this part of the cycle are on the order of a few centimeters (Bosellini and Rossi, 1974).

The subaerial part of the cycle is a reddish laminated limestone with sheet cracks and abundant vadose pisolites.

Figure 9. Schematic cross-section of the Latemar buildup, showing the two-fold facies division into a well-bedded inner facies with tepee intervals, and a basinward-dipping flanking facies (dashed lines); in this case, a zone of massive carbonate separates the two (Assereto and Kendall, 1977).


Inner facies
Tepee Interval
Massive zone
Flanking facies
1 km
0

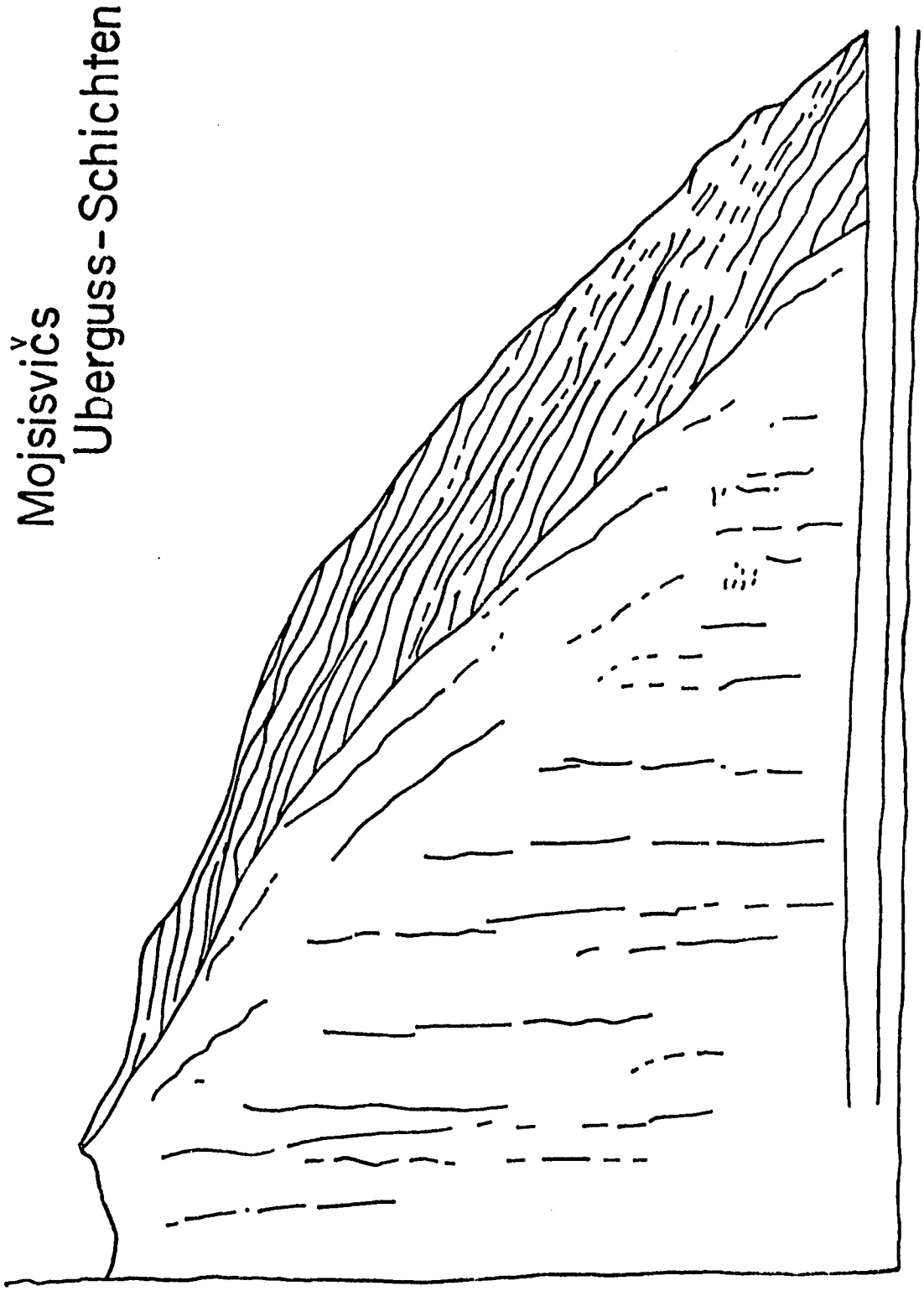
In the intertidal and subaerial members, intervals of peritidal deformation features, or tepee structures, occur. Excellent descriptions of these features may be found in Assereto and Kendall (1977). Where traceable, the tepee intervals are parallel to, and just landward of, the platform margin facies (fig. 9). They continue for long distances parallel to depositional strike, but occupy a zone of limited width. It has been suggested that the tepee intervals of the Latemar buildup represent a part of the physical barrier necessary to protect the internal lagoon from wave attack (Assereto and Kendall, 1977).

Bosellini and Rossi (1974) state that the subtidal part of the cycle dominates the lower and middle sections of the buildups, while the intertidal and subaerial components become more important near the top.

The Flanking Facies

The presence of a basinward-dipping crudely-bedded facies in the Sciliar Dolomite has been long recognized. The term Überguss-Schichten (overflow or covering beds) was applied to this facies by Mojsisovičs in 1879 (fig. 10). Mojsisovičs also recognized that the flanking facies represented deposits of what he termed the reef slope or Riffböschungen (Mojsisovičs, 1879, p. 486). Leondari (1967, p. 233) has divided the flanking facies into two types, depending on whether the buildup was prograding or retreating at the time of deposition.

Figure 10. Reproduction of Mojsisovičs original diagram depicting Überguss-Schicten (after Mojsisovičs, 1879, p. 169).


Mojsisvičs
Uberguss-Schichten

The flanking facies consists of poorly defined wedge-shaped beds of unorganized carbonate breccia and conglomerate. The component clasts range from sand-size grains to boulders several meters in diameter, and include laminated algal boundstones, micritic pelletoid limestone, and other rock types common to the upslope Sciliar Dolomite. Fibrous calcite cement is fairly common between clasts. Basinward dips of the flanking facies range from about 20 degrees to as much as 35 degrees.

Transition Between the Inner and Flanking Facies

The transition between the inner buildup facies and the flanking facies is usually a zone of massive carbonate (fig. 9). However, in many cases the transition is quite sharp, and the area that might correspond to a reef core is missing, the result of several phases of Trassic emersion and erosion.

Relationship Between the Carbonate Buildups and Basinal Units

In the European literature the term heteropic is used to describe two different but adjacent and synchronous facies. It was assumed for many years that many of the contacts between the Sciliar Dolomite and the basinal sedimentary rocks were heteropic boundaries. Detailed stratigraphic work has shown that this is not the case for most examples.

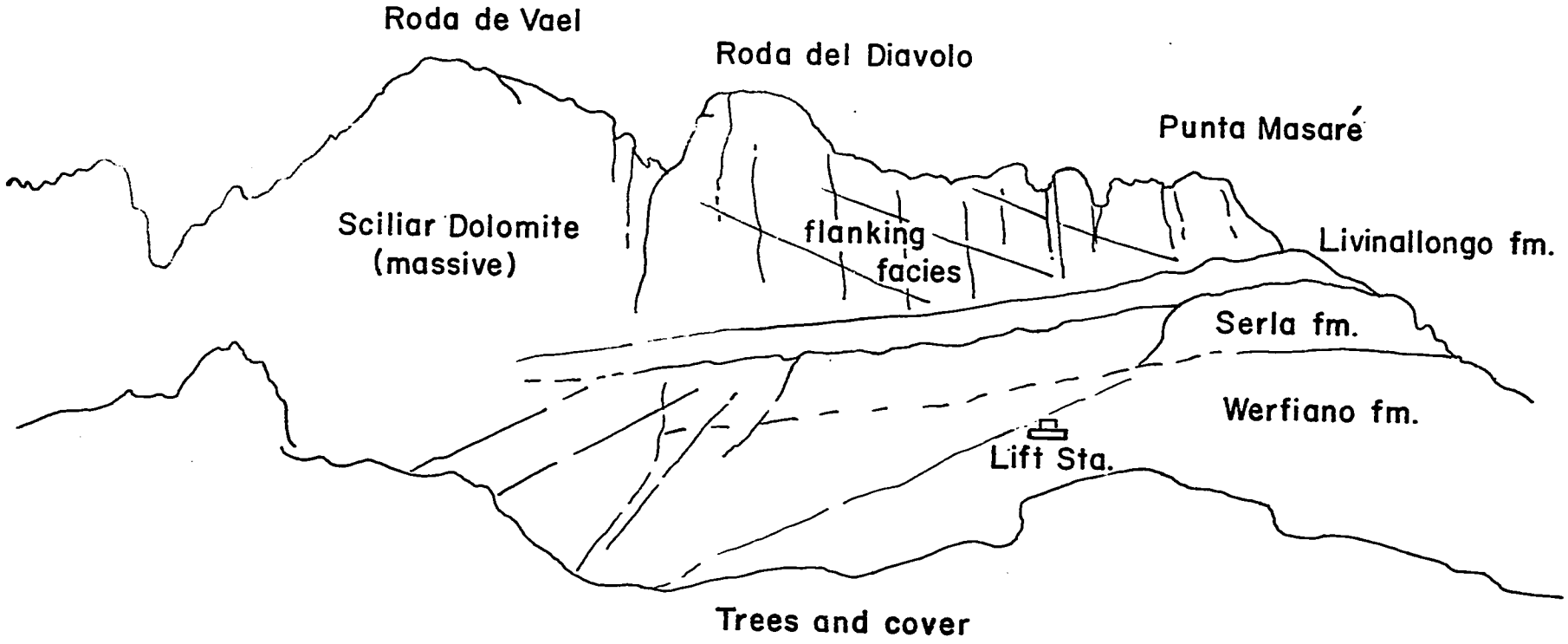
On the other hand, the Livinallongo formation is in part synchronous with, and in part underlies the Sciliar

Dolomite (fig. 9 and 11). Although the Sciliar Dolomite frequently begins from a core of Anisain carbonate, at some distance from that core the two separate, and the Livinallongo formation interfingers (fig. 9 and 11). With distance from the Anisian core the Livinallongo thickens and maintains an intertonguing relationship with the Sciliar flanking facies (fig. 11). From these relationships, it is obvious that the Livinallongo formation represents the "starved" basinal equivalent of the prograding Sciliar Dolomite.

No heteropic boundary exists between the carbonate buildups and the upper Ladinian volcanics. Where the contact between the two is exposed it is always sharp, and the volcanics wedge-out against the buildups (fig. 12). The reverse relationship has never been observed. The contact between the volcanics and the flanking facies of the Sciliar Dolomite is a depositional unconformity (Bosellini and Rossi, 1974); that is, the volcanic rocks were laid down horizontally against and on the originally dipping flanking facies (fig.12). As stated earlier, the volcanics filled the Ladinian basins to varying degrees, and in a few areas actually covered the carbonate buildups (Bosellini and Rossi, 1974). Cros and Lagny (1969) have documented a karst topography filled by volcanics on top of some of the buildups (e.g. Latemar).

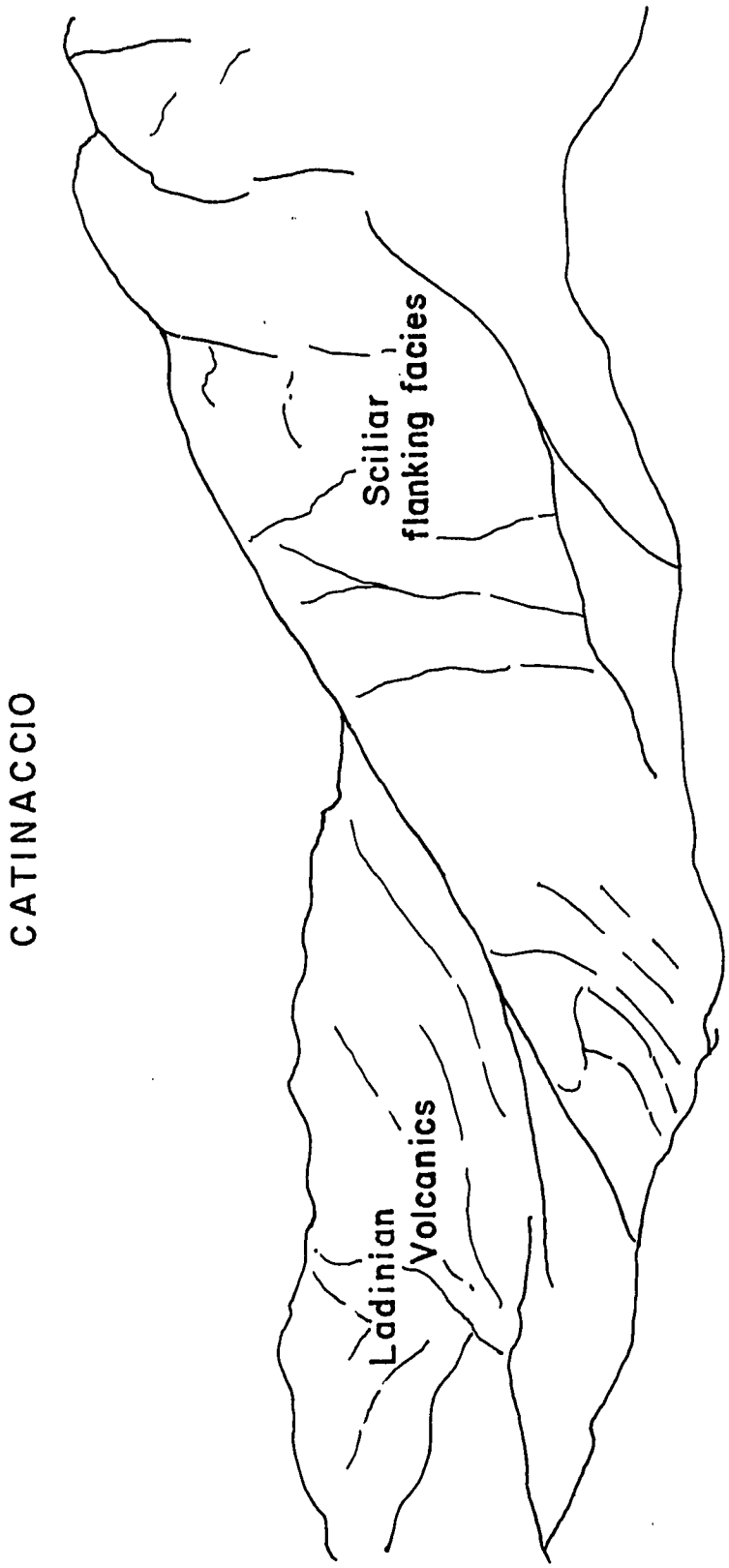
Apparently, there was little or no buildup growth taking place during deposition of the La Valle formation, as this unit contains little carbonate debris. If it is true that buildup growth was halted, then the La Valle

Figure 11. Sketch of the southern end of the Catinaccio buildup, viewed from Costalunga Pass, showing the relationships between the two Sciliar Dolomite facies and the underlying units.


Roda de Vael
Roda del Diavolo
Punta Masaré
Sciliar Dolomite
(massive)
flanking
facies
Livinallongo fm.
Serla fm.
Werfiano fm.
Lift Sta.
Trees and cover

Catinaccio

Figure 12. Sketch of the northern termination of the Catinaccio buildup, Val Duron, showing the Ladinian volcanics onlapping the flanking facies of the Sciliar Dolomite.


CATINACCIO
Sciliar flanking facies
Ladinian Volcanics

formation shares the same relationship with the Sciliar Dolomite as the Ladinian volcanics.

The La Valle formation represents the debris that was eroded from the exposed volcanics on the buildups and probably also from volcanic islands. This erosional debris was deposited in the inter-buildup basinal areas, and abuts against the flanking facies of the Sciliar Dolomite.

Buildup growth was active during deposition of the San Cassiano formation, as shown by the presence of equivalent age carbonate buildups such as the Sella Group, the large amount of carbonate debris included in the San Cassiano formation, and by intertonguing relationships between the upper Sciliar Dolomite and the San Cassiano formation.

Differentiation of the San Cassiano formation from the underlying La Valle formation and the overlying Raibliano formation is done primarily on paleontologic data. As a result, the unit includes many diverse facies, with complicated relationships (Bosellini and others, 1977; Fürsich and Wendt, 1977). The various facies and relationships within the San Cassiano formation will be discussed in detail in the section on sedimentology of the unit.

Relationship Between The Buildups and The Overlying Units

The rapid facies changes that characterize the Sciliar buildups and equivalent basinal units continue into the overlying Raibliano formation. These facies changes are not covered here because they are younger than the rocks dealt

with in this study (for details see Valduga, 1967). The lower contact of the Raibliano formation is of interest, however. Where in contact with the Sciliar Dolomite, the Raibliano formation rests above a pronounced disconformity, and frequently fills features of a karst topography.

The last layer of the "Dolomite sandwich" is the Dolomia Principale, a unit of relatively consistant facies throughout the Western Dolomites.

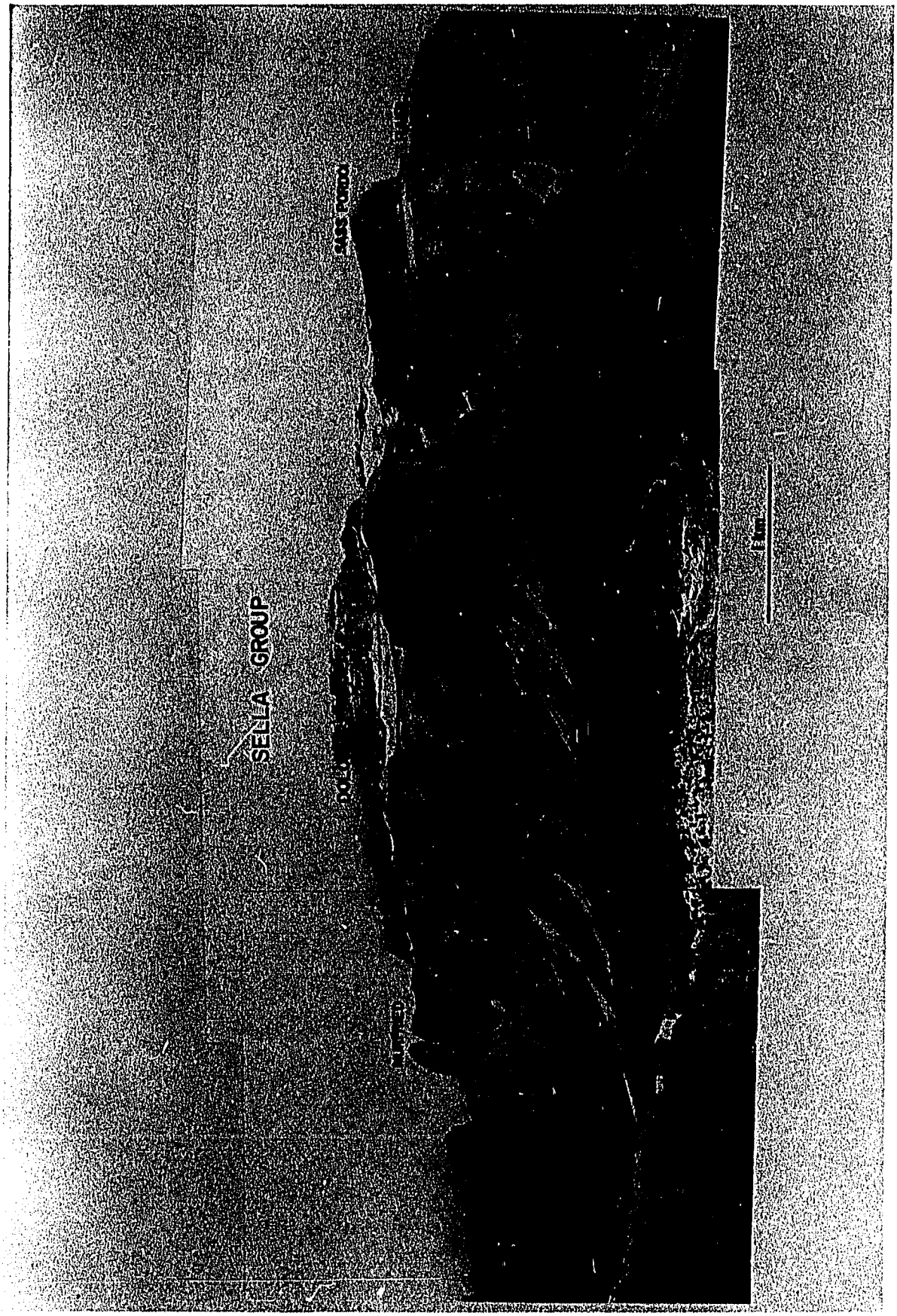
Present Day Morphology

The Dolomite Alps are known world-wide for their magnificant scenery, which is a direct reflection of the geology of the area. The carbonate buildups are far more resistant to erosion than the basinal units, and thus rise as craggy white towers above the green slopes of the intervening basins.

The basinal units are also subject to slumping and other downslope movements, creating a hummocky topography, and making detailed stratigraphic correlations difficult.

Uplift, differential erosion, mass wasting and glaciation have all combined to produce the present-day morphology of the Dolomites and the relationships between geology and topography that are so striking (fig. 13.)

Figure 13. The southern face of the Sella Group, viewed from Col Rodella, showing the present outcrop patterns and relationships between the San Cassiano formation, the Sciliar Dolomite, the Raibliano formation, and the Dolomia Principale. In particular, notice the presence of Cipit boulders in the San Cassiano formation.


SELLA GROUP
SASS PORDOI
1 km

SEDIMENTOLOGY OF THE SAN CASSIANO FORMATION

Introduction

The San Cassiano formation is the major host of the buildup-derived Cipit boulders. As such, an understanding of this unit is necessary in order to interpret the history of the boulders. For this purpose the existing literature was surveyed, and eight detailed stratigraphic sections of the San Cassiano formation were measured in the Western Dolomites with the following questions in mind: 1) What depositional environments are represented in the San Cassiano formation of the Western Dolomites? 2) What depositional processes operated within those depositional environments? 3) What were the sediment dispersal patterns? 4) What were the sources of sediment? and 5) What relationships do the Cipit boulders have with the rest of the formation?

Previous Work

The San Cassiano formation is known world-wide for its extremely diverse well-preserved fauna, of which about 1000 species have been described (Fürsich and Wendt, 1977). Because of its great paleontologic importance, the unit has attracted perhaps as much attention as the Triassic buildups themselves, and there is a large body of literature that deals with the faunal aspects of the formation (Münster, 1834; Wissmann and Münster, 1841; Gümbel, 1869; Loretz, 1875; Bittner, 1892,1895; Ogilvie Gordon, 1900; Broili, 1903; Leonardi, 1943; Leonardi and Lovo, 1950; Leonardi and Polo, 1952; Tacoli Lucchi, 1960;

Dieci and others, 1970; Zardini, 1973; Fürsich and Wendt, 1977; and many others). Investigations on the sedimentology and facies distributions of the unit are not as voluminous or complete.

One of the earliest descriptions of the unit is that by Münster (1834), who discussed the area near San Cassiano that was to become the type section. In a short note, Bronn (1845, reference in Ogilvie, 1893, p.5) presented one of the earliest hypotheses concerning the depositional environment of the San Cassiano formation. He stated that the San Cassiano fauna appeared to have lived in a shallow sea in the vicinity of cliffs and rocks where coral reefs were common. Other general descriptions of the San Cassiano formation and references concerning its stratigraphy can be found in Ogilvie (1892,1893) and Hummel (1928), among others.

In recent years, modern concepts have been applied to the study of the San Cassiano formation, and as a result a far better understanding of the sedimentology and facies of the unit is now possible. In this respect, the work of Fürsich and Wendt (1976,1977), and Bosellini and others (1977) are most important.

Fürsich and Wendt (1976,1977) have divided the San Cassiano formation and contemporaneous deposits into the following depositional environments: 1) submarine volcanic swells and volcanic islands, 2) nearshore backreef, 3) backreef, 4) carbonate platform, and 5) basinal. The

nearshore backreef environment is subdivided into a patch-reef facies and a inter patch-reef facies. The basinal environment is split into shallow marginal basins, basin slopes, and central basin environments. The Cipit boulders are considered separately as allochthonous basin elements. Only the backreef environment with its sponge patch reefs and the basinal environment are placed in the San Cassiano formation proper. Characteristic faunal assemblages with distinctive compositions and modes of preservation were found for each of the major depositional environments of the San Cassiano formation and their subdivisions (Fürsich and Wendt, 1977).

Although the San Cassiano is famous for its fossil content, the fossils are patchily distributed. In fact, most of the unit that is presently exposed is poorly fossiliferous at best. This makes detailed stratigraphic correlations within the unit quite difficult, and as a result little detailed stratigraphic work has survived the test of time. Only recently has the ammonoid biostratigraphy of the type section near Pralongia been established (Ulrichs, 1974). The lack of stratigraphic control and the overall shortage of outcrop make detailed regional facies reconstructions practically impossible at this time.

Bosellini and others (1977) have applied a different approach to the reconstruction of facies and depositional environments within the upper Ladinian and Carnian units of the Western Dolomites. Their work has produced a picture

that is quite different from that of Fürsich and Wendt, and it represents a change in the stratigraphic scheme of the Western Dolomites (fig. 14).

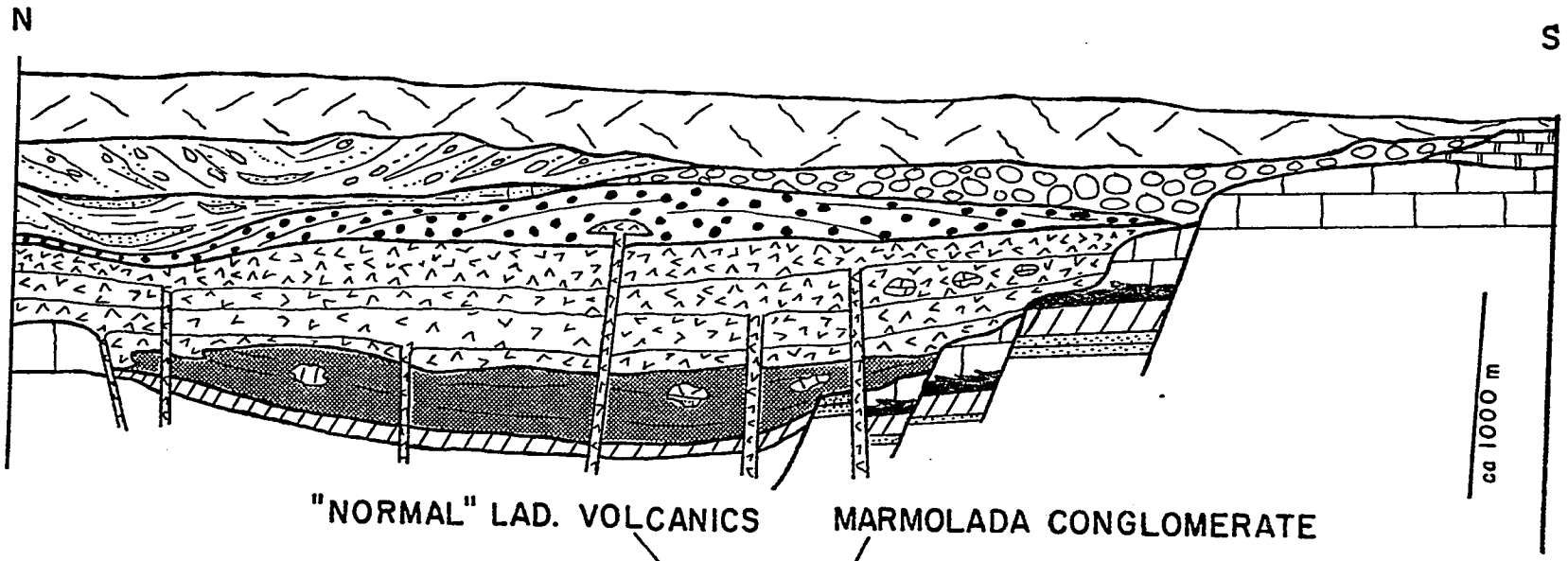
In brief, Bosellini and his co-workers (1977) state that the first Ladinain carbonate buildups were drowned during a distensive tectonic event associated with the late Ladinian volcanic episode. At the conclusion of the tectonic event, a new phase of carbonate growth was established above the site of the older buildups. Prolific carbonate production, and erosion, along a steep faulted margin led to the deposition of wedge-shaped units of megabreccia, now exposed at Denti di Terra Rosa and at Crepe Rossi. Beneath the megabreccia units is the Marmolada Conglomerate (Conglomerato della Marmolada), derived from the subaerial erosion of the Ladinian volcanics. Both the megabreccia beds and the Marmolada Conglomerate are placed in the upper Ladinian and lower Carnian stages. The majority of the Cipit boulders are found within the megabreccia units.

Bosellini and others (1977) suggest that the megabreccias are confined to a narrow southern belt (no more than a few km wide) along the margin of the upper Ladinian?-lower Carnian? platform, and that they pinch out rapidly to the north. They view the megabreccias as a thick (up to 300 m) prism of gravity-flow sediments deposited along the steep platform margin (Bosellini and others, 1977). The basinal areas removed from the platform margin did not experience megabreccia deposition, and received only

Figure 14. Schematic cross-section through the Val di Fassa area showing the relationships between the basinal units and the platform carbonates. Note in particular the wedge of carbonate megabreccia extending from the south to the north, and the three different platform carbonate units. See text for discussion.

(Bosellini and others, 1977)

VAL DI FASSA AREA



"NORMAL" LAD. VOLCANICS

MARMOLADA CONGLOMERATE

U. ANISIAN FORMATIONS

SCILIAR DOLOMITE

CARBONATE MEGABRECCIA

INCLINED MEGABRECCIA

WERFIANO FORMATION

LIVINALLONGO FORMATION

BUFFAURE VOLCANICS

U. LAD.-L. CARN. PLATFORM CARBONATE

BASINAL DEPOSITS, VOLCANIC & CALCAREOUS TURBIDITES

UPPER DOLOMITE, CARNIAN

hemipelagic and less-concentrated turbidity current flows.

The work of Bosellini and others (1977) has led to a new understanding of the relationships between buildup growth, destruction and basinal sedimentation. In their model, there are three periods of buildup growth - Ladinian pre-volcanic growth, post-volcanic upper Ladinian to lower Carnian growth, and a prograding later Carnian growth-separated by two phases of buildup destruction (fig. 14). The classical San Cassiano formation would encompass the megabreccia units and the more "distal" basinal deposits produced during and between the second and third phases of platform growth.

It must be emphasized that detailed stratigraphic correlation within the basinal units is very difficult. The relationships between the various basinal facies are not fully known. Additional painstaking paleontologic work is needed to verify the basinal facies picture presented by Bosellini and others (1977).

The facies schemes presented by Fürsich and Wendt (1977) and Bosellini and others (1977) are quite different from each other. For example, compare the backreef environment with sponge patch reefs and associated sedimentary rocks described by Fürsich and Wendt (1977) with the units of conglomerate and megabreccia of Bosellini and others (1977). In part, this difference is due to respective study areas. Bosellini and others (1977) concentrated on the area in and around Val di Fassa in the Western Dolomites,

while Fürsich and Wendt (1977) derived their ideas from areas more to the east, nearer Cortina d'Ampezzo. A combination of both facies schemes would adequately describe the variations within the sedimentary rocks of San Cassiano age.

For the Western Dolomites, the stratigraphic and sedimentologic work done in this study supports the findings of Bosellini and others (1977), with a few modifications.

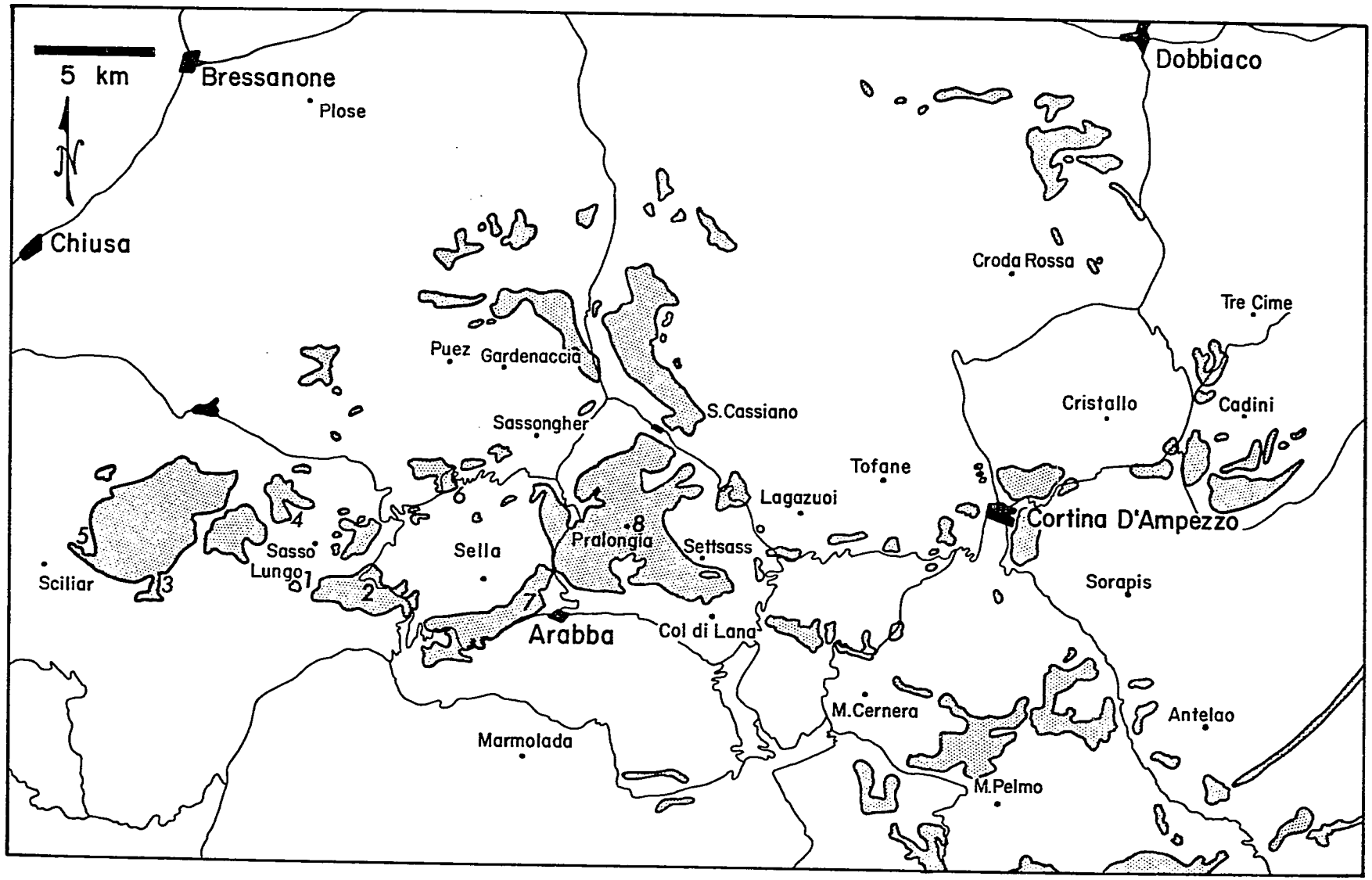
Measured Sections

Detailed stratigraphic sections were measured at eight separate localities (fig. 15). Each locality was given a geographic name and a reference number for convenience. These sections are as follows: 1) Sasso Levante, 2) Passo Sella, 3) Molignon, 4) Sasso Lungo NW, 5) Alpi Cepei, 6) Passo Gardena, 7) Arabba and 8) Pralongia (see Appendix 1 for detailed section locations).

Combined, the measured sections more than likely include the complete exposed stratigraphic range of the San Cassiano formation in the Western Dolomites, and provide a representative sample of the rock types that make up the formation.

The sections were measured, in most cases, centimeter by centimeter. The detailed bed by bed lithologic descriptions are not presented here, but are available on request. Plates 1 and 2 provide graphic representation of the measured sections of the San Cassiano formation, and the basis for

Figure 15. Outcrop pattern of the San Cassiano formation in the Western Dolomites. Numbers one through eight indicate the locations of measured sections. (after Fürsich and Wendt, 1977)


5 km
N
Bressanone
Plose
Chiusa
Dobbiaco
Croda Rossa
Tre Cime
Puez
Gardenaccia
Sassongher
S.Cassiano
Cristallo
Cadini
Tofane
Lagazuoi
Cortina D'Ampezzo
Pralongia
Settsass
Sella
Sasso
Lungo
Sciliar
Sorapis
Arabba
Col di Lana
M.Cernera
Antelao
Marmolada
M.Pelmo
1
2
3
4
5
7
8

sedimentologic interpretation.

Lithology

Six major rock types combine to make up the San Cassiano formation in the Western Dolomites: these are, 1) mudstone, 2) sandstone (mixed volcanic and carbonate), 3) carbonate grainstone or calcarenite, 4) conglomerate and breccia, 5) pebbly mudstone and 6) marl and marly limestone.

Mudstone

Plates 1 and 2 show that large portions of the measured sections are composed of what has been classified in this study as mudstone - a mixture of varying proportions of clay and silt-size material.

In general, the mudstone is dark brown to blackish brown when fresh, and weathers greyish brown to moderate brown on exposure (fig.16, 17). In the upper part of the Passo Sella section, the Arabba section, and the Pralongia section, however, the mudstone is medium to medium dark grey. The color change is related to the amount of carbonate present; that is, the higher the carbonate content, the lighter the color of the mudstone.

The mudstone is composed of a mixture of silt, clay and very fine grained sand (fig. 18A). Percentages of the different grain sizes vary, but silt and clay predominate, with sand-size material being a minor constituent.

Fossils are extremely uncommon within the mudstone; when present, they are confined to molds of pelagic bivalves and ammonoids.

Figure 16. Examples of bedding styles in the San Cassiano formation of the Western Dolomites.

A) Thin-bedded continuous sandstone beds and interbedded mudstone. Note the lack of thickness variation in both sandstone and mudstone units. Also note the number of very thin (less than 5 cm) sandstone beds in the predominantly mudstone interval (center). Section below Passo Sella.

B) Interbedded thin (to 50 cm) sandstones and mudstone with thicker (approx. 1.5m) conglomeratic sandstone bed (middle). Note the planar contacts and regular thicknesses of thin-bedded sandstones. The thicker sandstone bed thins somewhat to the right. Pole in the center of the photo is 1.5 m long. Sasso Levante section.

C) Isolated, shallow, sandstone/conglomerate-filled channel in predominantely mudstone section. Note planar contacts and consistent shape of sandstone beds. Channel is approxmately 2 m thick. Sasso Levante section.

D) Several stacked and slightly offset lens-shape conglomerate and sandstone beds, interpreted as the fill of shallow channels. Pole near center is 1.5 m long. Sasso Levante section.

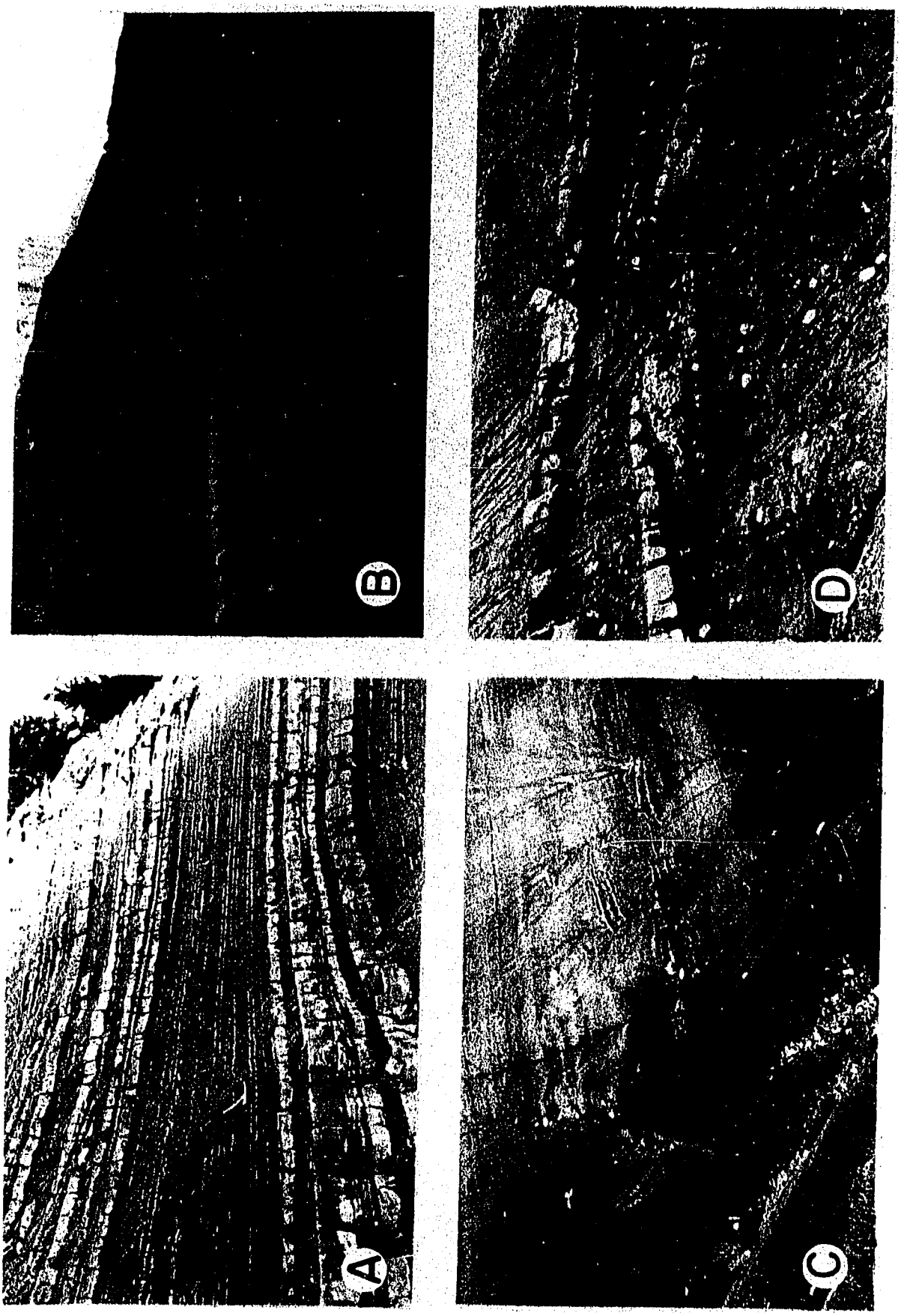

B
D
A
C

Figure 17. Overview of the Sasso Levante section, the longest section measured. The upward change in color of the sandstone beds (and the section in general) corresponds to the overall upward increase in carbonate content, indicating the changing character of provenance during San Cassiano sedimentation. The section is composed primarily of interbedded mudstone and thin sandstone beds. Note small, shallow conglomerate-filled channels near center and large carbonate boulders at the top of the section (upper left). The section is just over 400 m thick.

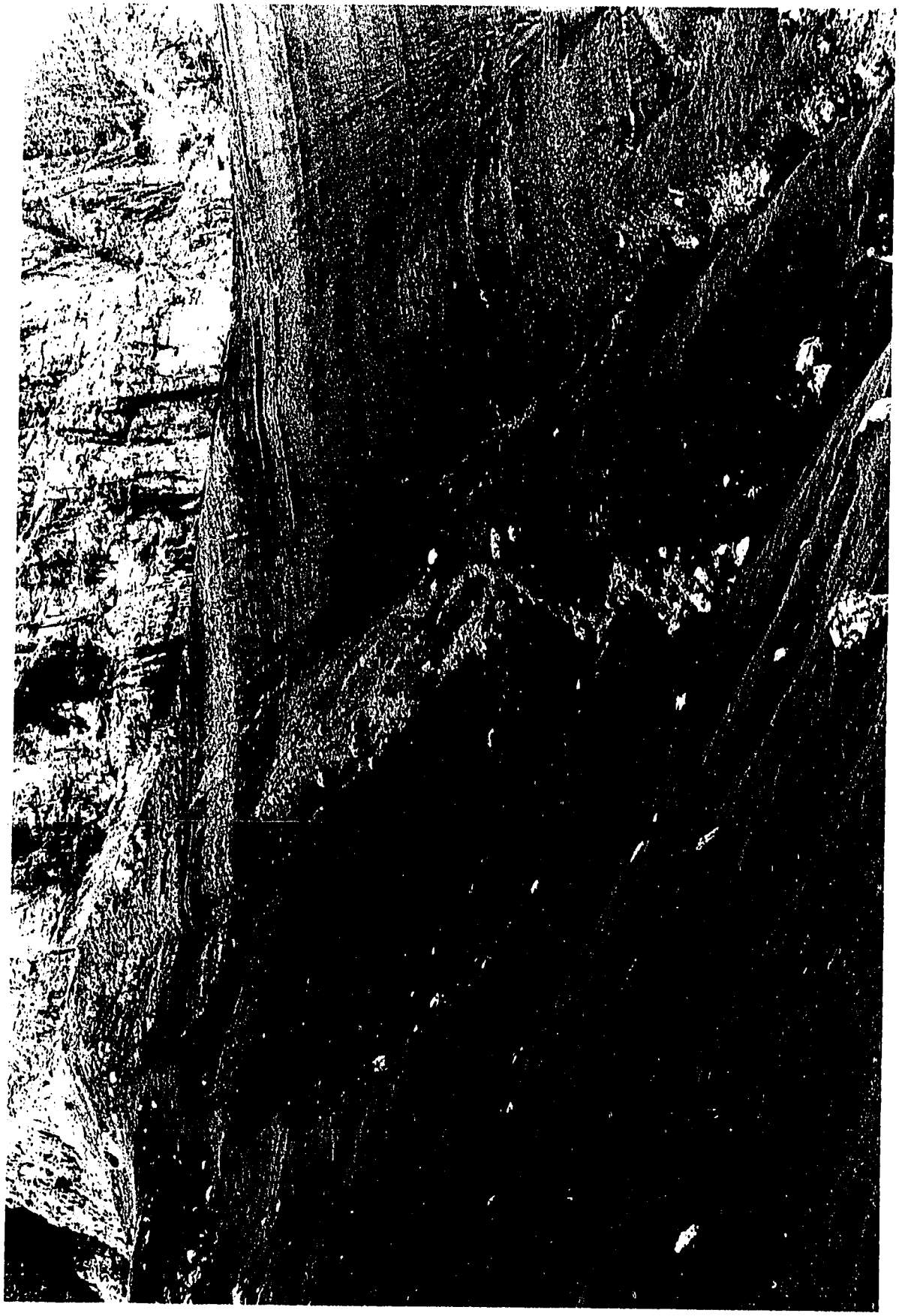


Figure 18. Photomicrographs of San Cassiano formation rock types.

A) Mudstone, composed of silt-size volcanic grains and clay particles. Sample from the Passo Sella section.

B) Volcanic sandstone composed primarily of rounded basic volcanic grains and scattered fossil fragments. Matrix is a mixture of silt-size volcanic material and clay particles of possible diagenetic origin. Sample from lower Sasso Levante section.

C) Carbonate sandstone or carbonate grainstone, composed of rounded fossil fragments, limestone lithoclasts, and scattered volcanic fragments. Matrix is carbonate mud. Sample from upper Sasso Levante section.

D) Oolitic calcarenite or grainstone, composed of ooids, rounded fossil fragments, and rare volcanic grains, some with oolitic coatings. Matrix is sparry calcite cement. Sample is from a graded bed in the Pralongia section.

A
1mm

B
1cm

C
1mm

D
5mm

In outcrop, the mudstone weathers to small angular shards that obscure the original bedding and sedimentary structures (fig. 16A), in some cases to such a degree that primary structures are not recognizable. On smooth surfaces (usually under running water) bedding styles and sedimentary structures are quite clear, however.

Commonly, the mudstone is either horizontally laminated to very thinly bedded or structureless. The laminations are parallel to slightly wavy, and continuous for at least a few meters. Disruption by burrowing is not commonly seen in the brown and black mudstone, but appears to increase with increasing carbonate content. It is possible that this observed increase is produced by greater color contrasts available in the calcareous mudstones, and not by increased bioturbation.

Included within the mudstone are abundant very thin to thin beds and stringers of sandstone. The sandstone beds are commonly graded, ranging from medium sand to silt-size particles. The sand-size clasts are primarily rounded volcanic rock fragments. Unidentifiable fossil fragments and limestone lithoclasts are also present.

The sandstone interbeds are of variable thickness (less than 1 cm to 30 cm thick), and pinch and swell along exposure. In extreme cases, isolated lenses of sandstone are surrounded by mudstone. The bases of the sandstones are sharp and commonly loaded into the underlying mudstone. The upper contact of the sandstone is either gradational, or

sharp and planar.

The amount of interbedded sandstone within the mudstone is variable and can be as great as 50% of the unit. Generally, sandstone interbeds make up between 10 and 30 percent of the unit.

Sandstone

Sandstone beds of varying thickness, shape and composition are common throughout most of the San Cassiano formation (plates 1,2).

The sandstones range in color from medium to dark grey when fresh and weather brownish grey to light brown. The changes in color are the result of varying composition. In the lower part of the formation the constituent particles are primarily rounded volcanic fragments (fig. 18B). The volcanic fragments are identical in composition to the older Ladinian volcanic rocks. Upward, carbonate particles become more important and eventually dominate the mineralogy of the sandstones (those sandstones composed of carbonate clasts will be described below as carbonate grainstones). In addition to limestone lithoclasts, abraded fossil fragments become more abundant upward. The most common fossil fragments are echinoid spines and mollusc debris. Occasional whole ammonoids and gastropods can be found.

Clasts of dark mudstone, identical to the interbedded mudstone, are present in the thicker sandstone beds. The clasts are usually elongate, and the long axes are

frequently parallel to bedding.

The vast majority of the sandstones encountered in the measured sections are graded beds. Grain sizes range from pebbles and granules at the base to very fine grained sand and silt at the top. In most cases the grading is not continuous. The bed begins with an interval of conglomerate or pebbly sandstone at the base, followed by a break in grain size distribution of perhaps two grain size units. The remainder of the bed grades continuously upward.

Other than graded bedding, recognizable sedimentary structures are not particularly common in the sandstone beds. Vague cross-stratification is present in some of the sandstone beds and fluid-escape structures can be found in the thicker beds. Horizontal lamination in the upper part of beds is the second most common sedimentary structure. The sedimentary structures that are present occur in a predictable vertical sequence. When all three types of structures mentioned are present in one bed the vertical sequence is graded bedding, cross-stratification, horizontal lamination or Tac(d)e of the Bouma sequence. The most common association of structures, however, is a Tabe Bouma sequence. In the Molignon section, several nongraded, low-angle cross-stratified sandstone beds are present.

Sandstone beds occur in two major shapes, uniform and lens-shaped. Beds with planar contacts and continuous thicknesses are common in many of the measured sections

(fig. 16a,b). Maximum thicknesses of this type of sandstone body reach about one and one half meters. Lens-shape sandstone beds of various sizes are found in nearly all measured sections (fig. 16c, plates 1,2). The lens-shape beds range from thin, laterally extensive bodies (50 cm thick and perhaps 50 m long), to lenses of amalgamated sandstones three to four meters thick that thin very rapidly. Both types of lens-shaped bodies have erosional lower contacts (fig. 16c), and are considered to represent the fill of channels of varying sizes.

A third type of sandstone bed also exists. These beds pinch and swell along strike, thickening to 10 or 20 cm and thinning to a few centimeters.

The bases of nearly all the sandstone beds appear to be erosional. In many cases, erosional relief can be seen on the base of the bed. Basal contacts which show no obvious erosional relief do exist, but the overlying sandstones almost always contain mudstone clasts, interpreted as clasts ripped up from underlying strata, located some distance up slope.

Sole markings are surprisingly rare. Bed bases are smooth or contain irregular, poorly defined markings. Directional features, such as flute and groove casts, were rarely observed. The paleocurrent data are discussed in a later section.

Calcarenite

Toward the tops of the Sasso Levante, Passo Sella and Passo Gardena sections a gradual change takes place in the composition of the sandstone beds, and they become true carbonate grainstones or calcarenites. This change is heralded by a change in outcrop color; the brownish greys of the volcanic-rich sandstones give way to the tans and yellowish browns of the calcarenites (fig. 17).

The particles that compose the calcarenites are of two main types, limestone lithoclasts and abraded fossil fragments (fig. 18c). Coated grains and peloids are present in subordinate amounts. In the Pralongia section a few thin beds of graded oolitic grainstone occur (fig. 18d).

Clasts of volcanic rock never completely disappear, and volcanic grains, some of them coated, can be found in every calcarenite bed. The majority of the limestone lithoclasts are algal boundstone and peloid packstone to grainstone fragments. Other lithoclasts include bioclastic wackestones and a few pieces of submarine cement (see section on Cipit boulder cements).

The fossil material present is mainly abraded fragments. Echinoid spines, pelecypod fragments, gastropods(whole and fragmented), algal debris, and pieces of Tubiphytes have been recognized.

The degree of abrasion of lithoclasts, individual grain types and fossil debris is similar, suggesting similar distances of transport.

Almost all the calcarenites are graded beds, similar to the volcanic sandstones described earlier. Grading is of both the coarse tail and distribution type (Middleton, 1967). In the uppermost part of the Passo Sella section a 10 cm thick inversely graded bed was encountered. Vague intervals of cross-stratification exist in many of the calcarenite beds. Intervals of horizontal laminations are also present. A complete Bouma sequence (Bouma, 1962) was never observed.

Bedding shapes displayed by the calcarenites are similar to those of the sandstones (fig. 17). Lens-shaped bodies are not uncommon, but most of the beds are relatively continuous across outcrop.

Basal contacts appear to be at least slightly erosional, and there may be as much as 25 cm of relief on the base of the bed.

Sole markings are more common in the carbonate grainstones than in the sandstones. The most common sole marking is a non-directional protuberance a few centimeters in diameter and perhaps one centimeter deep. Groove casts are also present.

In addition to the sole markings described above, burrows along the bases of the beds are common. These burrows are irregular traces about one cm across and a few mm deep. They also occur on the tops of beds. The trace fossil Chondrites is present in some of the calcarenite beds.

The upper contact of the calcarenite beds is usually planar, sharp, and abrupt. Thicknesses of the beds range from a few centimeters to about one and one half meters.

Conglomerate and Breccia

Conglomerate and breccia beds occur in all sections measured near the basin margins. These are of considerable importance because they contain almost all of the Cipit boulders found in the Western Dolomites. Only the sections near the centers of the San Cassiano basins (e.g. Pralongia) are free of these very coarse sediments.

Although lumped together, there are several types of conglomerates and breccias present in the measured sections. The conglomerates and breccias described here correspond in part to the Marmolada conglomerate, carbonate megabreccia, conglomerates of the upper Ladinian-lower Carnian basinal sequence, and the inclined megabreccia of Bosellini and others (1977) (see fig. 14).

Two major rock types compose the clasts of the conglomerates and breccias. These are rounded volcanic clasts and buildup-derived carbonate clasts. The volcanic components appear identical in compostion to the upper Ladinian volcanics described earlier. In most cases, the volcanic clasts are well rounded cobble-size triaxial ellipsoids. The degree of rounding indicates that the volcanic clasts have at least a partial subaerial history, and represent erosional products from volcanic islands and exposed buildup-covering flows. In rare cases, volcanic

pebbles show algal coatings, indicating a tenure in shallow agitated sea water. The volcanic clasts range in size from granules to boulders. No volcanic clasts greater than large cobble or small boulders were observed.

The limestone clasts are rounded and frequently have a pitted and corroded surface. They range in size from granules to boulders of several cubic meters. The characteristics of the limestone clasts are discussed in detail under the section on Cipit boulders.

In general, volcanic-clast conglomerates are more common in the lower parts of the measured sections and limestone-clast conglomerates increase upward. Mixtures of the two clast types exist in almost all proportions. Although carbonates dominate the clast composition in the upper parts of the sections the volcanic components never completely disappear and may be found in most conglomerate and breccia beds.

There are two major shapes of conglomerate and breccia beds. The first style of bedding is roughly lenticular (fig. 16d, plates 1,2). The lenticular beds of conglomerate thin over distances of tens of meters to feather edges, and where traceable, frequently split into several sandstone beds (plate 1). These lens-shaped beds are the result of channel incision and filling, and their exposed shape is a function of how the plane of outcrop cuts across the channel axis. The channels themselves are all relatively small, with maximum lateral dimensions of tens of meters

and vertical thicknesses (channel depths) of only a few meters. The bases of the channels are obviously erosional (fig. 17d, plates 1,2), and frequently cut out underlying units. It is not clear if the conglomerates have cut their own channels or if they represent the later fills of pre-existing channels. The channels usually contain more than one conglomerate or breccia unit, stacked one on top of another. Other types of stratification, such as cross-stratification, were rarely observed within conglomerate units.

Occasional tabular beds of conglomerate were noticed, but the degree of exposure did not allow their true shape to be worked out.

Within the lenticular conglomerates and breccia, clast organization is rare. In most cases, there is little evidence of sorting, and the clasts rarely showed imbrication. Where imbrication was noticed (lower part of the Passo Sella section, upper Molignon section) the long axes of clasts were parallel with inferred paleoflow directions, and were inclined up channel. Outcrop limitations and poor access made imbrication measurement difficult, and not enough data for statistical treatment could be collected.

Approximately 30 percent of the conglomerate beds measured are graded, and both normal and inverse grading are present. Beds that show inverse grading usually become normally graded in their upper parts.

Most of the lenticular conglomerates and breccias have

a very poorly sorted sandy matrix. Commonly, clasts touch within the matrix, but beds with matrix-supported clasts also occur.

The clast-supported conglomerates can be classified using the scheme of Walker (1975, 1978) as disorganized (no grading, no stratification, no imbrication), inverse-to-normally graded (no stratification, some imbrication), and graded (no inverse grading, no stratification, some imbrication). The disorganized conglomerate beds are most common, followed by graded beds, then inverse-to-normally graded beds. The matrix-supported conglomerate beds show little or no organization. A few exhibit poor inverse grading.

Surprisingly, large unbroken fossils occur in the conglomerates. Both high-spired gastropods and ammonoids were encountered.

The second major conglomerate and breccia bedding type is exhibited by the carbonate megabreccia wedge of Bosellini and others (1977). Part of the wedge is well exposed in the Molignon section, and is composed of tremendous tabular bodies of conglomerate and breccia with clasts reaching several meters in diameter (fig. 19). Because of the degree of exposure the true shape of individual megabreccia and conglomerate beds could not be worked out in detail.

The bases of the beds are sharp and usually erosional, frequently cutting into underlying units. The upper

Figure 19. Megabreccia beds exposed along the Denti di Terra Rosa - Molignon ridge.

A) Distant view of the ridge showing the apparent tabular bedding style of the megabreccia units. Darker units between beds of carbonate megabreccia are volcanic sandstones and conglomerates.

B) View of the NW end of the Molignon ridge. Note the apparent tabular nature of the beds and the tremendous size of some of the carbonate boulders.

A
B

surfaces of the beds are irregular, and large boulders project out of them. The projecting blocks formed topography on the basin floor and sedimentation was affected by their presence. Overlying beds thin over the protruding blocks and lenses of sandstone can be found pinching out between blocks.

The boulders of the megabreccia beds are primarily carbonate. Scattered rounded volcanic clasts also occur. Units of volcanic conglomerate and volcanic and carbonate sandstone are present between the megabreccia beds (fig. 19b).

The megabreccia and conglomerate units show no apparent organization other than rare inverse grading. Clasts are generally touching and not matrix supported.

Pebbly Mudstone

Pebbly mudstones comprise only a small proportion of the measured sections. This unit consists of granules, pebbles and occasional cobbles of limestone and volcanic rock suspended in a sandy-silty-clayey matrix. No internal structure is present in the beds, and there is no organization to the clasts.

In areas where exposure is good and bedding can be traced for long distances (on the order of a hundred meters), pebbly mudstone units can be seen to be lenticular. Basal contacts appear conformable without evidence of substantial erosion. Upper contacts are irregular.

Marl and Marly Limestone

Marl and marly limestone occur mainly in the northern part of the field area, and are common in the Pralongia, Arabba, and upper part of Passo Sella section.

The marls and marly limestones form beds that are more resistant to erosion than the surrounding mudstones. Contacts between the mudstones and more limy units are gradational, however.

The marls are medium grey to dark grey, contain faint horizontal laminations and indistinct peloids, and are irregularly burrowed. Scattered sand-size carbonate grains may be present.

The beds of marl and marly limestone are of consistent thickness along outcrop with maximum thicknesses reaching about one meter.

Other Rock Types

The rock types listed above adequately describe the lithologic variations present in the San Cassiano formation of the Western Dolomites. In addition to these rock types, two other units are shown on the legend of plate 1. These two units are massive carbonate and slumped or disturbed units. The massive carbonates represent tongues of material derived from adjacent buildups and form thick resistant ledges. The slumped or disturbed units are intervals of mudstone, sandstone and conglomerate that have undergone some degree of deformation. These intervals include relatively undeformed slide masses, complexely

folded units and sections that have been nearly completely disturbed and homogenized. Most of the intervals classified as slumps obviously formed during the San Cassiano sedimentation; that is, they are under- and overlain by undisturbed beds. In a few cases,however, it was not possible to tell if the deformation was structural or penecontemporaneous.. These units were simply labeled "disturbed".

Depositional Mechanisms

In general, past work on the Triassic of the Dolomites followed classical European methods. The stratigraphy and structure were investigated in detail, but the sedimentology of the units, and consequently depositional mechanisms, was largely ignored. Modern work is changing this situation, but the results have not yet been fully presented in the literature. In the recent works of Bosellini and others (1977) and Fürsich and Wendt (1977), turbidity currents and hemipelagic processes were emphasized as dominant depositional mechanisms within the San Cassiano basin. Data compiled during this study were used to construct a more detailed analysis of San Cassiano depositional mechanisms. This analysis is presented below.

The sedimentary structures and bedding styles of the sandstones, calcarenites, conglomerates and breccias indicate that sedimentary gravity flows of one type or another were responsible for nearly all deposition of sand-size and larger sediment in the San Cassiano basin. In the literature, four major types of sediment gravity flows have been recognized: turbidity currents, fluidized flows, grain flows, and debris flows. Each type can be characterized by a distinctive vertical sequence of sedimentary structures (Bouma, 1962; Middleton and Hampson, 1973; Walker, 1975). These sequences are now well established and will not be discussed in detail here.

Turbidity currents were the major depositional agent

of sand- to pebble-size sediment in the San Cassiano basin. In addition, debris flows and, to some extent, probable fluidized sediment flows also contributed coarse material to the basin's sediment budget.

Although the vertical sequences of sedimentary structures in most of the sandstone and grainstone beds indicate deposition from turbulent flow, many of the sequences are not well described by the classic turbidite model; that is, the Tabcde sequence of Bouma (1962; Walker, 1978). The most common sequences, as mentioned earlier, are Tacde,Tae, or Tabde.

In many cases, the middle range of the Bouma sequence (Tbc) was not developed or is missing. This, coupled with the discontinuous grading shown by a large number of the sandstone beds, could suggest that some of the sediment entrained by turbidity flows bypassed the areas of the measured sections, and was deposited farther basinward.

A few sandstone beds (Sasso Levante section, lower Passo Sella section) show evidence of being deposited by some type of fluidized sediment flow (Middleton and Hampton, 1973). These beds are, on the average, thicker than most of the sandstone beds, and range from about one to two meters thick. Sedimentary structures are poorly developed in this type of bed. The most common sedimentary structures are vague concave-upward dishes, interpreted as fluid escape structures. In addition, the beds are

usually poorly graded. Beds of this type compose less than five percent of the sandstones in the measured sections.

Traction processes were active at times in the basin and resulted in deposition (or reworking) of small amounts of sand and silt. Two types of traction deposits were recognized, thin-bedded cross-stratified sandstone beds that pinch and swell along strike, eventually grading to isolated ripples, and thicker isolated lens-shaped bodies of trough cross-stratified sandstone. The thin sandstone beds and isolated ripples occur in the sections dominated by mudstone (e.g. Sasso Levante, Passo Sella, and Passo Gardena sections). The isolated lens-shaped bodies are found in the Molignon section. No evidence of deposition from traction currents was found in the Pralongia section, which is far from the buildup margins.

Although the sedimentary structures indicate that these two types of sandstones were deposited by traction currents, it is likely that the traction currents were associated with turbidity current flow. The thin cross-stratified beds and isolated ripples are interpreted as having been deposited from the waning stages of a turbidity current, either from the lateral edges or the tail of a flow. As turbulence and velocity of a single flow decreases, the flow will lose ability to keep its coarser sediment in suspension. The flow will, however, retain enough energy to move and deposit some material by traction processes This is the standard explanation for the current laminated

and rippled units of the Bouma sequence.

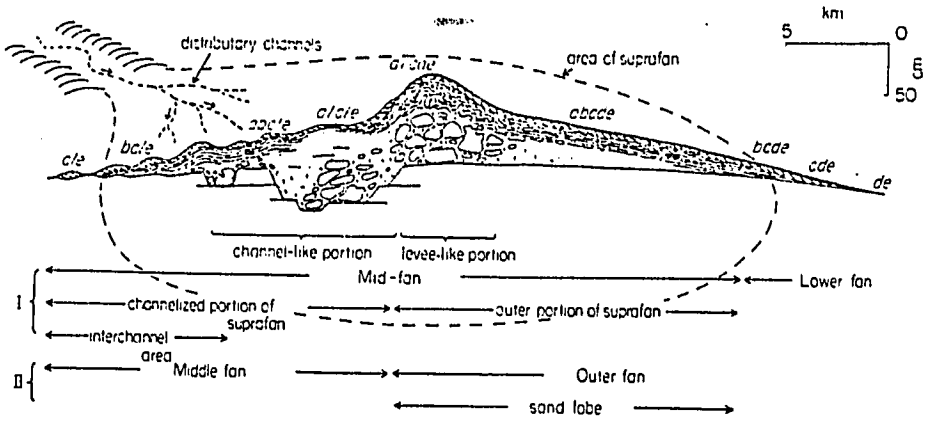
Because the thin-bedded cross-stratified sandstones do not usually include the lower members of the Bouma sequence (Ta,b), it is suggested that deposition took place near the lateral edges of a flow, where traction processes might dominate. Isolated sandstone ripples show that, at least in some cases, the depositing currents were sediment-starved.

Generally, outcrop characteristics and the degree of mechanical weathering of the surrounding mudstones makes lateral tracing of the thin-bedded cross-stratified sandstones impractical over large distances. A few beds, however, showed that laterally (in one direction) bed thickness increased and the lower portion of the Bouma sequence became more common.

Overall, the thin-bedded cross-stratified sandstone beds and isolated sandstone ripples are interpreted as the depositional products of turbidity currents that have overbanked shallow channels.

Similar sandstone beds have been described from an area of exceptional exposure in Japan by Hirayama and Nakajima (1977). By lateral tracing of individual beds they were able to document the relationships between sedimentary structures, bed thickness, and channeling (fig. 20). A similar relationship between the cross-stratified sandstones, isolated ripples, and channels is suggested for the San Cassiano formation.

Figure 20. Depositional model illustrating relationship between sedimentary structures, bed thickness, and channeling of a thick sandstone unit and its position on a submarine fan. I: topographic divisions of submarine fans by Normark (1970). II: submarine fan divisions of Mutti (1974). (Hirayama and Nakajima, 1977).


km
5
0
50
distributary channels
area of suprafan
abcde
bcde
cde
de
channel-like portion
levee-like portion
Mid-fan
Lower fan
I
channelized portion of suprafan
outer portion of suprafan
interchannel area
II
Middle fan
Outer fan
sand lobe

The relatively uncommon trough cross-stratified sandstone lenses of the Molignon section have a somewhat different origin. These deposits are found between boulders projecting from the top of megabreccia units, and in what appear to be small erosional depressions. Scouring around boulders of the megabreccias and subsequent filling of the depression with sand-size debris explain the lens-shape nature of these sandstones. Again waning phases of turbulent flows are thought to be responsible for deposition. Evidence of other types of traction deposits is absent from the Molignon section.

The channelized conglomerates also show evidence of being deposited by sediment gravity flows. Although most of the beds lack vertical sequences of sedimentary structures, clast imbrication, when present, indicates deposition from turbulent dispersion. The imbrication noted in the measured sections was of the long-axes-parallel-with-flow-direction type. Walker (1975) stated that this fabric is indicative of deposition from a form of clast dispersion above the bed. Even more convincing evidence is found if the channelized conglomerates are traced laterally. In many cases, the conglomerates pass into sandstones with well developed grading and other structures characteristic of turbidity current deposits. This suggests that conglomerate deposition near channel axes took place from high concentration turbidity currents that lost competence laterally.

The roughly tabular bodies of matrix-supported conglomerate/breccia and pebbly mudstone represent another type of depositional mechanism. These units show no evidence of channelling, little or no basal erosion, and few, if any, sedimentary structures. The dispersed nature of the clasts in a homogeneous matrix and the lack of sedimentary structures indicate that these units were deposited en mass as subaqueous debris flows. Plates 1 and 2 show that while this type of deposit is not uncommon, it makes up only a small proportion of the measured sections.

It is difficult to imagine the sedimentary processes that resulted in deposition of the megabreccias found in the Molignon section. Bosellini and others (1977) have suggested that turbidites and fluxoturbidites, documenting a phase of platform destruction, deposited the northward-thinning megabreccia wedge, of which the Molignon section is a part. The section does include ample evidence of deposition from turbidity currents, but it seems difficult to explain the tremendous beds of carbonate boulders by these processes alone. The units of megabreccia are devoid of sedimentary structures except for some crude grading. Boulders within the beds obtain sizes of several cubic meters and many project from the upper surface of the bed. There is no obvious evidence of large-scale channelling or erosion of underlying beds associated with the megabreccias.

The nebulous term fluxoturbidite has been applied to

these beds, but probably should be dropped for semantic reasons (Walker, 1970). Instead, it is suggested that rock slides/falls, debris flows, and highly concentrated turbidity currents deposited the megabreccia sheets. The apparent tabular shapes, the lack of sedimentary structures (with the exception of some reverse-to-normal and normal grading) and pronounced basal erosion, and the large sized of clases support this hypothesis. Rock slides/falls and debris flows most likely evolved into highly concentrated turbidity currents as water became increasingly incorporated into the flow downslope. Turbidity currents carrying less material dominated sedimentation between deposition of megabreccia beds.

Outcrop pattern and bedding shapes in the Western Dolomites show that the depositional mechanisms of the San Cassiano mudstones were more constant and widespread than those of the sandstones and other lithologies. Intervals of mudstone show far less variation in thickness than the sandstones and little to no evidence of rapidly changing hydraulic regimes. Graded bedding within the mudstones themselves was only rarely noticed. The lack of current-generated structures and the presence of Chrondites and associated trace fossils suggest deposition in a tranquil environment, below effective wave base. Consequently, it is inferred that most of the mudstone was deposited by hemipelagic processes. Mud was brought into the basin,

suspended by numerous processes, dispersed offshore, and gradually settled out in the basinal areas. The northern parts of the field area did not receive as much volcanic-derived mud and therefore have a higher carbonate mud content.

The occurrence of some graded bedding in the mudstone intervals suggests that part of the mudstone was deposited by turbidity currents, either from the tail of currents of from low-density flows carrying only fine-grained sediment (Rupke, 1975).

It was not possible to determine accurately the amounts of hemipelagic mud and turbidite mud in the field area, but the former appears to be much more abundant.

Interbedded with the hemipelagic mudstones are a few very thin beds of grey-green micritic limestone. Two possible origins are suggested for these limestones. First, it is possible that these beds are thin, muddy carbonate turbidites generated from the buildups. A vaguely graded, clotted texture reminiscent of peloids supports this hypothesis. Second, the micritic limestone could represent the background of pelagic sedimentation in the San Cassiano basin, similar to the type of sedimentation that produced parts of the Livinallongo formation. Sedimentation of volcanic-derived material was usually so voluminous that the pelagic component was drowned out, and only rarely were thin beds of pelagic carbonate produced.

Deposition of the San Cassiano formation represented by the measured sections appears to have taken place below wave base in tranquil water interrupted periodically by the introduction of several types of sediment gravity flows. None of the apparently shallower water features described by Fürsich and Wendt (1977) from the Eastern Dolomites were encountered.

Paleocurrents

Paleocurrent indicators in the San Cassiano formation of the Western Dolomites are surprisingly and frustratingly rare. Sole markings are generally poor, and limited to groove casts, burrow casts, and non-directional protuberances. Flute casts are practically nonexistent. Channel shapes, if properly exposed, can be used as indicators of local paleoslope, and, as mentioned earlier, some imbrication is present in conglomerates.

The paleocurrent data collected are far too meager to be statistically meaningful, but some generalization can be made. Sole markings indicate two major directions of transport, one perpendicular to buildup margins and one roughly parallel with the buildup margins. Channels exhibit variable trends, but most commonly trend obliquely to the buildup margins. Cobble imbrication in conglomerates show transport directions away from the carbonate buildups.

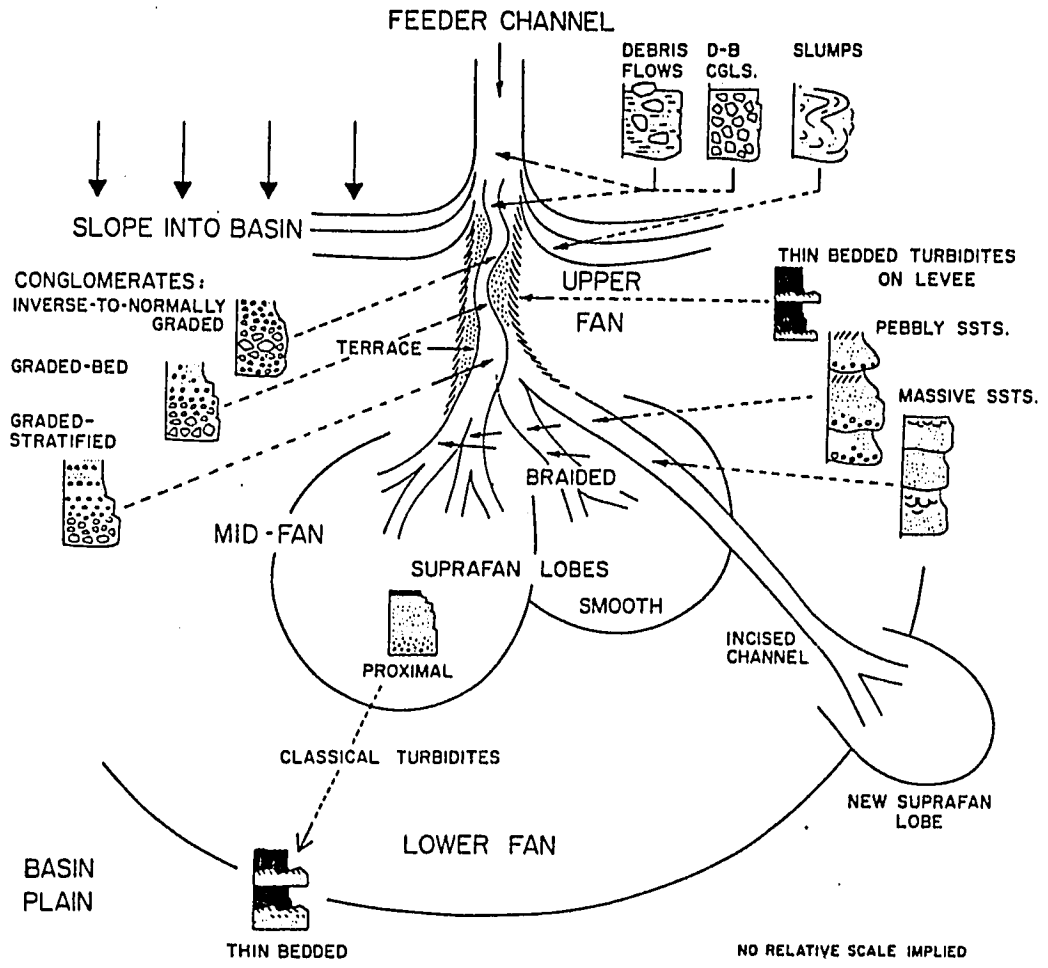
Depositional Models

In the past decade or so, a great deal of progress has been made in understanding turbidite-style sedimentation and the associated sedimentation packages. The information used to derive various depositional models has come from two sources; modern deep-sea fans and ancient deformed turbidite sequences (Walker, 1966; Shepard and others, 1969; Normark, 1970, 1978; Haner, 1971; Mutti and Ricci Lucchi, 1972; Walker and Mutti, 1973; Nelson and Nilson, 1974; Mutti, 1977). Out of this and other work, one basic fan model, relating facies to fan morphology, has evolved. Recently, Walker (1978) summarized this model and a representation of his summary is presented in figure 21. Walker's fan model will be used as a starting point to discuss the deposition of the San Cassiano formation.

Walker's model consists of an upper fan, characterized by a single leveed channel that may have a sinuous meandering thalweg flanked by relatively flat terraces, a middle fan built up by depositional lobes which shift position with time, and a smooth lower fan area basically indistinguishable from the basin plain. The depositional, or suprafan, lobes consisted of two parts, an inner area characterized by shallow nonleveed braded channels, and an outer smooth part that merges with the lower fan.

During progradation of a fan system a vertical sequence beginning with lower fan deposits and passing upward through the smooth portion of the depositional lobes and

Figure 21. Model of a submarine-fan deposition, relating facies, fan morphology, and depositional environment (Walker, 1978).


FEEDER CHANNEL
DEBRIS FLOWS
D-B CGLS.
SLUMPS
SLOPE INTO BASIN
CONGLOMERATES:
INVERSE-TO-NORMALLY GRADED
GRADED-BED
GRADED-STRATIFIED
TERRACE
UPPER FAN
THIN BEDDED TURBIDITES ON LEVEE
PEBBLY SSTS.
MASSIVE SSTS.
BRAIDED
MID-FAN
SUPRAFAN LOBES
SMOOTH
PROXIMAL
INCISED CHANNEL
CLASSICAL TURBIDITES
NEW SUPRAFAN LOBE
LOWER FAN
BASIN PLAIN
THIN BEDDED
NO RELATIVE SCALE IMPLIED

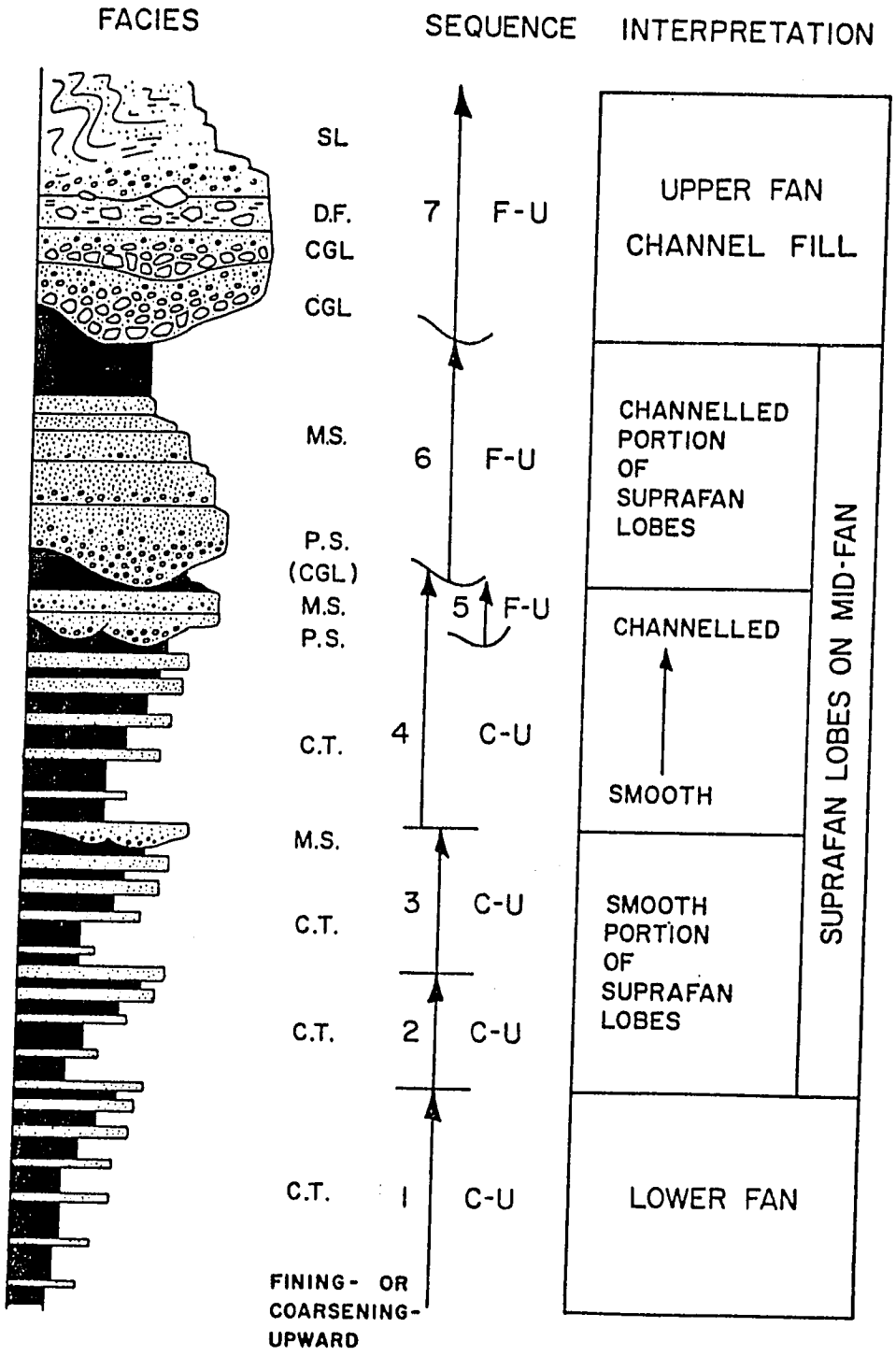
finally upper fan channel fill would be produced (fig. 22).

Walker stated that "This interpretation is based on the detailed morphology described by Normark (1978), the known relations among facies in ancient rocks, the abundance and depth of channeling associated with the various facies, and an unfortunately small number of recent sediment cores on modern fans" (Walker, 1978, p. 946). In other words, the model is based primarily on modern continental-rise fans with complex Pleistocene histories and ancient flysch deposits with complicated tectonic histories. Normark (1970,1974) has commented on the problems of extrapolating from modern environments to ancient examples.

Examination of plates 1 and 2 shows that a simple progradational fan sequence similar to that shown in figure 22 does not exist in the measured sections, even though the San Cassiano formation documents a period of basin filling by turbidite-style sedimentation. At first glance,the classic submarine fan model does not seem to apply. There is no evidence of one or more major feeder channels in the Western Dolomites, and classic channelized fan deposits are absent. There are two possible explanations for the lack of canyons and major channels: either they were not developed or they were not preserved in the rock record. Because of the overall lack of evidence of coarse channelized fan deposits, the first alternative is preferred.

Walker (1978) suggested two situations in which

Figure 22. Idealized progradational fan sequence. C-U represents thickening- and coarsening-upward sequence; F-U represents thinning- and fining-upward sequence; C.T., classic turbidites; M.S., massive sandstones; P.S., pebbly sandstones; CGL, conglomerate; D.F., debris flow; SL, slumps (Walker, 1978).


FACIES
SEQUENCE
INTERPRETATION
SL
D.F.
CGL
CGL
M.S.
P.S.
(CGL)
M.S.
P.S.
C.T.
M.S.
C.T.
C.T.
C.T.
7
F-U
6
F-U
5
F-U
4
C-U
3
C-U
2
C-U
1
C-U
FINING- OR COARSENING-UPWARD
UPPER FAN CHANNEL FILL
CHANNELLED PORTION OF SUPRAFAN LOBES
CHANNELLED
SMOOTH
SMOOTH PORTION OF SUPRAFAN LOBES
LOWER FAN
SUPRAFAN LOBES ON MID-FAN

classic turbidites occur without evidence of associated coarse channelized fans. The first of these is represented by turbidites deposited in prodelatic areas on the craton. For example, in the Susquehanna Valley area of Pennsylvania, Walker (1971) stated that there is no apparent bed thickness or grain-size trends within the 450 m thick sequence of Upper Devonian classic turbidites. When traced eastward toward the source, the sequences thicken upward into massive sandstones but do not exhibit the features of a channelized submarine fan (Walker, 1978).

The second example is turbidite deposition in exogeosynclinal (foredeep) trough, where paleocurrent flow is dominantly parallel with the basin axis (Walker, 1978). Sediment is thought to be supplied to the trough from many points along its margins, flow into the basin, then turn and flow parallel with the basin axis. The Carboniferous Stanley and Jackfork Groups of the Ouachita Mountains are examples of this type of turbidite association (Morris, 1974).

If classic fans develop in a situation of this type, they would develop along the margins of the trough. As the foredeep-thrust belt couple evolves, tectonic activity would probably destroy the marginal fans. The axial part of the trough would have the best chance of being preserved.

A vertical sequence of turbidites within a foredeep trough may have several different source areas, making thickening or thinning upward cycles virtually meaningless

or perhaps absent. As Walker (1978,p. 962) reminded, all of the prediction of facies relations implied by figure 21 is based upon the spreading of turbidity currents from a single feeder channel.

The San Cassiano formation of the Western Dolomites does not fall within either of the two situations discussed above. The presence of large Triassic deltaic and prodelatic environments in the Western Dolomites of the type described by Walker (1971) is unlikely, both on sedimentologic and paleogeographic grounds. San Cassiano-age delatic deposits are not known from the area, and the paleogeography suggests a fairly small basin with deeply embayed margins (Bosellini and Rossi, 1974), a situation not conducive to development of an extensive delta-prodelta system.

The area of the Western Dolomites was by no means an elongate foredeep during deposition of the San Cassiano formation, but the concept of many marginal source areas can be applied to the area and will be discussed later.

Recently, Mutti (1977) has published a depositional model for a sequence of distinctive thin-bedded turbidites in the Eocene Hecho Group of Spain. Many of the sedimentary features Mutti described are similar to features of the San Cassiano formation.

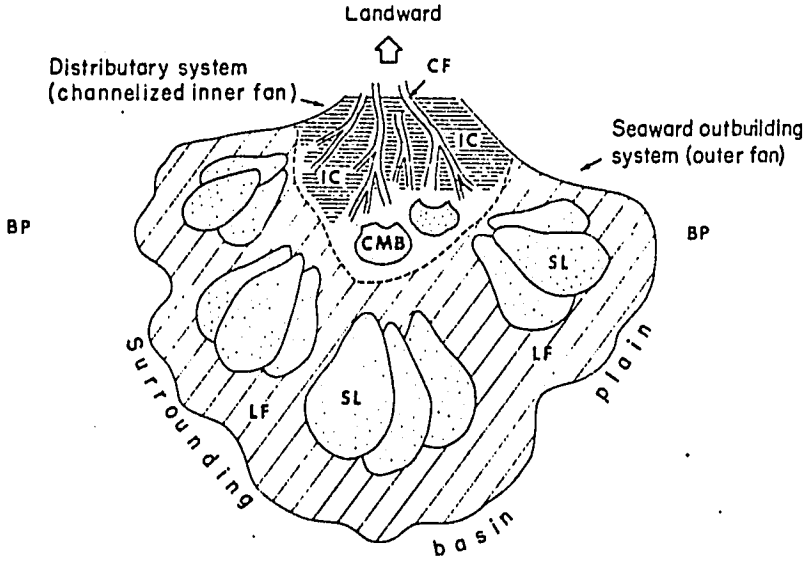
The lack of canyons and fan valleys separates the depositional model proposed by Mutti (1977) from the classic channelized fan model. Numerous smaller scale gullies

take the place of a large scale feeder channel system (fig. 23). The gullies are commonly less than 50 m deep and less than 300 m wide (Mutti, 1977). Mutti stated that these channels link the delta slope with the outer fan and comprise a distributary system roughly equivalent to both the inner and middle portions of the classic deep-sea fan model. The outer fan system consists of non-channelized bodies of sandstone arranged in progradational lobes. The lobes are enclosed in thin-bedded and finer grained lobe-fringe deposits.

The measured sections (plates 1,2), with the exclusion of the Moli̇gnon megabreccia section, show that the San Cassiano formation is composed of mudstone, thin-bedded turbidites, isolated channelized conglomerates, debris-flow beds, and slumped units. Thickening- and thinning-upward cycles are best represented in the lower part of the Passo Sella section, but they are poorly developed. The more basinal sections (e.g. the Pralongia section) are characterized by mudstones and marls with a few thin turbidite beds. The areal and vertical relationships of these rock types can be explained by a depositional model similar to the one proposed by Mutti (1977) for the Hecho Group combined with numerous marginal sediment sources.

Additional information useful in constructing a depositional model comes from the paleogeography of the San Cassiano basin and the postulated sediment dispersal

Figure 23. Depositional model proposed by Mutti (1977) for the Eocene Hecho Group of Spain. The model is not to scale and does not show the numerous small channels of the Hecho Group deposits. IC, inter-channel and levee; CMB, channel-mouth bar; LF, lobe fringe; BP, basin plain; CF, channel fill; SL, outer fan sandstone lobe (Mutti, 1977).


Landward
Distributary system
(channelized inner fan)
CF
Seaward outbuilding
system (outer fan)
IC
IC
BP
BP
CMB
SL
SL
LF
LF
Surrounding
basin
plain

directions within the basin.

Figure 24 is a paleogeographic diagram showing the inferred depositional margins of the San Cassiano basin (based on the work of Leonardi, 1967; Bosellini and Rossi, 1974; and this study). The extent of the buildup-covering Ladinian volcanic rocks is also shown. Additional volcanic islands most likely occurred near the southern margin of the basin, but were removed by Triassic erosion. The reconstruction shows that the source of volcanic sediment must have been to the south and west. Volcanic rocks have not been reported from other areas around the basin.

The combination of a major southern source for the volcanic component of the basin fill and paleocurrent date collected from basinal rocks allows the construction of a tentative sediment dispersal map for the San Cassiano formation (fig. 25). Two important directions of sediment transport are suggested. Most of the sediment entered the basin from the south or west, nearly perpendicular to the buildup margins. Within the basin sediment transport was mainly longitudinal, along the buildup margins. The overall basin gradient probably sloped to the east or southeast.

It is suggested that during erosion of the volcanics near the end of Ladinian time numerous streams and small rivers drained the area and introduced sediment into the basin. Instead of major canyon-channel systems, smaller scale channels dissected the basin margins and cut across

Figure 24. Hypothetical paleogeographic map showing the inferred basin margins during San Cassiano time (after Leonardi, 1967, and Bosellini and Rossi, 1974). Solid bounding lines are well located, dashed lines inferred with confidence, dotted lines represent postulated basin boundary. Shaded pattern indicates area of carbonate platforms, v-pattern indicates platform areas thought to have been covered by Ladinian volcanics (after Bosellini and Rossi, 1974). Lines perpendicular to the platform margins indicate areas where the foreslope facies is in contact with basinal units (after Leonardi, 1967). Note the indented nature of the basin margin and the elongated deposition troughs. Compare with figure 15 (outcrop pattern of the San Cassiano formation) and figure 26 (showing the present distribution of carbonate platform rocks).

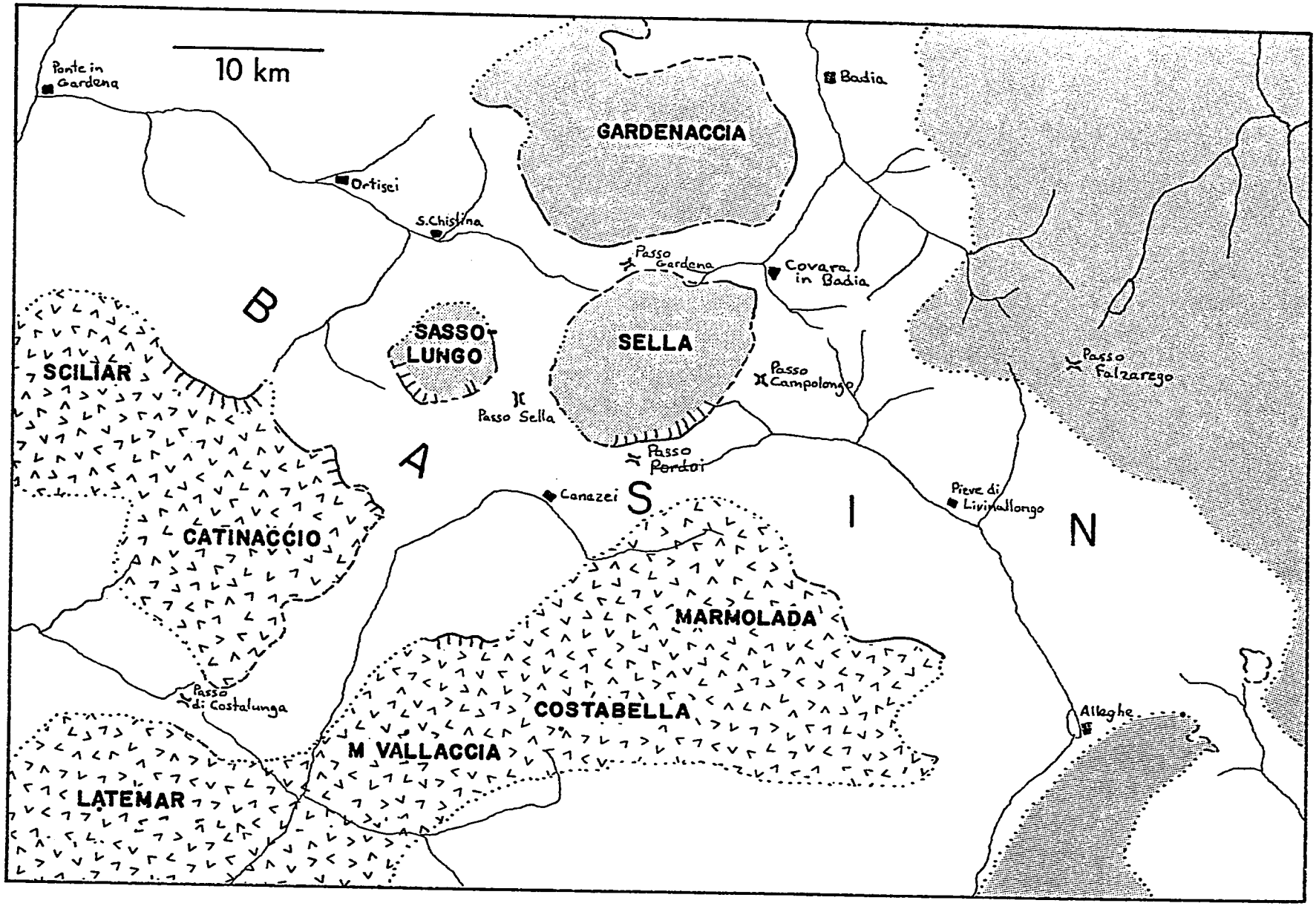
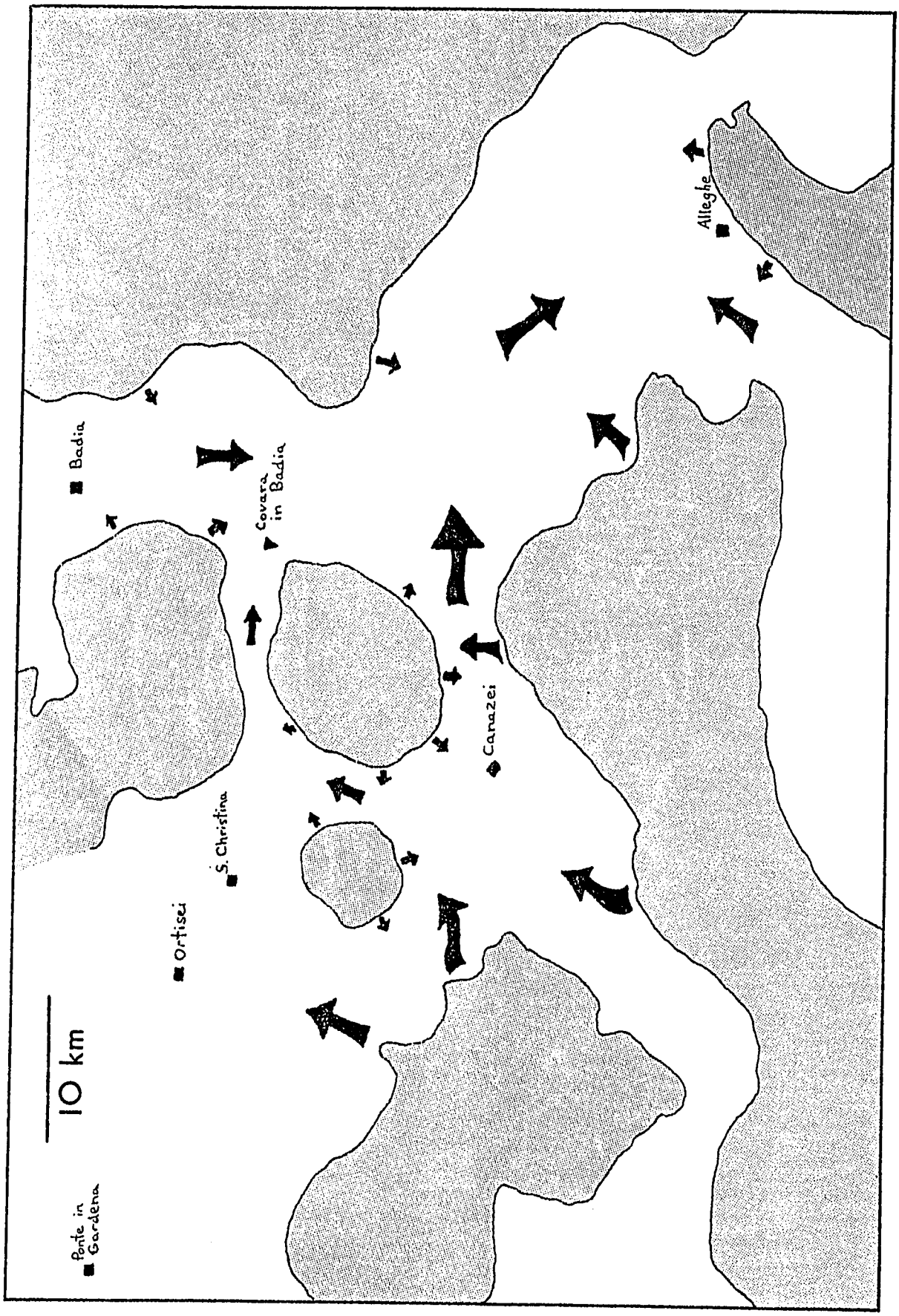

10 km
Ponte in Gardena
Badia
GARDENACCIA
Ortisei
S.Chistina
Passo Gardena
Covara in Badia
B
SASSO LUNGO
SELLA
SCILIAR
Passo Campolongo
Passo Falzarego
Passo Sella
A
Passo Pordoi
Canazei
S
I
N
Pieve di Livinallongo
CATINACCIO
MARMOLADA
Passo di Costalunga
COSTABELLA
Alleghe
M VALLACCIA
LATEMAR

Figure 25. Postulated sediment dispersal patterns for the basinal part of the San Cassiano formation. The dispersal patterns are tentative and based on sparse paleocurrent data, sediment provenance, and rock-type distribution. Shaded areas represent extra-basinal terrain. Arrows indicate assumed directions of sediment transport. The sizes of the arrows are roughly proportional to the amount of sediment moved through an area. Note that the areas which supplied volcanic sediment (i.e. the southwest margins) are considered to be more important than the areas supplying carbonate debris. This situation changed toward the end of San Cassiano deposition.


Ponte in Gardena
10 km
Ortisei
S. Christina
Badia
Covara in Badia
Canazei
Alleghe

the basin slopes. These channels fed a series of small over-lapping fan-shaped bodies at the base of slope. The fan-shaped bodies probably coalesced into a bajada-like apron along the southern and western basin margins. Smaller carbonate aprons flanked those areas not covered by the Ladinian volcanics,and these uncovered buildups probably continued to contribute carbonate sediment to the basin throughout San Cassiano sedimentation. The volcanic input was so great during deposition of most of the formation that the carbonate contribution in the Western Dolomites was effectively masked.

The sediment aprons along the basin margins were traversed by shallow narrow channels that acted as conduits for sediment transport. These channels supplied sediment both to the wedge-shaped aprons and to the more distal basinal deposits. The coarsest sediment was laid down close to the basin margins. Once away from the margins, conglomerates and breccias were confined to shallow channels. Overbanking of the channels led to the deposition of finer-grained material on the outer edges of the sediment apron. The channels also transported sediment away from the margins into a more basinal setting. Once off the marginal sediment aprons, transport became mostly longitudinal or parallel with the buildup margins. Numerous marginal sources supplied sediment to these deposits, and produced a confusing vertical sequence with numerous paleocurrent direction. Areas far removed from the basin margins received no

coarse sediment and deposition of mudstones and marls dominated.

Today outcrops of the San Cassiano formation in the Western Dolomites expose mostly the basinal marls and mudstones (Pralongia section), the longitudinally transported basinal deposits (lower Sasso Levante, Sasso Lungo NW, and lower Arabba sections), and the "distal" ends of the marginal sediment aprons (Sasso Levante and Passo Sella sectons). The coarser-grained, more "proximal" parts of the marginal sediment aprons are generally not exposed. The uppermost part of the Sasso Levante section might represent this depositional environemnt, however.

The megabreccia of the Molignon section represents a dramatic change in the style of sedimentation within the San Cassiano basin. Bosellini and others (1977) believe that the wedge of megabreccia was deposited during a late Ladinian-early Carnian phase of platform growth and erosion. The nature of the megabreccia wedge indicates far more platform destruction than growth, I believe. The tremendous number of large lithified carbonate boulders exhibiting evidence of rounding and karsting (see section on Cipit boulders) seems to call for exposure of a pre-existing carbonate terrain. I suggest that following sequence of events produced the megabreccia wedge. First, eruption and deposition of the upper Ladinian volcanics, followed by a period of erosion and sedimentation of volcanic debris. Second, an episode of faulting, associated with

the cessation of volcanic activity, that resulted in the exposure of the carbonate platforms, along the southern margin of the basin. The faulting occurred mainly in the area of volcanism and was concentrated along the buildup margins, perhaps reactivating pre-existing faults. Erosion along the steep scarps produced by faulting generated the boulders and other sediments of the megabreccias. Steep depositional gradients led to the rapid depositional of the northward thinning wedge. The faulting appears to have been episodic. The Molignon section shows three major episodes of carbonate megabreccia sedimentation, separated by intervals of less spectacular volcanic/carbonate-clast conglomerates and sandstones (fig. 19). Renewed movement along fault scarps produced renewed megabreccia sedimentation. When erosion and/or subsidence had sufficiently leveled topography, renewed carbonate production and buildup growth took place, and progradation of the buildup foreslope out over the megabreccia occurred. Evidence of this renewed growth and progradation is exceptionally well exposed at Denti di Terrarossa bordering Alpi di Suisi (fig. 19).

The relationship between the megabreccia wedge and the rest of the San Cassiano formation in the Western Dolomites is still not clear. There is evidence (e.g. the upper part of the Sasso Levante section) that the megabreccia is slightly younger than the rest of the sedimentary section described here. Careful

biostratigraphy based on Ulrich's (1974) ammonoid zones is needed to resolve the relative ages of the different parts of the San Cassiano formation.

THE CIPIT LIMESTONE BOULDERS

Introduction

The term Cipit limestone (Kalkstein von Cipit) was introduced by Richthofen (1860, p. 69) to describe layers of limestone boulders found at Alpi Cepei, the upper end of Alpi di Siusi. The term Cipit is apparently a variation of the word Cepei. Richthofen considered the boulders to be equivalent with parts of the San Cassiano formation. Presently the terms Cipit limestone and Cipit boulders are used for exotic limestone boulders found in the Middle and Upper Triassic basinal sequences of the Dolomites without much regard to age.

The Cipit boulders have been mentioned by many authors, but the results of a systematic detailed study have yet to be published. Mojsisovičs (1879) and Rothpletz (1894) believed the boulders to be blocks of reef material introduced into the basin by gravity sliding. On the other hand, several authors (Ogilvie, 1894; Salomon, 1895; Nöth, 1929; Van Houten, 1930; Valduga, 1962) attributed the Cipit boulders, or at least some of them to the growth of small coral colonies on the basin floor. Other explanations have called on a combination of both gravity sliding and *in situ* growth to explain the boulders (Leonardi, 1967, p. 319). Cros (1967c) believed many of the blocks to be derived from a combination of erosion, slumping, and plastic deformation during and after deposition. Finally, Fürsich and Wendt (1977)

and Biddle and others (1978) have again postulated a sub-aerial erosive origin for the Cipit boulders.

The majority of the Cipit boulders occur in the Western Dolomites (fig. 26). An examination of their distribution (fig. 26) shows that they never occur far from the buildup margins. All of the observed boulders were located within two kilometers of one of the carbonate buildups. The boulders occur singly, like the much photographed example exposed at Passo Sella (fig. 27), or in large groups, like the megabreccia beds of Denti di Terrarossa (fig. 19). They are frequently concentrated in channels and debris flows within the basinal sedimentary rocks. The boulders range in size from those with volumes of several cubic meters to fist-size cobbles and smaller. In fact, there appears to be a complete gradation from sand-size particles to boulders almost as large as automobiles. All have comparable compositions and origins.

The study of the Cipit boulders was approached in several ways. First, the boulders were treated as integral parts of the San Cassiano formation and were described in context with all other clasts in that formation. Second, the boulders were examined specifically for surface features, such as coloring, textures, coatings, encrust-ations, abrasion features, compostions, and so on. The sizes and size-distributions of the boulders were noted along with their frequency of occurrence. Hand specimens were examined with respect to internal compositon, lithology,

Figure 26. Distribution of the Cipit boulders in the Western Dolomites. Locations of boulders indicated by black dots (after Fürsich and Wendt, 1977). Note that the boulders are clustered near the buildup margins.

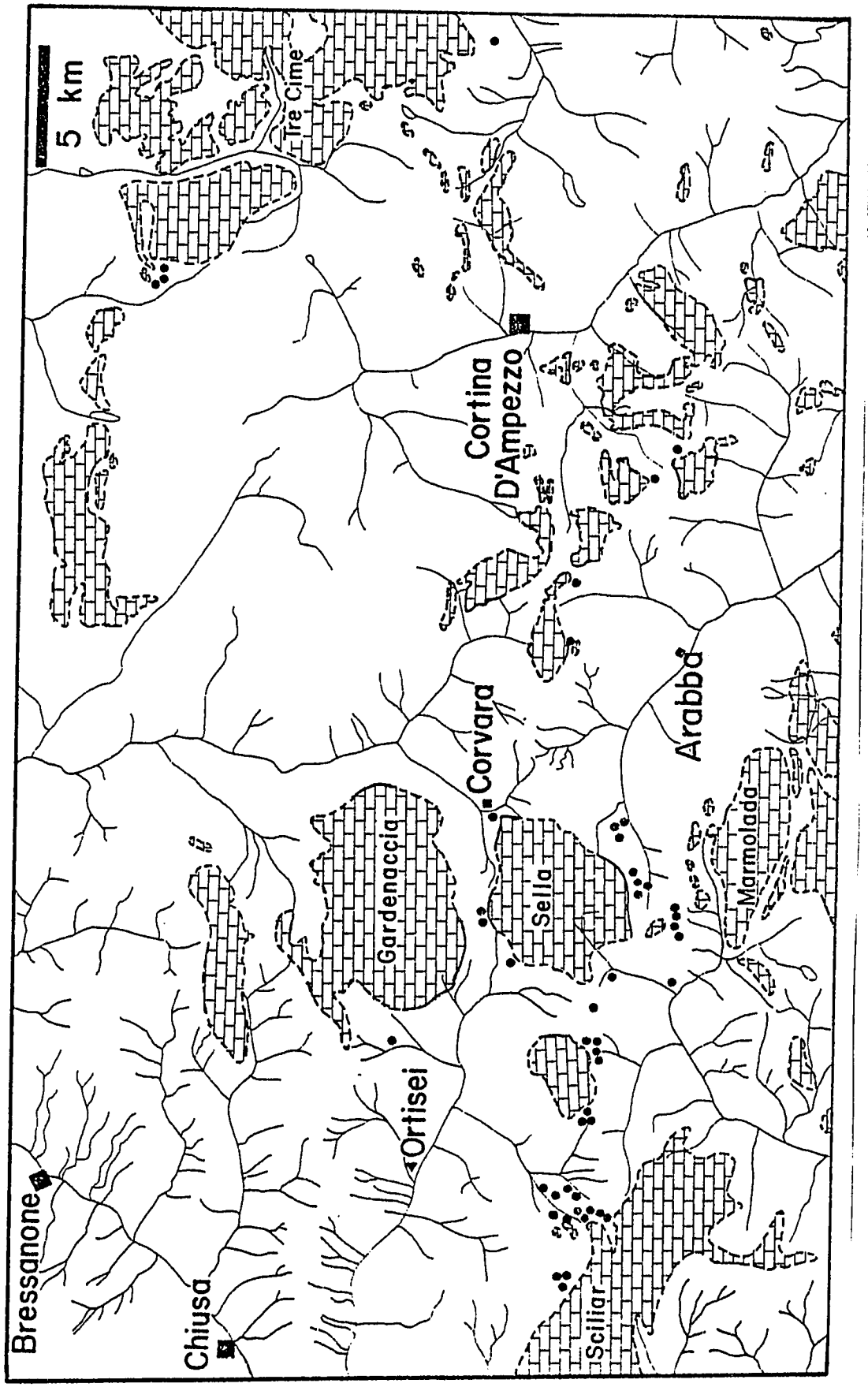

5 km
Tre Cime
Cortina
D'Ampezzo
Corvara
Arabba
Marmolada
Sella
Gardenaccia
Ortisei
Bressanone
Chiusa
Sciliar

Figure 27. A classic example of an isolated Cipit limestone boulder in the San Cassiano formation, Passo Sella. Note the rounded shape and the pitted surface texture of the boulder. The geologist is about 1.75 m tall.

texture, and organism content. Three hundred samples were selected for further analyses. Almost all of these samples were thin-sectioned, and over 250 thin-sections were examined. In addition, numerous large polished slabs were prepared and examined. A limited number of epoxy peels were also made.

The Exteriors of the Boulders

Surface Textures

Nearly all the Cipit boulders have rounded outlines, and many are quite well-rounded (fig. 27). There is no question that this rounding is, at least in part, an erosional feature. Numerous boulders showed truncated internal fabrics and fossil material. In contrast to the findings of Cros (1967c), no evidence of plastic or soft-sediment deformation of the boulders was observed. They appear to have been well lithified and hard before abrasion and rounding took place.

Superposed on the rounded outline of the boulders is a corroded, knobby surface, giving the limestone a nodular or pseudo-nodular texture (fig. 27). This texture results from the interplay of two factors, an original bulbous-like fabric produced during sedimentaion (this fabric most likely results from the growth of stromatolitic blue-green algae and will be discussed later), and solution phenomena that enhance the original texture.

Figure 28a illustrates an example of a nodular surface of a boulder believed to be formed by organic growth. The semi-circular mammelons on the surface are about five cm across, and when broken open, show a crinkly, laminated structure. The laminae are basically concordant with the outlines of the mammelons. The concordance between internal and external structures suggests that formation of the laminae controlled the shape of the knobs.

Figure 28b also illustrates a cavity in a boulder with a rounded, knobby surface. In this case, the surface features are the result of solution of the limestone. The cavity walls are clearly discordant with the internal features of the boulder.

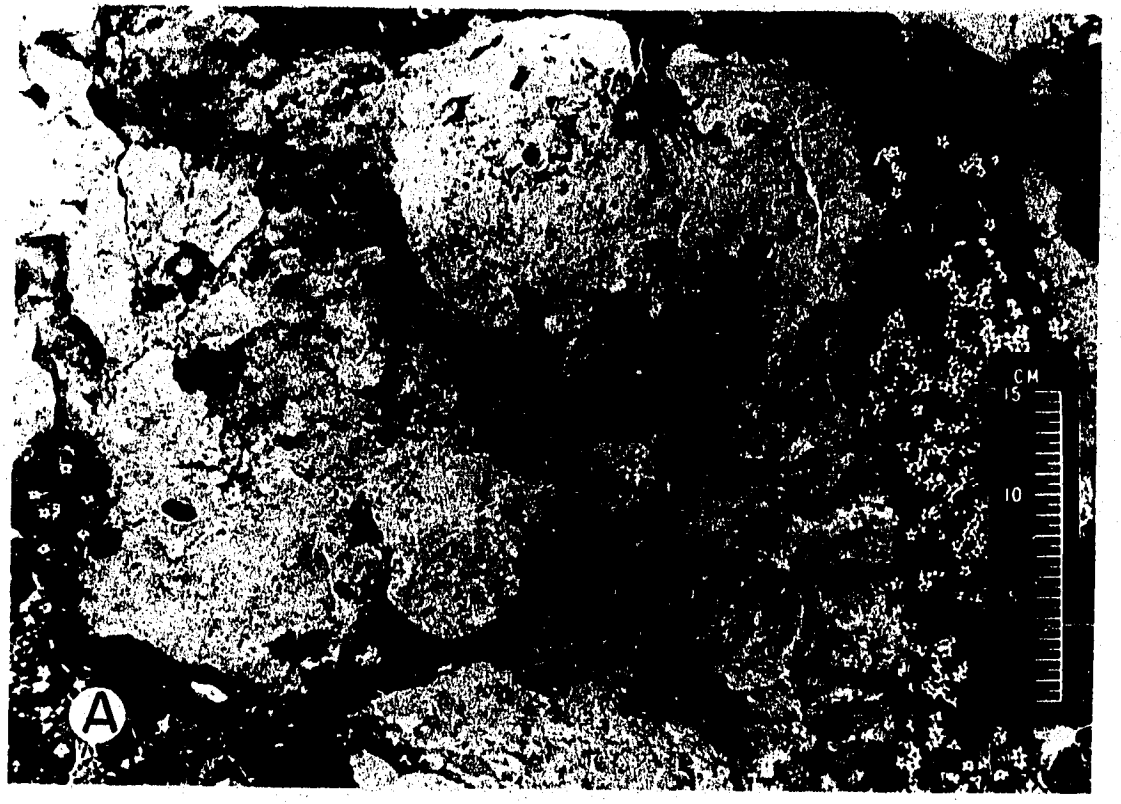
In most cases, the pitted, knobby surfaces of the boulders seem to result from a combination of internal structures and solution features. Original cavities formed during sedimentation later became conduits for solutions moving through the rock. The solutions dissolved some of the limestone, enlarged the existing cavities, and modified the original fabrics.

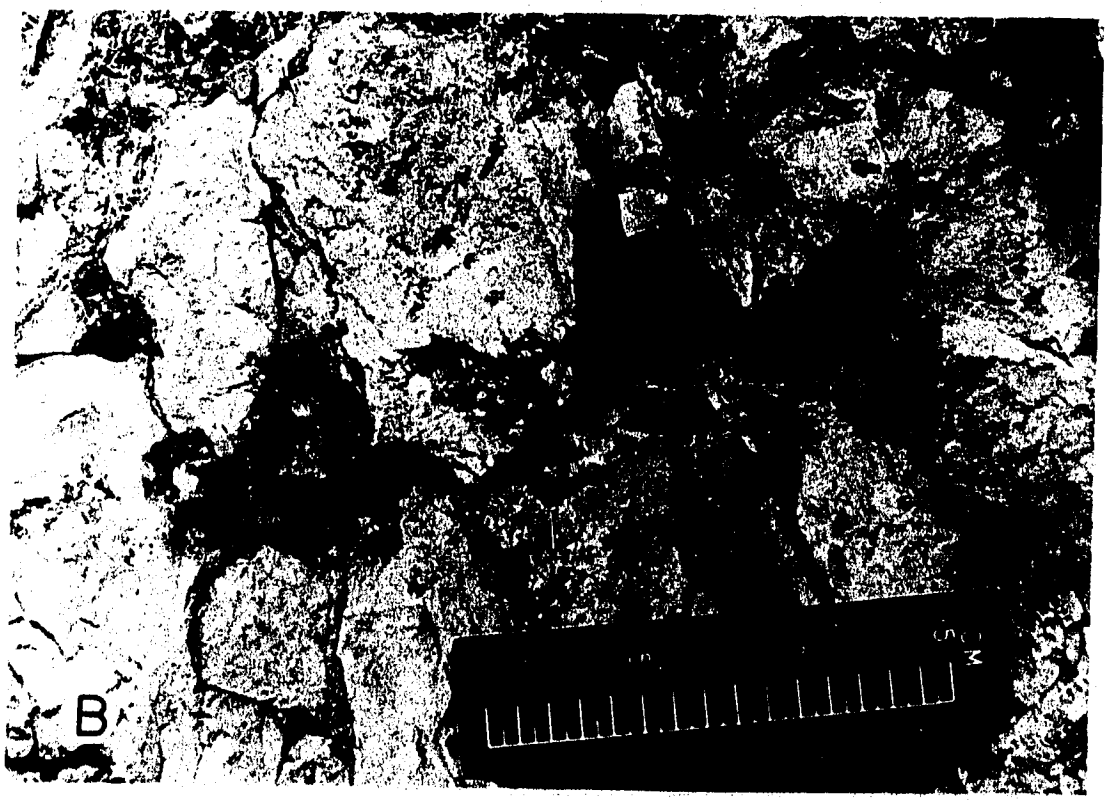
The distribution of the knobby surfaces on the Cipit boulders is not uniform. Development of a pitted, knobby surface is not uniform on individual boulders, nor is it equally well developed on all boulders in the field area. Variations occur on individual boulders; that is one side of a boulder may be substantially more corroded and nodular in appearance than the opposing side. Also,

Figure 28. Examples of two types of cavities found in the Cipit boulders.

A) Irregular-shaped cavity formed by algal growth and later enlarged by solution. Note the concordance between cavity walls and algal laminations. Sasso Levante section.

B) Irregular-shaped cavity formed by solution. Cavity crosscuts the fabric of the limestone. Sasso Levante section.


A
CM
15
10


B

boulders occurring in certain areas of the Western Dolomites lack well-developed pitted surfaces. This is the case in the megabreccia beds exposed along the Molignon ridge. Here, the boulders frequently have fairly smooth well-rounded exteriors and do not display a well-developed pitted surface.

In color, the boulder exteriors range from medium light gray and medium brownish gray to tan and organish tan.

Origin of the Surface Texture

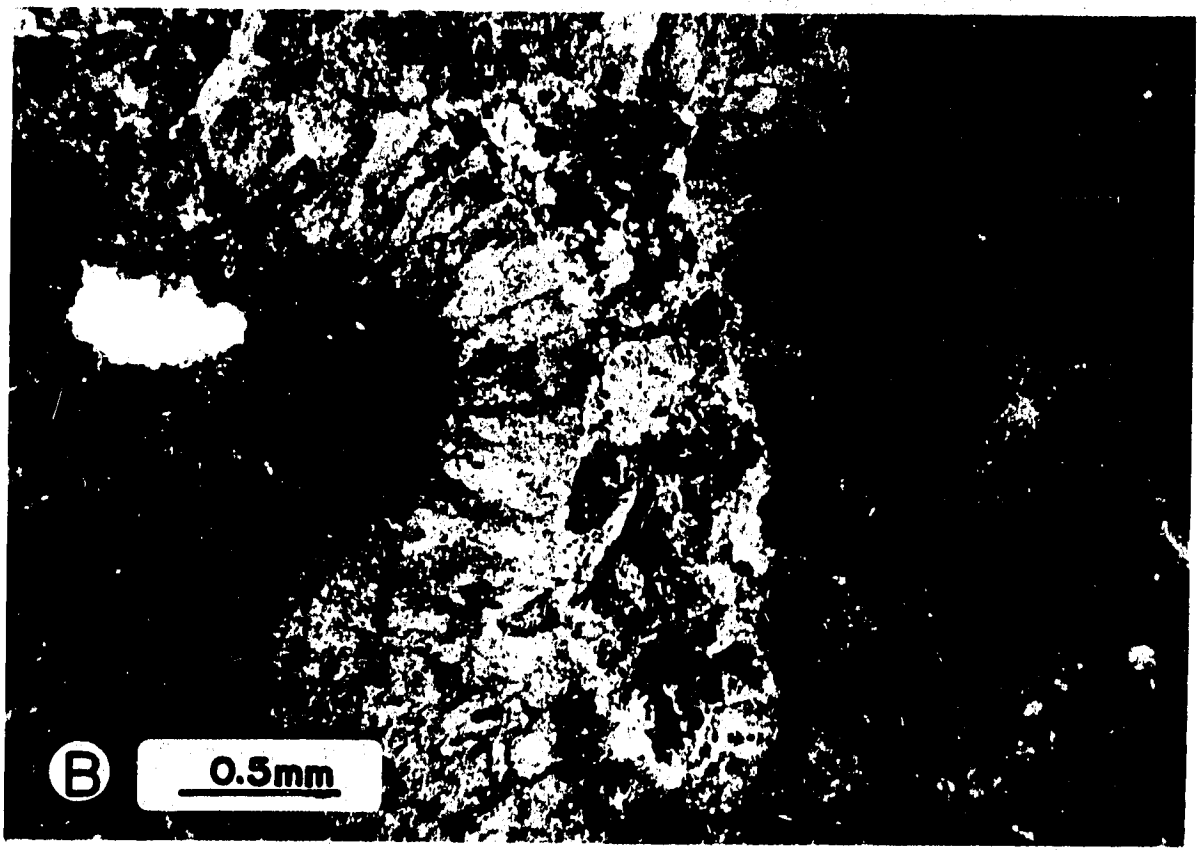
As previously mentioned, the pitted, nodular surface of the boulders is thought to result from the interplay of internal structure and dissolution processes. The dissolution features are believed to be expressions of karsting developed during exposure of the carbonate buildups. The karsting developed before the boulders were deposited in the basins. Abundant examples of solution cavities filled with basinal sediment can be found (fig. 29 A, B). The geopetal fills of volcanic sand often have different orientations than earlier carbonate geopetal sediments within the boulders (Fürsich and Wendt, 1977, fig.22). This shows that the boulders were transported before deposition of volcanic sediment in the solution cavities. The most likely time of deposition of the geopetal volcanic sediment was during and after transport of the Cipit boulders into the basin.

Figure 29. Cavities filled with volcanic sediment.

A) Example of a fairly large cavity lined with isopachous-fibrous cement and filled with sand- and silt-size volcanic rock fragments. Thin-section C-186.

B) Small cavity lined with isopachous cement and filled with volcanic debris. Thin-section C-179.

A
0.25cm


B
0.5mm

The orange-colored oxidized crusts on many boulders probably had a subaerial origin.

Encrustations and Borings

Organic enrustation is notably lacking from the surfaces of most Cipit boulders. Only one example of encrusting organisms was encountered during this study. A boulder from the Sasso Levante section had several small oyster-like bivalves encrusting a sheltered cavity. Fürsich and Wendt (1977) mentioned the occurrence of encrusting serpulids on some boulders from the Alpi di Siusi area.

Except for pits produced by modern lichens, no borings were noted on the surfaces of the Cipit boulders.

Several reasons can be suggested for the lack of encrustations: 1) bottom water conditions in the basin were hostile to life, 2) sedimentation rates were too rapid to permit encrustation, and 3) a detrimental combination of poor water conditions and rapid sedimentation inhibited encrustation. The lack of macroborings can be explained in a similar way.

Organisms

Accurate estimations on the amounts of various organisms in the Cipit boulders are very hard to make. The weathered surfaces of the boulders frequently obscured their contents, and most boulders are quite dense and very hard to fracture. These factors limited detailed field

determinations of organism types and contents to relatively small hand samples. It was obvious that concentrations of organisms varied within boulders, and care was taken to obtain representative samples. Identifications were made from thin-sections and polished slabs. It is believed that the samples provide a representative picture of the organisms present in the boulders and their relative amounts. Table 1 lists the major taxa observed, their relative importance, and their interpreted function.

Sediment Trapping Blue-Green Algae
(Spongiostromata)

The most ubiquitous organic structure found in the Cipit boulders is attributed to stromatolitic sediment-trapping blue-green algae. Zankl (1969) has described similar forms from the upper Triassic Dachstein Limestone of Southern Germany, and following the classification of Pia (1927) called them spongiostromata crusts. Pia (1927) suggested the term spongiostromata to cover a large number of presumed algal forms that show little or no internal structure, but do have a somewhat constant shape. Structurès formed by stromatolitic blue-green algae fall within this class.

In the Cipit boulders, the spongiostromata crusts consist of alternating darker and lighter crinkly laminations (fig. 30 a,b). The laminations are less than 1/10 millimeter thick on the average with the lighter laminae being the thicker of the couplet. The lighter

TABLE 1

MAJOR TAXA IN THE CIPIT LIMESTONE BOULDERS AND THEIR INTERPRETED FUNCTIONS

Taxa	Framework	Encruster	Sediment Producer
Blue-green algae (Spongiostromata)	-	***	*
Blue-green algae ("Porostromata")	?	***	**
Red algae (*Solenopora*, *Parachaetetes*)	*	*	**
Dasycladacean algae	-	-	*
Calcareous sponges	*	**	**
Hydrozoans	*	*	-
Coral	**	-	**
Tubiphytes	**	*	**
Foraminifera	-	*	*
Microtubus	-	*	-
Bivalves	-	-	**
Gastropods	-	-	**
Cidarid echinoids	-	-	**
Crinoids	-	-	**
Brachiopods	-	-	*
Collenella ?	*?	*	-
Problematica A	-	***	-

*** Primary importance

** Secondary importance

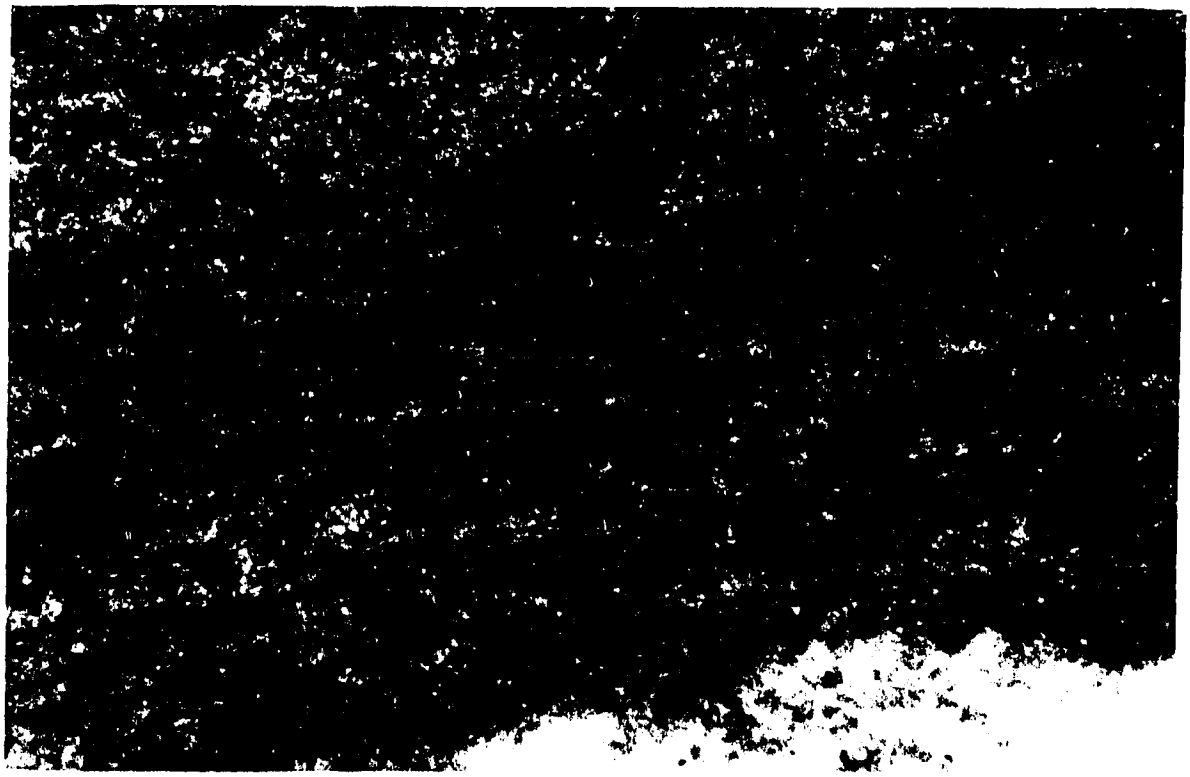
* Minor importance

- Not observed

Figure 30. Laminations produced by the growth of sediment-trapping blue-green algae.

A) Alternating light and dark laminae attributed to the growth of stromatolitic blue-green algae. Thin-section C-24.

B) Algal laminations in a peloidal micritic matrix. Thin-section C-4.



laminae are composed of silt, sand, and mud-size carbonate fragments. The darker laminae have a vague filamentous structure in thin-section. In hand specimens the laminations show up as wavy, irregular, light-colored features.

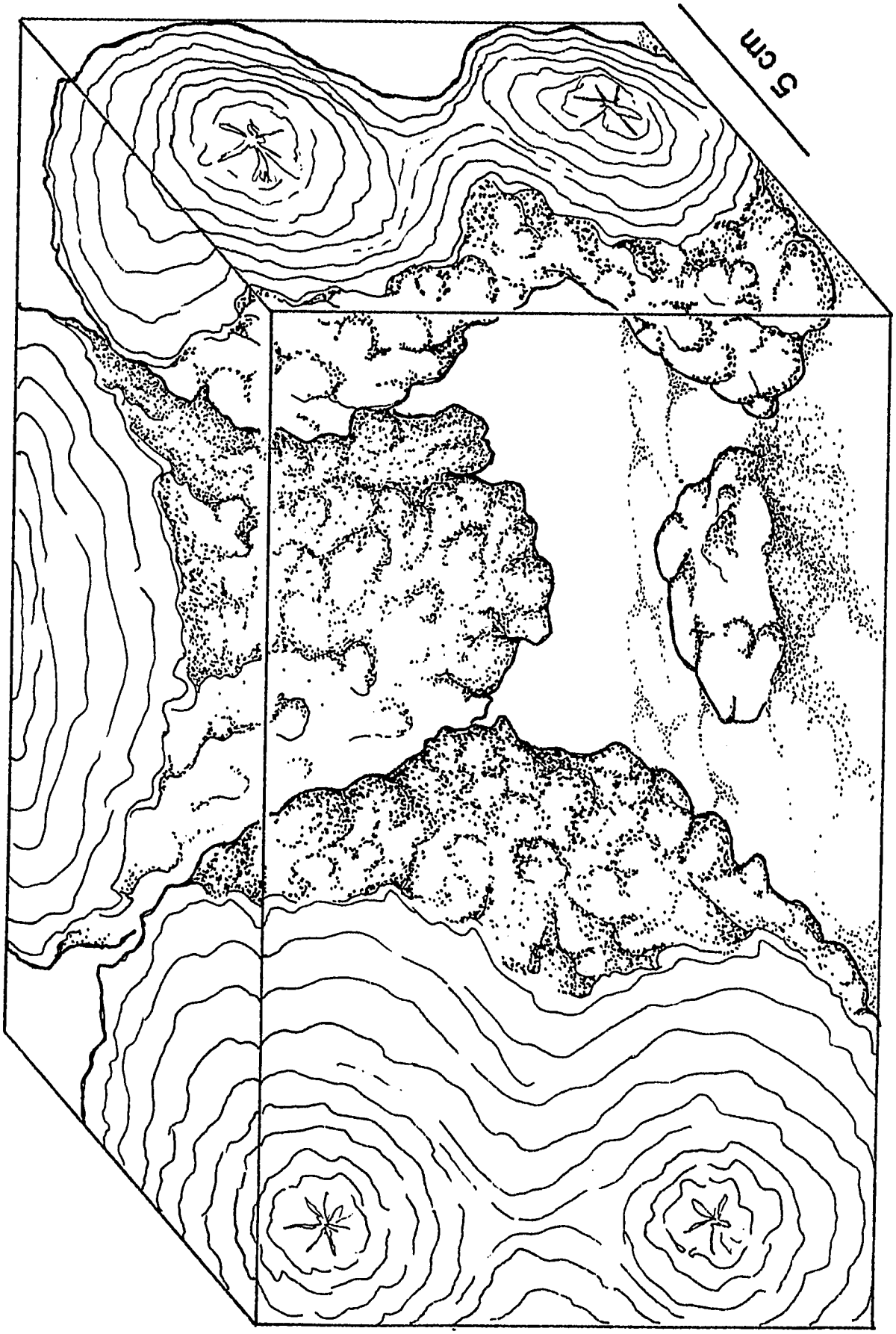
The sediment-trapping blue-green algae are present primarily as encrustations on other organisms, submarine cements, lithoclasts, and other algal accumulations. The encrusting form of the algae acts to bind the sediment and organisms together in a cavity-rich type of boundstone (fig. 28, 31). In addition to encrustations, reworked clasts of laminated algal material were also seen.

Laminated algal or spongiostromata crusts were observed in about 75% of the Cipit boulders examined. In some examples, the boulders were formed almost entirely by laminated algal crusts.

Nodular or Crustose Blue-green Algae
("Porostromata")

The term "Porostromata" was introduced by Pia (1927) to describe fossil algae with a microstructure consisting of bundles of well-defined tubes. The systematic position of these algal forms is uncertain, but Pia (1927) believed that they belong either to the green or the blue-green algae. Later, Pia (1937) restricted the term "Porostromata" to the genera Girvanella and Sphaerocodium, and classified the other branched filamentous forms (e.g. Ortonella, Hedstroemia) with the codiacean green algae. In re-examining the classification of these algal forms,

Figure 31. Schematic representation of the cavity-rich fabric produced by the coalescing growth of stromatolitic blue-green algae. Individual mammelons are about 5 cm across. Compare with the fabric illustrated in figure 28A.



(Zankl, 1969)

Wray (1977) concluded that they are most similar to filamentous growth forms that probably belong to the blue-green algae. Wray's (1977) classification is followed here, and the forms of "Porostromata" that were found in the Cipit boulders are placed with the blue-green algae.

Two tubular bundle forms, interpreted as fossil blue-green algae, occur in the Cipit boulders and have been identified as Girvanella sp. and Cladogirvanella cipitensis.

Girvanella occurs as encrusting masses on various organisms and types of debris, and consists of tubular filaments of uniform diameter with relatively thick micritic walls. Tubules are about 30 microns across but vary somewhat. The filaments are intertwined and form a dense felt-like mass. Branching of the tubules was not observed. Similar filaments occur loose within peloidal sediment. These filaments have also been classified as Girvanella, but they are not very abundant.

In addition to the encrusting masses and loose filaments, Girvanella has been identified as the major component of coated grains and oncoids that occur in the Cipit boulders. The oncoids consist of a nucleus, usually a skeletal grain or intraclast, and a laminated coating up to a few centimeters thick. In most examples, the laminated coatings are nearly devoid of structures and are at best only vaguely laminated. A few examples, however, show coatings composed of Girvanella tubules very similar

to the Girvanella tubules described earlier, and many of the laminated oncoids show faint remnants of Girvanella-like tubules. As a result, it is concluded that most of the oncoids found in the Cipit boulders were formed by Girvanella, but for some reason the tubular structure has been poorly preserved or obliterated. It is possible that the oncoids that fail to show any evidence of Girvanella were formed by encrustations of the same blue-green algae responsible for the stromatolitic crusts so common in the boulders. In addition to encrustation by algae, the oncoids were colonized by sessile foraminifera.

It is possible that the oncoids described above as foraminifera-Girvanella oncoids correspond to oncoids described as Sphaerocodium oncoids by Leonardi (1967, fig. 125-128). The Sphaerocodium oncoids of Leonardi occur in the Sciliar Dolomite and have been severely altered by dolomitization. In fact, Leonardi stated "Sulla Alghe non abbiamo dati molto precisi se non per quanto riguarda gli Sferocodi, Alghe cianoficee dalla forma sferica, dalla structura ad involucri gross-olanamente concentrici e dal diametro di 3-4 cm" (Leonardi, 1967, p. 217). In other words, the oncoids were classified as Sphaerocodium oncoids based on their gross concentric structure and size, which is similar to Sphaerocodium nodules from the Raibliano formation, and not their internal microstructure. It seems likely that the oncoids of the Cipit boulders are the

undolomitized equivalents of the Sphaerocodium oncoids of of Leonardi. The characteristic microstructure of Sphaerocodium is absent from the oncoids of the boulders.

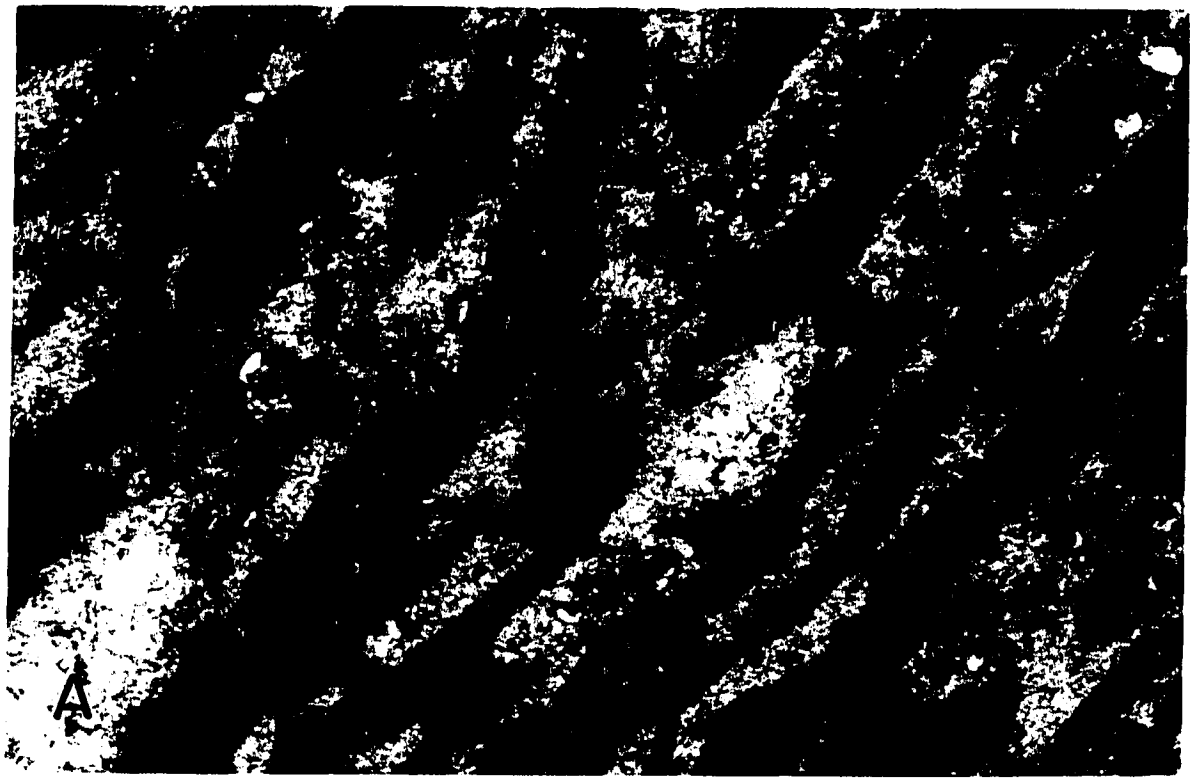
The second type of structured blue-green algae is more common and has a bunch-shaped or crustose form. It consists of dense filamentous tubules packed in bunch-like groups (fig. 32a). Tubules are about 150 to 300 microns in diameter and branch frequently, both at oblique and right angles (fig. 32a). The tubules themselves are composed of interwoven filaments reminiscent of Girvanella. The filaments are about five microns in diameter and sometimes bifurcate. The tubules form hemispherical bunches up to five or six centimeters in diameter. Growth began on some type of stable substrate as an interwoven encrustation. The tubules branch out and up from the encrusting base and form a rounded bunch-shaped mass. Ott (1966) described a shrub-shaped calcareous algae from the Cipit boulders very similar to the form described above. Ott named this algal growth form Cladogirvanella cipitensis and placed it in the blue-green algal family Porostromataceae.

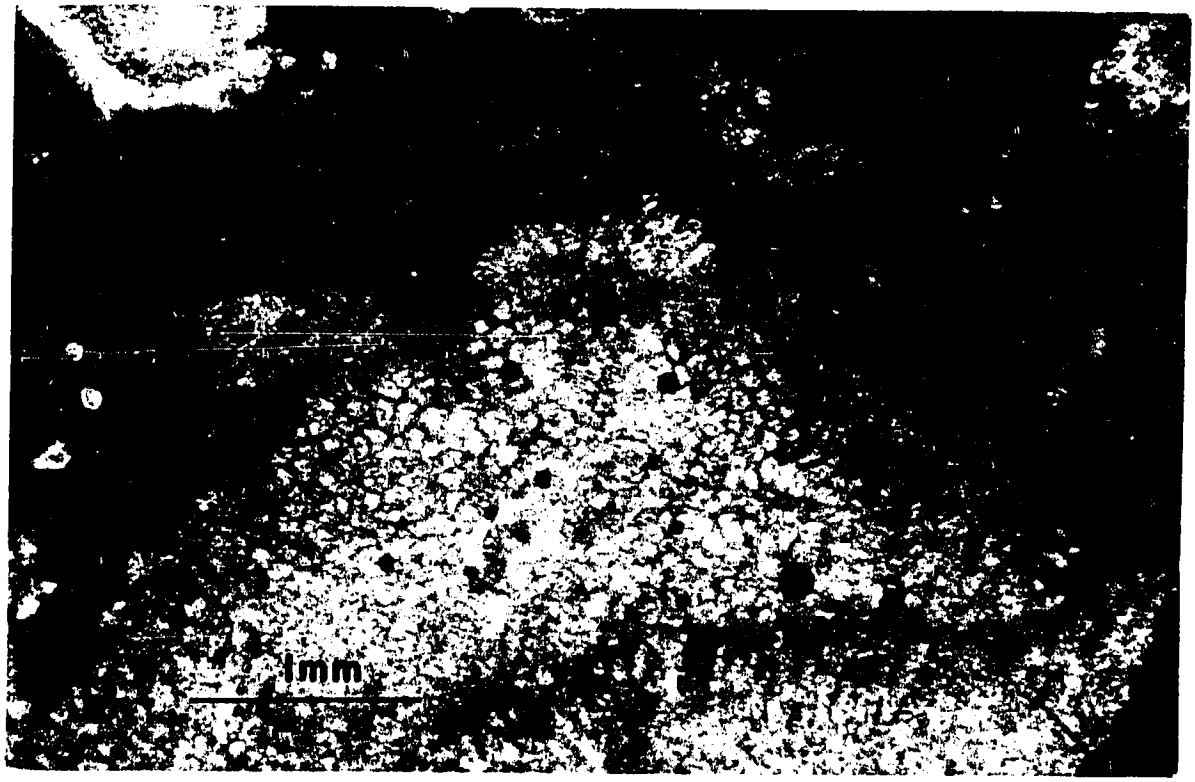
Dasycladacean Algae

Dasycladacean algae are well represented in the shallow-water interior facies of the Dolomite buildups. They are quite common and in certain areas form dasycladacean grainstones. In contrast, dasycladacean algae are rare in the Cipit boulders and are present only as poorly

Figure 32. A) Longitudinal section of the blue-green algae Cladogirvanella cipitensis. Thin-section C-73c.

B) Section through a growth of red algae, tentatively identified as Parachaetetes sp. Thin section C-131.


A


1mm

preserved fragments.

Red Algae

The red algae, tentatively identified as Parachaetetes, occurs sporadically in the Cipit boulders. In cross-section, it is composed of polygonal cells about 80 microns across. In vertical section, the cells are arranged in a radial pattern with regularly spaced cross-partitions (fig. 32B). The growth form of this organism is nearly hemispherical nodular masses. In most cases, Parachaetetes was observed encrusting other organisms (fig. 32B). Minor amounts of Parachaetetes occur as clasts in the sediment. Over all, this organism is not common in the Cipit boulders.

Another form of red algae, Solenopora, was also tentatively identified as occurring in the boulders. The scarcity and poor preservation of this form made the identification questionable however.

Calcareous Sponges

Two major orders of calcisponges are present in the Cipit boulders, Pharetronida (Inozoa) and Thalamida (Sphinctozoa). The Pharetronida are of minor importance; most of the calcisponges belong to the order Thalamida. This relationship is opposite than noticed by Fürsich and Wendt (1977) for patch reefs in the San Cassiano formation of the Eastern Dolomites. They reported that pharetronids are more common in the patch reef associations

than other calcisponges.

The Thalamida calcisponge skeleton consist of a straight, curved, or branched series of hollow spheroidal bodies. Spicules are uncommon or absent. Thin vaulted diaphrams, called vesiculae, occur within the chambers (fig. 33). Chambers are up to about one cm across. The length of the entire fossil is up to 10 cm.

Preservation of the calcisponges is usually very good, with micro-structures retained in fine detail. Some occur in growth position, but most do not. Those calcisponges that are not in growth position appear to be whole or nearly whole specimens that have not suffered much transport or abrasion.

Calcisponges are fairly common in the Cipit boulders, but do not occur with the frequency or concentrations reported by Fürsich and Wendt (1977) from the San Cassiano patch reefs of the Eastern Dolomites. The calcisponges occur primarily as isolated individuals. Their main role seems to have been one of encrustation, although they may have also provided some small amount of framework.

Amblysiphonella, Cryptocoelia zitteli (fig. 33 A), Dictyocoelia manon, Follicatena cautica, and Uvanella irregularis (fig. 33B) have been identified in the Cipit blocks.

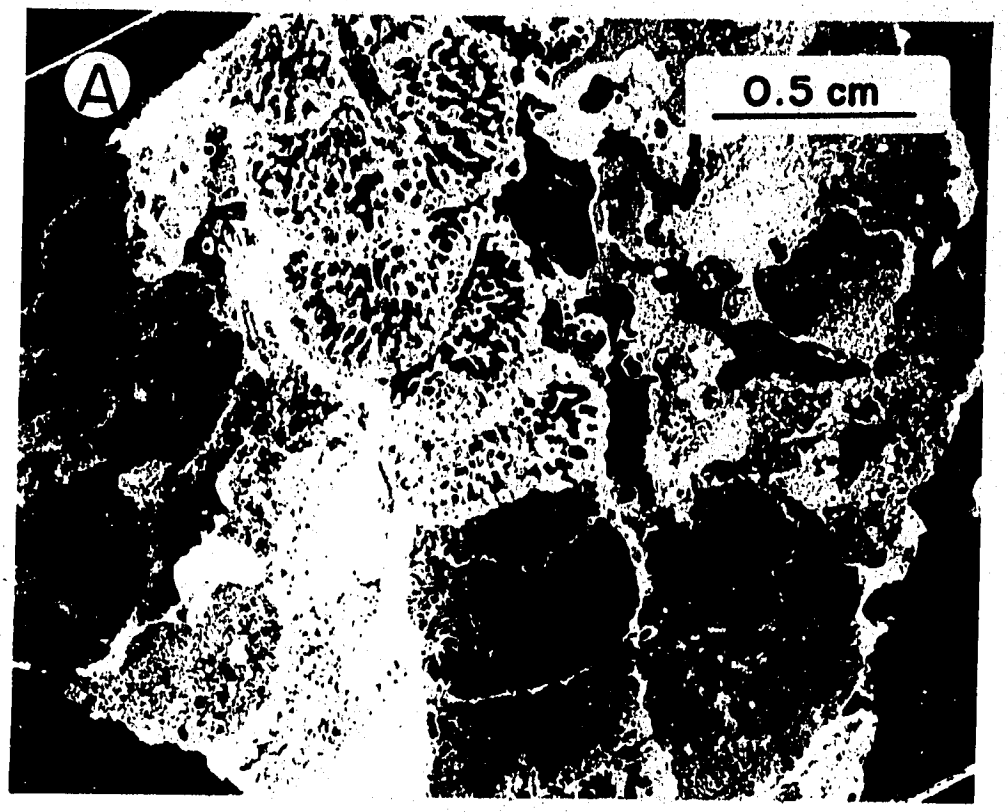
Tubiphytes

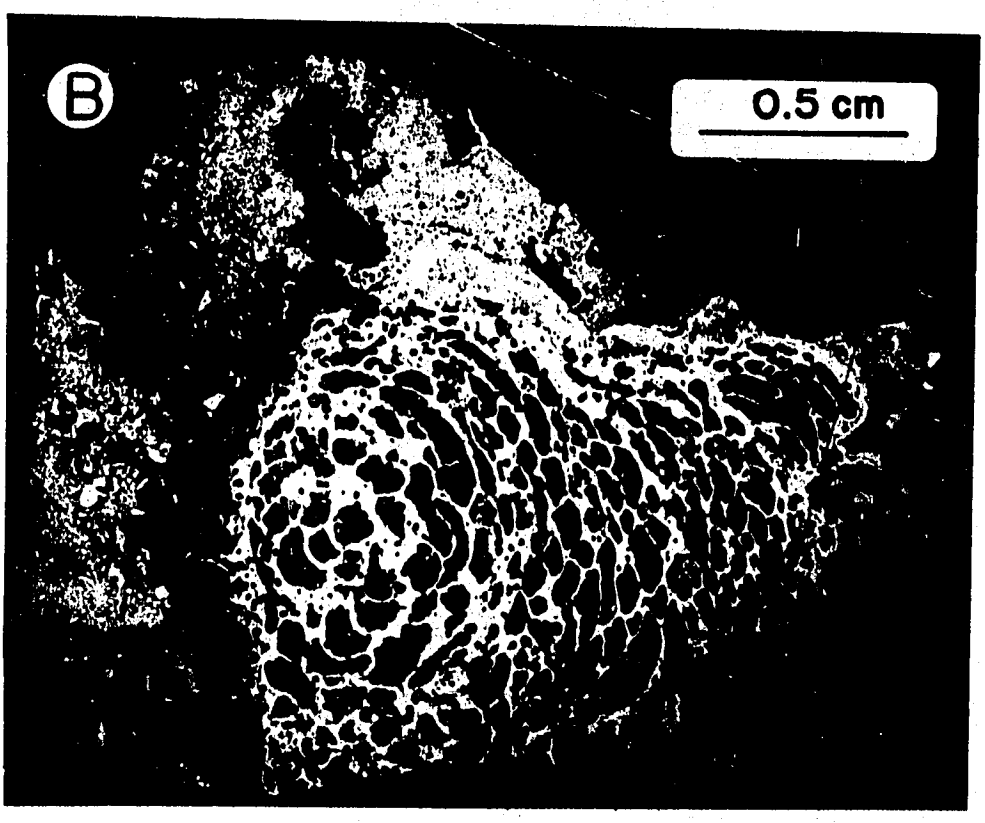
One of the most common organisms in the Cipit boulders, Tubiphytes obscurus Maslov is an encrusting organism of

Figure 33. Selected examples of calcisponges from the Cipit boulders.

A) Longitudinal section of the calcisponge Cryptocoelia zitteli. Negative print. Thin-section C-20.

B) Section through the encrusting calcisponge Uvanella irregularis. Negative print. Thin-section C-176.


A
0.5 cm


B
0.5 cm

uncertain systematic position. It was originally described by Maslov in 1956 as a type of algae. Other workers have called it a hydrozoan (Newell and others, 1953; Konishi, 1959). Recently, Babcock (1974) reviewed the systematics of Tubiphytes and decided that it is not related to either hydrozoans or blue-green algae. The biologic affinities of Tubiphytes remain uncertain.

Tubiphytes consists of stacked mammelon units that are circular to ovoid in cross-section (fig. 34 A,B,C). Individual mammelons vary in size and range from about 0.5 mm to 2.5 mm across and up to 2 mm in length. The mammelons are stacked in chain-like groups up to 1 cm long (fig. 34A). In cross-section, the center of the mammelon is characterized by a circular smooth-walled tube 25-200 microns in diameter (fig. 34B,C). The tube is usually filled with sparry calcite.

Tubiphytes plays two major roles in the sedimentary rocks of the Cipit boulders, that of an encruster and that of a framework producer. Tubiphytes forms frameworks by false branching (encrustation of Tubiphytes by more Tubiphytes) and by encrusting other organisms. More importantly, Tubiphytes acts to bind organisms together by encrusting surfaces and forming a boundstone texture. Clasts of Tubiphytes make up a minor portion of the sediment of the boulders.

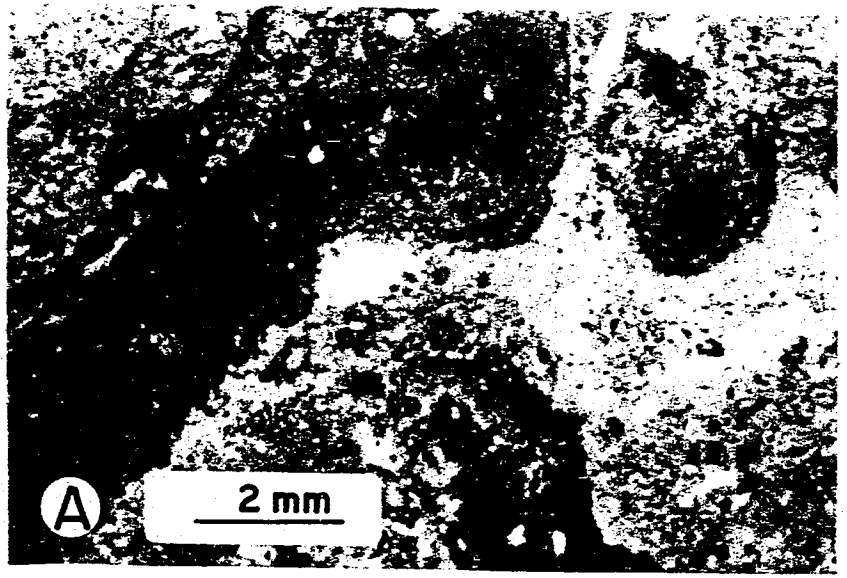
Figure 34. Diverse sections through the problematic organism Tubiphytes obscurus Maslov.

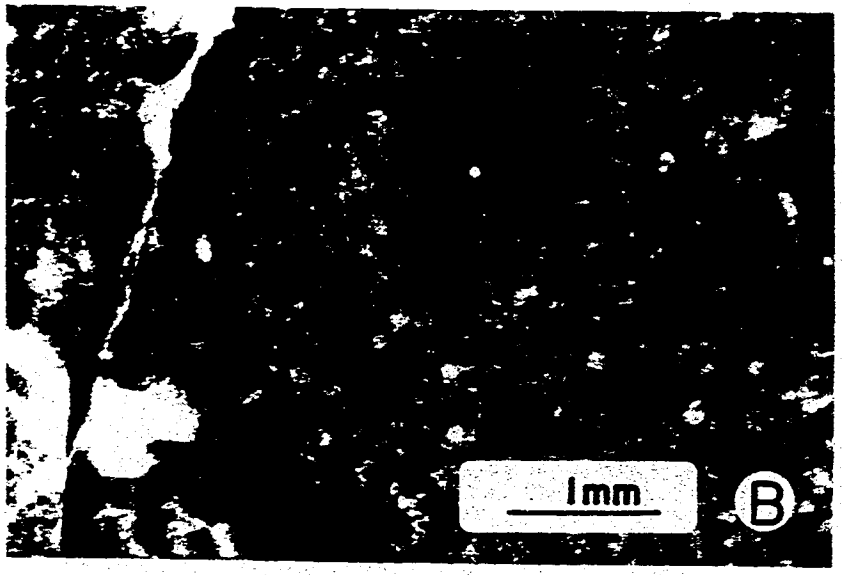
A) Oblique section through a fragment of Tubiphyties showing the stacked characteristics of the mammelons. Thin-section RZ-1-77A.

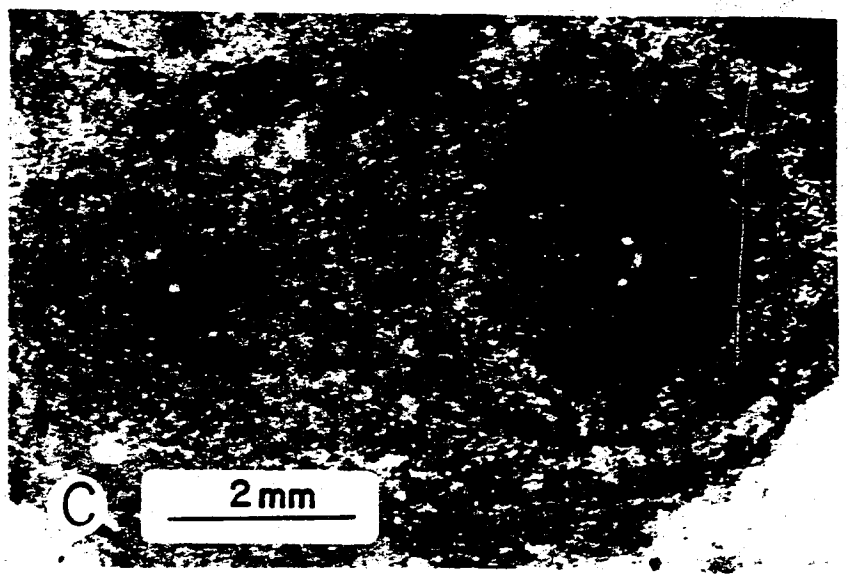
B) Cross-section of Tubiphytes. Note the irregular internal structure and well-defined axial tube. Thin-section C-17.

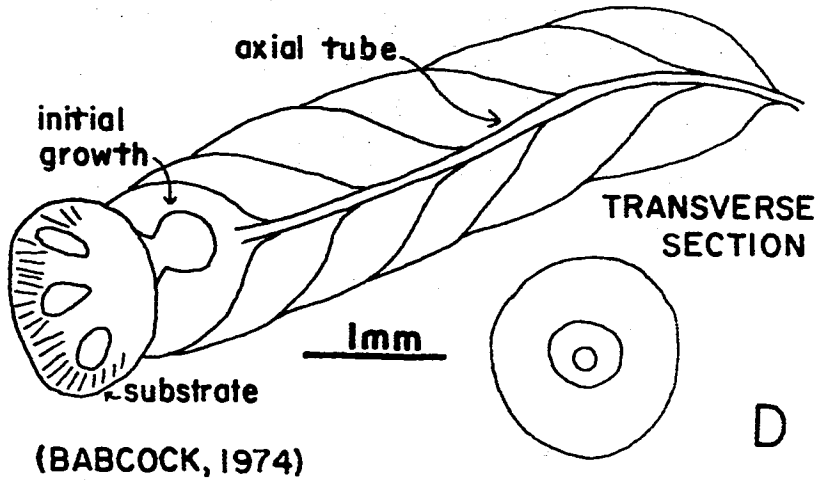
C) Cross-section of two joined mammelon units, both exhibiting a smooth-walled axial tube. Thin-section C-1A.

D) Schematic longitudinal and transverse sections of Tubiphytes obscurus Maslov.









(BABCOCK, 1974)

Corals

Corals have been reported from the Cipit boulders for many years and have been cited as one of the major points of evidence indicating coral construction of the Dolomite buildups. Corals are present in the boulders, but not with the frequency or numbers cited by previous workers.

The corals of the builders represent both solitary and colonial scleractinian corals of the astrocoeniid, montlivaltiid, and thamnasteriid groups. The most common corals are of the "Thecosmilia" and "Montlivaltia" types. Cuif (1965, 1974) has suggested that both "Thecosmilia" and "Montlivaltia" are invalid generic names. As a result of Cuif's work these genera will be enclosed in quotation marks when referred to.

The corals occur primarily as tubular, branching, finger-like clusters (fig. 35). The tubules range in diameter from a few millimeters to several centimeters (fig. 35A, B).

The corals are frequently in growth position in the boulders and are present as framework constructors. A few examples of corals acting as encrusters were noticed. The corals are usually encrusted by a variety of other organisms, the most common of which are algae.

The occurrence of coral in the Cipit boulders is not uniform throughout the field area. Corals are not overly abundant in the boulders of the Sasso Levante section for example. The boulders of the Alpi di Siusi area seem to

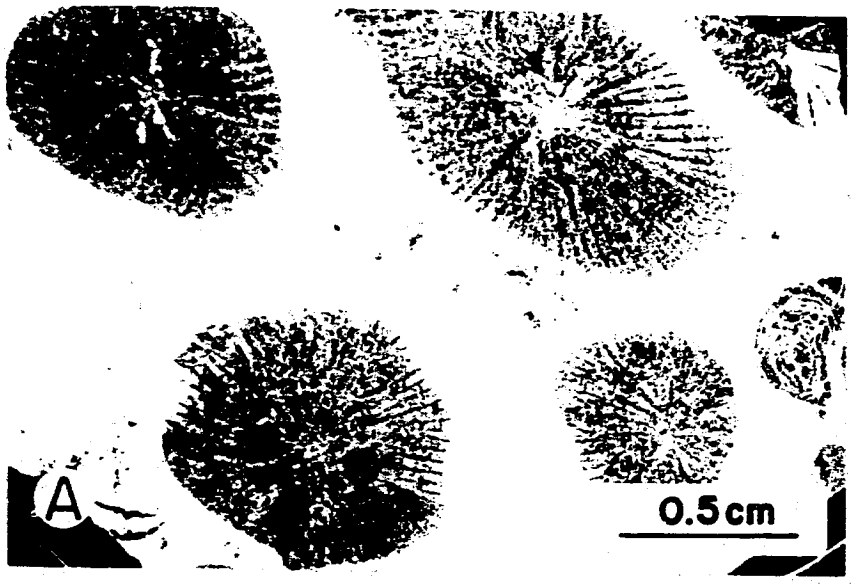
Figure 35. Examples of branching "Thecosmilia"-like corals found in the Cipit boulders.

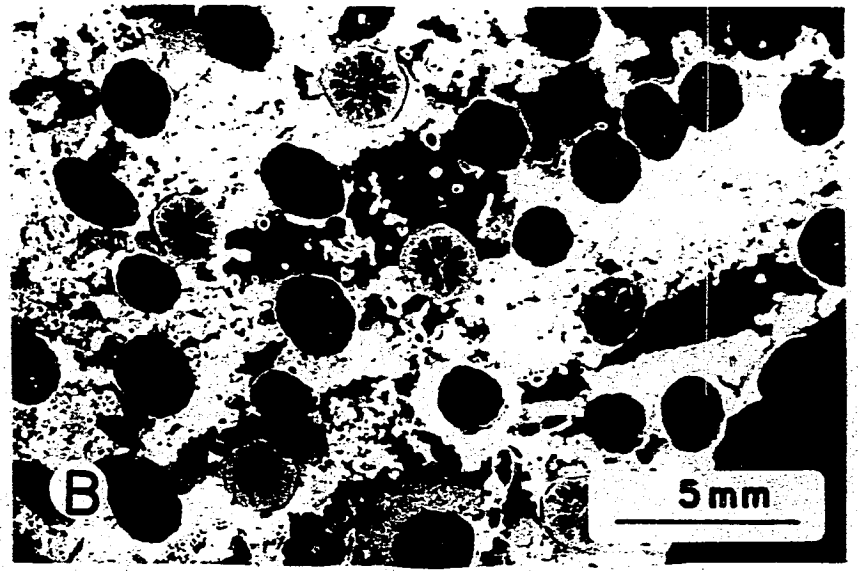
A) Cross section of "Thecosmilia" sp. Negative print. Thin-section C-119B.

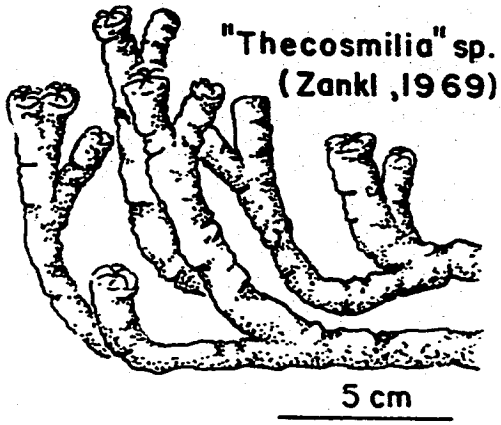
B) Cross-section of a small "Thecosmilia"-like coral colony. Note the presence and orientation of geopetal sediment around the coral. This sediment indicates that the colony is not in growth position but has been displaced. Negative print. Thin-section C-152.

C) Cipit boulder composed entirely of a "Thecosmilia" colony. Sample from Alpi Cepei.

D) Schematic drawing of "Thecosmilia" sp. showing the branching and digitate habit of the coral.







D

have the greatest concentration of coral.

All in all, coral is only a secondary component and frameworker builder in the limestone of the Cipit boulders.

Hydrozoans

Hydrozoans are uncommon, but they do occur in the Cipit boulders, both as contributors to framework and as encrustations. The preservation of the few examples that were observed was not good enough to allow exact identification of the hydrozoans.

In areas where hydrozoans formed a type of framework by mutual encrustation, a cavity-rich texture was produced. The void spaces were later filled with calcareous internal sediment.

Hydrozoans are only a minor portion of the biologic components of the Cipit boulders examined during this study. Fürsich and Wendt (1977) did not mention hydrozoans in connection with the Cipit boulders, and stated that stromatoporoids are absent.

Foraminifera

Foraminifera occur commonly in the Cipit boulders, but are of minor importance. The most abundant types are sessile and encrusting. Both agglutinating types and miliolids occur (fig. 36). Foraminifera are frequently associated with the stromatolitic blue-green algae.

Zankl (1969) reported that foraminifera played an

Figure 36. Other organisms found in the Cipit boulders.

A) Cross-sections of the coral Margarophyllia sp. Polished slab AS-5-77.

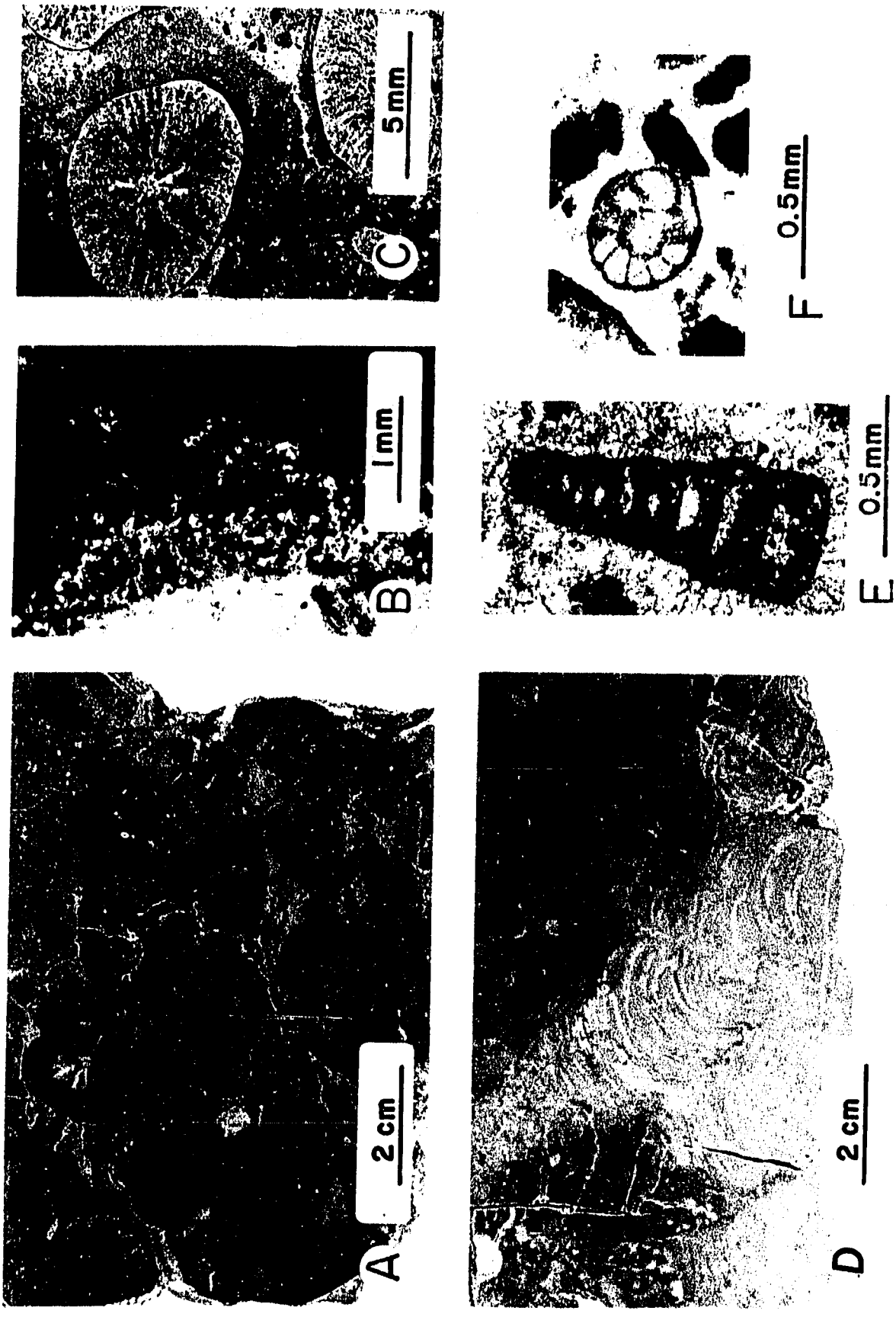
B) Problematica A, encrusting the outer wall of a coral fragment. The encrustation is essentially structureless. Small light-colored hexagons are diagenetic ? quartz crystals. Thin-section C-132.

C) Problematica A, encrusting a "Thecosmilia"-like coral Note the lack of internal structure in the encrustation. Negative print. Thin-section C-135.

D) Collenella. Polished slab, sample from the Molignon ridge.

E) Agglutinating foraminiferan. Thin-section RZ-1-77.

F) Rotalid foraminiferan. Thin-section C-187.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important role in the building of the Upper Triassic Dachstein reefs of southern Germany. In many of his polished sections, foraminifera made up more the 10% by volume of the total mass (Zankl, 1969, p. 46). In the Cipit boulders of the Western Dolomites foraminifera are far less important, and are estimated to form less than two or three percent of the rock by volume.

Echinoderms

Both crinoids and echinoids are present in the boulders. Crinoids occur as fragments, isolated columnals, and stem sections up to about 10 cm long. The genera Encrinus and Pentacrinus are both represented.

Cidarid echinoid fragments, primarily club-shaped spines, were frequently observed.

Both crinoids and echinoids were minor sediment contributors.

Molluscs

Bivalves, gastropods and cephalopods all occur as minor constituents of the Cipit boulders. Examples of whole articulated bivalves and complete gastropods are present along the fragmented specimens. Bivalves and gastropods are not very abundant and cephalopods are rare. None of the molluscs were identified beyond class level.

Brachiopods

Brachiopod fragments are uncommon, and were considered to be only minor contributors to the sediment of the Cipit boulders. A few articulated brachiopods were observed.

Problematica

Several problematic organisms are present in the Cipit boulders. Of these, the most common are an unidentified encrusting organism designated Problematica A and a form of Mircotubus. In addition, the problematic organism Colenella was also observed.

One of the most important (volumetrically) problematic organism recognized in this study is a structureless encrustation, called here Problematica A. The encrustation consists of crypocrystalline micrite devoid of laminations or other structures (fig. 36B). Small euhedral quartz crystals are frequently found within the encrustation (fig. 36B). Problematic A encrusts the other organisms found in the Cipit boulders; sponges and corals appear to be particularly susceptible to this type of encrustation.

The biologic affinities of Problematica A are uncertain, in fact its lack of structure could suggest that it is not even organic. The encrusting habit of Problematica A is very similar to that of the stromatolitic blue-green algae so common in the Cipit boulders, however, and it is

suggested that Problematica A is related to these algae.

Problematica A is a major encrusting element in many Cipit boulders.

Microtubus consists of small smooth-walled micritic tubules about 0.1 mm thick and is encrusting in habit. Fügel (1964) described Microtubus as a polychaete worm, but but this interpretation has been questioned by Zankl (1969), who suggested that Microtubus is possibly related to the agglutinating foraminifera. The exact affinities of Microtubus are unclear.

Cros (1974a) has reported Microtubus from the Ladinian limestone at Agnello in the Western Dolomites.

An encrusting organism, tentatively identified as Collenella, was observed in numerous blocks exposed along the Denti Terrarossa ridge. This organism is composed of stacked columns of overlapping curved plates (fig. 36C). The thickness of the plates is variable, but averages about one millimeter.

Johnson (1942) described the genus Collenella and placed it with the stromatolitic algae. He stated that it consisted of laminations composed of filaments, which formed an irregular mat (Johnson, 1942). A re-examination of Collenella by Babcock (1974) has shown that while Collenella mimics the general form of stromatolitic algae, it is composed of a rigid framework of skeletal plates and not of trapped and bound sediment. He concluded that Collenella is more closely related to stromatoporoids.

Where observed in the Cipit boulders along the Denti di Terrarossa ridge, Collenella exhibited an encrusting habit. It is possible that Collenella also formed some framework.

Although Collenella was fairly abundant at a few localities, its lack throughout the rest of the field area indicates that it was only of minor importance.

Sediment Composition and Textures

On the basis of examinations of thin-sections and polished slabs, the grain types and sedimentary textures of the limestones that form the Cipit boulders were determined.

Grain Types

Like many limestones, the sediment of the Cipit boulders is usually bimodal in size distribution. The sediment is a mixture of mud, silt-, and sand-size particles and much coarser fossil material, which is either present as bioclasts or as structural framework and encrustations. This section deals with the sand-size and smaller grains of the Cipit boulders.

Peloids or pellets are the most common silt- or sand-size particles present in the sediment. Because the exact origin of these particles is unknown, the nongenetic term peloid will be used to describe rounded to irregular-shaped, cryptocrystalline, primarily structureless grains (fig. 30A, 37). The peloids probably

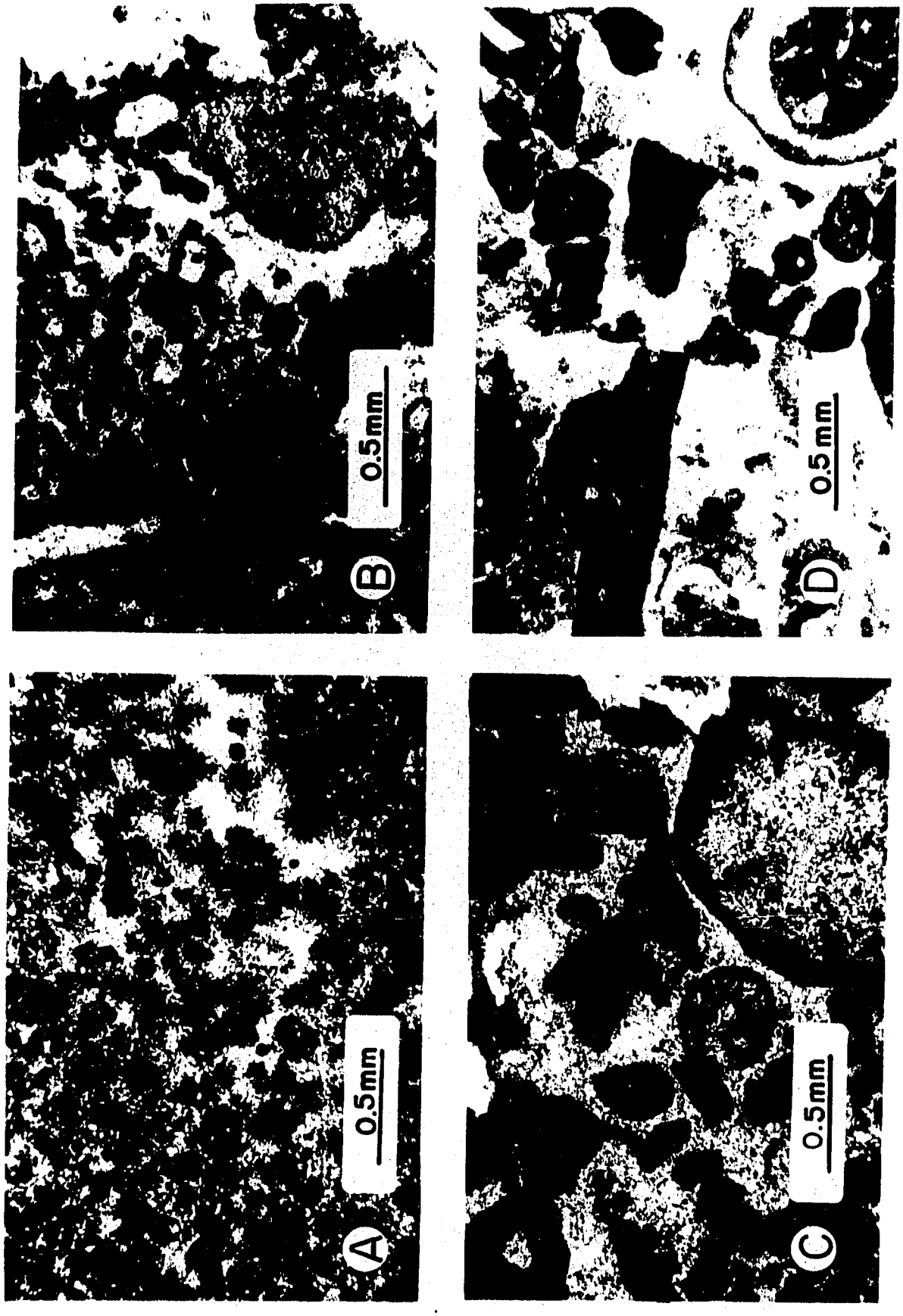
Figure 37. Detrital grain types of the Cipit boulders.

A) Silt-size peloids composed of micrite. Note the regularity of shapes and sizes. This regularity could be taken as a suggestion that the peloids are true fecal pellets. Thin-section C-127.

B) Irregular silt-size peloids and micritized grains. These peloids probably resulted from the micritization of skeletal fragments and other grains. Large grain in the lower left is an echinoid fragment. Thin-section C-148.

C) Peloids and skeletal grains in a sparry cement matrix. The large grain in the lower left is an echinoid fragment. Thin-section C-37.

D) Interclasts composed of algal laminations with peloids and scattered skeletal fragments in a sparry matrix. Thin-section C-109.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had several different origins. Those that are rounded and elliptical in shape and of a consistent size (fig. 37A) could be true fecal pellets produced by mud-ingesting organisms (e.g. gastropods). Many of the irregularly shaped micritic peloids (fig. 37B) probably are not fecal in origin and could have formed by micritization of skeletal fragments, organic agglutination, or by inorganic accretion (see Bathurst, 1971, p. 84, for a discussion on peloid formation).

Most of the peloids are silt-sized, although a small percentage are very fine sand sized.

A small percentage of lumps or aggregates of peloids were encountered. Coated grains were uncommon and ooids were not observed.

Micritic carbonate composes a significant portion of the sediment found in the Cipit boulders and is second in abundance only to peloids. The micrite occurs as trapped sediment associated with stromatolitic algal encrustations (fig. 30, 38A), as sediment deposted in shelter cavities (fig. 38B), and, more rarely, as matrix between bioclastic and intraclastic grains (fig. 38C, D).

The percentage of micrite in individual samples is variable and an average micrite content for the Cipit boulders would be hard to compute. In the thin-sections that were examined, the micrite content varied from a trace to as much as 30-40 percent of the sediment.

The origin of the micrite is questionable, although

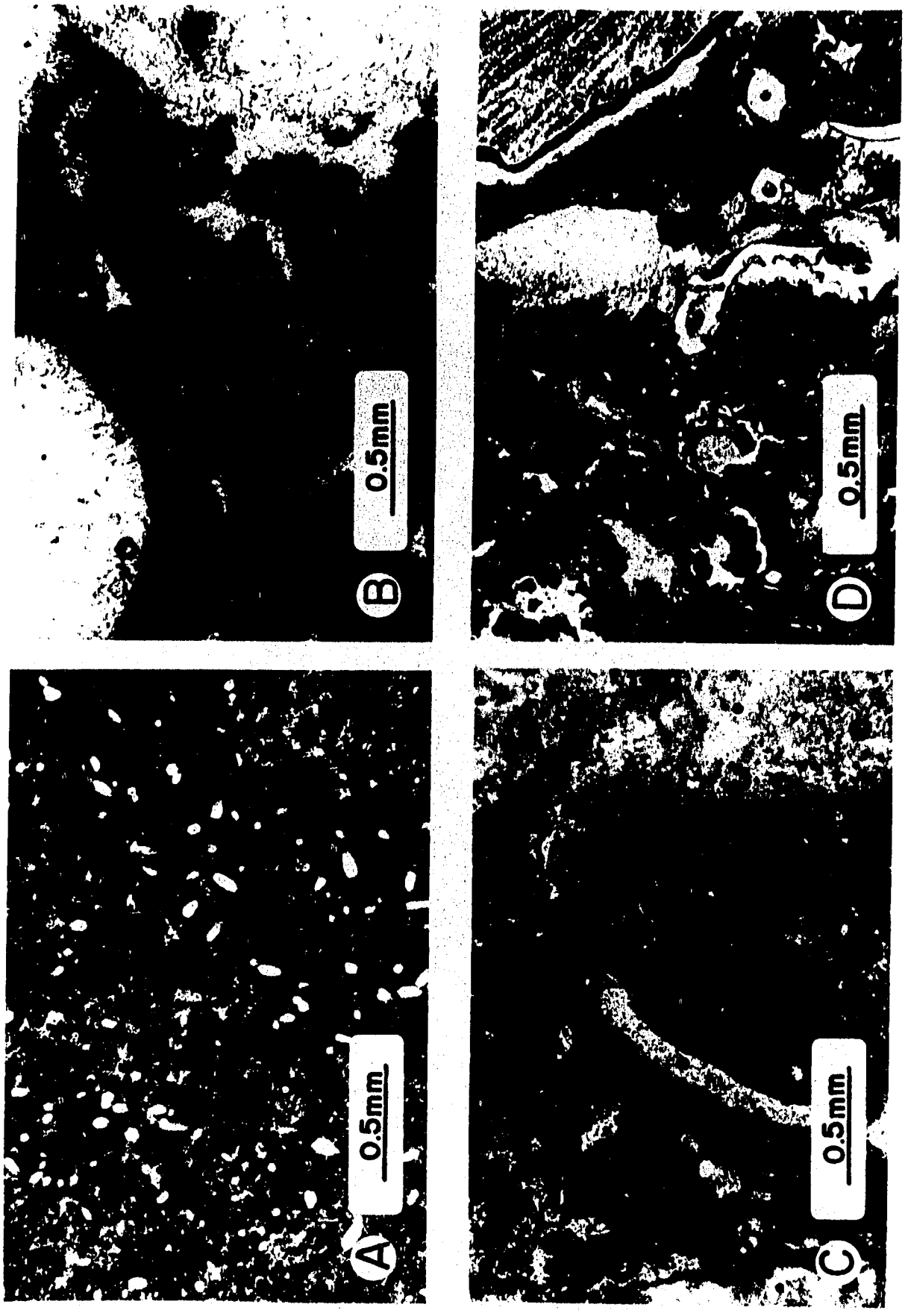
Figure 38. Modes of occurrence of micrite in the Cipit boulders.

A) Micrite trapped by the growth of stromatolitic blue-green algae. Clear grains are doubly terminated quartz crystals. Thin-section C-120.

B) Micrite deposited in a shelter cavity beneath a fragment of coral (upper right). The micrite is associated with peloids and silt-size skeletal grains. Thin-section C-87.

C) A bioclastic wackestone with abundant micrite forming the matrix between skeletal grains. Thin-section C-135.

D) Micrite deposited as matrix between lithoclasts and skeletal grains. Thin-section C-48.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most of it undoubtedly reached its final site by sedimentary processes. Evidence for deposition of micrite as detrital sediment can be found in sedimentary structures preserved in sheltered cavities and in the geopetal nature of many micritic accumulations. The possibility that some of the micrite found in the Cipit boulders may represent an early synsedimentary cement will be discussed in the section on diagenesis.

The presence of mud-sized sediment in limestones has been used to imply conditions of calm water during deposition of the sediment (Dunham, 1962). The presence of substantial amounts of micrite in the limestones of the Cipit boulders could be taken as an indication of calm water and low turbulence during deposition, or at least of the absence of currents strong enough to remove the micrite. However, other factors must also be considered.

The presence of organisms capable of creating an organic baffle can have considerable influence on the deposition and preservation of lime mud. Davies (1970) demonstrated that substantial amounts of lime mud and silt can accumulate in high-turbulence environments when an organic baffle is present. In Shark Bay, western Australia, the baffle is provided by sea-grass communities. The sea-grass promotes fine-grained sedimentation by trapping particles (presumably by reducing currents) and stabilizing the substrate with a root and rhizome network (Davies, 1970). Although organisms capable of creating

a baffling effect are frequently soft-bodied and not preserved in lithified sediment, their presence can be indicated by encrusting organisms without a preserved suitable substrate (Davies, 1970).

It is possible that an organic baffle of some sort influenced the deposition of fine-grained sediment found in the limestone of the Cipit boulders. Frequently, Tubiphytes encrustations, foraminiferans, and other encrusting organisms are present in the sediment of the boulders without a proper substrate, perhaps indicating that a non-preserved organic baffle was once present. The most likely components of such a baffle were probably various types of non-calcareous algae. Preserved framework-building organisms such as calcisponges and corals could have added to the baffling effect.

The common stromatolitic algal crusts also influenced the preservation of fine-grained sediment. Algal mats are well known for their ability to trap and bind fine-grained material that normally would not be deposited in intertidal and nearshore environments (Ginsburg and Lowenstam, 1958). Sediment intertwined with laminations interpreted as the remains of blue-green algal mats indicate that the algal crusts of the Cipit boulders had the same sediment-trapping ability.

Recognizable skeletal grains are present in the sediment of the Cipit boulders, but not in great abundance (fig. 37C). These grains are composed of organisms

interpreted to have lived on or near the cite of deposition of the limestone that composes the Cipit boulders (see section on the origin of the boulders below). Fragments and grains derived from other environments, such as the lagoonal environment characterized by dasycladacean algae, are present only in trace amounts. These exotic fragments are frequently highly micritized and poorly preserved.

The most common skeletal fragments are pieces of Tubiphytes, crinoids, cidarid echinoids, various types of calcareous algae, bivalves, and gastropods. The fragments are generally not badly abraded or micritized. Skeletal debris is frequently coated by algae or other encrusting organisms.

Intraclasts are not common in most of the limestone that forms the Cipit boulders, but they do occur (fig. 37D). The intraclasts are pieces of algal boundstone that do not seem to have traveled very far; at least they lack signs of substantial abrasion.

In addition, to the carbonate particles found in the Cipit boulders, a small amount of volcanic material is present. The volcanic grains are silt- to sand-size particles and are an integral part of the original sediment. The grains are similar to the Ladinian volcanics described earlier, although their small size makes it difficult to determine their exact composition. These grains should not be confused with later volcanic sediment that fills diagenetic and depositional cavities in the boulders.

Some of the Cipit boulders are conglomerates or breccias composed of cemented clasts of previously lithified limestone. The clasts vary in size from granules to small cobbles and are subrounded to angular. This type of Cipit boulder is the least common and was found primarily along the Denti di Terrarossa ridge.

Lithology

Several major rock types are represented in the Cipit boulders. These are, in decreasing order of abundance; various types of boundstones, peloid packstones, bioclastic wackestones and packstones, peloid wackestones and grainstones, limestone conglomerates and breccias, and rare bioclastic grainstones. Lime mudstones are absent.

Boundstones

A boundstone (Dunham, 1961) is defined as a rock whose original constituents were bound together at the time of deposition. In the Cipit boulders, the interplay of framework-building organisms, organic encrustation and synsedimentary cementation combined to produce a wide variety of boundstone types (fig. 39). The most common types of boundstones are in order of importance: 1) 1) stromatolitic algal boundstones, 2) algal-Tubiphytes boundstones, 3) encrusted coral boundstones, 4) nodular algal-boundstones, and 5) other types of minor boundstones, such as Collenella boundstones and hydrozoan boundstones. These boundstones combine to form 60 percent of the Cipit

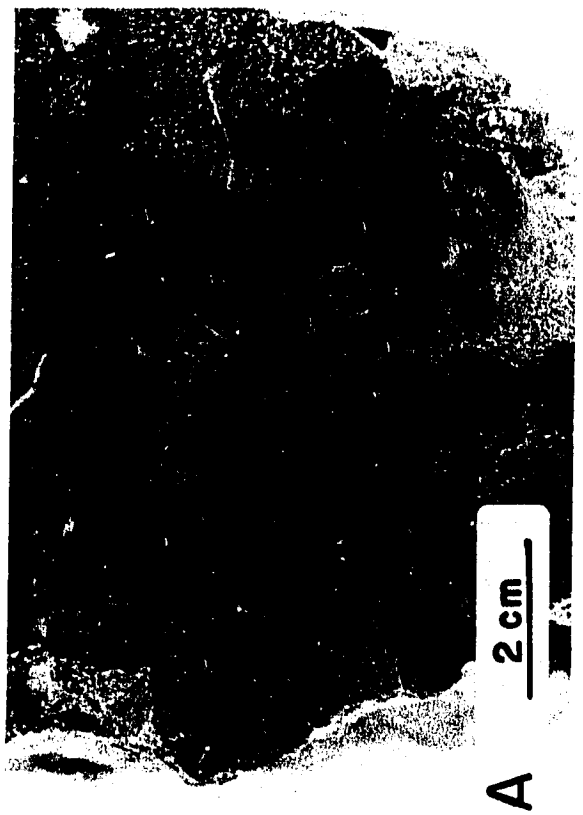
Figure 39. Boundstones

A) Cladogirvanella cipitensis and encrusting blue-green algal boundstone. Cladogirvanella forms small bush-like nodules which are encrusted with stromatolitic blue-green algae. Polished slab, sample C-187.

B) Nodular algal-boundstone formed by encrustation of blue-green algae around a skeletal nucleus, in this case calcisponge tests. Polished slab, sample RZ-4-77.

C) Margarophyllia sp. boundstone, Polished slab, sample AS-5-77.

D) Stromatolitic-algal submarine-cement boundstone with a large submarine cement filled cavity. A- stromatolitic algal laminations and internal sediment, IF- isopachous-fibrous submarine cement, RF - radial-fibrous submarine cement, D - dolomite silt. Polished slab, sample RZ-1-77.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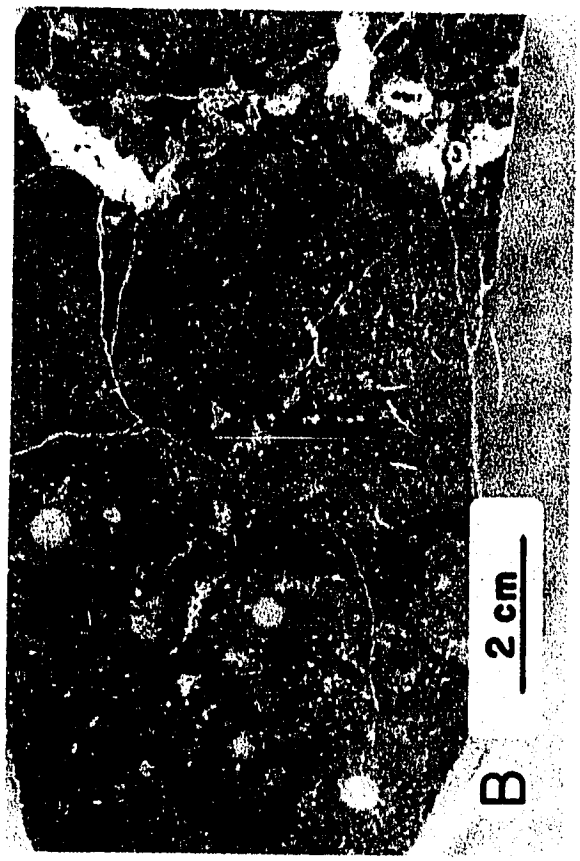
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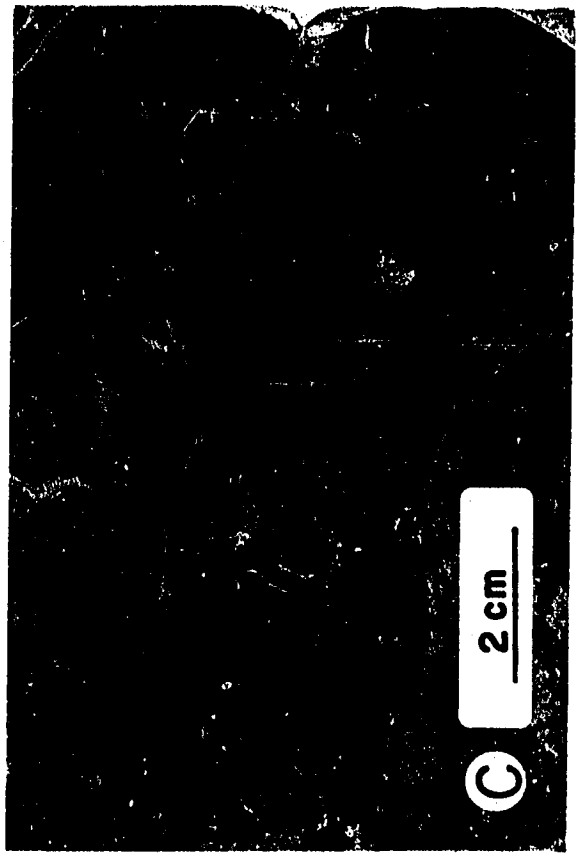
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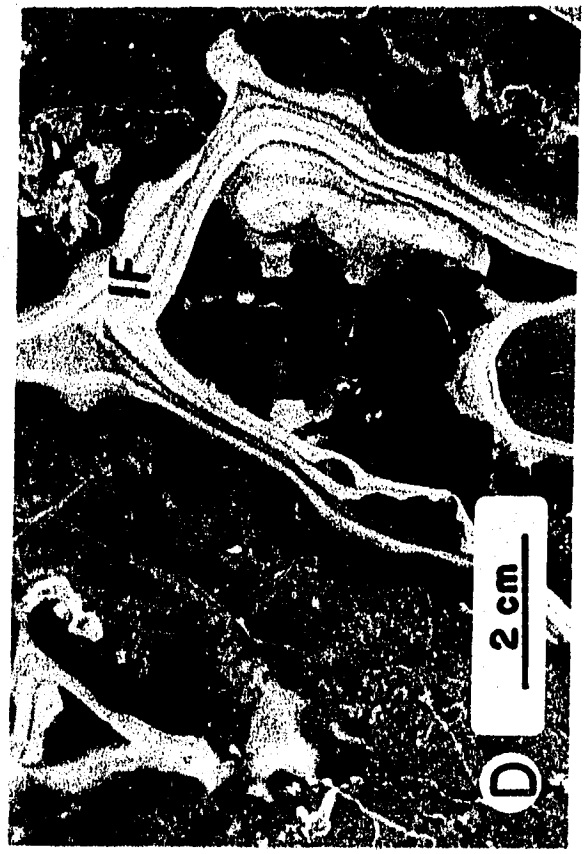
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boulders chosen for examination in this study.

The stromatolitic algal boundstones are formed by successive encrustation of the substrate by stromatolitic laminations. The algae encrusts itself, sedimentary grains, and any organism that happens to be present. The resultant texture is cavity-rich (fig. 28A, 31). The cavities are filled or partially filled with locally derived sediment, which is usually composed of peloids and some skeletal debris. The internal sediment is commonly encrusted by later stages of algal growth. Synsedimentary cements are common. Similar textures, produced by spongiostromata crusts, have been described from the Upper Triassic Dachstein Limestone of southern Germany by Zankl (1969).

Algal-Tubiphytes boundstones are similar to the stromatolitic algal boundstones, but with the addition of significant amounts of Tubiphytes. This boundstone texture is also rich in constructional cavities. Tubiphytes occurs as encrustations on the algal substrate and other organisms. and as clasts without an identifiable substrate. Synsedimentary cement is an important element of this type of boundstone.

Encrusted coral boundstones are not as common as the algal and algal-Tubiphytes boundstones, but do form about 15 percent of the Cipit boulders that were examined. Corals form the the most conspicuous element and provide the framework in this type of boundstone. The corals are most commonly "Thecosmilia" and related forms (fig. 35, 39C).

Associated with the coral are varying amounts of calcisponges, coralline and red algae, Tubiphytes, and other problematic organisms (fig. 36). The framework elements are encrusted by algae, Tubiphytes, Problematica A, and foraminifera. Synsedimentary cement is present, but is not as common as in the two preceding types of boundstones. Internal cavities within the boundstone are filled with detritus from the surrounding organisms, peloids, and later sparry cement (fig. 35, 38B).

The nodular algal boundstones are similar to the stromatolitic algal boundstones described earlier. The primary difference is that the nodules all appear to have a skeletal nucleus of some sort. The most common nucleus seems to be the skeletons of calcisponges (fig. 39). The nodules themselves are composed of sediment trapped by the algae. Interestingly, when several examples of this type of boundstone were thin-sectioned, evidence of the original binding organism disappeared. In thin-section the texture of the sediment is one of a peloid packstone, and evidence of organic binding is missing, even though the algal laminations are clearly visible on polished slabs (fig. 39). This type of texture makes up only a few percent of the boundstones found in the Cipit boulders.

Other types of boundstones (Collenella boundstones, hydrozoan boundstones) are present in very limited amounts.

Other Rock Types

In addition to the boundstones, several other types of carbonates are represented in the Cipit boulders. The most common of these are peloid packstones. The peloid packstones are composed primarily of silt-size micrite peloids with varying amounts of skeletal fragments and other debris (fig. 37). Micrite forms up to 30 percent of the rock, but all gradations from peloid packstone to wackestone and grainstone are present.

Bioclastic wackstones and packstones are also represented in the Cipit boulders, but are not particularly abundant. The skeletal grains are derived from the organisms found in the Cipit boulders. Intact skeletal grains are common. A few examples of bioclastic grainstones were noted, but these are rare rock types in the Cipit boulders.

Limestone conglomerates and breccias account for a small percentage of the Cipit boulders. The conglomerates are composed of fragments of lithified limestone similar to the limestones that make up most of the Cipit boulders; that is, the clasts are fragments of algal boundstones, peloid packstones and so on. The limestone conglomerates were common only at a few localities, most notably the Denti di Terrarossa ridge.

Cavities and Cavity Fill

One of the most conspicuous elements of the Cipit boulders are cavities or filled cavities. These important features are pervasive and occur in numerous shapes and sizes. In this discussion, the term cavity will be applied both to present-day voids and to past cavities now filled with internal sediment or cement. The cavities are both fabric-selective and non fabric-selective (Choquette and Pray, 1970). Following the terminology of Choquette and and Pray (1970) eight different types of cavities or pores were recognized. In order of importance, the cavity types are: 1) growth framework, 2) vug, 3) channel, 4) interparticle, 5) shelter, 6) intraparticle, 7) stromatactis-like, and 8) fenestral (fig. 40).

Fabric-selective Cavities

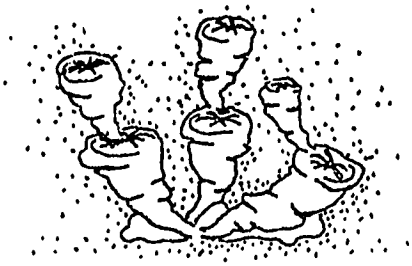
The most important type of fabric-selective cavity is the constructional or growth-framework cavity (fig. 40A). These cavities are formed by the growth of the various organisms found in the boulders and are most common in the boundstones. All of the boundstone fabrics were originally cavity-rich. The cavities range from less than one centimeter to as much as 25 cm across and are probably part of a larger interconnected network. Shapes are geneally irregular and controlled by the growth forms of the organisms, although modificiation by late solution is common. The cavities are commonly filled with synsedimentary internal

Figure 40. Cavity types common in the Cipit boulders (see text for discussion).

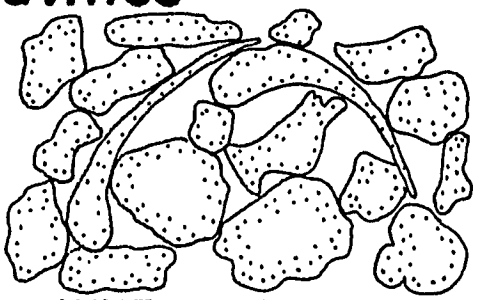
A) Fabric-selective cavities.

B) Non fabric-selective cavities.

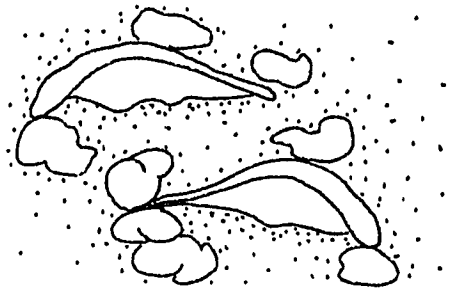
A. Fabric-Selective Cavities



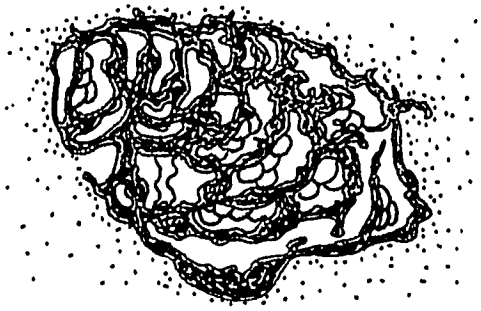
GROWTH FRAMEWORK



INTERPARTICLE



SHELTER



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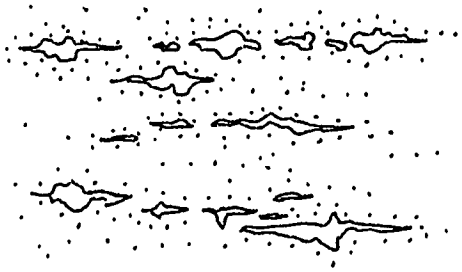
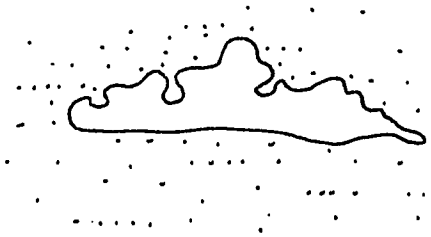


FENESTRAL



STROMATACTIS-LIKE

B. Non Fabric-Selective Cavities

VUG

CHANNEL

sediment, submarine cement, later dolomite silt, or late spar cement.

Small pores spaces between sedimentary particles form the second most abundant type of fabric selective cavity in the Cipit boulders (fig. 40B). These cavities are small and are usually smaller than the surrounding particles; that is the particles all show some form of support. Sizes of these cavities range from a few microns to as much as a centimeter in diameter. Most of the interparticle porosity is less than three millimeters across. This type of cavity is usually filled with a late generation of sparry cement (fig. 37A), but in some cases synsedimentary fibrous cement fills the pores.

Shelter porosity (fig. 40A) is common in most of the rock types that compose the Cipit boulders. This type of cavity is formed by the sheltering capabilities of skeletal material in the sediment. The cavities are usually flat-bottomed with the upper surface conforming to the shape of the individual skeletons. This type of cavity is fairly small, ranging from a few millimeters to several centimeters across. Calcisponges, corals, molluscs, and algal fragments are the most common roof-forming organisms. This type of cavity is usually filled with geopetal carbonate sediment and a later generation of sparry calcite.

Most of the organisms that occur in the boulders possess some type of intraparticle porosity (fig. 40A). These cavities are small, all being less than about five

millimeters across. Most are the result of decay of soft tissue within the organisms, but some of the cavities probably represent original void space within the skeleton. In addition to cavities within skeletal material, a small amount of intraparticle porosity exists within the intraclasts and other detrital grains. This form of intraparticle porosity seems insignificant, however. Most commonly, intraparticle porosity within the Cipit boulders is filled with a late generation of spar cement. Marine fibrous cement and sedimentary fillings are also seen.

Fenestral cavities are not common but were recognized in a few of the Cipit boulders that were examined (fig. 40A). This type of cavity generally has a flat bottom and a somewhat irregular top. The size of the pore is larger than the detrital material that composes the roof; that is, the grains above the cavity are unsupported. Cavity lengths are up to two centimeters, and they are present in aligned groups and clusters, forming a typical fenestral fabric (fig. 40A). The fenestral cavities are frequently spar filled or contain later volcanic-rich internal sediment.

In addition to the types of cavities mentioned above there are numerous cavities of unknown origin (fig. 40A). All of these cavities have unsupported roofs. The sizes of the cavity are too large to be explained by grain support. Sizes vary from cavities a few centimeters across and perhaps one centimeter high to voids eight by five centimeters

in dimension. Many of the cavities have flat bottoms and irregular roofs (fig. 40A), and resemble stromatactis cavities (see Heckel, 1972). Other cavities have odd outlines (e.g. rounded central cavities with numerous projecting "arms").

Stromatactis-like cavities have been described from many carbonate buildups and have been assigned many different origins.

Bathurst (1959) suggested that unsupported cavities similar to those described above were the result of decay of soft-bodied organisms. Carozzi and Textoris (1963) believed that Silurian stromatactis cavities from Indiana were formed by the sheltering action, and eventual dissolution, of fistuloporid bryozoans. Heckel (1972) attributed the origin of Devonian stromatactis from New York mud mounds to sediment creep or internal collapse.

The stromatactis-like cavities from the Dolomites do not show any evidence of support by organisms. These cavities probably had several different origins, all of which produced voids with similar shapes. Sediment creep, decay of soft tissue, and enlargement of pores by solution are all possible mechanisms of formation.

The odd-shaped cavities with projecting arms are more problematic. About 20 cavities of this type were encountered during field work. Their sizes range from a couple centimeters to almost 10 cm in diameter. The origin of these cavities is uncertain, but they could represent

void space created by the decay of anemone-shaped soft-bodied organisms.

Non-Fabric-Selective Cavities

Vugs and channels (fig. 40B) are the two types of non-fabric-selective cavities found in the Cipit boulders, and these are second in abundance only to the growth-framework cavities. The vugs and channels are the result of Triassic solution during periods of karsting. These cavities come in many different shapes and sizes and are up to 25 cm in diameter. In some examples these cavities appear to cut completely across depositional fabrics, but most commonly they seem to enlarge pre-existing constructional cavities (fig. 28). The cavities formed by solution are either open or filled with vadose sediment, volcanic debris, and sparry cement.

Cavity Fills

A large number of cavities in the Cipit boulders are presently filled, either partially or completely, with sediment or cement. Both the sedimentary fills and the cements can be separated into material that was deposited at roughly the same time as the surrounding limestone, or as material that was emplaced much later.

Synsedimentary Fills. Two types of synsedimentary cavity fillings are present, internal carbonate sediment, and synsedimentary or submarine cements. Constructional

cavities form one of the primary sites of submarine cementation in the limestone of the Cipit boulders. These cements are the subject of the next section, and will not be discussed here.

The internal carbonate sediment is composed of mud-, silt-, and sand-size debris arranged in geopetal fashion at the bottom of the cavities. Rarely, constructional cavities are entirely filled with this material. The carbonate sediment consists of material derived from close by the depositional site, and its compositon is basically the same as sediment outside the cavity. Small amounts of volcanic clasts occur uncommonly in the fill. Occasionally, lamination and cross-stratification may be observed in the geopetal fillings. The internal sediment is either brown or brownish grey in color.

This type of internal sediment is the result of sedimentary processes that acted during the deposition of the limestone that forms the boulders.

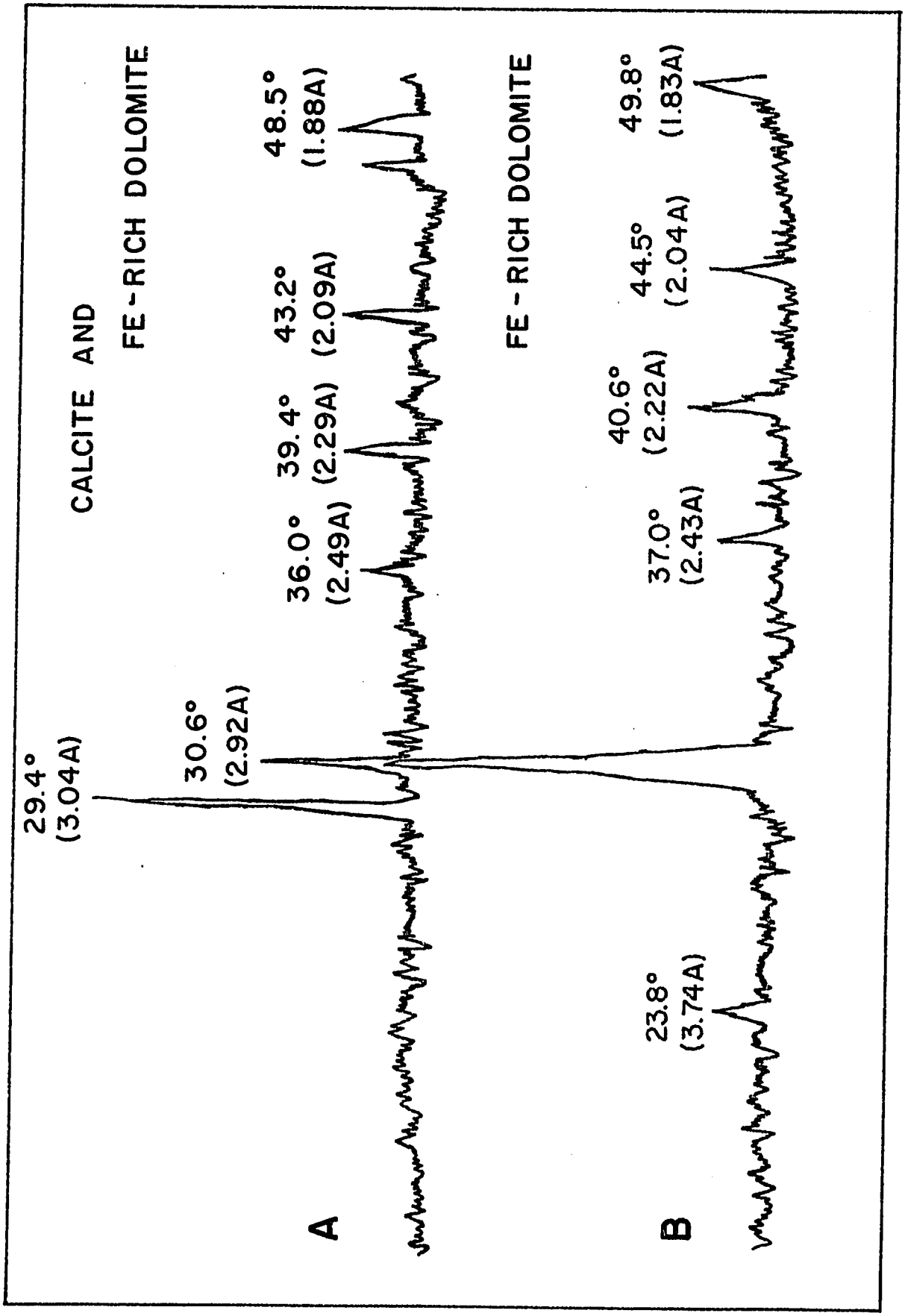
Post-sedimentary Fills. Two other types of geopetal fills are present, a dolomite/iron oxide internal sediment, and a fill composed mainly of volcanic clasts.

The first type is visually quite conspicuous and forms orange-brown patches where exposed on the surface of the boulders. It is composed of well-sorted silt-sized rounded clasts (fig. 41) and a powdery orange-red clay-size material. The orange color grades to browns and greys away from the exposed surface of the boulders. The fill is

Figure 41. X-ray diffractograms of cavity filling material found in the Cipit boulders.

A) X-ray pattern produced by a sample of orange-red clay-size material filling a solution cavity in a boulder. The only peaks on the pattern are those of calcite and iron-rich dolomite. This suggests that the clay-like powder is amorphous and probably composed of hydrated iron oxides.

B) X-ray pattern of a sample of well-sorted silt-size cavity fill. The peaks are those of iron-rich dolomite.


A
CALCITE AND
FE-RICH DOLOMITE
29.4°
(3.04A)
30.6°
(2.92A)
36.0°
(2.49A)
39.4°
(2.29A)
43.2°
(2.09A)
48.5°
(1.88A)
B
FE-RICH DOLOMITE
23.8°
(3.74A)
37.0°
(2.43A)
40.6°
(2.22A)
44.5°
(2.04A)
49.8°
(1.83A)

geopetal and occurs mainly in cavities that were formed or enlarged by solutions. X-ray diffractograms show that the particles of this type of fill are composed of iron-rich dolomite and amorphous iron oxides (fig. 41). The Fe dolomite/Fe oxide internal sediment may either partially or completely fill the cavities. Lamination and cross-stratification are common.

This type of cavity fill apparently originated during periods of Triassic exposure and karsting. The dolomite represents material concentrated by solution of surrounding limestone and deposited by vadose waters in cavities and channels within the remaining limestone. The dolomite/iron oxide internal sediment was formed before and during formation of the Cipit boulders themselves. Bosellini and others (1977) have used this material as evidence of paleokarst in the Western Dolomites.

The second type of post-sedimentary cavity fill was emplaced after the boulders were created and consists mainly of volcanic grains (fig. 29). This material frequently has a different orientation than the other geopetal fills and seems to be concentrated in the outer part of the boulders. The volcanic-clast fillings were most likely formed during and after the time the boulders were being moved into the basin.

Those cavities that were not completely filled

by one of the above internal sediments commonly have a late generation of iron-rich spar cement filling the remaining space. This cement will be discussed in a later section.

Diagenesis of the Cipit Limestone

Examination of the thin-sections collected during this study quickly showed that diagenesis played a major role in producing and modifying the limestone that composes the Cipit boulders. In some cases, carbonate cements are volumetrically more important than all the other components of an individual boulder combined. An understanding of the successive diagenetic events of the Cipit boulders is necessary if their history is to be reconstructed. Also, much can be learned about the development of the carbonate buildups through a diagenetic study of the boulders.

Little has been published concerning the diagenesis of the limestone that comprises the boulders. In two massive works on the Dolomites (Leonardi, 1967; Cros, 1974a) this subject is mentioned only in passing. Scherer (1977), in a paper on the preservation of aragonitic skeletons from the San Cassiano formation, has discussed several cement generations in the boulders, and has suggested changing pore solutions as a cause. He recognized four successive cements within skeletal cavities in boulders sampled at Staulin (near Cortina d'Ampezzo) and Molignon. These cements are, from earliest to latest, low-Mg calcite,

siderite, barite, and ferroan calcite (Scherer, 1977).

The results of this study show that the boulders have experienced a complex and varied diagenetic history that has included several episodes of cementation, conversion of high-Mg calcite and aragonite to more stable carbonate phases, formation of zoned Fe-rich dolomite, and production of solution features related to karsting.

Extensive cementation of the limestone that forms the Cipit boulders was the earliest diagenetic event and one of the most important. Therefore the cements of the boulders will be discussed first.

Cements

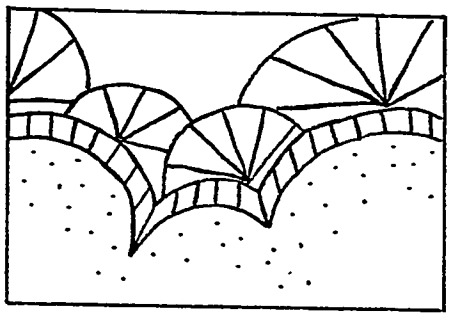
Five, and possible six, major types of cements have been recognized in the boulders, and all are carbonates (fig. 42). The distinctions between cement types are based on morphologic and chemical criteria. In addition, the cements have been classified as either marine or non-marine in origin.

Submarine Cements

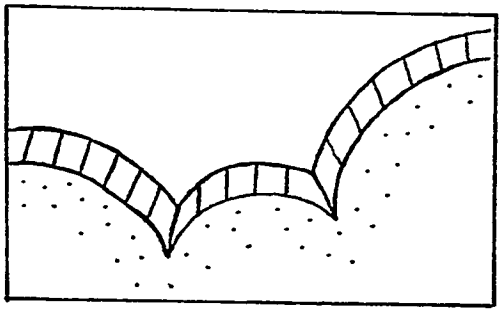
In recent years, the importance of submarine cements has been recognized, and their widespread occurrence well documented (MacIntyre and others, 1968; Krebs, 1969; Shinn, 1969; Land and Goreau, 1970; Ginsburg and others, 1971; Schroeder, 1972; Friedman and others, 1974; Ginsburg and James, 1976). Three, and perhaps four, of the cement types that occur in the Cipit boulders are believed to be

Figure 42. Major cement types identified in the Cipit boulders.

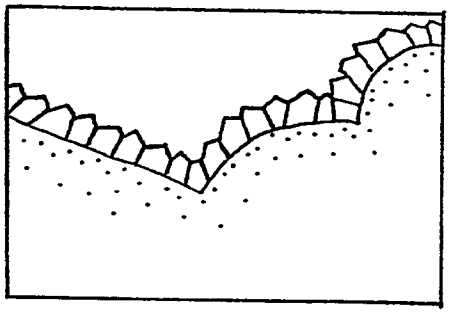
Major Cement Types



Radial Fibrous

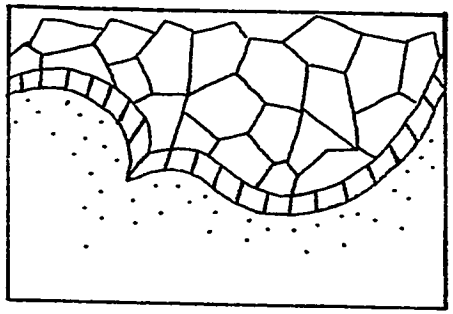


Isopachous Fibrous

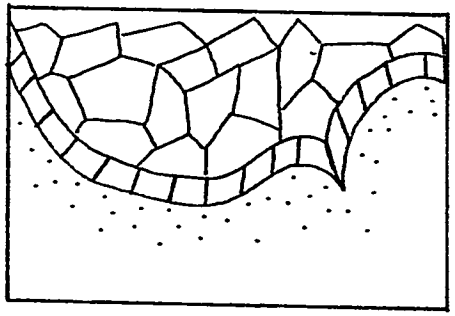


Isopachous Bladed

Submarine



Sparry Calcite



Ferroan Spar

Nonmarine

submarine in origin. These are radial-fibrous, isopachous-fibrous, isopachous-bladed, and perhaps a micritic cement (fig. 42).

Radial-Fibrous Cement. The radial-fibrous cement found in the Cipit boulders occurs as hemispherical nodules composed of fibrous crystals (fig. 43, 44). In thin-section the cement crystals appear as fan-shaped arrays. Maximum lengths of the fans range from less than 0.5 mm to several centimeters. In polished slabs, the radial-fibrous cement is light brown to greyish brown in color (fig. 40D), apparently resulting from numerous small inclusions. These inclusions are easily visible in thin-sections and are present as very small equant blebs or elongate needles (fig. 45).

The radial-fibrous cement described here is similar to submarine botryoidal aragonite detailed by Ginsburg and James (1976) and the submarine radial-fibrous cements described from the West Texas-New Mexico Permian Reef by Babcock (1977) and Yurewicz (1977).

Several lines of evidence lead to the conclusion that the radial-fibrous cement of the Cipit boulders is submarine in origin. First, the crystal forms of the radial-fibrous cement suggests that the fan-shaped arrays were originally composed of aragonite. Although the cement fans are now either low-Mg or ferroan calcite, the origin crystal outlines have been retained. The crystals are elongate

Figure 43. Radial-fibrous cement.

A) Radial-fibrous cement, left, encrusted by dark algal laminations. Radial-fibrous cement has been replaced by a mosaic of equant sparry calcite. Scale bar - 1.0 mm. Thin-section C-186.

B) Radial-fibrous cement fans that have retained their fibrous character. Individual cement fans are separated by thin films of micrite. Scale bar - 1.0 mm. Thin-section c-1b.

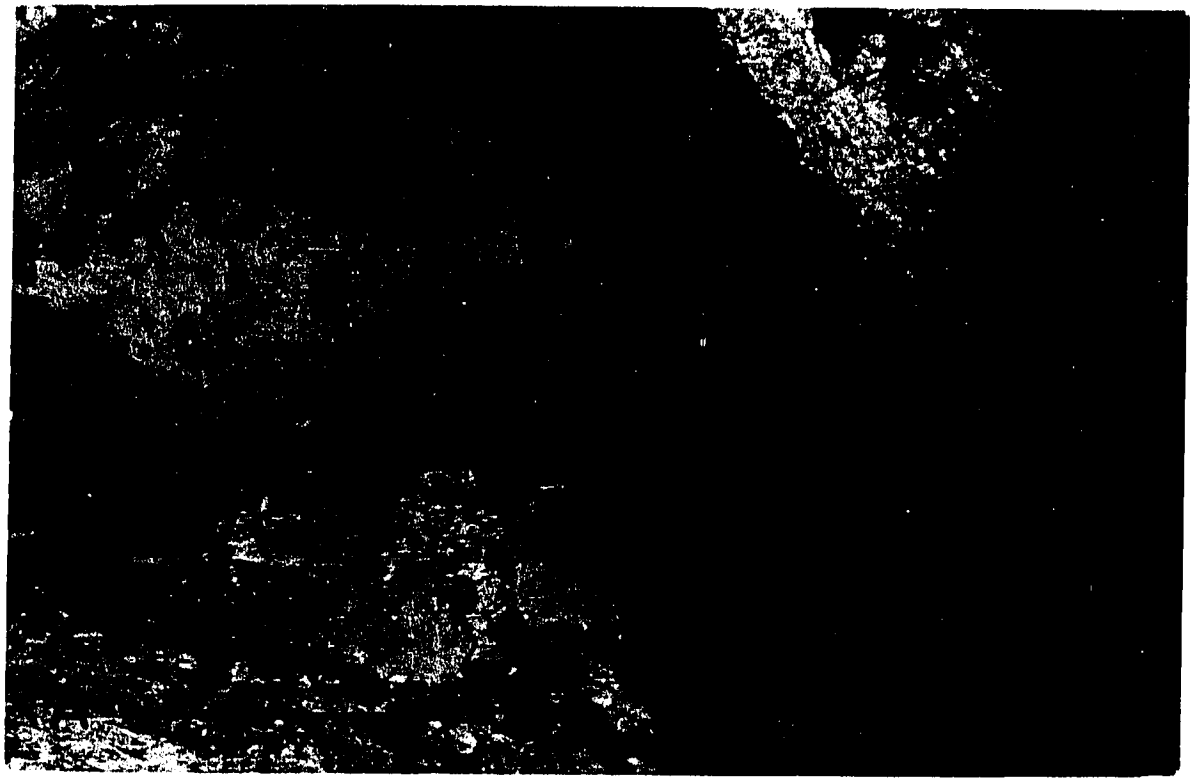


Figure 44. Radial-fibrous cement fans, interlayered with isopachous-fibrous cement, coating the wall of a cavity in a boundstone.

RADIAL-FIBROUS CEMENT FANS

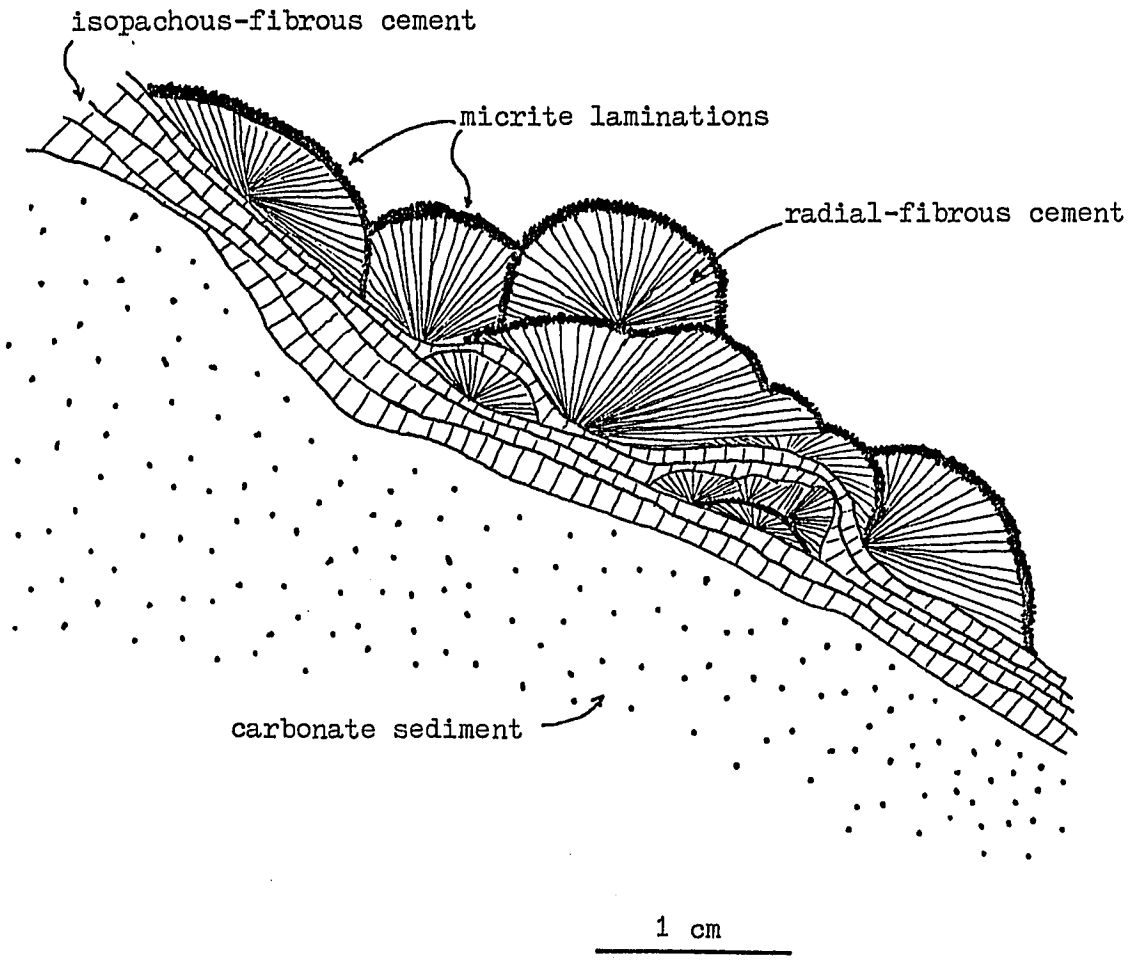


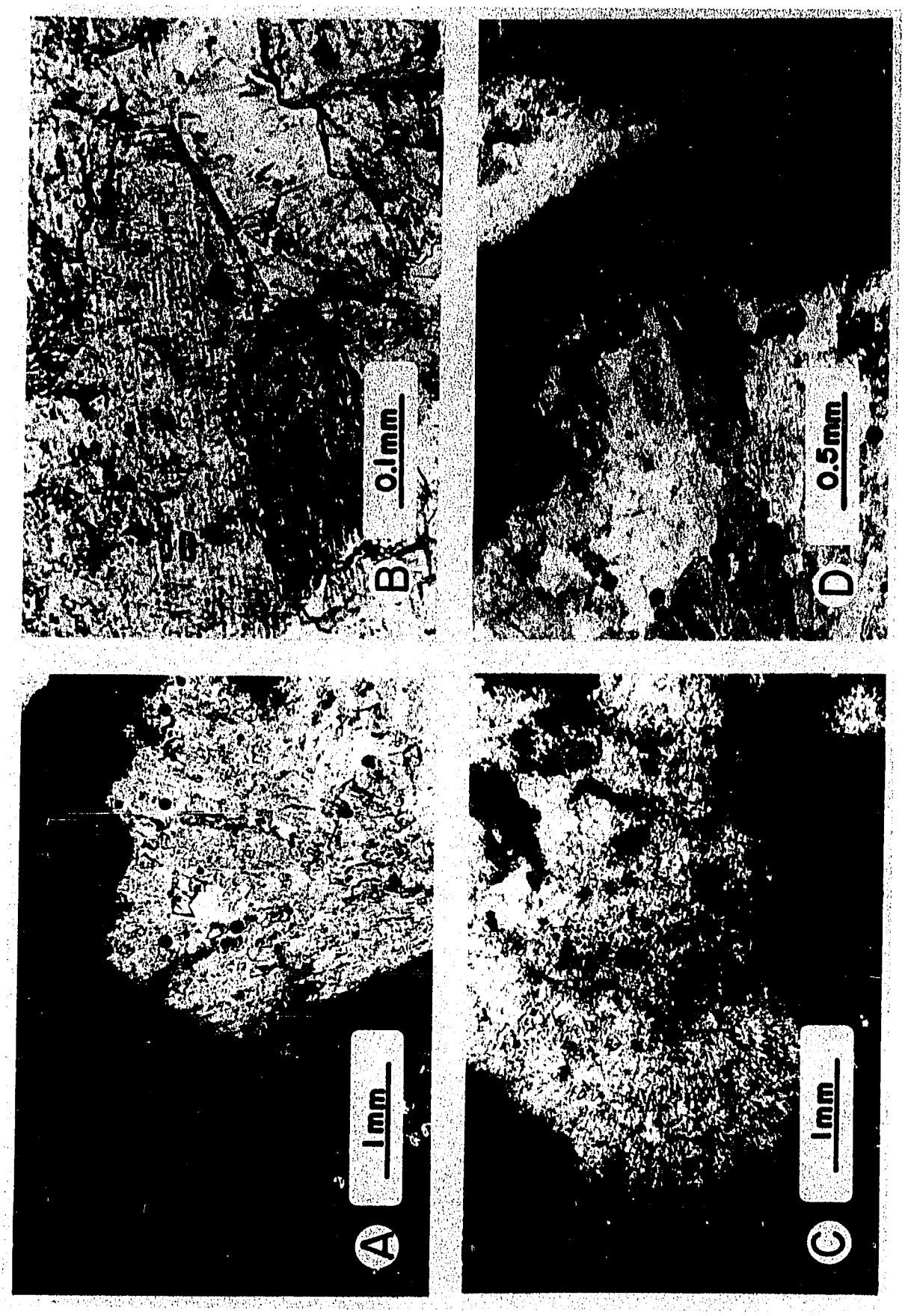
Figure 45. Radial-Fibrous Cement

A) Small radial-fibrous cement fan presently composed of equant low-Mg calcite. Note square ends of crystals and their slightly feathery terminations. Thin-section C-186.

B) Close up of equant calcite grains within a radial-fibrous cement fan. Note the linear inclusions within the calcite. These are thought to be remnants of the original aragonite trapped within the replacing calcite. Thin-section C-186.

C) Radial-fibrous cement with peloid inclusions. The outer edges of the cement are coated with laminated micrite. Thin-section C-21.

D) Radial-fibrous cement fans that has been replaced by equant sparry calcite. Note the square terminations of the cement and the coating of algal-laminated sediment. Cross-nicols, thin-section C-186.


A
1mm
B
0.1mm
C
1mm
D
0.5mm

and their terminations are square-ended and somewhat feathery (fig. 43, 45). Folk and Assereto (1976) have shown that features similar to these probably characterize aragonite cement that has been inverted to a more stable calcite phase. Second, the radial-fibrous cement contains numerous, very small (a few microns wide, tens of microns long) needle-shaped inclusions (fig. 45). These inclusions show higher relief in one crystallographic direction than the surrounding calcite host. It is possible that the inclusions represent remnants of aragonite left behind after incomplete conversion to calcite. The needle-like inclusions are elongated parallel to the long axis of the cement fans (fig. 45). Because aragonite cements are precipitated in only a few environments (the submarine environment being one of the most important), the original aragonitic composition of the radial-fibrous cement can be used as supporting evidence for a submarine origin of that cement.

The relationships between other components of the boulders and the radial-fibrous cement provide more compelling evidence for a submarine origin of the cement. Numerous examples of peloids included the cement fans (fig. 45) suggest that the cement incorporated the peloids during growth. The peloids are believed to be marine in origin. To be incorporated within the cement, the peloids would have to be placed on a crystal growth surface during precipitation of that cement. This is most likely to

Figure 46. Abundant radial-fibrous cement growing around a calcisponge nucleus. Cement fans are separated by intervals of laminated micrite. Thin-section C-34.

to happen in the submarine environment.

The radial fibrous fans are commonly coated with layers of micrite with algal laminations (fig. 43, 46). Two possibilities are suggested to explain this relationship. First, the radial fibrous cement was growing on the seafloor and provided a substrate for algal encrustation. Second, the cement nodules were growing just below the sediment-water interface and were deforming soft, pliable algal mats by their growth. In either case, cement precipitation took place at the time of sediment deposition close to the sediment water interface.

In addition, the radial fibrous cement is in places intercalated with other cements believed to be submarine in origin (see below).

Radial fabrous cement is an important component of many Cipit boulders, particularly those composed of algal submarine-cement boundstone.

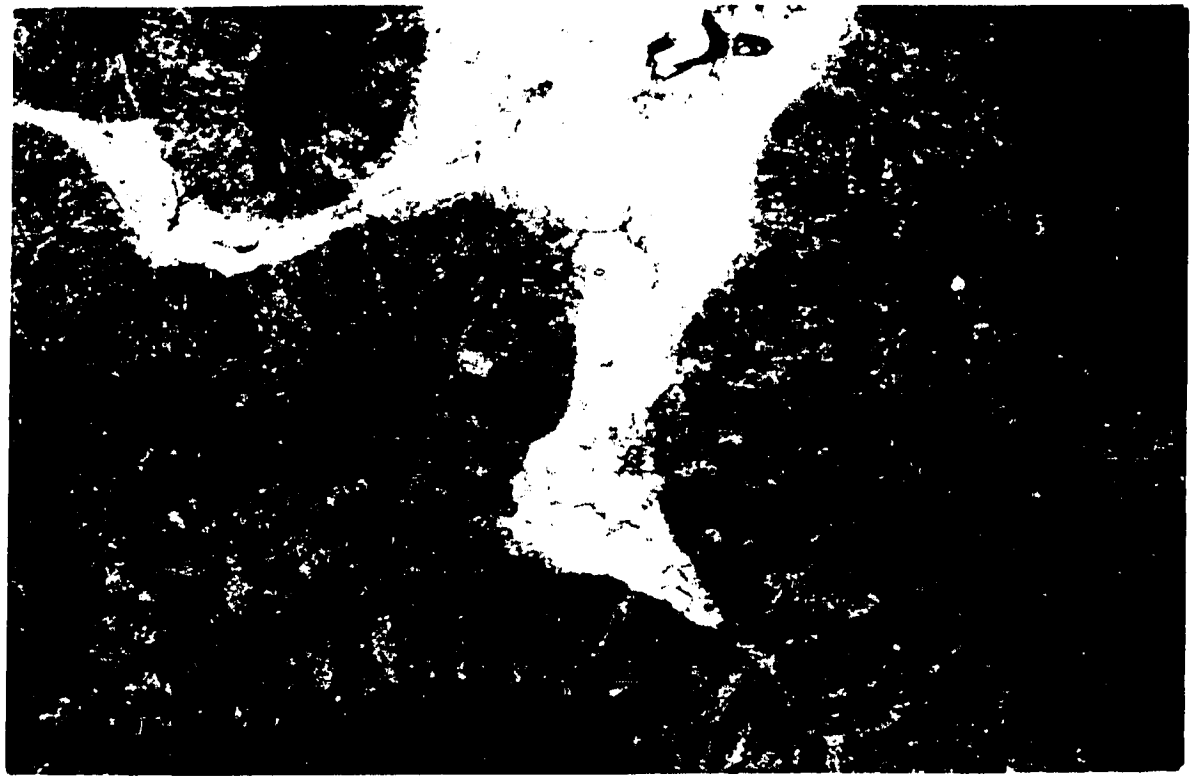
The amount of radial fibrous cement varies from boulder to boulder and is not evenly distributed through individual bounders. In some samples radial fibrous cement forms well over 50% by volume of the rock (fig. 46).

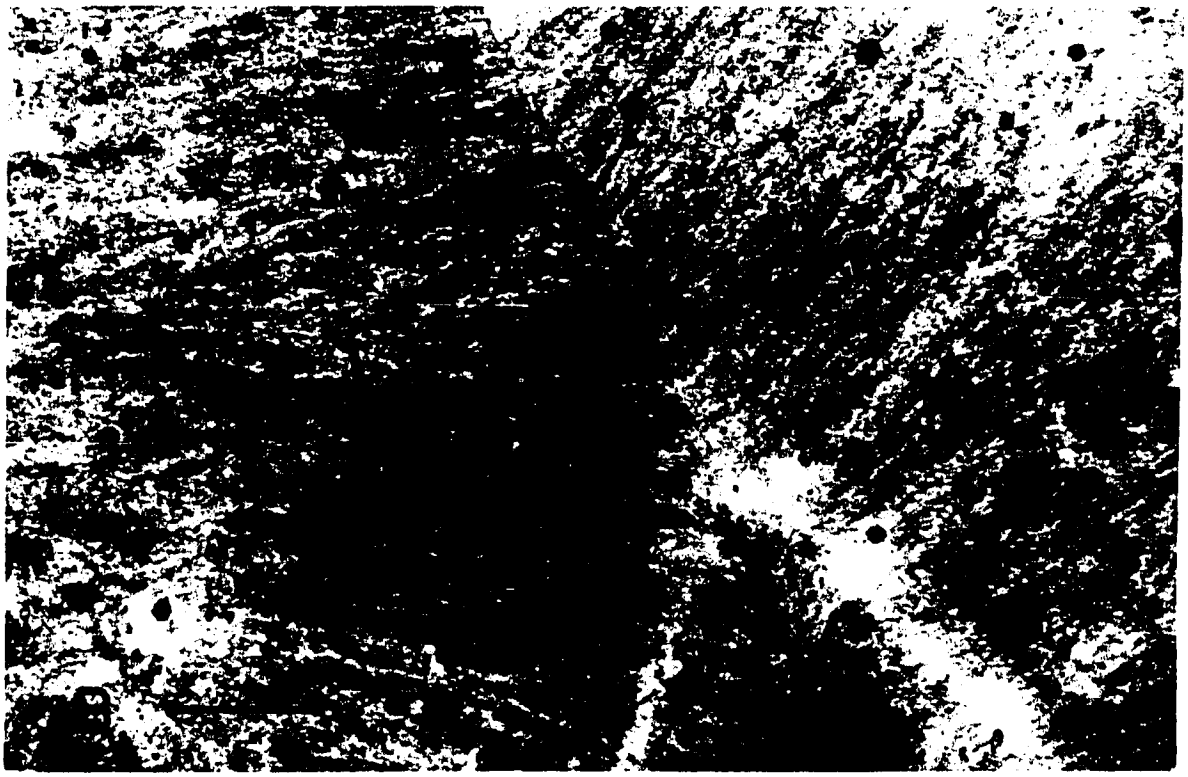
Isopachous-fibrous Cement. Isopachous fibrous cement is formed by fibrous crystals that line or coat cavity walls and grains with a uniform thickness of cement (fig. 47A). The lengths of individual fibrous crystals range from 0.5 to 2.5 mm long. Commonly several bands or generations

Figure 47. Isopachous-fibrous cement

A) Inclusion-rich isopachous-fibrous cement lining the walls of a small cavity. Note the uniform thickness around the cavity. Scale bar = 1 mm. Thin-section C-8.

B) Close-up of inclusion-rich isopachous-fibrous cement illustrating the fibrous habit of the crystals and a straight compromise boundary between bundles of crystals growing from opposite walls. Dark spots are bubbles produced during the thin-section process. Scale bar - 0.01 mm. Thin-section RZ-2.





of isopachous cement are superposed creating sequences up to 2 cm thick (fig. 39D). In cross-section, bundles of fibers have a ragged interlocking appearance (fig. 48B). In hand specimen, the cement is mildy white in color (fig. 39D) and in thin-section it is a dirty brown (fig. 47). Both colors are the result of extremely abundant microscopic inclusions. These inclusions appear to be both liquid and unidentified solid phases. The density of inclusions is not uniform throughout the isopachous-fibrous cement, but increasing in some places (fig. 48A) and decreasing in others. The isopachous-fibrous cement is presently non-ferroan low-Mg calcite.

This cement occurs in several types of cavities within the boulders. The most common occurrence is as linings of cavities several millimeters to several centimeters across. This type of cement also occurs as the binding agent between peloids, lithoclasts, and skeletal grains in some cases (fig. 49A), and can as well be found lining intraparticle cavities (fig. 49B).

The isopachous-fibrous cement is believed also to be submarine in origin. In several examples layers of isopachous-fibrous cement are interlayered with intervals of normal marine sediment (fig. 50) that includes peloids, agglutinating foraminifera and bivalves. The isopachous-fibrous cement was also occasionally observed to alternate with radial-fibrous cement, also believed to be marine. Limited isotopic data support a marine

Figure 48. Isopachous-fibrous cement

A) Isopachous-fibrous cement lining the walls of a depositional cavity. The cement becomes more inclusion-rich toward its outer edges. The final cement generation in the cavity is one of ferroan spar. Scale bar - 1 mm. Thin-section RZ-2.

B) Cross-section through bundles of isopachous-cement crystals. Note the ragged interlocking texture. Scale bar - 1 mm. Thin-section G-98.

A

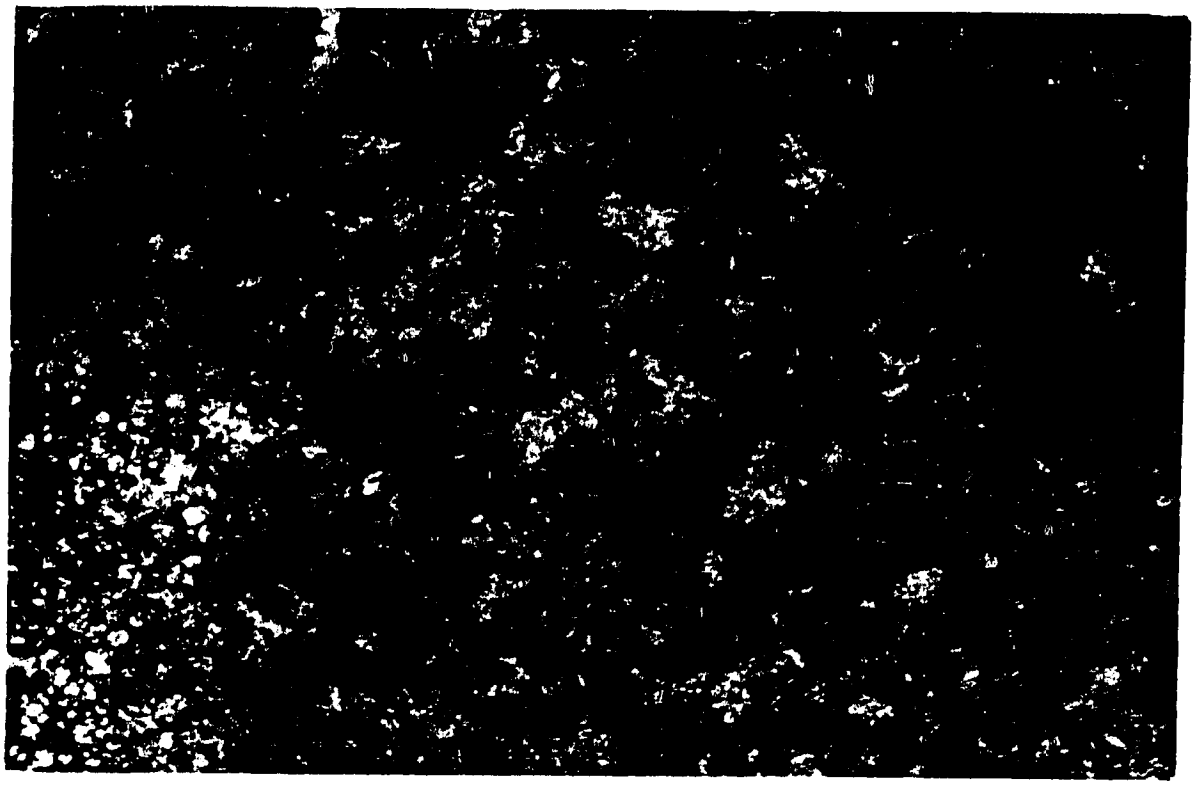


Figure 49. Isopachous-fibrous Cement.

A) Isopachous-fibrous cement filling pore-space between peloids and skeletal grains of a carbonate grainstone. Thin-section C-68.

B) Isopachous-fibrous cement lining the intraparticle porosity of a calcisponge. Thin-section C-174.

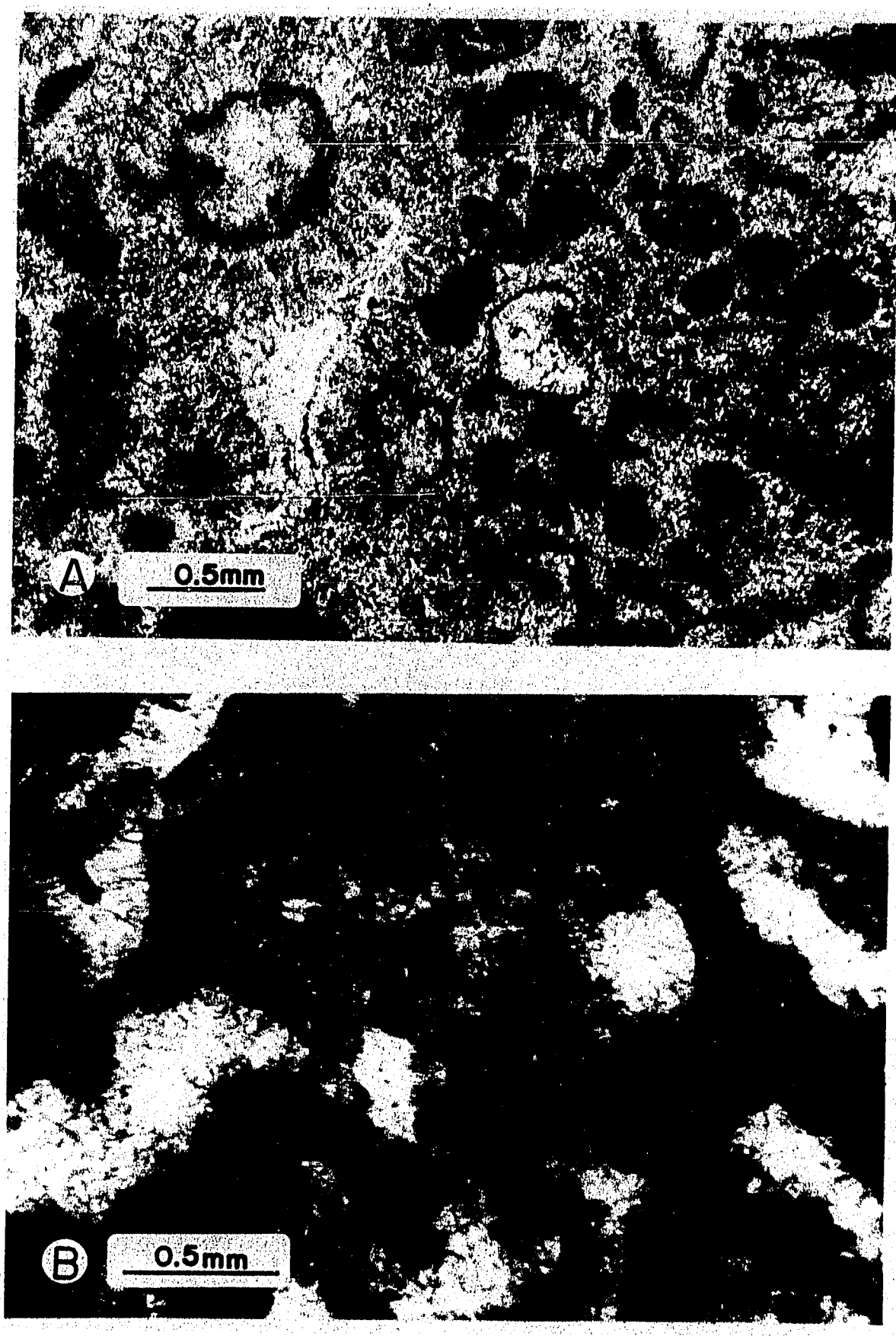

A
0.5mm
B
0.5mm

Figure 50. Isopachous-fibrous cement lining a depositional cavity. Several generations of isopachous-fibrous cement are present in this thin-section. Note particularly the alternation of isopachous-fibrous cement and apparently normal marine peloidal sediment. Light areas near the top of the picture are radial-fibrous cement. Dark area in the center is a final cavity fill composed of dolomite grains and amorphous iron oxides. Thin-section RZ-2.

1mm

origin for both types of cement (see below).

The isopachous-fibrous cements are not as abundant in the Cipit boulders as the radial-fibrous cements but are still common. Usually they form only a small percentage of the volume of a given sample.

Isopachous-Bladed Cement. The isopachous-bladed cements are composed of crystals with a length-to-width ratio of 1½:1 and 6:1 (Folk, 1965). The isopachous-bladed cements are clear and composed of nonferroan calcite. This type of cement occurs as linings on various grain types in packstones and grainstones.

The isopachous-bladed cements are believed to be submarine in origin also, but the evidence is not as clear as for the two previously described cement types. The conclusion that the bladed cements are submarine is based on relationships with other components of the boulders. Where documented submarine cements occur in the same sample as isopachous bladed cement, the bladed cement seem to be either older or synchronous with the marine cements. That is, a bladed cement binds grains together in a framework with a variety of cavities, which are in turn lined with marine cements.

The isopachous bladed cements are quite subordinate in the Cipit boulders and were only occasionally encountered.

Micritic Cement?. Submarine cements composed of micritic high-Mg calcite have been described by several authors (see, for example, Ginsburg and others, 1971; Schroeder, 1972), and are no longer considered uncommon in reefal environments. It is possible that part of the micrite that occurs in the Cipit boulders formed as a submarine precipitate. Evidence supporting this hypothesis is very limited, however. In one thin-section, micrite was found lining the walls and ceiling of a small cavity that contained peloidal sediment on its floor. The micrite coating was of fairly constant thickness and could be interpreted as a type of cement. Other interpretations are also possible, and with the shortage of positive evidence it is not possible to state conclusively that some of the micrite was deposited as a submarine cement.

Nonmarine Cements

Two important cement types presented in the Cipit boulders are thought to be nonmarine in origin. These cements are both composed of sparry calcite, but one is low-Mg calcite and the other is ferroan calcite (fig. 42).

Low-Mg sparry Calcite Cement. Clear sparry low-Mg calcite cement is a common cement in the Cipit boulders and occurs in several different sites. This type of cement is found replacing fossil material, filling intraparticle porosity, and as the last or next-to-last cement generation filling interparticle voids (fig. 51C). The sparry

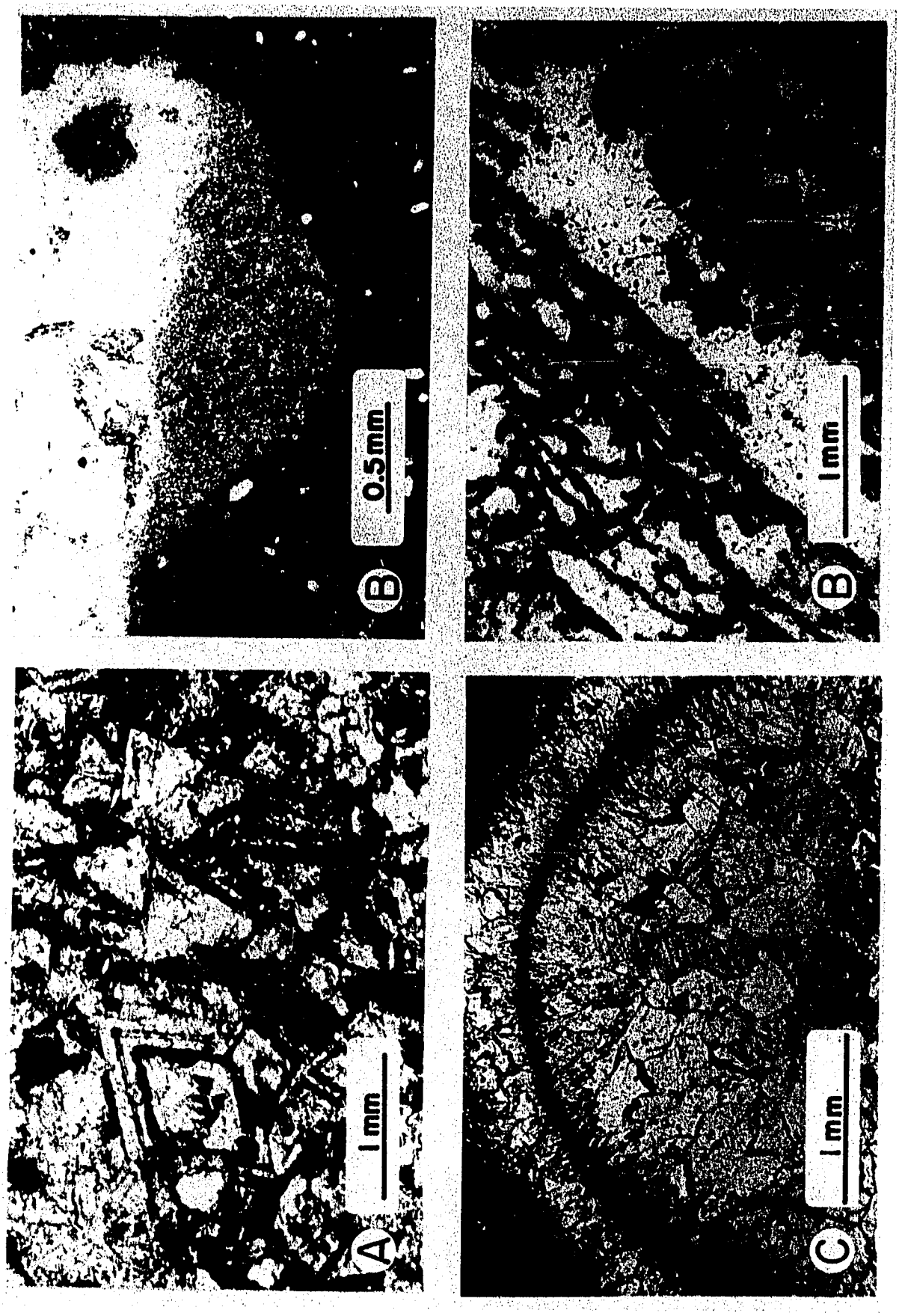
Figure 51. Diagenetic features

A) Zoned iron-rich dolomite rhombs replacing a coral fragment. Within the sample, dolomite occurs as isolated rhombs and as clusters of rhombs within the fine-grained matrix. Thin-section C-86.

B) Crystal silt perched in a solution cavity within an algal boundstone. The crystal silt is composed of rounded dolomite grains. Thin-section C-120.

C) Equant spar filling on intraparticle void, in this case, the chamber of a gastropod. Thin-section C-37.

D) Equant spar filling interparticle void-space between detrital grains and Cladograpsanella filaments. Thin-section C-13c.


A
1 mm
B
0.5mm
B
1 mm
C
1 mm

calcite is usually equant but can also occur as an acicular or bladed cement. The characteristics of the crystal bouldaries (Bathurst, 1971, p. 417-425) show that most of the low-Mg calcite is a void-filling cement, although some may represent a neomorphic replacement of earlier carbonate.

Ferroan Sparry Calcite. The last generation of cement in the Cipit boulders examined during this study is formed by ferroan calcite (fig. 51D). The presence of iron in the cement was determined by staining the samples with a potassium ferrocyanide solution (Evamy, 1969). A limited amount of atomic absorption data show iron contents range from a low of 0.39 wt percent Fe to a high of 1.15 wt percent Fe. With the exception of iron content, the characteristics of the ferroan calcite cement are identical with the low-Mg sparry calcite cement.

Geochemistry of Cements

To assist with the interpretation of cement origins, a limited number of cement samples were analyzed for iron, strontium, and carbon and oxygen isotopic composition. The difficulties experienced in obtaining a pure sample of sufficient volume of the different cement types proved to be the limiting factor in these analyses. The isotope analyses were performed at the University of Texas Marine Science Laboratory at Port Aransas, Texas. The atomic absorption analyses were provided by Dr. Rudy Schwarzer of Texas Southern University. The data are

presented in figure 52.

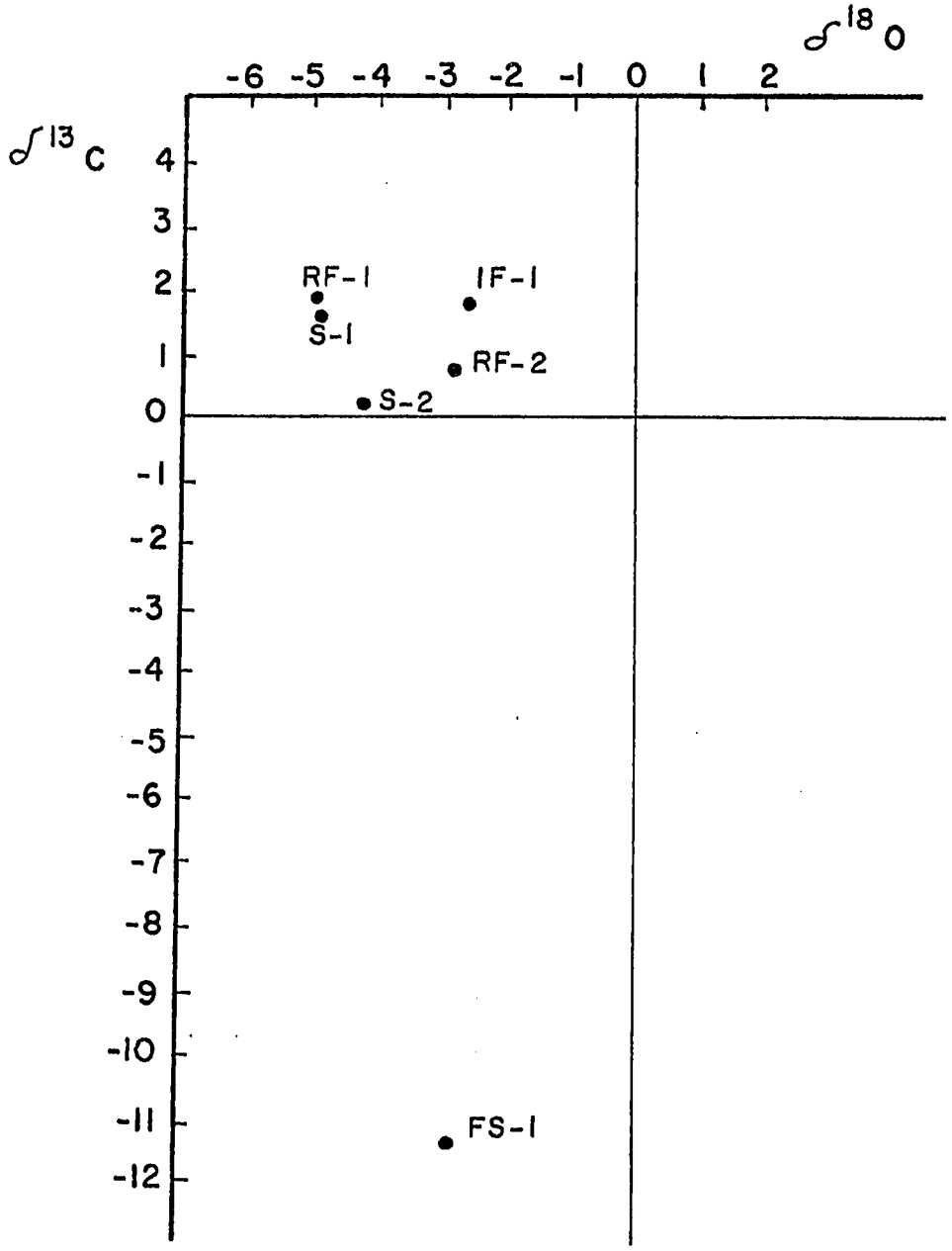
Interestingly, the isotopic compositions of all the samples except the ferroan spar FS-1 plot within the isotopic range typical of marine limestones (Hudson, 1977). Petrographic evidence shows, however, that the radial-fibrous cements and probably the isopachous-fibrous cements have undergone a mineralogic change that most likely included a solution-reprecipitation reaction. If so, the reprecipitated cement should have rapidly equilibrated with the precipitating solution, which is not believed to have been marine. It appears that the submarine cements have retained their marine isotopic signature through the various diagenetic events which have affected them. This is understandable for the carbon isotopic composition (carbon reservoirs in most pore solutions are small), but less easily explained in the case of the oxygen isotope (Hudson, 1977). Sample FS-1 is quite depleted in heavy carbon, and probably formed in an organically influenced environment.

In the samples analyzed, strontium content varies from 241 ppm in the nonferroan calcite spar sample to 560 ppm in an isopachous fibrous cement. These values are within the range of stronium content shown by most ancient limestones but far lower than the 8,200 ppm predicted for inorganically preciptated aragonite in equilibrium with the seawater at 27°C (Kinsman, 1969).

The trace element data presented in figure 52 is

Figure 52. Stable isotope and trace element data from selected samples of carbonate cements from the Cipit boulders. Isotopic compositions are relative to the PDB_I standard. RF-1, radial-fibrous cement; RF-2, radial-fibrous cement; IF-1, isopachous-fibrous cement; S1, slow-Mg sparry cement; S-2, low-Mg sparry cement; FS-1, ferroan sparry cement.

ISOTOPE AND TRACE ELEMENT DATA



SAMPLE	$\delta^{13}C$	$\delta^{18}O$	Fe (wt %)	Sr (ppm)
RF-1	1.89	-5.04	1.15	310
RF-2	0.80	-2.98	0.39	510
I-F-1	1.82	-2.65	0.12	560
S-1	1.76	-5.01	—	—
S-2	0.14	-4.14	0.02	241
FS-1	-11.37	-2.88	0.57	431

too meager to allow binding conclusions to be made, but does support the following hypotheses: 1) the transformation of original aragonite and probably high-Mg calcite to low-Mg and ferroan calcite resulted in the loss of strontium to circulating pore fluids, and 2) the concentrations of strontium and iron in the resultant calcite indicate that these pore fluids were not marine (see Scheres, 1977, for a discussion of trace element concentrations in skeletal material and carbonate cements from selected Cipit boulders).

Sites and Sequences of Cementation

Submarine cementation took place in two locations along the buildup margins, within cavities constructed in lime boundstones, and in particulate lime sediment, either at or just below the sediment-water interface. Formation of radial-fibrous cement occurred in both areas, the cement is found lining cavities and either deforming or being encrusted by algal laminations. The isopachous-fibrous cement primarily occurs as a cavity lining. This cement was probably precipitated in a loosely connected pore and cavity system slightly removed from the sediment-water interface. The sites of formation of isopachous-bladed and micritic cement (if it occurs) are less certain. Tidal pumping and wave action along the buildup margins provided the water exchange necessary for cementation.

The two submarine cements were found associated with

each other within construction cavities in algal boundstone (fig. 39D). Where the two cements occurred together, they form an alternating sequence of radial-fibrous cement, then multiple generations of isopachous-fibrous cement interrupted by radial-fibrous fans, followed by a final generation of isopachous-fabrous cement (fig. 39D).

The low-Mg and ferroan calcite sparry cements formed within void space in an already lithified rock. The low-Mg calcite preceded the ferroan spar, which was the final cement to form in the Cipit boulders.

Neomorphism

The term neomorphism was defined by Folk (1965) to include all transformations between a mineral and itself or a polymorph, regardless of the size of the new crystals or whether the process took place by inversion or recrystallization. Presently, the vast majority of carbonate in the Cipit boulders is either low-Mg calcite or ferroan calcite. Many of the skeletons were originally aragonite (Scherer, 1977) but have inverted to low-Mg calcite and have been changed to ferroan calcite. Evidence presented here and theoretical consideration of crystal growth (Folk, 1974) strongly suggest that the submarine cements were originally composed of aragonite (radial-fibrous cement) or high-Mg calcite (possibly isopachous-fibrous cement). These too have inverted to a more stable calcite.

Most of the radial-fibrous cement has been

neomorphosed to a mosaic of equant sparry calcite (fig. 45), although examples that have retained a fibrous crystal habit are common (fig. 43). The isopachous-fibrous cement, on the other hand, has retained its fibrous habit, but is now composed of low-Mg calcite.

Complete skeletons and skeletal fragments from boulders in the Western Dolomites all have been subjected to some degree of aggrading or degrading neomorphism. This is in sharp contrast with the well-preserved skeletal material recovered from the San Cassiano formation in the Eastern Dolomites (Wendt, 1974; Scherer, 1977).

Recrystallization of micrite to microspar has taken place, but seems to be minor.

The sparry cements show no sign of neomorphism.

Dolomite

The Cipit boulders escaped the pervasive Late Triassic dolomitization that had such a profound affect on the carbonate buildups. However, dolomite does occur in some of the boulders, both as a replacement mineral and as detrital grains filling solution cavities.

Euhedral dolomite rhombs occur sporadically in many boulders, and replace both skeletal material and detrital carbonate. The rhombs are zoned (fig. 50A) and are ferroan dolomite. Maximum crystal size is about 1 mm.

The detrital dolomite occurs as crystal silt in solution cavities (fig. 50B), and is also ferroan dolomite.

Dolomite grains that compose the crystal silt are rounded.

The fact that many solution cavities are filled or partly filled with ferroan dolomite shows that dolomite was present in the carbonate buildups before karsting and solution took place or, in other words, before the boulders were produced. This relationship shows that small amounts of ferroan dolomite were formed early in the history of the buildups and that this dolomite was concentrated as an insoluble residue during karsting episodes, then transported and deposited within the limestone as crystal silt.

THE MIDDLE TO UPPER TRIASSIC BUILDUP MARGINS

Origin of the Cipit Boulders

The rock types represented in the Cipit boulders show that the overwhelming majority of boulders were derived from buildup margin facies. The rock types that represent the interior facies of the buildups have been well-documented and are distinctive; they are composed of dasycladacean algae packstones/grainstones and subtidal-intertidal-supratidal cyclic sedimentary rocks (Bosellini and Rossi, 1974). These rock types are poorly represented in the Cipit boulders. The foreslope facies of the buildups is also well known, and consists of cemented breccias and conglomerates with varying amounts and types of matrix. These rocks are also rarely found in the Cipit boulders.

The rock types that commonly occur in the boulders are various boundstones and associated rock types, peloidal packstones/wackestones, bioclastic wackestones/packstones. The fauna present in these rock types indicate normal marine conditions (see below), and the textures (e.g. organic and submarine-cement boundstones) strongly suggest that the buildup margins furnished the boulders. The above lines of evidence lead to this conclusion.

The degree of rounding, oxidized surface rinds, pitted and corroded surface textures, and abundance of solution features within the boulders show that the boulders underwent varying degrees of karsting, and probably had at least a

short subaerial history. If this is so, the buildup margins must have been exposed several times during sedimentation of the La Valle and San Cassiano formations. Independent evidence for periods of Triassic karsting has been supplied by Cros and Lagny (1969), Bosellini and Rossi (1974), and Bosellini and others (1977).

Two factors worked in combination to expose the Dolomite buildups, eustatic sea level changes and tectonic activity. Of the two, tectonic activity was most important and led to the localization of individual buildups, and provided a mechanism to create distinctive histories individual buildups (see section on the origin and location of Dolomite buildups). Renewed episodic faulting associated with the cessation of volcanism produced steep scarps, from which the tremendous megabreccia wedge was derived.

Once the boulders were in the basin, the surrounding sediments protected them from further alteration (particularly dolomitization) and preserved them for future study.

The Significance of Organisms

Although the detailed paleontology and paleoecology of the Cipit boulders were not the primary objectives of this study, these aspects provide some interesting information on the environments of the Triassic buildup margins.

First, a diverse group of taxa is represented in the Cipit boulders. Phyla present include thallophyta,

porifera, coelenterata, protozoa, brachiopoda, mollusca, echinodermata and several types of problematica. Leonardi (1967, p. 255-259) presented a tremendous species list for the Ladinian-Carnian carbonates. Although he apparently lumped all of the material from the Ladinian-Carnian facies together, the list is still impressive, and many of the organisms probably occurred along the buildup margins. The most common fossils of the Cipit boulders are blue-green algae, Tubiphytes, calcisponges, corals, crinoids and echinoids, and foraminifera. The types of organisms and their diversity show that the majority of Cipit boulders were deposited in normal-marine tropical waters (Stehli and others, 1967; Yurewicz, 1976).

Second, a large number of the organisms present in the boulders were epifaunal suspension feeders who obtained their food from the water column. The suspension feeders include all the calcisponges, coelenterates, crinoids, foraminifera, and some bivalves. Deposit feeders apparently were not common along the buildup margins. Grazers and browzers were somewhat more abundant, represented mainly by gastropods that lived on the abundant algal growth.

The large number of suspension feeders found in the Cipit boulders suggests that 1) the water column was nutrient-rich, 2) the water was not overly turbid, and 3) the substrate was firm, facilitating attachment of the sessile organisms (Yurewicz, 1974). This supports the conclusion that the buildup margins were the site of

early organic stabilization and submarine cementation.

The Presence of Corals

As stated in the introduction, the presence of corals in the Dolomite Alps has been recognized for a long time. Their recognition has had a profound effect on the models put forth to explain the Triassic buildups. Because of this, it is necessary to comment briefly on the occurrence of corals in the Cipit boulders and on the nature of Middle and Late Triassic corals.

It has been known for a long time that the "Thecosmilia"-like and related corals occurred in a wide variety of depositional environments (e.g. from backreef lagoons to basinal settings), and several mechanisms have been used to explain this diversity of occurrence (see Zankl, 1969). Recently, Stanley (1977) has carefully examined Middle to Late Triassic corals and their modes of occurrence and has arrived at some interesting conclusions. He showed that the coral occurred both with and without associated algae and in shallow- and deep-water accumulations. The scleractinian corals were just beginning to evolve during the first half of the Triassic, and Stanley (1977) concluded that during their early history these corals were ahermatypic; that is they lacked symbiotic zooxanthellae.

As some of the scleractinians became hermatypic, their rates of calcification increased, allowing them to dominate shelf-margin assemblages. The transition from

ahermatypic to hermatypic apparently did not take place until latest Triassic time, and until then scleractinian corals were only subordinate members of the buildup margin assemblages.

Cross-Section Through a Ladinian Buildup Margin

Areas where the transition between the flat-lying internal facies and the steeply dipping flanking facies of the buildups may be seen are rare in the Dolomites. This is precisely the relationship one needs to document to make quality reconstructions of the buildups, but unfortunately few examples are to be found. The area called Pale di San Martino on the southern edge of the field area provides an exception and exposes a cross-section through the margin of a Ladinian buildup.

Pale di San Martino

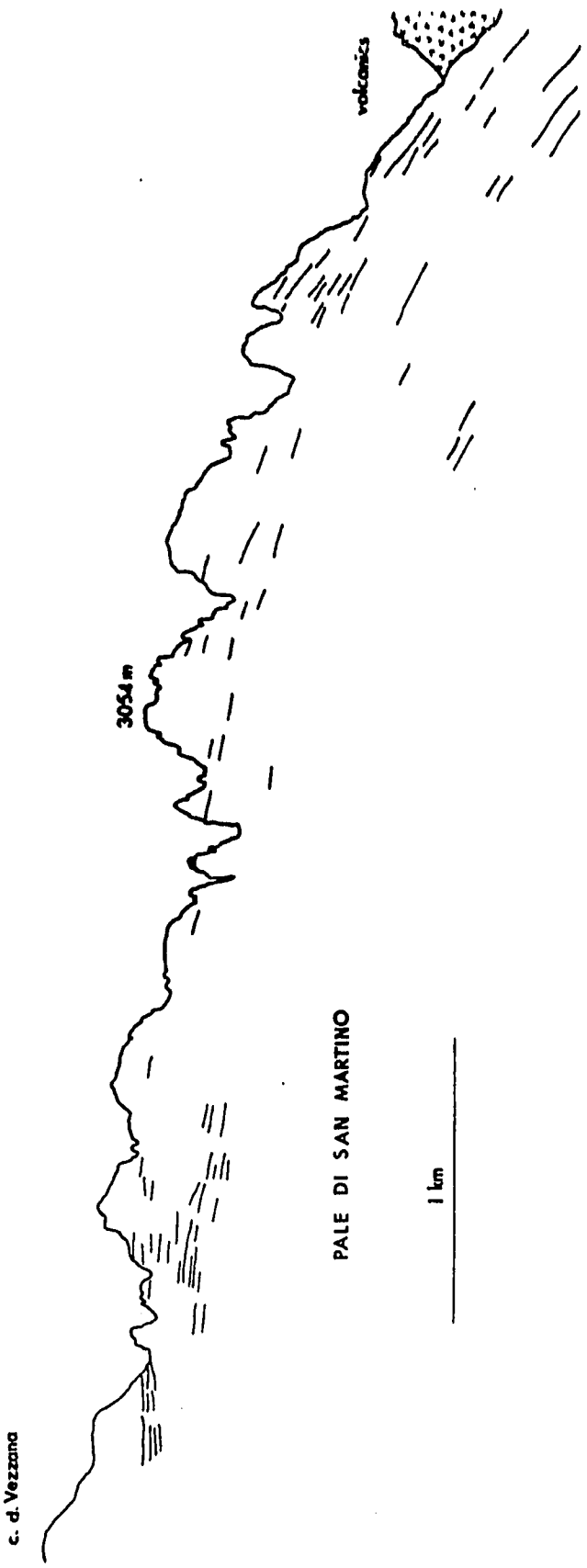
Access is gained to the Pale di San Martino area through the town of San Martino di Castrozza. There, a chair lift and tramway can be used as transportation to the Altopiano delle Pale di San Martino. This area is a fascinating high plateau that exposes the interior of a Ladinian buildup.

Subtidal-supratidal cyclic limestones with tepee structures are well exposed here. In addition, a deep valley terminates the northwestern edge of the Altopiano and on the southeastern side of this valley a cross-section through the buildup margin is exposed. The area has been

mapped as Ladinian Sciliar Dolomite and appears to be structurally undisturbed or perhaps only slightly faulted. The exposure runs from Cima di Vezzana, below which flat-lying cyclic dolomites can be seen, to an area to the northeast where volcanic rocks pinch out against the foreslope facies of the buildup (fig. 53). The exposure is very steep, and the rocks are entirely dolomite.

Figure 53 was constructed from a mosaic of photographs of the area. The short lines represent visible bedding. Apparent bedding planes are easily seen in both the interior part of the buildup (left side of figure) and the steeply dipping flanking beds (right side of figure). The interior beds are either flat lying or dip at a very low angle; the flanking beds dip basinward at apparent angles up to 35°. In the area of transition between the interior and flanking beds, bedding is not as clearly defined. This is the position of the buildup margin. The bedding here is discontinuous and apparent bedding planes less common. The bedding appears to form a gentle transition from the flat-lying facies to the flanking facies. There is no abrupt buildup margin, but rather a zone of gentle curvature. The lack of bedding could be the result of the types of sediments that formed the margin. Organically bound and submarine cemented areas might produce such a bedding pattern.

Figure 53. Schematic drawing (traced from a photomosaic) of a cliff-face in the Pale di San Martino area showing the transition from the flat-lying interior facies to the steeply dipping foreslope facies of a Ladinian buildup. Volcanics at the right are basically flat lying. Note the gentle transtion between the buildup interior and the basin and the overall lack of bedding in the area of the buildup margin.


volcanics
3054 m
PALE DI SAN MARTINO
1 km
c. d. Vezzana

Comparison With Similar Carbonate Buildups

Comparison with carbonate terrains of similar ages and compositions should provide some information that would be helpful in interpreting the Dolomite buildups. The two examples chosen for comparison are the Middle Triassic Wetterstein Limestone of Austria and the Permian Reef Complex of West Texas and New Mexico.

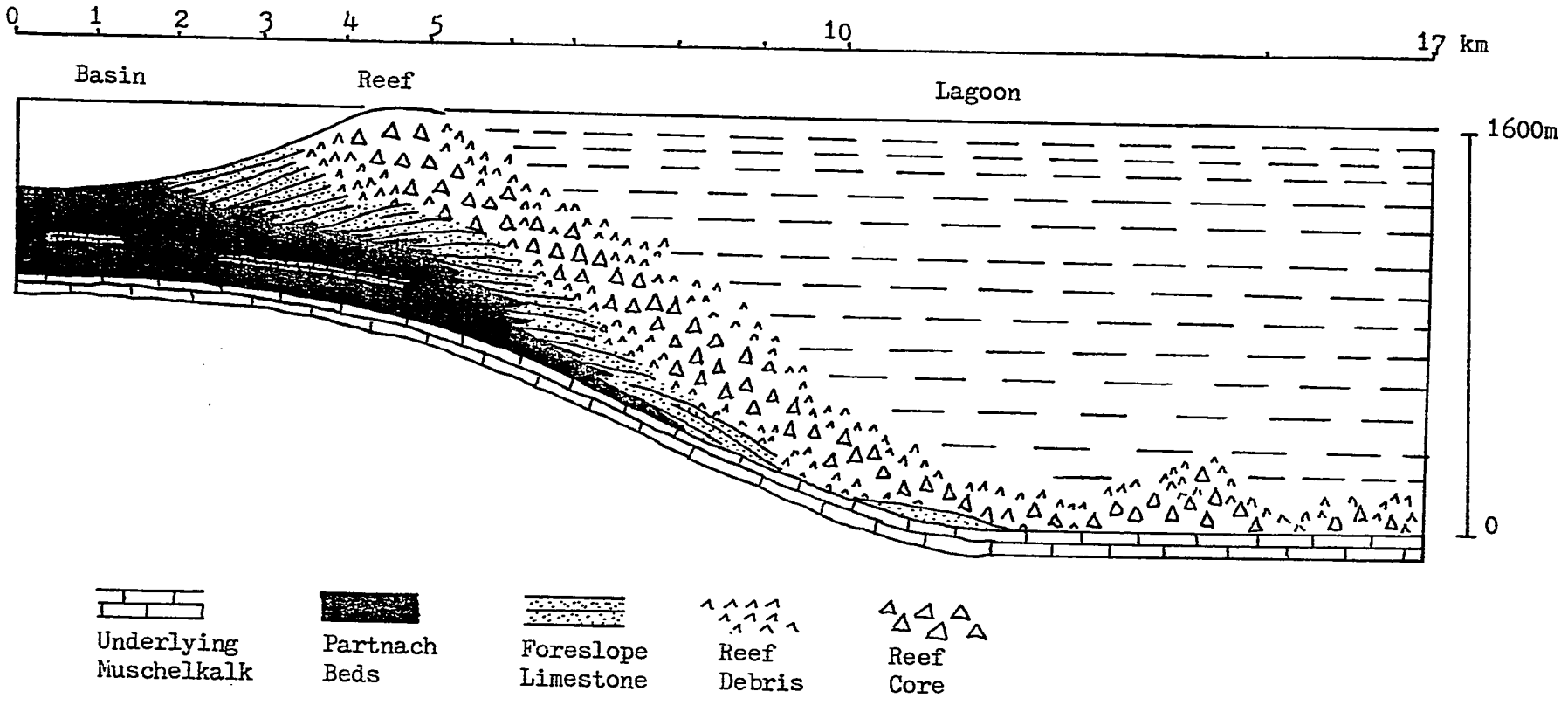
The Wetterstein Limestone

Ott (1967) studied the calcisponges of the Wetterstein Limestone and, in addition, provided information on the distribution of other organisms and facies within the formation. He showed that the Wetterstein buildup consisted of an internal lagoon characterized by the presence of dasycladacean algae, a reef core, and a reef foreslope. The organisms of the reef core were dominated by Tubiphytes obscurus, Sphinctozoan calcisponges, the calcareous algae Cladogirvanella cipitensis, Syringopora vermicularis, the pharentronid Holocoelia toulai, and the delicate corals Calamophyllia cassiana and Margarosmilia sp. (Ott, 1967, p. 64). Blue-green and red algae were also present.

Ott (1967) does not discuss in detail the distribution of boundstones and associated reef-core rock types, but does provide a cross-section through the reef core (fig. 54). His diagram shows a slightly prograding massive reef-core with a fairly abrupt basinward margin and steep slopes.

Figure 54. Ott's (1967) cross-section through the Ladinian Wetterstein Limestone reef of Austria.

CROSS-SECTION THROUGH THE LADINIAN WETTERSTEIN LIMESTONE



The Permian Reef

Recent work by Babcock (1974, 1977) and Yurewicz (1976, 1977) has shown that the Capitan Limestone of the Permian Reef complex was a submerged shelf-edge carbonate buildup bound by organic activity and submarine cementation. The shelf margin was dominated by a diverse fossil assemblage that included abundant calcisponges, Tubiphytes obscurus, the red alga (?) Archaeolithoporella, bryzoans, and several types of problematica.

The submarine cements found in the Capitan Limestone were volumetrically important and assisted in stabilizing the substrate. Yurewicz (1978) recognized three types of submarine cements, radial-fibrous cement, isopachous-fibrous cement, and isopachous-bladed cements.

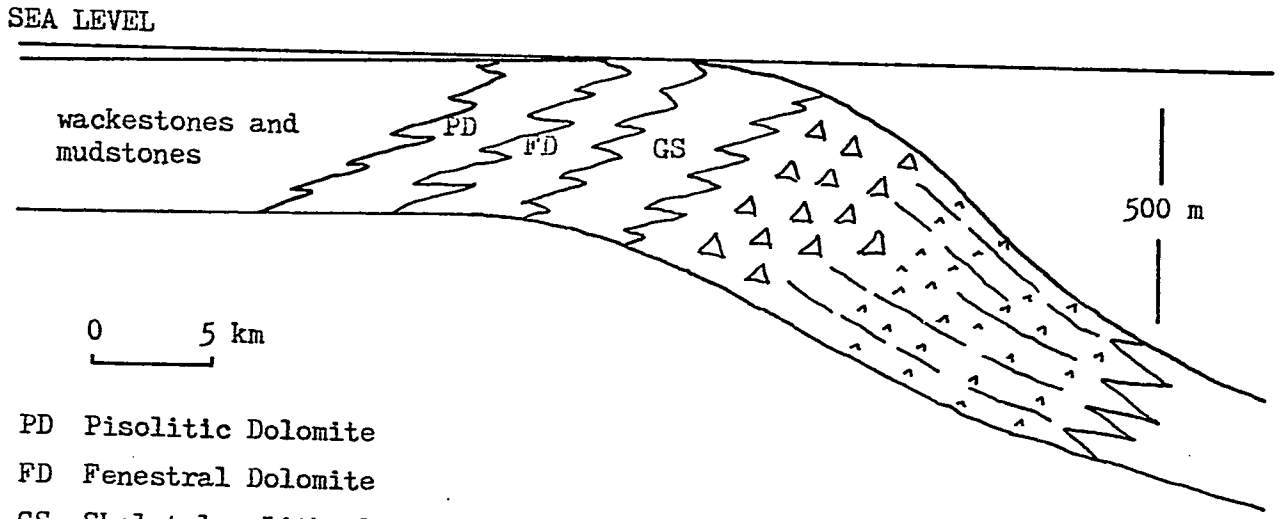
Yurewicz showed that the lower Capitan Limestone was deposited in low-turbulence waters ranging from perhaps 30 m to 200 m deep. Depositional slopes probably ranged from about 15 to 30 degrees (fig. 55). Babcock (1974) indicated that the upper Capitan Limestone was deposited in shallow, moderately turbulent water, showing that the sequence shoaled upward with time.

The short summaries of Wetterstein Limestone and the Permian Reef complex show that both have many similarities with the Dolomite buildups. The faunal contents are strikingly similar. In the case of the Wetterstein Limestone many of the same species found in the Cipit boulders are present. The faunal similarity between

Figure 55. The depositional profile proposed by Yurewicz (1977) for the late Guadalupian Permian Reef. Note the slightly downslope position of the massive boundstone facies and the gentle slopes of the reef.

DEPOSITIONAL PROFILE OF THE LATE GUADALUPIAN PERMIAN REEF

Restricted platform Carbonate high Subtidal platform edge



PD Pisolitic Dolomite

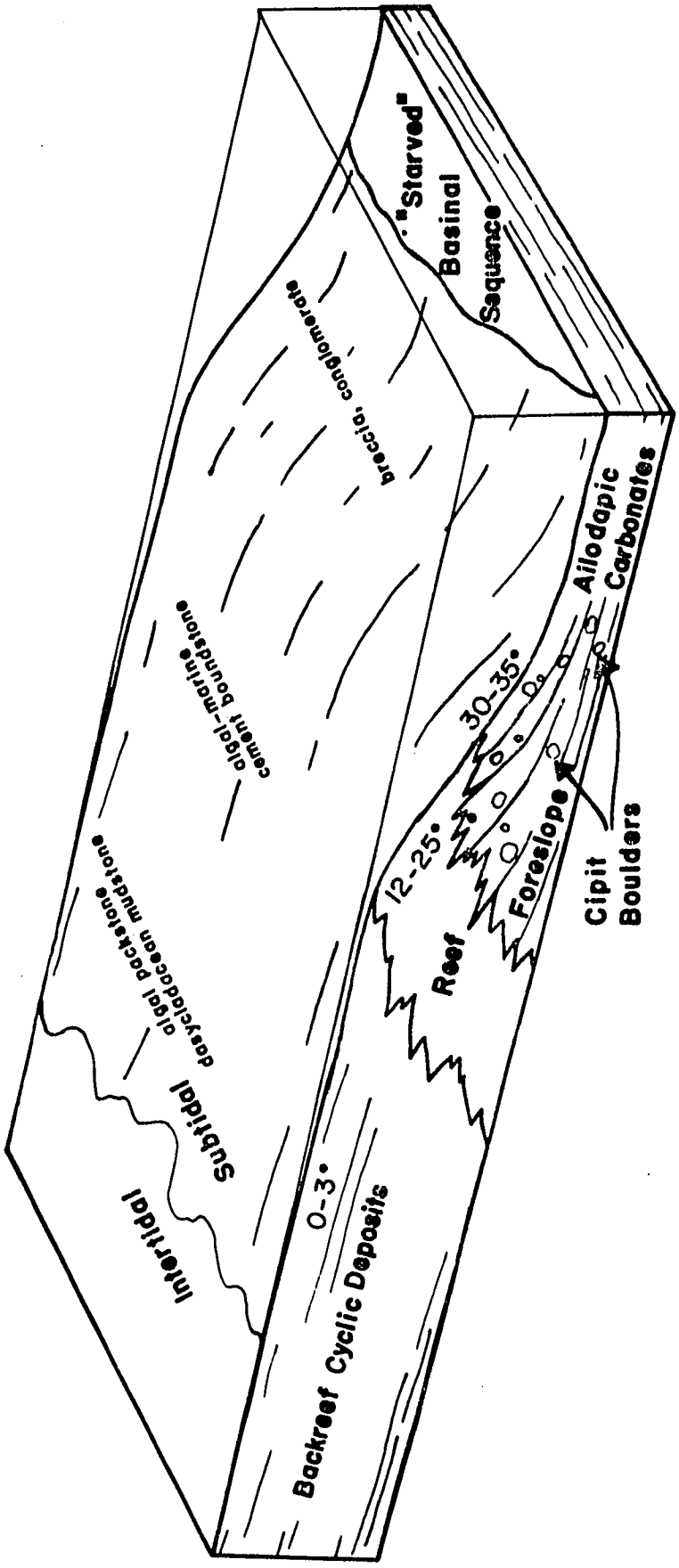
FD Fenestral Dolomite

GS Skeletal - Lithoclastic Grainstones

Reef Core

Reef Debris

Figure 56. Theoretical model depicting the relationships between the various facies and depositional slopes of a slightly prograding, pre-volcanic Ladinian buildup of the Dolomite Alps. See text for discussion.


"Starved" Basinal Sequence
Breccia, conglomerate
Cement boundstone
algal-marine
Allodapic Carbonates
30-35°
12-25°
Foreslope
Reef
Cipit Boulders
algal packstone
dasycladacean mudstone
Subtidal
Intertidal
0-3°
Backreef Cyclic Deposits

the Permian Reef margin and the Cipit boulders ends at the generic level (e.g. same genera of calcisponges) but is still striking considering the amount of time and distance (even pre-drift distance) that separates the two areas. The depositional profile proposed by Yurewicz for the Permian Reef (fig. 55) looks very much like the profile of the Ladinian buildup at Pale di San Martina (fig. 53).

A Model for Some of the Dolomite Buildup Margins

Using all of the information cited above on faunal content, submarine cements, rock textures, and buildup margin profiles, a model for the Dolomite buildup margins can be constructed. This model is summarized in figure 56.

The model depicts a slightly prograding Ladinian pre-volcanic buildup. The buildup interior is formed by extensive subtidal and intertidal flats. Sediments in the interior of the buildup are dominated by cyclic flat-lying dasycladacean-rich packstones/wackestones, stromatolitic mudstones, and a few subaerial horizons.

The foreslope facies of the buildup is composed of conglomerates and breccias with varying degrees of muddy matrix. Clasts are sometimes cemented together by an isopachous fibrous cement (Bosellini and Rossi, 1974, fig. 11). Depositional dips of the foreslope facies are steep and can reach 35 degrees. Downslope and basinward, the foreslope facies passes into a starved basin sequence

composed of carbonate turbidites, nodular limestones, and other pelagic deposits.

The buildup margin consists mainly of boundstones formed by framework-producing and encrusting organisms and, in places substantial amounts of submarine cements. The dominant buildup margin organisms include encrusting blue-green algae, Tubiphytes obscurus, calcisponges, "Thecosmilia"-like corals, and some problematica. The formation of the boundstones did not produce distinct bedding, but instead yielded a more massive unit. The marginal area gently connected the interior and flanking facies. Depositional slopes ranged from about 10 to 25 degrees. Water depths above the marginal facies ranged from perhaps 20m to a 200m maximum.

The actual bound and cemented area probably did not provide the physical barrier necessary to protect the internal lagoons. This barrier was possibly formed by landward carbonate sand shoals, or by a zone of emergent limestone with peritidal features as suggested by Assereto and Kendall (1977).

The Cipit boulders shown in the model (fig. 56) were derived from seacliffs that exposed the algal submarine-cement boundstones during eustatic or structurally induced sea-level drops. Some of the boulders originated during normal buildup growth, but the majority show evidence of karsting indicating some degree of buildup destruction.

CONTROLS ON THE ORIGIN AND LOCATION OF THE DOLOMITE BUILDUPS

In the introductory section on the Dolomite Alps a tectonic event was suggested as a controlling factor over the location of the various Triassic Dolomite buildups. Although this hypothesis is not new (A. Bosellini, 1977, pers. comm.), it needs to be developed further.

The pattern of the Dolomite buildups is unlike that of modern shelf-edge or fringing reefs. Instead of having developed along roughly linear trends, the Dolomite buildups exhibit a patchy distribution with numerous embayed margins and even a few isolated atoll-like bodies (fig. 24). Several lines of evidence suggest that this pattern is controlled by underlying fault-bounded basement blocks.

It is well known that individual carbonate buildups in the Dolomites had separate and individual histories of development. For example, the maximum growth of the Cernera buildup took place in the late Anisian, while the greatest development of the Selia Group occurred during the Carnian, indicating differing rates of subsidence, sedimentation, and growth. In addition, Cros and Lagny (1969) recognized multiple phases of Middle Triassic karst development, but not all of the episodes of karsting are present on all of the Dolomite buildups, nor do they appear to be exactly synchronous everywhere.

The two facts cited above show that many of the buildups had separate histories of subsidence and growth

or exposure and partial destruction. Because of this, eustatic sea level fluctuations can be ruled out as a major cause of Triassic karsting. Instead, tectonic activity is deemed a more logical cause.

As mentioned earlier, there is evidence indicating that a doming event took place near the time of the Scythian-Anisian boundary, creating the present-day thickness pattern of the Lower Triassic Werfiano formation (fig. 4). It is suggested that rupture and subsequent collapse of the domal uplift produced numerous intersecting normal faults and a complex pattern of basement blocks, above which the Dolomite buildups began to develop.

In a series of clay-cake models, Cloos (1939) showed that domal uplifts tend to fracture in trilete patterns with fracture sets separated by roughly 102 degrees. This pattern develops because it presumably involves the least amount of work (Burke and Dewey, 1973). Cloos also showed that with gentle arching a complex pattern of intersecting fractures developed near the junction of the three arms (Cloos, 1939, fig. 17-18, p. 429). All of these fractures represent potential fault planes.

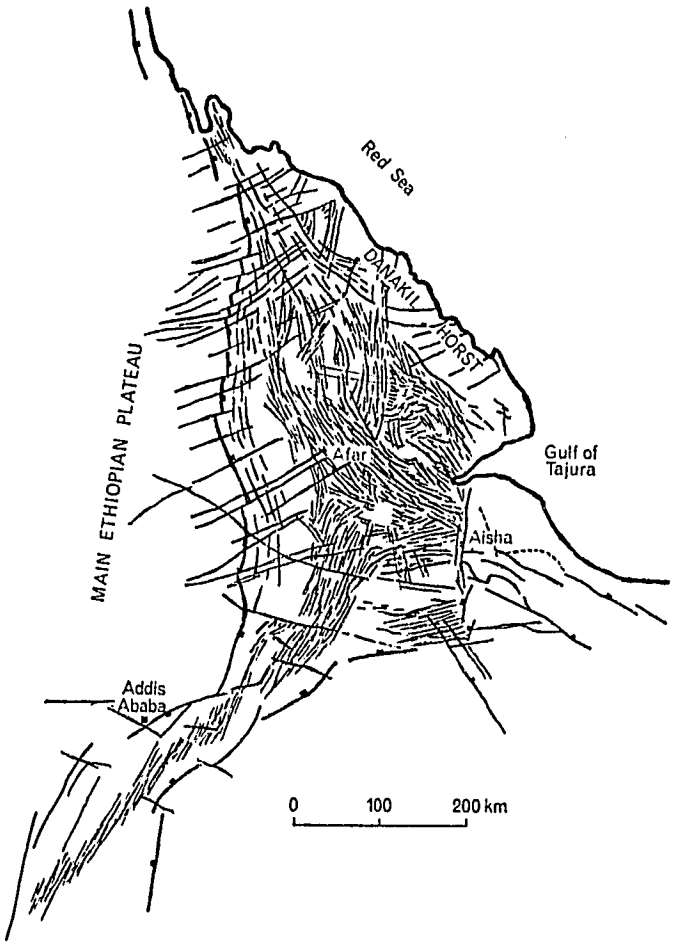
Actively evolving three-armed graben systems, or triple junctions, show fault patterns similar to those of the clay-cake models. The Afar triangle of Ethiopia, for example, is a well known triple junction. The Red Sea, The Gulf of Aden, and the Ethiopian graben system form the three arms, and the Afar area is the center or eye of the

triple junction. At the center of the triple junction the fault pattern is extremely complex (fig. 57). The intersection of the various fault trends has created numerous basement blocks with differing amounts of structural relief (Black, 1973). In the proper marine environment, these basement blocks could provide the starting points for reef development.

In the Dolomites, direct evidence of fault-bounded basement blocks beneath the individual buildups is lacking. However, in addition to the individual buildup histories of subsidence and karsting, two other lines of evidence indicate the presence of pre-existing faults in the area of the buildup margins. First, the Ladinian volcanics are thickest near the margins, suggesting the possibility of fault conduits in that area. Second, the faulting that destroyed the edges of some buildups at the end of the Ladinian stage appears to have been concentrated along the buildup margins (see Bosellini and others, 1977), perhaps indicating reactivation of pre-existing faults.

Rapid, prograding buildup growth during periods of relatively little structural activity could effectively mask the underlying faults and basement blocks. A similar situation has been postulated for the Bahama Bank area (Ball, 1967). Based on seismic and gravity data Ball (1967) suggested that the original configuration of the Bahama Banks area was fault controlled, and that the

Figure 57. Fault pattern of the Afar triangle area, Ethiopia. Note the complex intersecting pattern and numerous potential basement blocks (Baker, 1970).


Red Sea
DANAKIL HORST
MAIN ETHIOPIAN PLATEAU
Afar
Gulf of Tajura
Aisha
Addis Ababa
0
100
200 km

present relief was produced by carbonate sedimentation. Today, there is little or no surface reflection of the underlying faults.

By combining the Middle Triassic doming with subsequent graben development subsidence, the carbonate growth on fault blocks, depicting the location and development of the Dolomite buildups can be suggested.

Phases of Middle Triassic rifting have previously been recognized in the central Mediterranean region (Scadone, 1975) and have been related to the beginning of fragmentation of Pangaea (Hsü and Bernoulli, 1978). In the area of the Dolomites, this rifting even possibly began with a subcrustal thermal disturbance that resulted in the formation of a domal uplift. As crustal distension continued, the uplifted area fractured and produced a trilete graben system roughly in the area of the Western Dolomites. It is possible to recognize two arms of this system; the third arm has been destroyed by Alpine deformation.

For some reason, the rift system aborted soon after formation, and only minor amounts of extension and crustal thinning were produced. A period of subsidence, necessary to restore isostatic equilibrium, followed. Carbonate buildups were established on top of some of the basement blocks near the center of the triple junction. These buildups grew into the upper Anisian and Ladinian buildups of the Dolomites.

Marine conditions prevailed throughout the development of the Dolomite rift, a situation that is unlike present day graben systems found in continental crust. Perhaps the position of the Dolomite area near the continental margin of the Triassic Tethys Ocean (Bosellini and Hsü, 1973, and fig. 5) allowed marine conditions to become established early in the history of the rift. A position near the margin of the Tethys Ocean would indicate that thinned continental crust underlay the area of the future Dolomites before rifting began. If so, the thermally-induced uplift may never have raised the area much above sea level. Marine water could have invaded the area at the onset of graben development.

After the period of relatively constant subsidence, accomodated by differential movement between fault blocks, a renewed episode of extension occurred. The Ladinian alkalic volcanism resulted. Renewed faulting at this time also exposed parts of some buildups and led to the deposition of the wedge of megabreccia. The extension produced was not very great, however, and took place duinrg a short interval of time. The Dolomites then slowly subsided throughout the rest of the Triassic. Sedimentation kept pace with subsidence, as evidenced by the great thickness of the Upper Triassic shallow-water Dolomia Principale.

Areas of carbonate buildups with similar origins and histories undoubtedly exist, but references to them

are scarce. The Blake Plateau-Bahama Banks area was probably initiated in a similar manner during the separation of North America and Africa (Sheridan and Osburn, 1975), but in this case rifting was complete and an open ocean-facing margin was produced, allowing the development of a long linear reef tract. It is possible that the Sirte Basin triple junction (Burke and Dewey, 1973) and its subsurface carbonate rocks also had a history of development similar to that of the Dolomites.

CONCLUSIONS

1) The La Valle and San Cassiano formations document the filling of Triassic interbuildup basins in the Dolomite Alps and provide a record of the development of the area.

2) In the Western Dolomites the La Valle and San Cassiano formations form a shoaling upward sequence, and are composed of material eroded from volcanic-covered buildups, volcanic islands, and the carbonate buildups themselves.

3) Slope, submarine fan, and basin plain environments compose the La Valle - San Cassiano interval in the Western Dolomites. No major feeder canyons were recognized. It is hypothesized that numerous small canyons and channels cut across the slope and supplied the fans with sediment. As a result, major channelized submarine fans did not develop. Instead, small overlapping fan bodies were formed.

4) Sedimentary gravity flow (mainly turbidity currents, but also fluidized sediment flows and debris flows) and hemipelagic processes deposited nearly all the sediment in the basinal areas of the Western Colomites.

5) Once in the basinal areas, sediment was transported both perpendicular to and parallel with the buildup margins. The major sediment sources were to the south and west of the field area.

6) The megabreccia beds represent the exposure and destruction of the buildup margins along the southern edge of the field area. The megabreccia beds were deposited by combined rock falls/slides, debris flows, and highly concentrated turbidity currents.

7) The Cipit limestone boulders occur as integral parts of the basinal units and are erosional remnants of the buildup margin facies. Boulders of buildup interior and foreslope facies are rare.

8) The Cipit boulders show evidence of exposure and karsting. The solution cavities, pitted surfaces, and rounding were produced during erosion and subaerial exposure of the boulders.

9) Various types of boundstones compose most of the Cipit boulders. The most important organic binding agent was sediment-trapping blue-green algae. Tubiphytes, calcisponges, foraminiferans, other algal taxa, and problematic organisms assisted in stabilizing the substrate. Coral provided some framework, but was not the major constructing organism.

10) Submarine cements, formed primarily just below the sediment-water interface provided additional stability to the buildup margin facies. Two major morphologies of submarine cement were recognized, isopachous-fibrous and botryoidal-fibrous. An unknown amount of micrite cement

may also be of submarine origin.

11) Organic encrustation, binding, and framework growth, combined with precipitation of submarine cements, created an upward growing, potentially wave-resistant buildup margin.

12) Later diagenesis of the buildup margin facies resulted in conversion of aragonite and high-Mg calcite to low-Mg calcite through neomorphic processes, precipitation of ferroan calcite, formation of small amounts of zoned Fe-rich dolomite, production of solution cavities during karsting, concentration of amorphous Fe-oxides and dolomite silt in the cavities, and finally cementation by ferroan calcite of geopetal volcanic sediment in the solution cavities.

13) The preserved geometry at Pale di San Martino shows that the buildup margin facies of the pre-volcanic buildups gradually steepened from the horizontal interior facies to the steeper foreslope facies. Steep, abrupt buildup margins are not present.

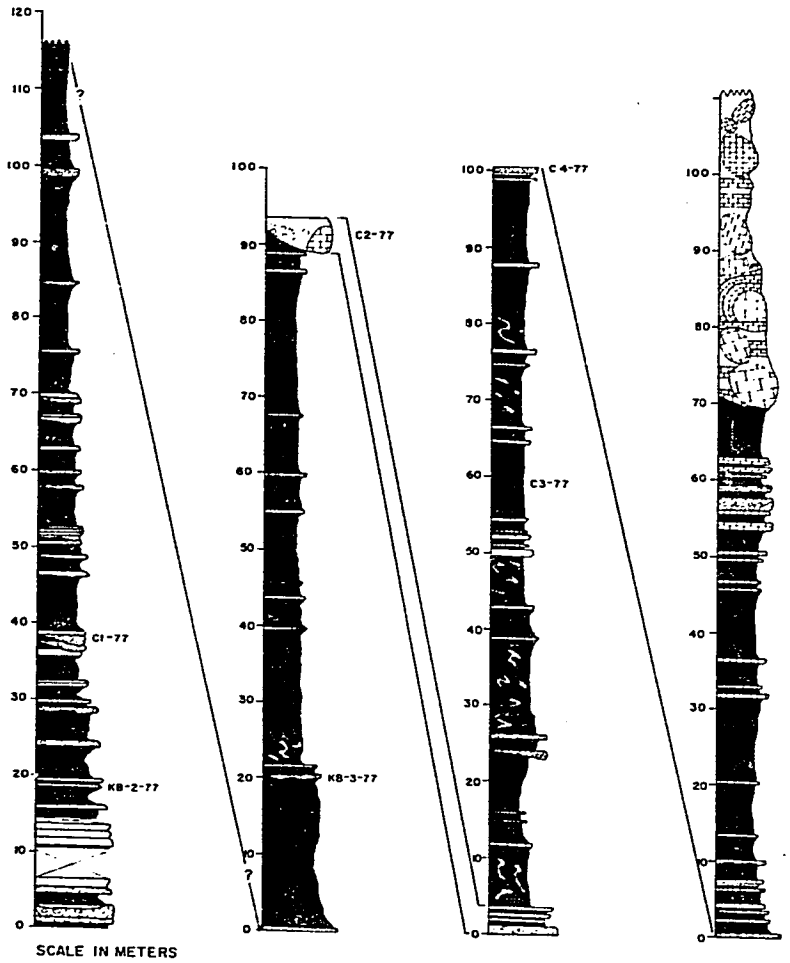
14) The composition of the buildup margin facies, as judged from the Cipit boulders, is similar to both the Permian Reef of West Texas and the Middle Triassic Wetterstein Limestone of Austria. The marginal facies of the Permian Reef is apparently one of massive boundstone, while the Wetterstein Limestone marginal facies consists of small

patch reefs in a sea of debris. Although no direct evidence of the distribution of Dolomite buildup marginal boundstones exists in the Cipit boulders, the lack of boulders of cemented debris makes the Permian Reef a more attractive analogy.

15) The Dolomite buildups developed above fault blocks produced by the foundering of a thermally induced Middle Triassic dome. The doming event was part of the Triassic rifting episodes that took place around the western end of the Tethys Ocean, preceeding the opening of the North Atlantic and Pennine Oceans.

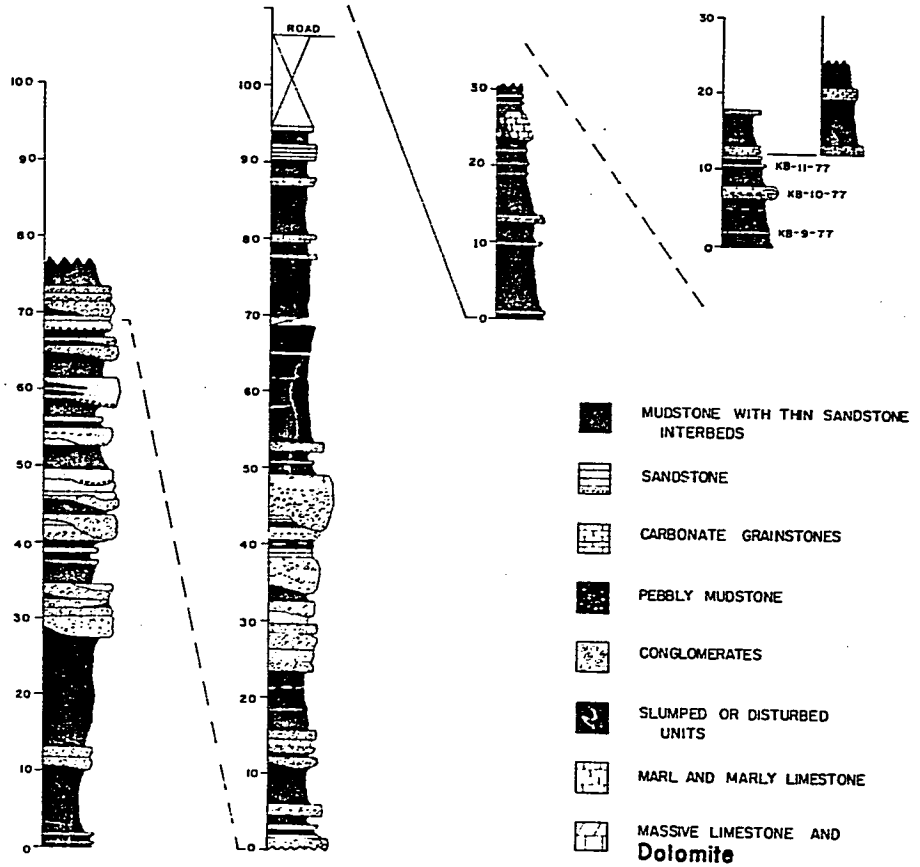
PLATE I MEASURED SECTIONS

SASSO LEVANTE



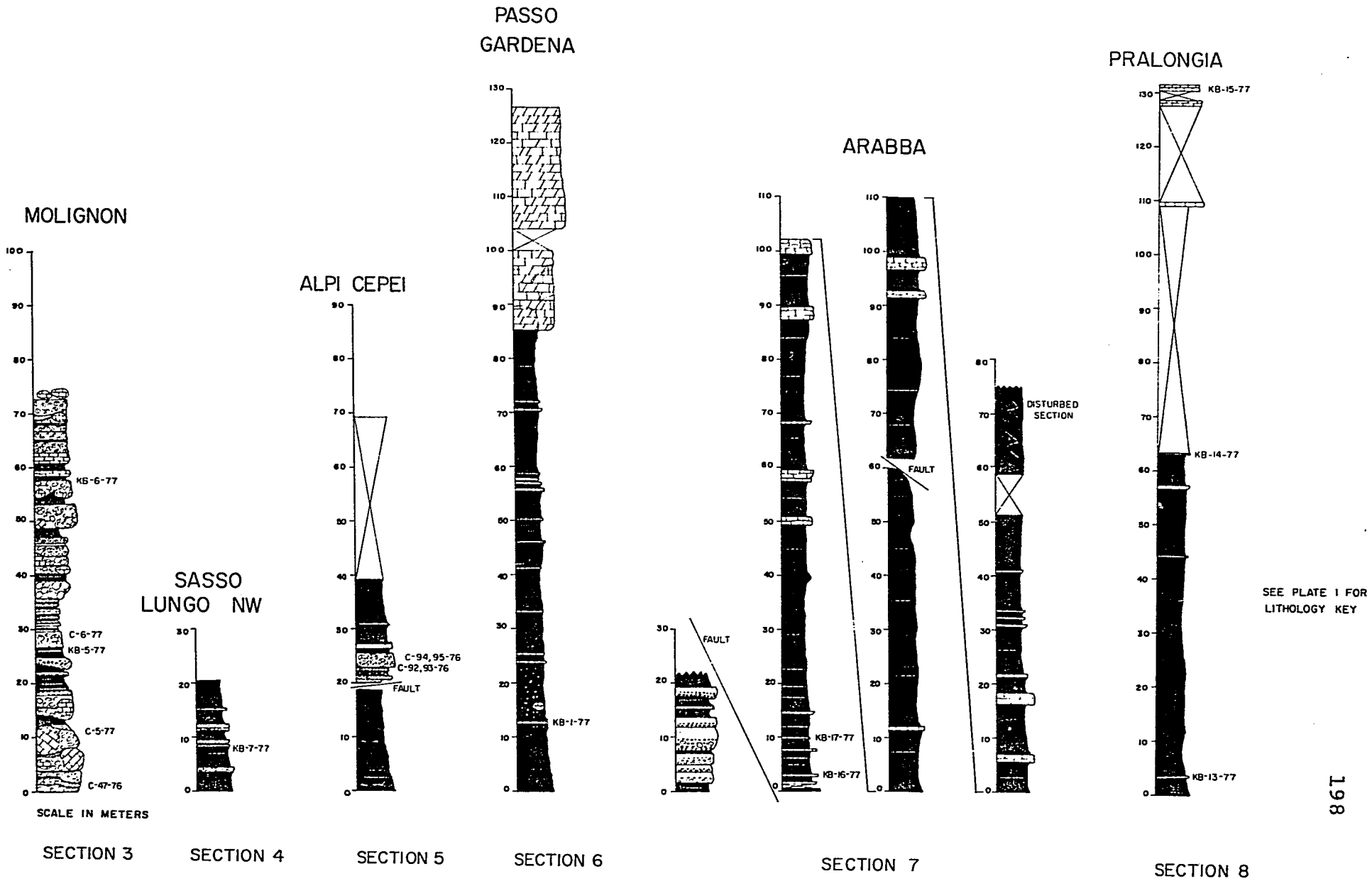
SECTION 1

PASSO SELLA — COL DE TOI



SECTION 2

PLATE 2 MEASURED SECTIONS



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APPENDIX A

LOCATION OF MEASURED STRATIGRAPHIC SECTIONS

Areas for prospective section measuring were selected from the Italian Geological Survey's geologic map of Italy (Bolzano sheet, 1:100,000 scale) and the Istituto Geologico dell' Universita di Ferrara Carta Geologica della Val di Fassa (1:25,000). Of the areas inspected eight were chosen for measurement.

The geographic names and trail numbers used to identify section localities were taken from two sources: 1) the 1:50,000 Istituto Geografico Militare map of Italy, first and second editions 1968-1970, and 2) popular walking guide maps known as Carte dei Sentieri e Rifugi or Wanderkarte, 1:50,000 scale, published for tourist use. The Istituto Geografico Militare maps are far superior to the walking guides, but are not as easily obtained. The walking guides are available at most bookstores, tobacco shops and tourist shops. The Istituto maps are available only at a few larger bookstores and are not always in stock. In addition, the Touring Club Italiano published good maps of the area at a 1:50,000 scale also.

Section 1

Location: Southeast side of the Sasso Lungo Group, below peak named Sasso Levante, east of the Pian dei Sassi. Section was measured on the prominent SE-facing exposure, beginning at the intersection of trail 617 and stream gully.

Section has been mapped as entirely San Cassiano formation (Leonardi, 1967). Several "minor" structural complications were crossed during measuring, all of which are believed to be landslide and slump phenomena. Strike and dip at base of section N62E, 29NW.

Section 2

Location: In the area of Passo Sella. The section is broken into four parts due to correlation difficulties. The lowest part of the section begins in a stream bed in the upper reaches of Val Piana below (to the south) of Hotel Maria Flora. Exposure is a north-facing slope. Strike and dip at base is N75W, 22NE. Part two of the Passo Sella section is located upstream from part one approximately 100m. Section is exposed on the west side of stream and ends at Col di Toi. Strike and dip at base is N80E, 20NW. Part three of the section begins directly behind Hotel Maria Flora on the Passo Sella road. Strike and dip at base, N35E, 15NW. Part four is located above the Passo Sella road on the south side of the rock formation known as the Locomotiva. Bearing from Col Rodella-N53E, Sella lift station top-N72W. Strike and dip at base, N5E, 14E.

Section 3

Location: On ridge directly above the Molignon hut (bearing N55W), beginning on the left side of a prominent gully. Strike and dip at base N31E, 18NW.

Section 4

Location: Near the base of the NW side of Sasso Lungo peak. Section is located in a small depression approximately 400 m NE of Piz Ciaulong (peak 2114). Area on map is labeled M. de Soura. Strike and dip at the base, N77W, 13S.

Section 5

Location: In stream gully at the base of Laste di Terra Rossa. Bearing from M. Pez, N79W. Section is exposed on south facing wall of stream cut.

Section 6

Location: Located on south side of road from Passo Gardena to Covara, approximately 1.5 km from Passo Gardena. Bearings, peak 2592 of Piz da Cir group, N23W; base of ski lift on the Grand Pre, N65E. Strike and dip at base of section is N54E, 26SE.

Section 7

Location: Section begins in a stream gully one km above turn 8 on the Arabba-Passo Pordoi road. Stream crossed the road at the 1700 m marker. Exposure faces to the SE and is tectonically distrubed to some degree. Strike and dip at base of section is N40E, 17NW.

Section 8

Location: Section is located approximately 500 m from peak 2171m in the Pralongia area. Exposure is a NE facing

slump/landslide headwall, just south of the Pralongia trail. Section was measured on what appears to be a rotated slump block. Strike and dip at base of section is N25W, 22NE.