SEDIMENTOLOGY AND PALEOGEOGRAPHY
OF A
DEVONIAN TURBIDITE BASIN IN ARGENTINA

By

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ABSTRACT

The area studied lies in central western Argentina, just east of the Cordillera of the Andes, in the geological province named the Precordillera. This thesis describes the sedimentology and paleogeography of the Punta Negra Formation (Middle to Upper Devonian). This formation is well exposed over the central Precordillera by a series of thrust faults which trend north-south. The Punta Negra Formation was deposited on a continental borderland and its distribution and lithofacies were controlled by two north-south trending rises: the Zonda-Villicum arc, on the east, and the Tontal arc, on the west.

The Punta Negra consists of gray shales and conglomerates, on the east, and of olive-green graywackes and shales, with few paraconglomerates, on the west. The eastern lithofacies is considered to have been deposited on a slope bordering the mainland, and the western lithofacies - which includes most of the outcrops of the Punta Negra Formation - is thought to be a submarine fan deposit. The submarine fan occupied a small basin restricted by the two rises above mentioned. This submarine fan does not fit well in proposed models because the upper and middle fan sections - with deep channels and numerous conglomerates - seem to be absent. Only the outer fan morphology is recognizable. This deviation from the model is attributed to the effect of submarine topography. The source area lay to the southeast, on the mainland.

The graywackes that form the submarine fan were transported mainly as high density turbidity currents. But in the last stages

of deposition, grain flow and debris flow mechanisms also acted on the sediment. The result of this combination of mechanisms was a complex grading pattern. In most beds one finds: (i) a thin fine-grained layer at the base; the grain-size rapidly increases and, then, follows (ii) a slight inverse grading which extend up to the middle of the bed, (iii) the central portion of the beds are usually structureless and, finally, follows (iv) a normal grading into the shale layer on top.

A reconnaissance field study of the Regional Geology of the Precordillera was carried out, in order to better establish the paleogeographic setting of the Punta Negra Formation. The rock sequence studied extends from the Precambrian to the Devonian, inclusive, with three intervening unconformities. The Precambrian is barely exposed on the east and consists of schists. The Cambro-Ordovician consists, on the east, of 2000 m of shallow water limestones unconformably overlying the Precambrian basement. On the west, shales, turbidites and a few conglomerates probably represent slope, rise and abyssal plain sediments; paleocurrents are mainly from the north. The Ordovician on the west contains pillow lavas and ultrabasic bodies but there is no evidence of an underlying continental basement or of western sediment sources. The Cambro-Ordovician assemblage suggests the existence of a passive, Atlantic-type continental margin. Following a Late Ordovician tectonic distrubance, Silurian and Devonian sedimentation was wholly clastic and controlled by submarine rises. One such rise, the Tontal arc, acted as a barrier to the westward movement of much of the clastic sediment, which paleocurrent and petrography indicates was derived from the shield to the east. Marine sedimentation over the old continental shelf, east of the Tontal arc, was brought to a close by the deposition during the Devonian of thick turbidite beds in at least two submarine fans, with paleocurrents predominantly from the east and south.

ACKNOWLEDGEMENTS

The writer wishes to express his gratitude to Dr. G. V. Middleton for his supervision of the work for this thesis.

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CHAPTER ONE

INTRODUCTION

1.1 Purpose of the Study

During the Paleozoic, a large marine sedimentary basin developed in what is now central western Argentina and adjoining parts of Chile. The rock record extends from Precambrian to Permian, interrupted by at least four unconformities. Overall, the rocks are mainly sedimentary, although in the Upper Paleozoic, igneous and pyroclastic rocks become very abundant. The Paleozoic erathem outcrops on both sides of the Cordillera of the Andes: in coastal Chile and in western Argentina. The exposures of these Paleozoic rocks in Argentina constitute the geographical and geologicial province named the Precordillera. This thesis deals exclusively with the Precordillera.

The Precordillera has been moderately well studied from a paleontological and stratigraphical point of view , but several important stratigraphic problems remain unsolved, either because fossils are absent in some rock units or because the fossils that have been found do not allow a precise determination of their age. The present work was, above all, sedimentological in scope, and complemented previous stratigraphical studies.

The main subject of this thesis is the sedimentological description and paleogeographic reconstruction of the Punta Negra Formation (Middle to Upper Devonian). The lithology of this formation is interesting for although it consists of thick and massive turbidites, they are fine-grained and conglomerates are scanty. The Punta Negra Formation is partly interpreted as a submarine fan. Differences with other submarine fans are pointed out and the importance of submarine topography in the development of the sedimentary facies is stressed.

In order to better understand the evolution of the basin and the paleogeography of the Punta Negra Formation, the underlying rock units were also studied. The results of these observations are presented in the second section of this thesis. The author wishes to stress that this part of the work is of a reconnaissance nature.

This work is only a first step in the study of the sedimentology of the Precordillera. But even apart from specific conclusions concerning the Punta Negra Formation, the author believes that it has contributed significantly to the Regional Geology of this region.

1.2 Geographic setting

The Precordillera is a mountain chain about 100 km wide and 400 km long, extending from, approximately, latitude 29S to 34S, in a north-south trend (Fig. 1).

The Precordillera lies east of the Cordillera of the Andes and flanks it very closely, separated by a continuous valley joining the localities of Rodeo, Calingasta, Barreal and Uspallata (Figs. 1 and 2). Both to the north and to the south, this valley gradually rises until it finally disappears and the Precordillera and the Cordillera join in one morphostructural unit. Eastwards, the last elevations pertaining to the Precordillera are the Zonda-Villicum Ranges. Farther east there is a vast alluvial plain on which the city of San Juan is built.

The Precordillera includes two parallel north-south trending range systems; the Punilla-Tigre-Tontal-Villavicencio Ranges along the center and the Villicum-Zonda Ranges along the east (Fig.2). Relief is high. The maximum elevations exceed 4000 m in the Tontal Range south of the San Juan river. The Zonda Range reaches 2000 m. The San Juan River flows at about 1000 m above sea level. Mountain slopes are relatively smooth except along limestone outcrops, which form scarped ridges.

Climate is semiarid with mild winters and hot summers. Vegetation is scarce and of the shrub type. Natural outcrops are abundant and well exposed and, in addition, roadcuts provide excellent exposures.

1.3 Previous Work

Since the turn of the century a large number of geologists have worked in the Precordillera. The foundations for the stratigraphy were laid by several German geologists (Bodenbender, 1902; Stappenbeck,

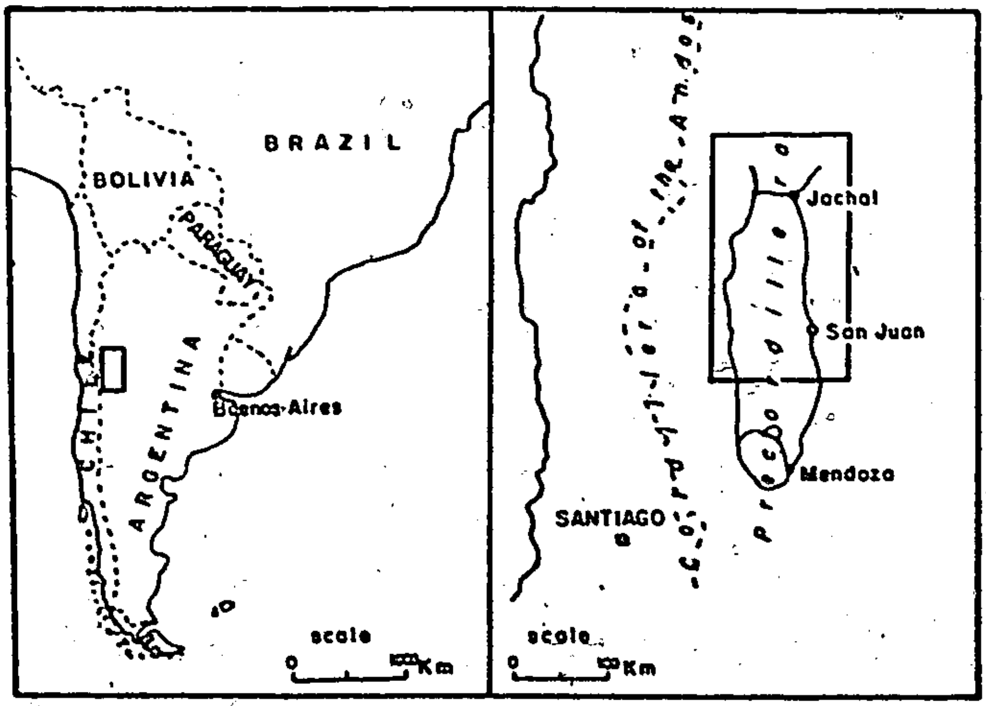
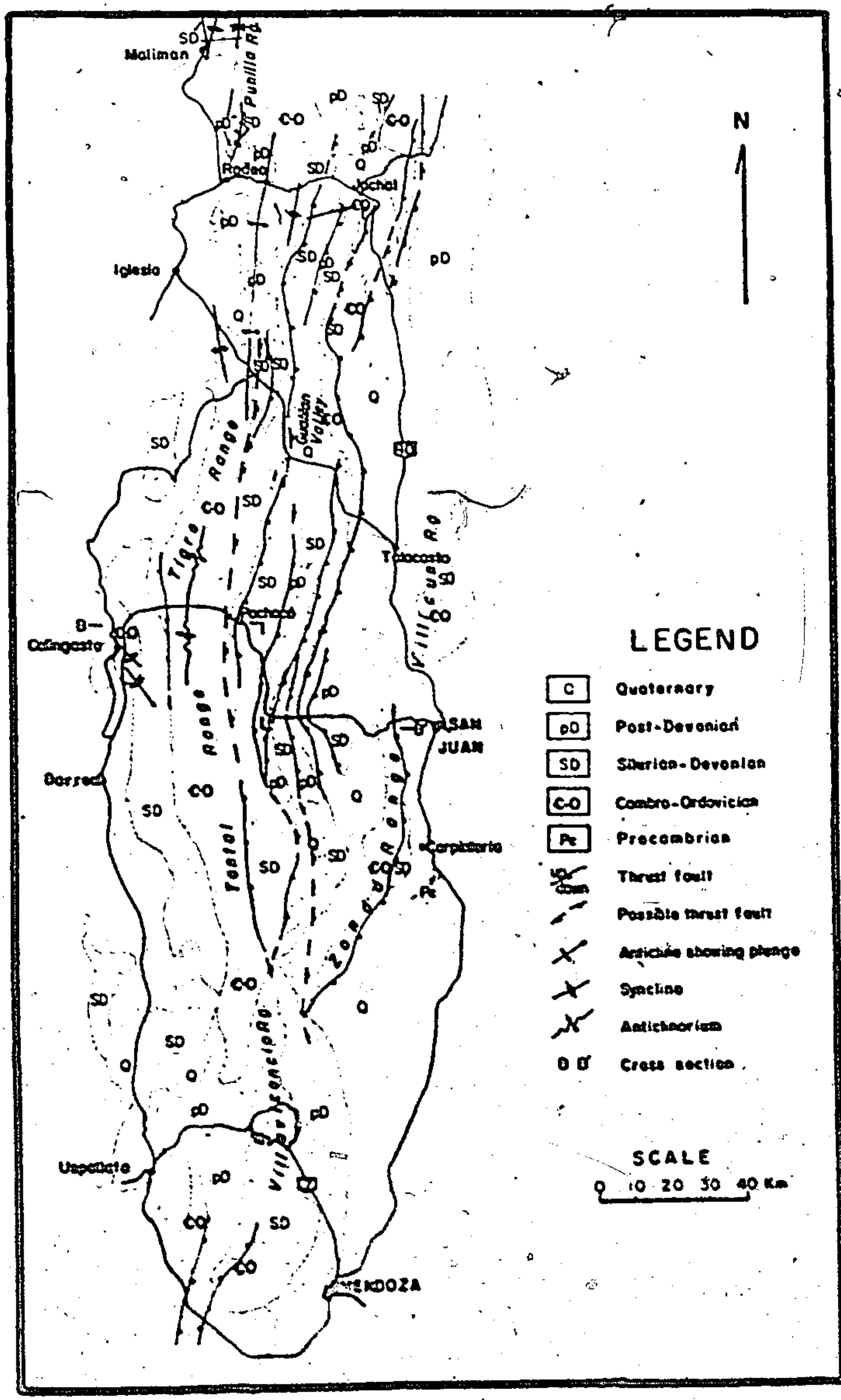


Fig. 1. Location maps for the studied areas.

Figure 2. Simplified geologic and structural map of the Precordillera.


N
Maliman
Rodeo
Jachal
Iglesia
Pachaco
Calingasta
SAN JUAN
Carpinteria
Uspallata
MENDOZA
Tigre Range
LEGEND
Quaternary
Post-Devonian
Silurian-Devonian
Cambro-Ordovician
Precambrian
Thrust fault
Possible thrust fault
Anticline showing plunge
Syncline
Anticlinorium
Cross section
SCALE
0 10 20 30 40 Km

1910; Keidel, 1921). Very good field geologists and stratigraphers, they showed a working methodology excellent for that time, namely the use of Paleontology and Structural Geology as means for solving the Stratigraphy. Their ideas influenced many later geologists and only in the last decade has modern Sedimentology begun to be practised, although with limitations.

Despite the vast amount of individual work done on the Precordillera, it has been only partially mapped. At least one third of the area awaits mapping in an adequate scale. Baldis (1970) compiled existing information plus his own observations, in the first attempt to make the stratigraphical nomenclature uniform and to determine the major facies changes in the Precordillera. But he limited his studies to the Devonian and, in particular, to the Lower Devonian. He compiled a map at a scale 1:100,000, covering the area between the latitudes of Jachal and Carpinteria, east of the Tontal-Tigre Ranges to the Zonda-Villicum Ranges. As a result of the present work this map has been significantly modified but it provided a good geologic basis for the field work.

Aerial photography covers the whole area at a scale of approximately 1:50,000. Topographic maps cover most of the area but not in a uniform scale. A combination of photographs and maps at scales 1:100,000 and 1:200,000 was employed.

The only previous detailed work done on the Punta Negra Formation, was a bed-by-bed thickness measurement and petrography of a section exposed along the San Juan River (Gonzalez-Bonorino, 1970). The measured section is incorporated in the present thesis as section V.

Field work for this thesis took about 90 days divided in two seasons: August, 1971, and June 17th to August 15th, 1972. The first field season was employed in a reconnaissance of the stratigraphy and sampling and observations on the Punta Negra Formation, and the rest to the Regional Geology. The greater part of the work was carried out in the central and eastern Precordillera, that is, east of the Tontal-Tigre Ranges between the Jachal and San Juan rivers. Other areas were visited only briefly.

1.4 General stratigraphy and structural geology

The following figures should allow the reader to follow the description of the general stratigraphy and the structural geology of the Precordillera: Figure 2 which is a simplified geologic and structural map: Figure 3 which is a schematic stratigraphic section of the Precordillera and illustrates the general stratigraphic relations and major facies changes: Figure 4 which is an east-west cross-section of the Precordillera along the San Juan River. In first place, a brief summary of the general stratigraphy is presented, following which the structural geology is discussed. A fuller description of the stratigraphy and the evidences for the environmental interpretations, will be given under Regional Geology.

The oldest rocks exposed in the Precordillera are probably late Precambrian in ago; they outcrop in a small hill 40 Km south of the city of San Juan (Fig. 2). They consist mostly of quartzose schists. Outside the realm of the Precordillera, to the east and north, the Precambrian basement rises to the surface and outcrops are much more extensive.

The Cambrian and Ordovician systems generally cannot be distinguished in the field, so they will be described jointly as the

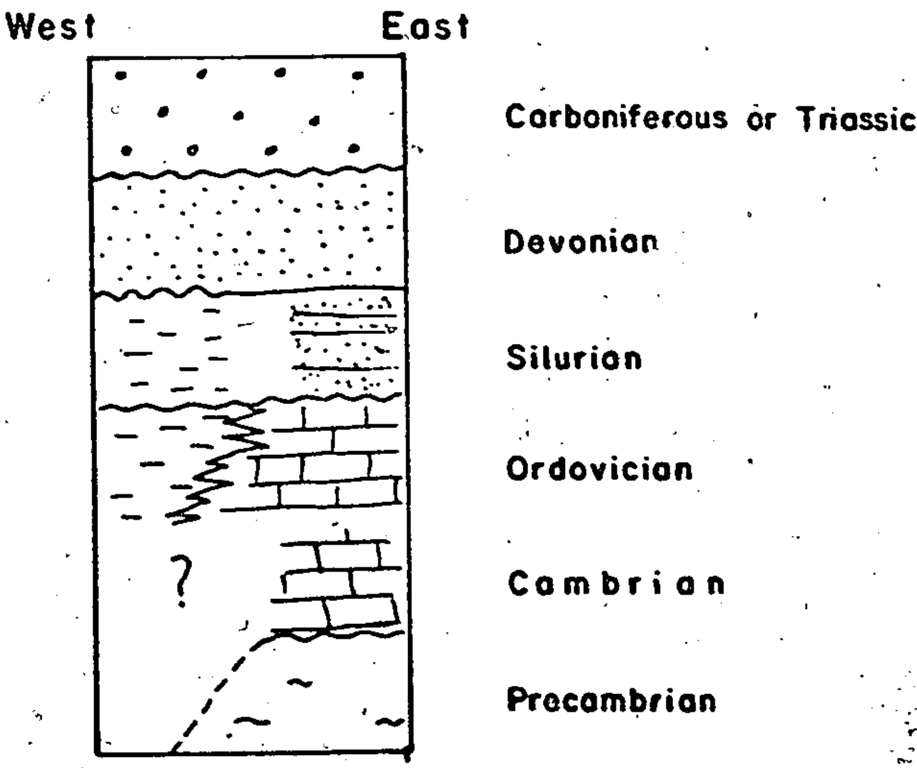


Fig. 3. Generallized stratigraphic section of the Precordillera.Itshows major facies changes and stratigraphic relations.

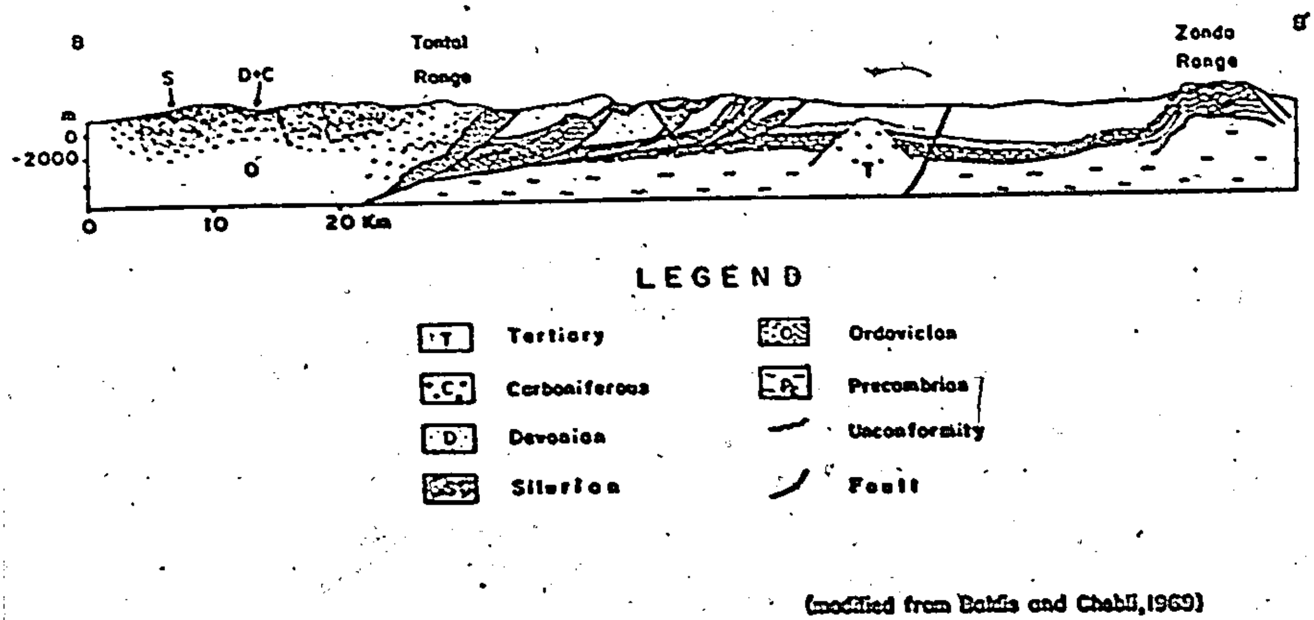


Figure 4. Geologic and structural cross-section of the Pre-Cordillera. For location see Figure 2.

Cambro-Ordovician. The only certain Cambrian outcrops are fossiliferous limestones outcropping in the Zonda-Villicum Ranges. The Cambro-Ordovician can be divided in two regional lithofacies: limestones, east of the Tontal-Tigre Ranges, and clastics, west of, and including, these ranges. The limestones show stromatolites and mudcracks in some areas, and are bioclastic in others; they are considered shallow-water marine deposits. The clastics consist mostly of turbidites and shales. The actual transition between these two facies was not observed, so the tapering out of the limestone under the Tontal Range shown in Figures 3 and 4 is hypothetical. The maximum exposed thickness of the Cambro-Ordovician is of the order of 3 km. A regional unconformity is postulated between the Precambrian and the Cambro-Ordovician, judging from the change in lithology and the absence of metamorphism in the limestones, but the contact between both units was nowhere observed.

The Silurian system is composed of fine-grained sediments; commonly thin, fine sandstone or siltstone beds alternating with shales. East of the Tontal Tigre Ranges, where it overlies the limestones, the base of the Silurian system is marked by a thin chert conglomerate, evidencing an erosional unconformity. In the western Precordillera the only known Silurian outcrops are near Calingasta and consist of purple shales. Since they rest on Ordovician shales and this area is much deformed, it is not possible to be sure whether or not there is an angular unconformity between the two systems. Overall, the Silurian is sandier in the east than in the west. This is shown diagrammatically in Figure 3. The maximum thickness is about 800 m. near Jachal. The Silurian sediments east of the Tontal-Tigre Ranges, covering the

Ordovician limestones, are thought to have been deposited in a shelf environment.

The Devonian system is best developed over the area east of the Tontal-Tigre Ranges; west of these ranges the exposures are much smaller. Over the eastern area the Devonian is apparently conformable on the Silurian, in general, but locally it may rest directly on the Ordovician or erode into the Silurian. On the west, its relation with the underlying units was never clearly observed. The Devonian system is generally sandy and, in some parts, conglomeratic; overall, the grain-size decreases from east to west. East of the Tontal-Tigre Ranges, two lithofacies can be distinguished, based mainly on the sand/shale ratio : (i) north of the Gualilan Valley and around Jachal (Fig. 2), the Devonian consists of turbidites and green shales; the shales are greatly predominant in the lower part of the section and the turbidites are slightly predominant in the upper part. These sediments are tentatively interpreted as submarine fan deposits. (ii) south of the Gualilan Valley and along the San Juan River (Fig. 2), the sand/shale ratio is much higher. In this region two units were distinguished in the field. A lower Devonian unit, with massive bioturbated fine sands and silts below and purple shales at the top, and a Middle to Upper Devonian unit, with olive green graywacke turbidites and dark gray intercalated shales. The latter rock unit is the Punta Negra Formation, which will be described in detail later. The Punta Negra Formation is considered to be a submarine fan deposit. Nothing specific can be said about the Lower Devonian unit except that it appears to have been deposited in relatively shallow marine waters.

The Carboniferous was not studied in any detail. East of the

Tontal-Tigre Ranges, it consists of fluvial sandstones and shales; locally conglomerates are abundant. It rests with an angular unconformity on the Devonian or on the Ordovician.

Probable Permian deposits are present west of the Tigre Range. They consist of volcanic breccias, tuffs and lavas. They appear to rest unconformably on the Devonian.

Cenozoic deposits are widespread throughout the Precordillera. They are mostly alluvial fan sediments and rest unconformably on older rock units.

The regional strike of the beds in the Precordillera is NNE-SSW, the dip commonly varies between vertical and moderate to the west. The tectonic trend is roughly north-south. Three distinct regional tectofacies are present:

(i) western Precordillera. In the Tontal Range along the San Juan River, folding is tight. Some open folds can be seen in the outcrops east of a line joining Calingasta to Barreal, especially around Calingasta, but the structures become more complex towards the core of the Tontal Range. The rocks that form the nucleus of the Tontal-Tigre Ranges show low-grade dynamic metamorphism. Large scale faulting is absent in this western sector.

(ii) central Precordillera. East of the Tontal-Tigre Ranges and west of the Zonda-Villicum Ranges thrust-faulting is the main tectonic feature. Each block is bounded by near-vertical North-South trending faults and is tilted to the west. The oldest rocks ever exposed along the fault planes are the Ordovician limestones. Baldis and Chebli (1969) suggested that the faults originate within or at the base of the limestone unit. Figure 4 illustrates their interpretation with some modifications. Minor folding is present throughout but deformation increases going west. All the bed-by-bed sections of the Punta Negra Formation were measured within this tectofacies.

(iii) eastern Precordillera. East of the Zonda-Villicum Ranges deformation is very strong. The pre-Carboniferous sediments are tightly folded and dipping vertically while the younger rocks are much less deformed; the angular unconformity is of the order of 60°.

Two important orogenic movements affected the Precordillera during the Paleozoic: one at the end of the Ordovician and beginning of the Silurian, and the other during the Late Paleozoic. However, the final modelling of the topography is the result of strong tectonism during the Pliocene and Pleistocene (Herrero-Ducloux, 1963).

The stratigraphic and structural relation between the Precordillera and the Cordillera of the Andes is not well known. The oldest rocks in the Cordillera are probably Middle Paleozoic, although a few outcrops of Early Paleozoic metamorphics may be present along its eastern border (Caminos, 1972). The Middle and Lower Paleozoic are represented by marine deposits which underlie the Cordillera and reappear along the Pacific coast.

A good deal of confusion concerning the evolution and stratigraphy of the Cordillera and Precordillera, stems from the Precambrian age attributed by some geologists to the metamorphosed rocks in central Chile. The most important summary works accessible to northamerican geologists, are Gerth (1955), Munoz-Cristi (1956) and Zeil (1964). None of the three authors is very sure about the Precambrian age that they propose, Munoz-Cristi (1956, p. 195) makes clear that the Precambrian age is doubtful, and so does Zeil (1964, p. 47). In spite of all doubts, this interpretation has led some authors to believe that the Paleozoic Cordillera was ensialic and, furthermore, had a western source (Frakes and Crowell, 1969, p.1032). Several radiometric dates and regional mapping in Chile (Gonzalez-Bonorino, 1971; Munizaga and others, 1973), as well as the work by the present author in the Precordillera of Argentina, strongly suggest that no Precambrian rocks outcrop west of the Tontal Ranges, and that the metamorphic rocks in Chile are Upper Paleozoic in age.

The Paleozoic erathem is overlain to the west of the Precordillera, by a thick sequence - in the order of 15 km - of Mesozoic and Cenozoic evaporites, shallow water marine and continental sediments, tuffs and lavas, which form the Andes. During the Cenozoic orogeny the Cordillera was thrusted to the east and the long Rodeo-Uspallata valley was downfaulted (Gonzalez-Bonorino, 1950).

CHAPTER TWO

PUNTA NEGRA FORMATION

2.1 Definition

In 1946, O.I. Braccaccini separated under the name "Punta Negra complex" a very distinctive rock unit which lay between Lower Devonian marine fossiliferous shales and Carboniferous continental sandstones along the San Juan River. The base is transitional to the Lower Devonian and the top is an unconformity below the Carboniferous. Based on the stratigraphical relations and plant remains he attributed it to the Middle and, partly, Upper Devonian (Braccaccini, 1946; 1949). Only much later (Padula and others, 1967) was a formational name substituted for "complex" : Punta Negra Formation.

The classic outcrops for the Punta Negra Formation are exposed along the San Juan River, where it runs from west to east at the latitude of the city of San Juan. In this type section it consists of dark olive green graywackes and even darker shales. Only a few percent of the beds are thicker than one meter but the sand/shale ratio is high. Grain-size at the base of the beds generally does not exceed medium sand. Sole marks are not very frequent nor well developed.

Baldis (1970) made the first attempt at a sedimentological study of the Punta Negra Formation. In a work dealing mainly with the Lower Devonian of the Precordillera, he mapped the Punta Negra as extending all over the central Precordillera, from north of the Jáchal River to south of the San Juan River and west of the Zonda-Villicum Ranges up to, and including, the Tontal-Tigre Ranges. He noted lithological differences from the classic outcrops both in the Tontal region and in the northern Precordillera, but interpreted these variations as facies changes.

As a result of the present work the geographic distribution of the Punta Negra Formation has been radically changed. The rocks that form the Tontal-Tigre Ranges are thought to be Ordovician instead of Devonian and, thus, not a lateral variation of the Punta Negra. As for the Devonian outcrops in the northern Precordillera, they are undoubtedly partly coeval with the Punta Negra but the source area, and to a great extent the source lithology, for these rocks is completely different and separate from the source area that contributed sediment to the Punta Negra exposed along the San Juan River. On this basis, which is purely sedimentological, it was decided to exclude this area from the Punta Negra Formation. A further change is proposed, and this time it is an extension of the name. East of the Villicum Range, there is a Devonian sequence of which the upper part is tentatively considered a lateral equivalent of the Punta Negra Formation and included under this name. The evidences for these interpretations are discussed in the section dealing with Regional Geology.

Thus defined the Punta Negra Formation extends south of the Gualilan Valley to about 60 Km south of the San Juan River and from the eastern flanks of the Tontal-Tigre Ranges to east of the Villicum Range. Presumably it originally existed east of the Zonda Range but has been eroded away.

2.2 Methods of investigation

Field work was carried out mainly along the roads and nearby exposures. Roadcuts were extremely helpful when measuring the bed-by-bed sections in the Punta Negra Formation. The only important geographic barrier is the San Juan River. A road runs alongside it, on its right margin, and most of the data was collected along this road. But the outcrops in the left margin could not be visited.

The measurement of the bed-by-bed section constituted the bulk of the field work in the Punta Negra Formation. Concurrently with the measurement of the sections, the maximum grain-size at the base of the beds was estimated with the aid of a hand lens, sole marks and internal sedimentary structures were recorded and samples collected.

During the field work for this thesis four sections were measured; three along the San Juan River between the Zonda Range and Pachaco, and the fourth, 15 km NW of Talacasto (Fig. 2). A fifth section, along the San Juan River, that had been previously measured (Gonzalez-Bonorino, 1970), is incorporated in this thesis. Each section was measured from the base to the top of the Punta Negra Formation. For each turbidite the thickness of the sand unit and the shale unit were recorded separately; the distinction between these units was not difficult because of the rapid grading. If the beds were not accessible for direct measurement their thicknesses were estimated, fortunately this situation arose very seldom. Where the beds were completely covered by detritus the total thickness of the covered sector was measured. Small folds and faults are present but infrequent, and generally the beds could be traced from one side of the structure to the other. An exception is Section VII near Pachaco, where only the lower half of the section could be measured because folding became too complex in the upper part.

In the laboratory a computer program was written to calculate moving average of the bed-thicknesses and plot it in two different fashions, namely, against cumulative thickness and ordinal bed number. The latter graph was employed to introduce corrections in the former for parts of the sections that were not measured. The moving averages were made over groups of 10,25 and 50 beds in order to choose the most illustrative graph. The moving average graphs presented in this paper were made over groups of 10 beds and have cumulative thickness as the ordinate.

From the same raw data average bed-thickness, bed-thickness distribution and sand-shale ratio for each section were calculated.

The paleocurrent directions were corrected for tectonic tilt in the field by measuring the angle between the strike line of the bed and the lineation of the sole mark, and adding, or subtracting, this angle from the strike angle.

Graded bedding was the only sedimentary structure studied in detail. In order to complement field observations, 8 sandstone beds and one pebbly mudstone were sampled. The samples were taken normal to the base of the bed at different heights, trying to cover particularly the whole thickness of the sand unit because in this part most variations in grading occur. In one bed that tapered out laterally, samples were taken both vertically and laterally along the bed in order to detect lateral grading. Depending on the thickness of the turbidite up to six samples were taken in one bed. In total 38 thin sections were studied for grading. The thin sections were cut normal to the bedding place but not necessarily parallel to the grain orientation. The grain-size analysis was performed on the thin sections using a Shadow-master projection apparatus with a magnification of 100 times. In each thin section, the long axes of 100 quartz grains larger than 4 phi were selected at grid points, in order to obtain volume percentage. Grains were classified in 0.5 phi intervals.

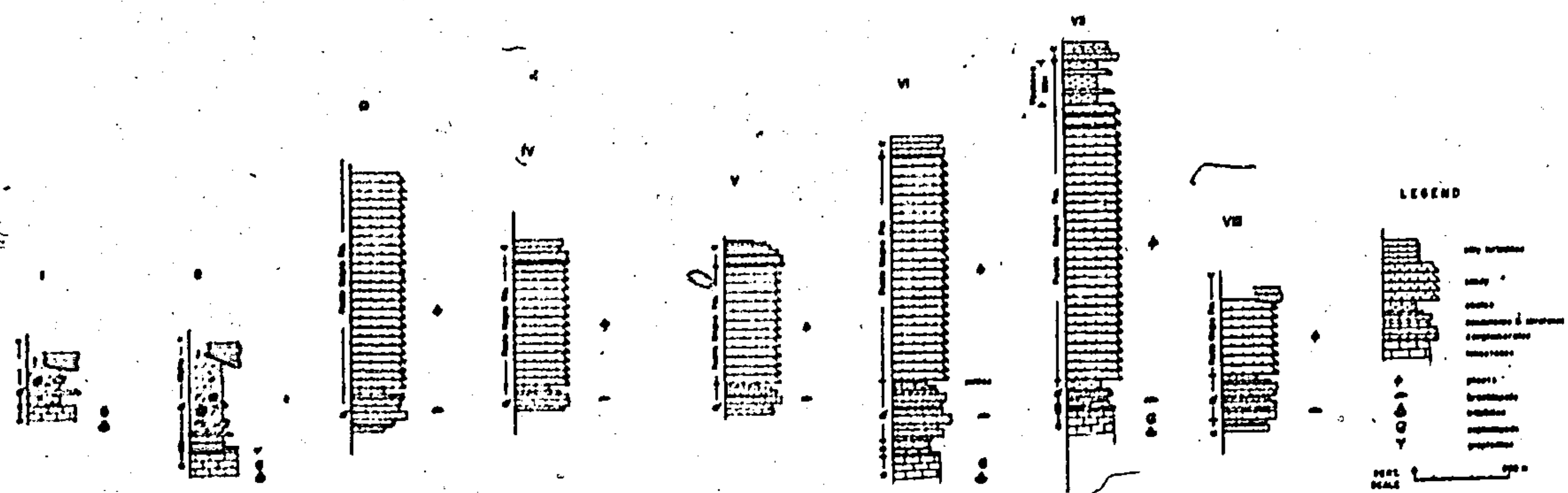
The mineralogical composition was studied qualitatively on all the thin sections, which amount to about 50, and quantitatively on 7 samples from 5 beds. Three samples from one bed were studied to determine the vertical mineralogical variation. The mineral proportions were determined by point-counting either 150 or 300 grains per thin section; 300 grains were counted when studying the vertical variation because greater precision was needed.

The roundness of quartz, feldspar and rock fragments was determined on 150 grains from two thin sections, by comparison with Scheiderhöhn's (1968) roundness table. Shape (elongation) was measured in 100 quartz grains from two thin sections; it was computed as the ratio of the minimum apparent diameter to the maximum apparent diameter. The maximum apparent diameter is the longest dimension of the grain as seen in thin section, and the minimum apparent diameter is the maximum width of the grain normal to the longest dimension.

2.3 Facies changes

The description of the facies changes of the Punta Negra Formation will be illustrated by sections II through VIII presented in Figure 5. Figure 6 gives the geographic locations of the sections and makes reference to detailed geologic maps or cross-sections of the areas where the sections were measured (Figs. 14 - 16). In sections II and III, the thicknesses for the Punta Negra were measured from aerial photographs once the structure was known. In the remaining sections the thickness for the Punta Negra is the cumulative thickness obtained from the bed-by-bed sections. The thicknesses for the Lower Devonian were taken from Baldis (1970) and those for the Silurian from different sources and rough estimates in the field. The detailed geologic maps were drawn using topographic base and general framework of Baldis (1970).

Figure 5. Schematic stratigraphic and lithologic sections of the central Precordillera, over the area occupied by the Punta Negra Formation.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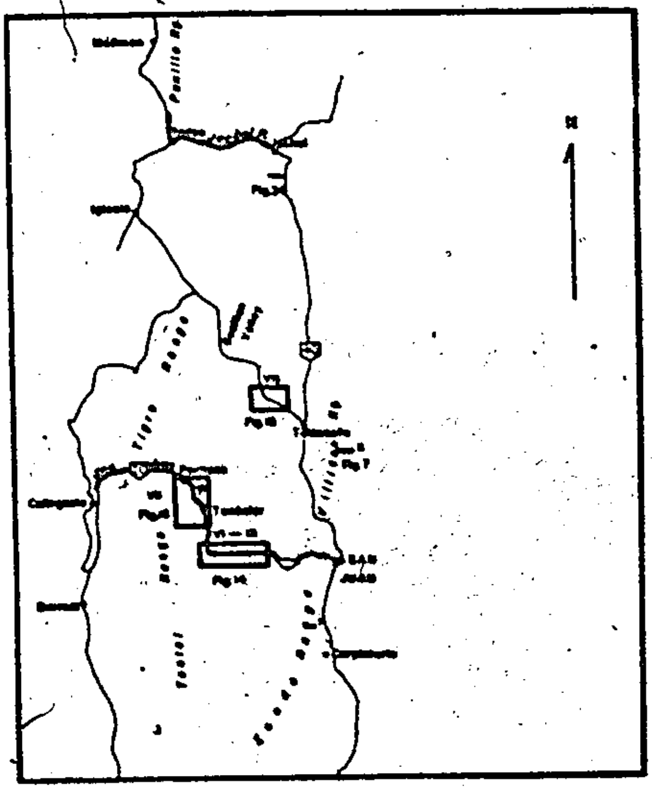


Figure 6. Reference map for the geographic location of the detailed sections and the detailed geologic maps and cross-sections of the Punta Negra Formation.

more or less modified by personal observations and reinterpretations. All the cross-sections were drawn in the field.

The Punta Negra Formation was divided into two facies on the basis of lithology, namely, facies A, east of the Villicum Range, and facies B, over the central Precordillera.

Facies A consists of gray-green shales and siltstones with fine-grained graywacke lenses or thin beds of irregular thicknesses (section II of Fig. 5 and Fig. 7) . Shale greatly predominates over graywacke. The graywacke lenses commonly are a few cm thick and 20 or 30 cm long; they lack internal structures. The shales are intensely bioturbated in parts.

Embedded in this fine-grained lithology are medium- or coarse-grained sandstones and pebble and cobble conglomerates. The sandstones are lithic arenites and form structureless lenses about 1 m long; they are interpreted as the filling of small channels. The conglomerates form elongate lenses 1 to 2 m thick and a few m long. The clasts are subrounded to rounded and consist mainly of metaquartzites with subordinate amounts of igneous and limestone clasts. Packing is tight and the clasts are often in contact. The matrix is medium- or coarse-grained sandstone. Most of the clasts are aligned but do not show imbrication. In some cases, the conglomerates have a banded appearance given by internal sandstone beds or lenses; the sandstone in these beds is identical to that forming the matrix. Both the upper and lower boundaries of these beds are rather sharp but, in general, the lower boundary is transitional to the conglomerate. The upper boundary of these internal sandstone beds is usually deformed by clasts from the conglomerate above sinking into the sandstone.

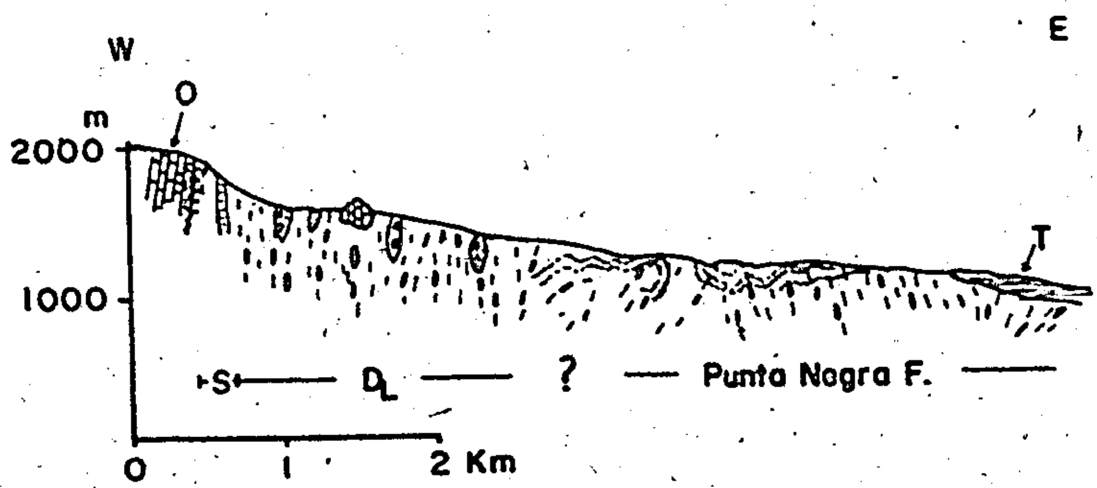


Fig. 7. Cross-section east of the Villicum Range.

See Figure 2 for general location.

Facies A is characterized by the discontinuity of the bedding. Turbidites or any laterally continuous sandstone beds are very scarce.

The base of the Punta Negra in facies A could not be precisely defined because the lithology of the Lower Devonian is very similar. Its top is an angular unconformity with the Tertiary. Presumably, facies A originally extended also east of the Zonda Range and some outcrops directly west of Carpinteria may belong to this facies, but farther south it was eroded during the Carboniferous (see section I of Fig. 5).

Facies B extends west of the Zonda-Villicum Ranges, its areal extent is greater than facies A and it is better exposed. Its relation with the Lower Devonian varies little; there is a gradual but very rapid transition between both units (Fig. 8). The top of the Lower Devonian is characterized by the presence of a few meters of laminated purple shales. Very near the top of this shale unit thin graywacke beds occur and green shale partly substitutes for the purple. In about a meter or so the purple shales completely disappear and thicker turbidites become common. The base of the Punta Negra Formation was arbitrarily fixed where the purple shales disappear. The top of facies B is a low angle unconformity below the Carboniferous. The transition between facies A and B was completely eroded when the Zonda-Villicum Ranges formed.

Facies B consists of a monotonous sequence of alternating graywackes and shales. The graywackes are dark olive green, medium-grained and well indurated. The shales are dark gray to almost black and laminated. The sandstones always grade up into the shales. Plant fragments are rather common in the shales or the silty portions of the

Figure 8. View of the sharp contact between the purple and green shales of the Talacasto Formation below, and the sandstones of the Punta Negra Formation above. Location is that of Section III, along the San Juan River.

beds; some of the recognized genera are: Haphlostigma, Cyclostigma and Sporongites (Padula and others, 1967). Also a few remains of crinoids and bivalves were found by Baldis (1970).

The graywacke beds are usually separated by only a shale parting but the shales may reach several meters in thickness (Figs. 9 and 10). Several paraconglomerates (for definition see A.G.I. Glossary of Geology; in this thesis the term is used to include pebbly sandstones and mudstones) are present in this facies; they decrease in frequency to the west until they appear no more west of section V; none were found in section VIII. They have well rounded pebbles and cobbles of metaquartzites and very few schist, or granitic clasts; in only one bed two small limestone fragments were found. The matrix is shale or sandy shale, the proportion of sand in the matrix apparently diminishes westwards. The thickest paraconglomerate seen was a pebbly mudstone 7.5 m thick, in section V, but usually they are about 1 m thick. The sandstones and shales in facies B are considered deposits of turbidity currents. The sandstone-shale sequence is free from chemical and biogenic sediments.

Erosion seems to have been slight judging from the predominantly flat bottoms of the turbidites and absence of shale clasts in the sandstones (Fig. 11). The deepest channel observed is shown in Figure 12. On the other hand, amalgamation is common in beds thicker than 20 or 30 cm, and wedging or tapering out of the beds is rather common (Figs. 9 and 13). Indirect evidence for the absence of large and deep channels in this facies is that the limestone forming the Zonda-Villicum arc - which could not have been very deeply buried at the beginning of the deposition of this facies B - was not eroded. In the

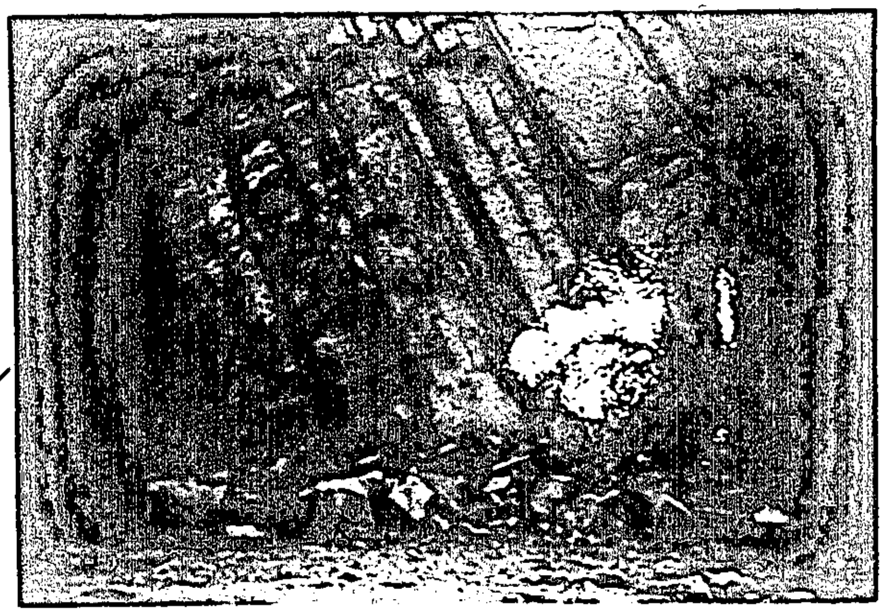


Figure 9. Punta Negra Formation in Section V. Massive turbidites with little shale in between. A shaly unit appears to the left. Note some wedges and amalgamation. Base to the left (East). Thicker bed on right is 1.2 m thick.

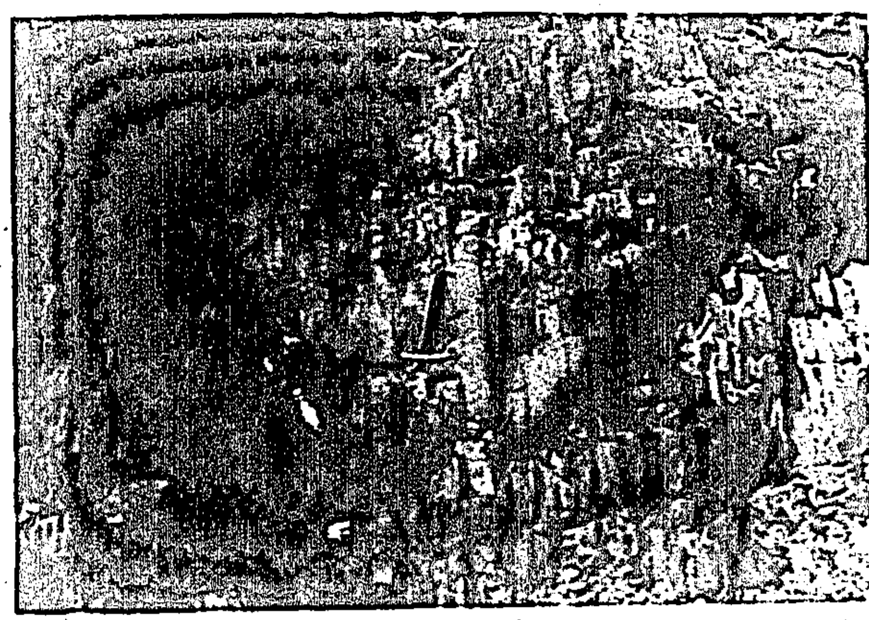


Figure 10. Punta Negra Formation in Section V. Shaly unit with a few thin turbidites. Base to the left (East).

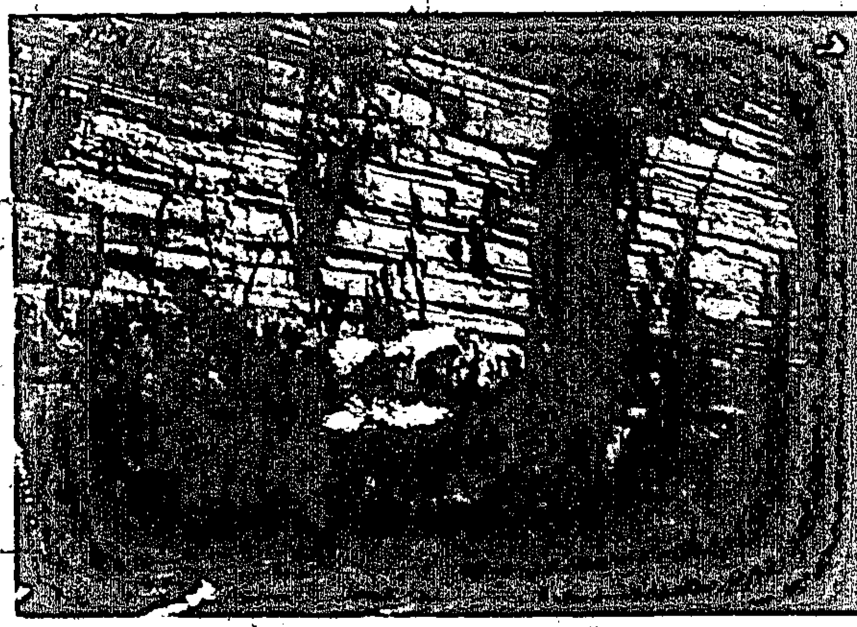


Figure 11. Punta Negra Formation in Section VIII. Note even bedding, flat bases and abundant amalgamation. Shale is very scarce. The outcrop is about 9 m high.

Figure 12. Punta Negra Formation in Section VI. Channel erosion (by the hammer); this is the deepest channel seen in Punta Negra. Base is to the left (East).

Figure 13. Punta Negra Formation in Section VI. Peculiar channel(?) Beds are massive and with little shale. The lower part of the section shows thinner bedding and more shale. Base to the left (East). The thickest bed is about 60 cm thick.

opinion of the author, channels - shallow as they may be - are necessary to funnel the turbidity currents downslope and deposit medium- or thick-bedded turbidites. On the other hand, a large sediment influx and fast build-up of the fan might hinder the development of localized sites of erosion. It is suggested that the channels used by the turbidity currents were just relative depressions flanked by previous turbidites. Such seems to be the case in the outer fan portions of modern submarine fans (Nelson and Kulm, 1973).

The thickness of facies B increases irregularly to the west, from about 700 m at section IV to about 1700 m at Section VII (Fig. 5). Section III is anomalous in that the Punta Negra is thicker than at section IV, immediately to the west (Figs. 5 and 14). Section VIII, the thinnest, is interpreted as the margin of the Punta Negra submarine fan because farther north the Punta Negra Formation is absent and another submarine fan, with a different source area, is present (Figs. 5 and 15). Section VI is interesting because the Punta Negra begins with a shale unit 50 m thick instead of sandy turbidites. The shales are almost black, laminated, with silty laminae and occasional thin-bedded turbidites; they are identical in all respects to shales farther up in the sequence, clearly within the Punta Negra Formation. Finally, in section VII, the westernmost section, note the presence of the Pachaco Member (Figs. 5 and 16). This member consists mainly of green shales with intercalated siltstones and calcareous siltstones, and some sandy turbidites. Its lithology contrasts sharply with the Punta Negra outcrops along the San Juan River, in colour and abundance of shale. Nevertheless, the passage between the typical Punta Negra and this member is transitional by increase in the amount of shale intercalated between the graywackes (Fig. 17). The Pachaco Member evidences inter-

Figure 14. Geologic map and cross-section along the east-west course of the San Juan River in the central Precordillera. The detailed sections were measured in each of the thrust-faulted blocks, from the base to the top of the Punta Negra Formation. The roman numerals indicate the approximate location of the sections. See Figure 6 for the general location.

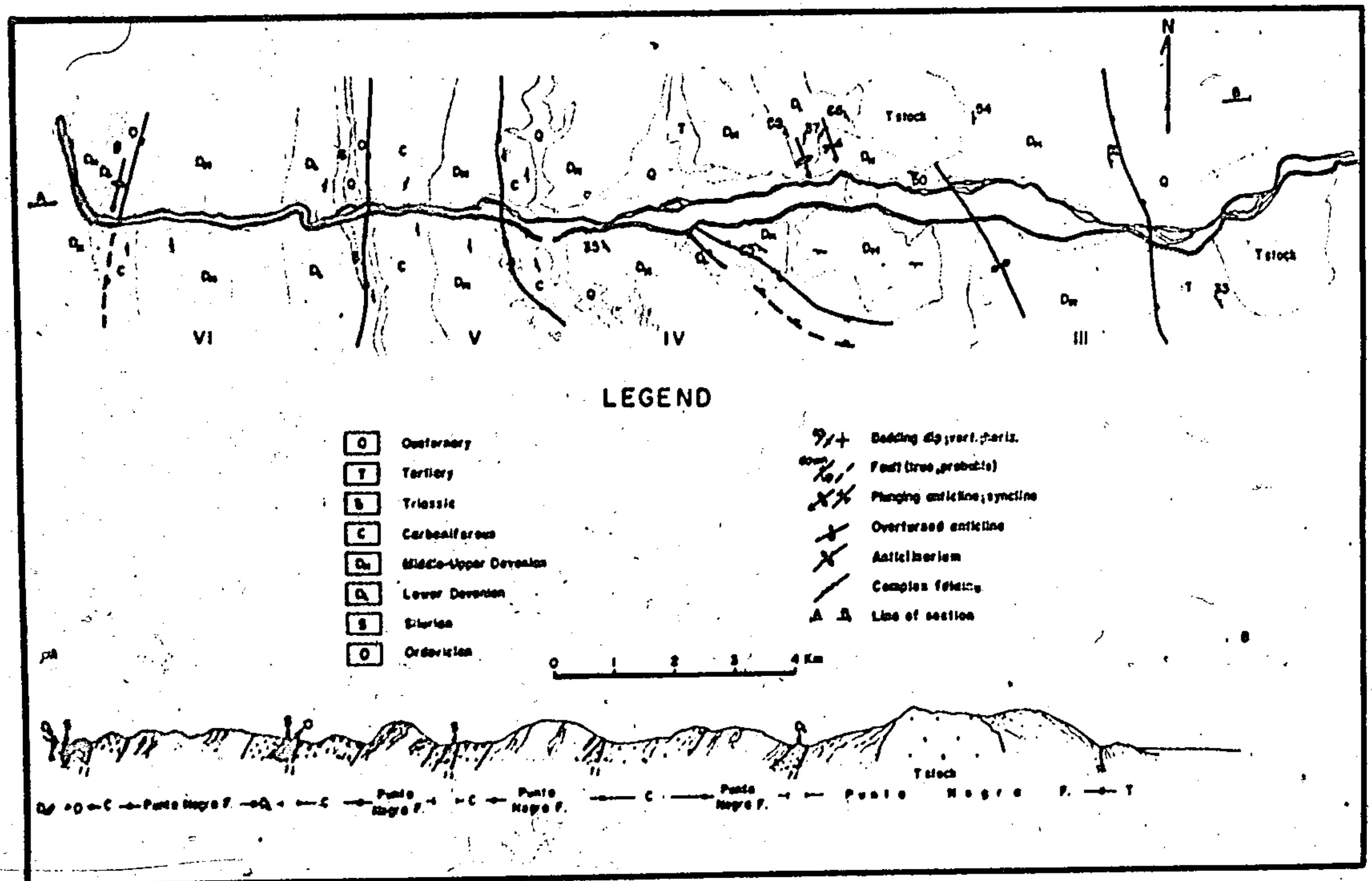
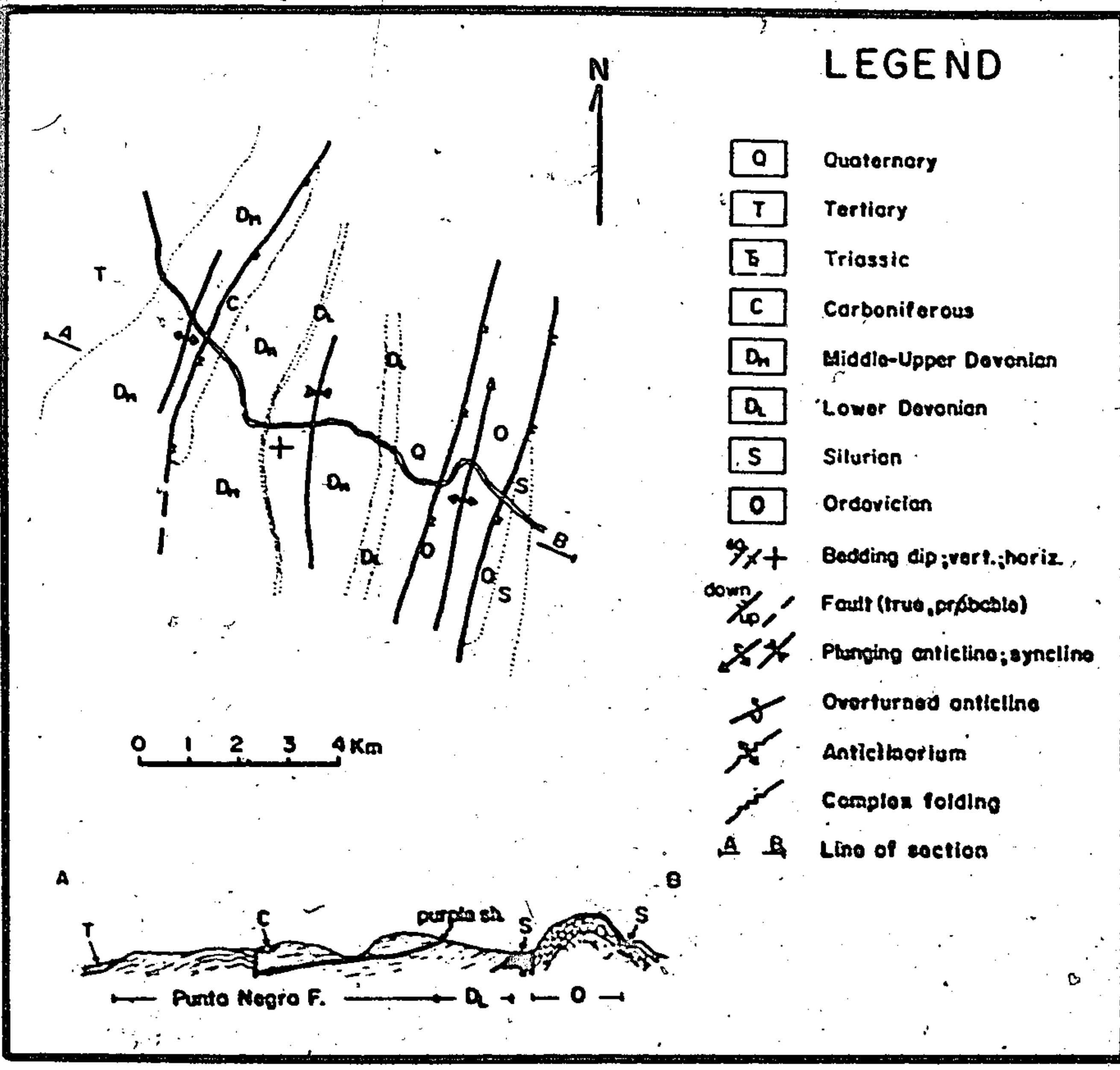
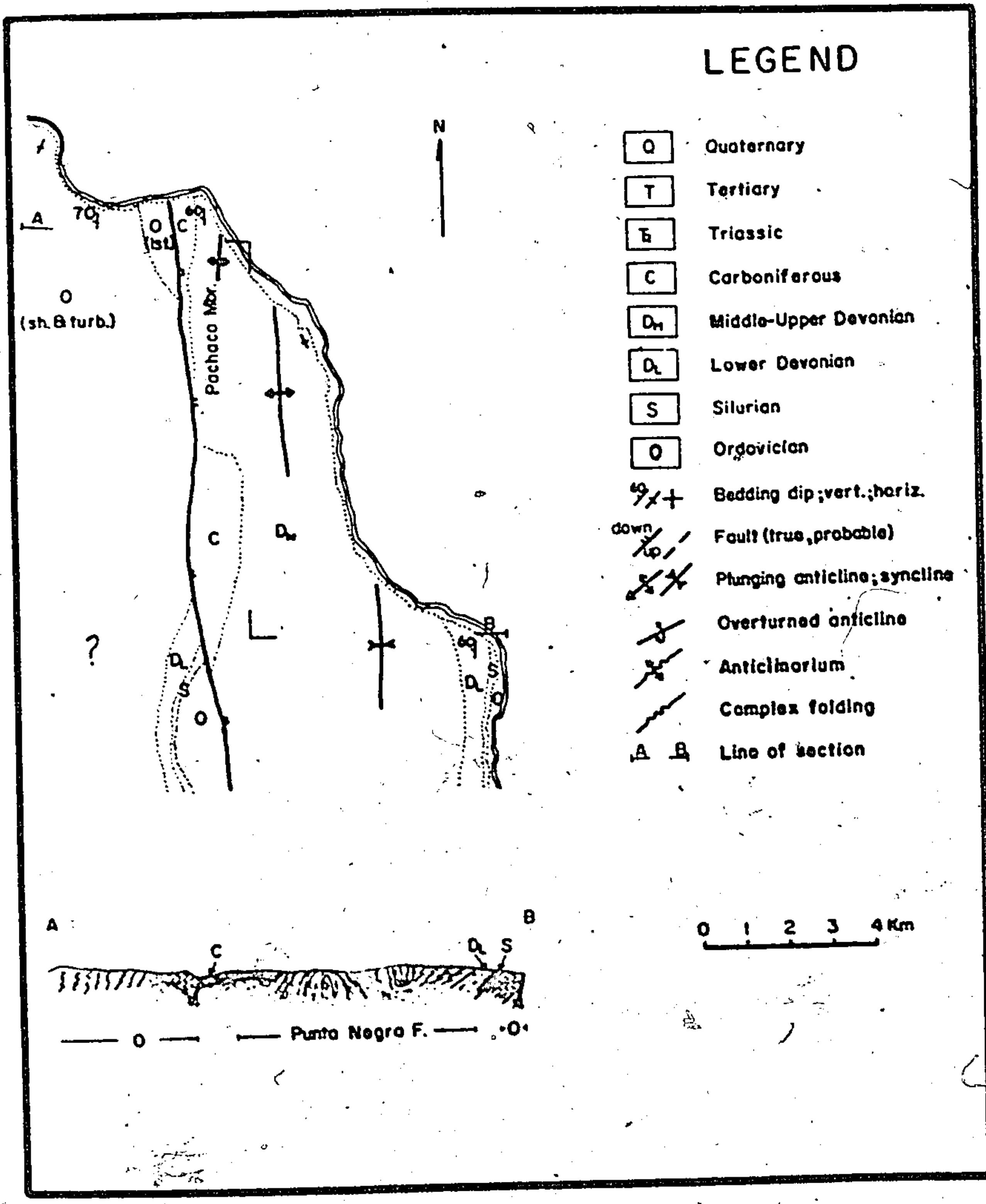

N
VI
V
IV
III
T stock
LEGEND
Quaternary
Tertiary
Triassic
Carboniferous
Middle-Upper Devonian
Lower Devonian
Silurian
Ordovician
Bedding dip; vert.; horiz.
Fault (true, probable)
Plunging anticline; syncline
Overturned anticline
Anticlinorium
Complex folding
Line of section
0 1 2 3 4 Km
Punta Negra F.
C
Punta Negra F.
Punta Negra F.
T

Figure 15. Geologic map and cross-section 20 km NW of Talacasto along the road joining Talacasto and Iglesia. Section VIII was measured in this area. See Figure 6 for the general location.



N
LEGEND
Q Quaternary
T Tertiary
Triassic
C Carboniferous
Middle-Upper Devonian
Lower Devonian
S Silurian
O Ordovician
Bedding dip; vert.; horiz.
down
up
Fault (true, probable)
Plunging anticline; syncline
Overturned anticline
Anticlinorium
Complex folding
A B Line of section
0 1 2 3 4 Km
T
C
Q
O
S
A
B
purple sh.
Punta Negro F.
O

Figure 16. Geologic map and cross-section along the San Juan River, SE of Pachaco. Section VII was measured in this area. See Figure 6 for the general location.



LEGEND
Q Quaternary
T Tertiary
Tr Triassic
C Carboniferous
DM Middle-Upper Devonian
DL Lower Devonian
S Silurian
O Ordovician
Bedding dip; vert.; horiz.
Fault (true, probable)
Plunging anticline; syncline
Overturned anticline
Anticlinorium
Complex folding
A B Line of section
0 1 2 3 4 Km
N
Pachaco Mbr.
O (sh. & turb.)
O (lst)
Punta Negra F.

Figure 17. Punta Negra Formation in Section VII near Pachaco. Lithofacies transitional to the Pachaco Member. Note abundance of shale. Base to the right (West).

fingering with the submarine fan to the north.

2.4 Bedding characteristics and stratigraphic correlation

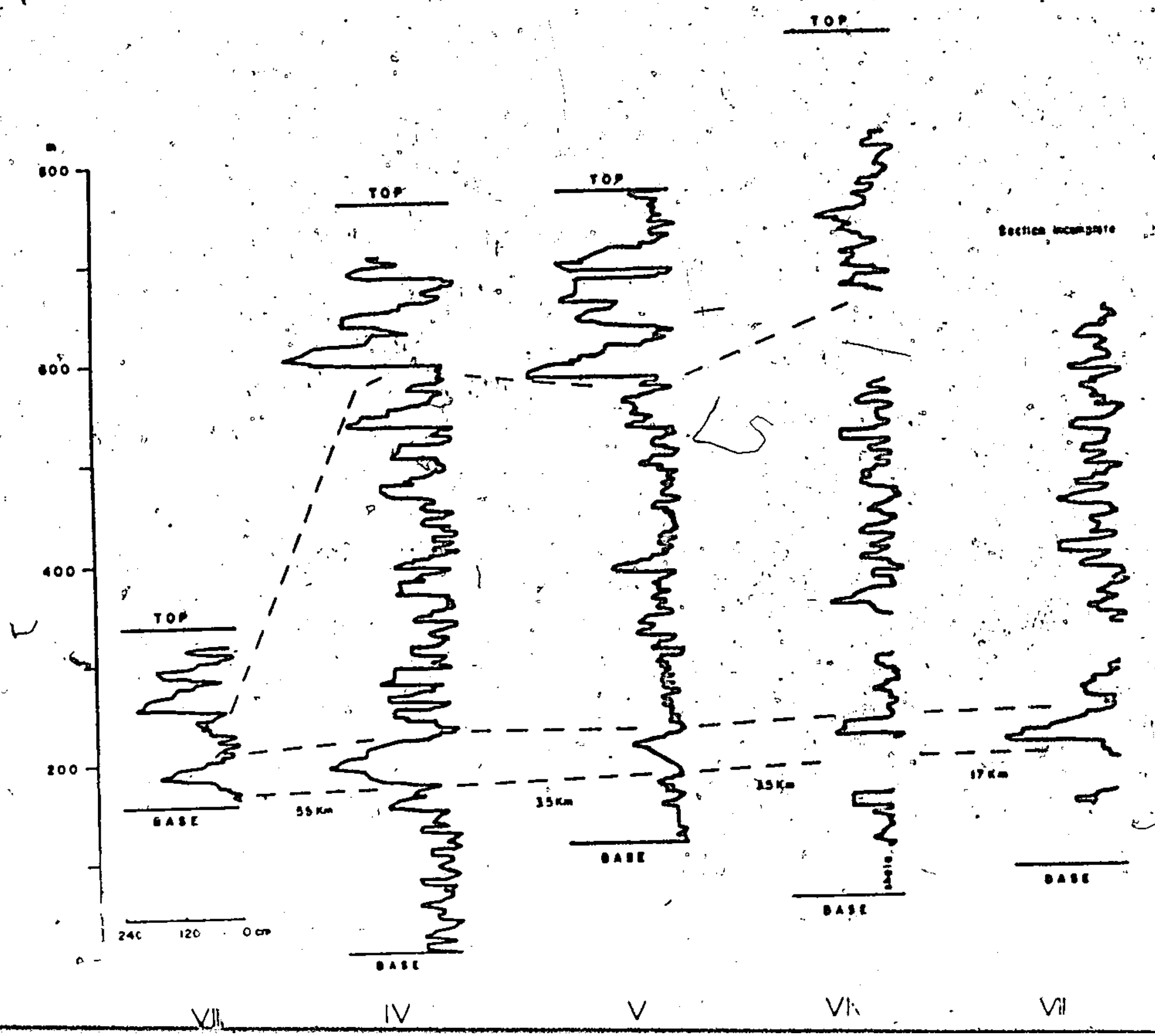
The purpose in measuring the detailed bed-by-bed sections was to study the vertical and lateral variations in bed-thicknesses and sand/shale ratios and attempt a stratigraphic correlation among the sections. Five such sections are herein presented in Figure 18. Three were measured along the San Juan River where it runs from west to east (Figs. 6 and 14), another near Pachaco (Figs. 6 and 15) and the fifth 15 Km NW of Talacasto (Figs. 6 and 16). The sections are numbered by roman numerals running from IV to VIII, corresponding to sections in Figure 5. The geologic cross-sections accompanying the detailed geologic maps, are drawn to the same scale as the maps. The sections cover the northern half of the Punta Negra Formation. No detailed sections were measured in the outcrops east of the Villicum Range.

Bed-thickness distributions

Approximately 5300 sand-shale units were measured in the field. Figure 19 shows the distributions for (i) all the sand-shale units, (ii) only the sand portions and (iii) only the shale portions, for comparison. As measured in the field, a sand-shale unit does not necessarily correspond to one turbidite, it is just an unbroken thickness of sand which grades upwards into a shale unit without intervening sand. Consequently, sand portions may be aggregates of amalgamated beds and the shale portions may be aggregates of shale deposited by different turbidites.

The complete bed and sand curves follow each other very closely. There is a slight skewness to smaller sizes but the lognormal

Figure 18. Moving average plots of complete bed thicknesses versus cumulative thickness for each section. Kilometers between sections indicate their geographic separation. Blanks in the plots are due to non-measurement. The two thicker-bedded levels are correlated by the broken lines.



m
800
600
400
200
0
TOP
BASE
240
120
0 cm
55 Km
35 Km
35 Km
17 Km
Section incomplete
VII
IV
V
VI
VII

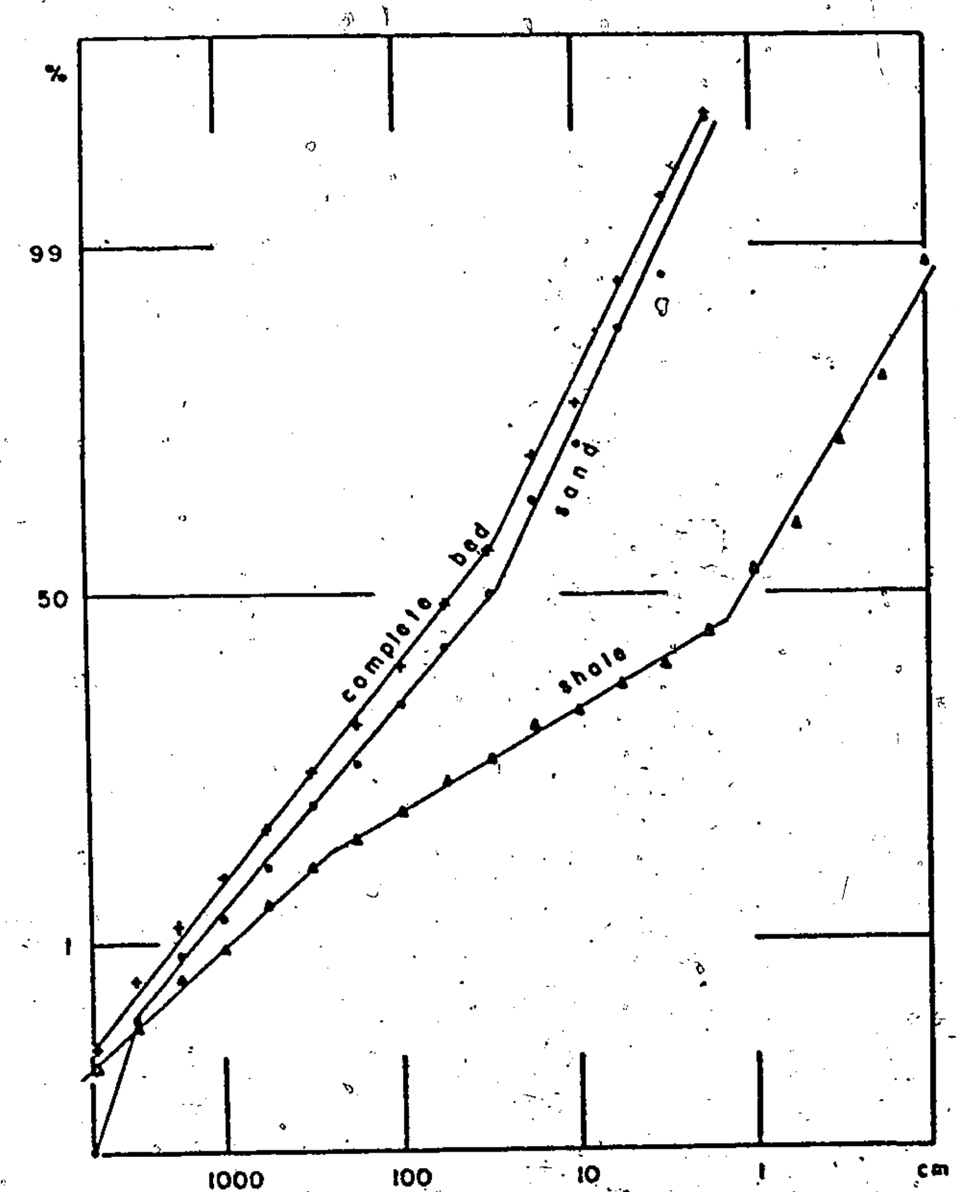


Figure 19. Logarithmic-probability plots of the thickness distributions for (i) the complete beds, (ii) the sand layers only and (iii) the shale layers only. Approximately 5300 beds were measured.

statistical model seems appropriate. The shale thicknesses have a higher variance and the skewness is more marked. Note that below the 50% line the curves show a greater frequency of thick layers. It is suggested that this is due to amalgamation and aggregation of shale layers and that if each turbidite had been measured individually, the distribution would be more lognormal.

The correlation between thicknesses of the sand and shale portions in each sand-shale unit, computed for each section separately and all the beds together, is close to zero, i.e. there is no correlation.

The correlation between maximum grain-size at the base and sand layer thickness for 438 beds was about 0.7.

Stratigraphic correlation

Figure 18 presents the moving averages for the complete bed thicknesses vs. cumulative thickness for each of the sections. Section V is the only complete one, the blanks in the others are due to covered areas and in section VII a few hundred meters may have been omitted from the upper part because the tectonic deformation did not allow measurement. The indicated kilometers between sections give their straight line separation, measured at their bases.

Two thicker-bedded levels are evident: the lower one appears in all five sections and the upper one in only four. The graphs are aligned on the lower level. Each of these levels is interpreted as a moment of greater sediment influx, mostly controlled by orogeny. The sections show that correlations over several km in medium-bedded turbidite sequences are unreliable unless closely spaced sections are measured and some sure plane of reference is available. Bed-by-bed correlation is impossible due to amalgamation; most single beds cannot be followed for more than 100 m. Figure 20 illustrates the

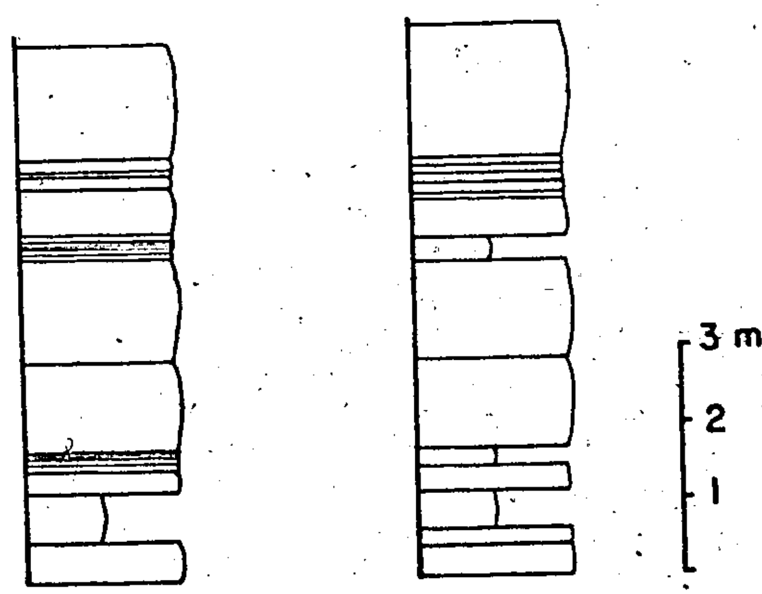


Figure 20. These two short sections only 8 m apart illustrate the very rapid changes in bedding characteristics that occur in the Punta Negra Formation. Note that the shale layers are generally very thin. Location is that of section VII.

rapid change in bedding with two short sections only 8 m apart, on both sides of a roadcut near Pachaco. Note that only the thicker beds remain unaltered over this very short distance and also that the shale layers are so thin that they could not all be drawn even at this scale.

Lateral Variations

Table I presents the means and variances for the thickness of the sand and shale layers, as well as the overall sand/shale ratio and maximum sand-thickness for each section. The maximum sand-thickness is the average of the 10 thickest sand layers in each section. Note that section III has been added, as compared with Figure 18. Section III is only 70 m thick but it was deemed important because it is the easternmost exposure of the Punta Negra Formation along the San Juan River (see Fig. 14 for location). The base of the Punta Negra does not outcrop in this area so the vertical position of the section within the formation could not be determined. This is the reason for not including it in Figure 18.

Ideally one would expect the mean and maximum sand-thickness and sand/shale ratio to decrease, and mean shale-thickness to increase downcurrent. However, the lateral variations in these parameters are irregular. It would not be surprising that Section VIII deviated from any pattern formed by the other five sections because it is rather remote from them geographically. The maximum sand-thickness value in section VIII is not the highest but the mean sand-thickness and sand/shale ratio are greater than in the other sections.

Strictly speaking, section III, because it is so short, may not be representative of the Punta Negra in this area. Nevertheless

Bed thicknesses and

sand/shale ratios

Section	Number of Beds	Mean sand thickness (cm)	Mean shale thickness (cm)	Sand/shale ratio	Maximum sand thickness (cm)
III	169	32.2	9.7	3.3	220
IV	1190	41.9	18.3	2.3	597
V	1677	29.7	9.5	3.1	576
VI	1142	31.8	19.9	1.6	350
VII	838	40.0	12.8	3.1	404
VIII	305	42.5	8.5	5.0	428

TABLE I

qualitative field observations in scattered outcrops nearby suggest that it probably is a good approximation; only the maximum sand-thickness might have increased somewhat had the total section been measured. Note that the mean sand-thickness is relatively small but the sand/shale ratio is relatively high compared with the other sections.

Considering sections IV, V and VI, there is an overall decrease in mean and maximum sand-thickness and in sand/shale ratio away from the source area. But, interestingly, in section VII these parameters increase again rather abruptly.

An explanation for these variations will be attempted when discussing the paleogeography of the Punta Negra and the importance of submarine topography in controlling sedimentation.

Sedimentary cycles

It has been shown by workers such as Kimura (1966) and Mutti and Ricci Lucchi (1972), that turbidite sequences may present a cyclic variation of the bed-thicknesses. The interpretation of these cycles varies for different authors, for example, Kimura believes that transgression-regression is the main control, while Mutti and Ricci Lucchi distinguish two cycle types: thinning-upwards and thickening-upwards. The former would be characteristic of the channelized middle fan area, and would result from gradual abandonment of the channels. The latter would be characteristic of the outer fan lobes, and would be formed during progradation of these lobes.

Figure 18 shows both cycle types including several peaks that are symmetrical. Perhaps the thinning-upwards type is slightly more numerous.

2.5 Sedimentary structures

Some clear evidence of slumping was observed in the Punta Negra. Several small folds and one recumbent fold about 60 cm in half wavelength (length of the overturned limb) were seen at section III, and one recumbent fold about 1 m in half wavelength was seen at section VI.

Sole Marks

Out of approximately 1700 beds whose bases were more or less exposed, about 70% had flat bottoms and no sole marks, 20% showed load casts only, and about 10% had flow structures of different kinds. Some beds were smoothly undulated at the base. Worm tracks were found in one percent of the beds. They were generally of the morphological type called repichnia by Seilacher (1964). Repichnia groups the "trails of burrows left by vagile benthos during directed locomotion." (Seilacher, 1964) The tracks found did not serve to determine the water depth.

The load casts are generally small, about 5-10 cm in diameter but some as large as 40 cm occur. Deformation of the underlying bed is slight, in general; flame structures pointing downcurrent are present. There may be a slight positive correlation between bed-thickness and size of load casts, for the larger sizes are never found in the thinner beds; the reverse does not hold.

Flutes are scanty; longitudinal ridges and furrows are the most common of the flow marks directly produced by turbulence. Frondescent casts and delicate flute casts are also present.

Tool marks such as grooves or prod casts are ubiquitous but prods appear to be more commonly associated with the thinner turbidites.

Internal Structures

Bouma's complete sequence is practically never present. The most common sequence of structures is a massive interval occupying most of the bed, which grades upwards into shale. In Bouma's (1962) terminology it would be called Ta,e. The second most frequent sequence but very subordinate to the first, is a massive interval which grades to a laminated interval which, in turn, grades to shale. Some of the thinner beds are laminated throughout and grade into shale; usually the grain-size in these beds does not exceed fine sand grade. But even among the thin sand beds, the common sequence is Ta,e. Ripple forms and, in particular, ripple cross-lamination, are almost completely absent from the sandy turbidites in the Punta Negra. A few beds show good convolute lamination.

The laminated interval usually occupies less than one fourth of the thickness of the bed and it immediately precedes, and grades into, the shale layer. Grain-size in the laminated interval is in the fine sand and coarse silt range. Laminations are parallel and only a few mm thick. In thin section, the laminae show variations in grain-size and content of mica and heavy minerals, the mica and heavy minerals being associated with finer sizes. The laminae are very diffuse and the change in grain-size is small. In some cases the lamination could be seen by naked eye in the thin section but was almost invisible under the microscope. In the absence of a rippled interval there is no obvious way of distinguishing between upper and lower flow regime parallel lamination (Blatt and others, 1972, p.123). Some of the thick beds show gross, faint lamination at any level.

The absence of ripples in these turbidites is interesting because the grain-size is generally appropriate for their formation and, in a waning turbidity current, the current velocity should pass a stage where it is also appropriate. The rippled interval would be expected to occur approximately where the laminated interval occurs, and in this region the grain-size ranges from fine sand to coarse silt. Unfortunately, most of the experiments on origin of sedimentary structures have been performed using coarser grades (see Southard, 1971, for a summary) or finer, as those by Rees (1966) who used fine silt.

Rees worked with material finer than 10 microns in a waning current. His experiments yielded two types of sedimentary sequences: (i) upper flow regime plane bed to ripple forms to lower flow regime plane bed and (ii) upper flow regime plane bed to lower flow regime plane bed. The formation of ripples, according to Rees, was controlled by two more or less independent factors, namely, the amount of sediment in suspension and the bed shear stress necessary for eroding the bed. If enough sediment was put in suspension, ripples would form even with erosion not taking place. With a fine-grained (hydrodynamically smooth) and cohesive sediment, the threshold stress for erosion may be high enough to prevent erosion during the range of stresses appropriate for ripple formation. In these conditions the appearance of ripples would depend on the amount of sediment in suspension. This is thought to be the case for the fine sand and coarse silt fraction of the Punta Negra because it contains abundant micaceous matrix which may produce some cohesion. Therefore, if the amount of sediment in suspension is small, ripples will not form. Although this does not seem a very likely situation for a turbidity current, when the mechanism of deposition of the Punta Negra graywackes is discussed, it will be shown that perhaps it was the case.

The shale units always show laminations except where they are bioturbated, but bioturbation is not very common. The laminations are parallel or slightly undulating. The laminae consist of darker micaceous material alternating with quartz silt; within many of the quartz silt laminae the heavy minerals form layers one grain diameter thick. It is common, in the Punta Negra Formation, to find shale units several tens of cm of even a few meters thick without intervening sands (Fig.10). Such a thickness of laminated shale cannot be attributed to one turbidity current; such units must surely be aggregates of numerous episodes of sedimentation. These shale units are homogeneous throughout and have one characteristic in common: they show silty laminae or lenses. Interestingly, the presence of these silty laminae was always recognized when the shale units were thicker than 2 or 4 cm (there is no sharp boundary), but not when they were thinner. It is suggested that only the part of the shale lacking the silt laminae belongs to the same turbidite as the underlying sand, which it grades into. Pelagic shale was never recognized.

It was stated above that the thicker shale units show silty laminae or lenses, each of these little beds grades into shale but their bases are not sharply defined. The latter observation is a matter of definition because when the bases were sharply defined, the units were recorded as turbidites. In point of fact, there seems to be a transition between the little units and better defined turbidites and it is only a matter of grain-size whether the base is well defined or not. The silty lenses in some cases resemble lenticular bedding but only seldom does internal ripple cross-lamination appear. Since the silt is rather well sorted it may happen that the lamination is not visible.

Well developed ripples were found on the top surfaces of two beds in the upper part of section V. In one of the beds the ripples show an interference pattern and in the other, a sinuous pattern, in plan view. Presumably, the interference ripples were formed either by bottom currents or by wave action but not by turbidity currents.

Graded bedding is one of the most diagnostic characteristics of sedimentation from turbidity currents and it is present in most strata of the Punta Negra Formation. As stated above, the massive interval in these beds may occupy the greater part of the thickness. The interval is massive because it does not show any laminations but it is not structureless in as much as it has some sort of grading. Quantitatively, grading is the most important internal sedimentary structure in the Punta Negra.

The procedures employed for the study of grading were outlined in section 2.2 (Methods). The thin sections were cut normal to the bedding but not necessarily parallel to the grain orientation and consequently the apparent grain-size may vary with their section orientation. Middleton (1962), for similar graywackes, found empirically that this variation may be as large as 0.24 phi.

To test the consistency of the operator, a t-test for paired means (Dixon and Massey, 1969, p. 121) was run over 4 slides. One hundred quartz grains were measured on each slide and the experiment spanned a period of two consecutive days. First, all sections were measured once and, afterwards, they were measured again. The results are presented in Table II; they fail to show that the operator is not consistent so the hypothesis of operator consistency is accepted. The confidence interval for the mean values was calculated as less than 0.2 phi at the 5% level.

Operator consistency test for means

Thin Section	Mean Size Original	Mean Size Duplicate	Mean Size difference (d)	Σd^2	Var(d)	t
P9	2.39	2.18	0.21			
P14	2.47	2.31	0.16	0.094	0.011	2.69
P15	1.77	1.69	0.08			$t_{.975,3} = 3.18$
P16	1.86	1.73	0.13			
		$\Sigma d =$	0.58			
		$\bar{d} =$	0.14			

$H_o : \mu_1 = \mu_1'$ is accepted

TABLE II

Table III summarizes pertinent data for each of the beds studied in the laboratory. The maximum size is the average of the ten largest grains.

Figure 21 shows the grain-size distributions for the same samples plotted on phi-probability paper; recall that the silt fraction was not measured so the distributions appear to be truncated. In Figure 22 the mean and maximum grain-size are plotted against the position in bed, to show vertical variations. Note that the distributions within each bed are parallel (Fig. 21) and that the curves for mean and maximum size generally have the same trends (Fig. 22).

The mean size was not measured in bed Fb-t because it was too fine-grained, only the maximum sizes are presented; this bed is laminated throughout. Bed G_{1-2} is a more representative example of the thin beds; in this case most of the sand portion does not seem to be graded but it does grade into shale at the very top. Some beds are structureless or show irregular grading, such as P_{8-12} and I_{1-4}. Amalgamation could cause irregularities but some thick beds were observed which have faint internal lamination or banding without evidence for amalgamation.

Several of the beds show a well defined inverse grading in their lower half. Accepting a maximum error of about 0.4 phi (the sum of 0.24 phi, due to thin section orientation error, and 0.2 phi, the confidence interval for the means) in the computation of the means one finds by studying Table III, that most of the differences between adjacent means are statistically significant. As a confirmation, t-tests were performed on the size data from three beds to determine whether the apparent inverse grading in the mean size was statistically significant. The samples employed were P_{14}-P_{15}, A'(b)-B' and 110_5-110_4. In all three

Grain-size data

Sample	Section	Bed Thickness(1)	Sample position (2)	Sedimentary structures	Means	Maximum Size
P12			99	massive	2.21	0.42
P11	V	102(0.1)	77	do.	2.44	0.50
P10			70	do.	2.12	0.32
P9			30	do.	2.28	0.40
P8			4	do.	2.55	0.71
P17			46	laminated	4.23	2.08
P16			32	massive	1.79	0.07
P15	V	60(55)	15	do.	1.73	0.55
P14			2	do.	2.39	0.80
P34			11	laminated	3.10	1.70
P33			6	massive	2.76	1.15
P32	VII	13(0.1)	2*	do.	2.44	0.90
P32(a)			0.5*	do.		1.02
G2	VI	11(160)	9	massive	2.49	0.57
G1			2	do.	2.32	0.67
F_t	VI	9(1)	7	laminated		1.90
F_b			2	massive		1.25
C			29	do.	3.01	1.40
B		30(0.5)	15	do.	2.62	0.59
A			2	do.	2.57	0.97
C'(b)			29.5*	faintly lam.	5.	
C'(a)	VI	30(0.5)	28*	massive	2.34	0.55
B'			15	do.	2.04	0.42
A'(b)			2*	do.	2.42	0.65
A'(a)			0.5*	do.	3.	1.72
A'''		4(0.5)	2	do.	2.24	0.69
110_2			225	laminated	3.5	1.63
110_3			195	massive	2.95	1.55
110_4	VI	240(12)	120	do.	1.83	0.50
110_5(a)			2	do.	2.32	0.38
110_5(b)			0.5			2.00
I4(b)	VI		43*	laminated?	2.60	2.30
I4(a)		47(3)	42*	massive	1.95	0.70
I2			20	do.	2.91	0.90
I1			4	do.	2.07	0.75
Z4	VI	750 (paracongl.)	710	do.	5.0(3)	
Z1			50	do.	3.9(3)	

(1) First number is sand thickness, second is shale thickness in cm.
(2) Position was measured in cm from the base.
(3) Grain-sizes larger than 4 phi were measured for these samples.
* Indicates samples within the same thin section.

TABLE III

Figure 21. Phi-probability plots of the grain-size distributions measured from thin sections. The symbols indicate only relative position of the samples; for exact position see Table III.

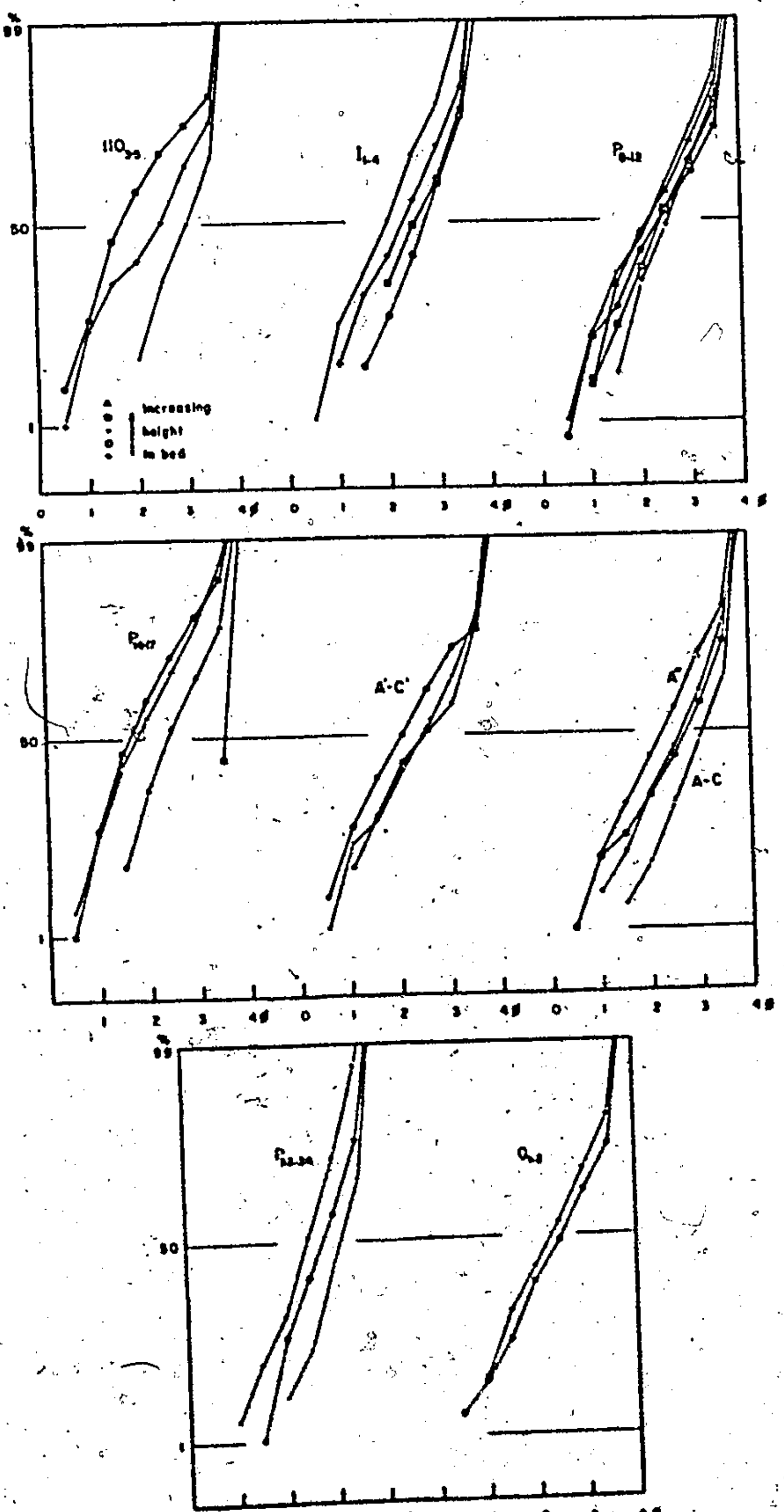
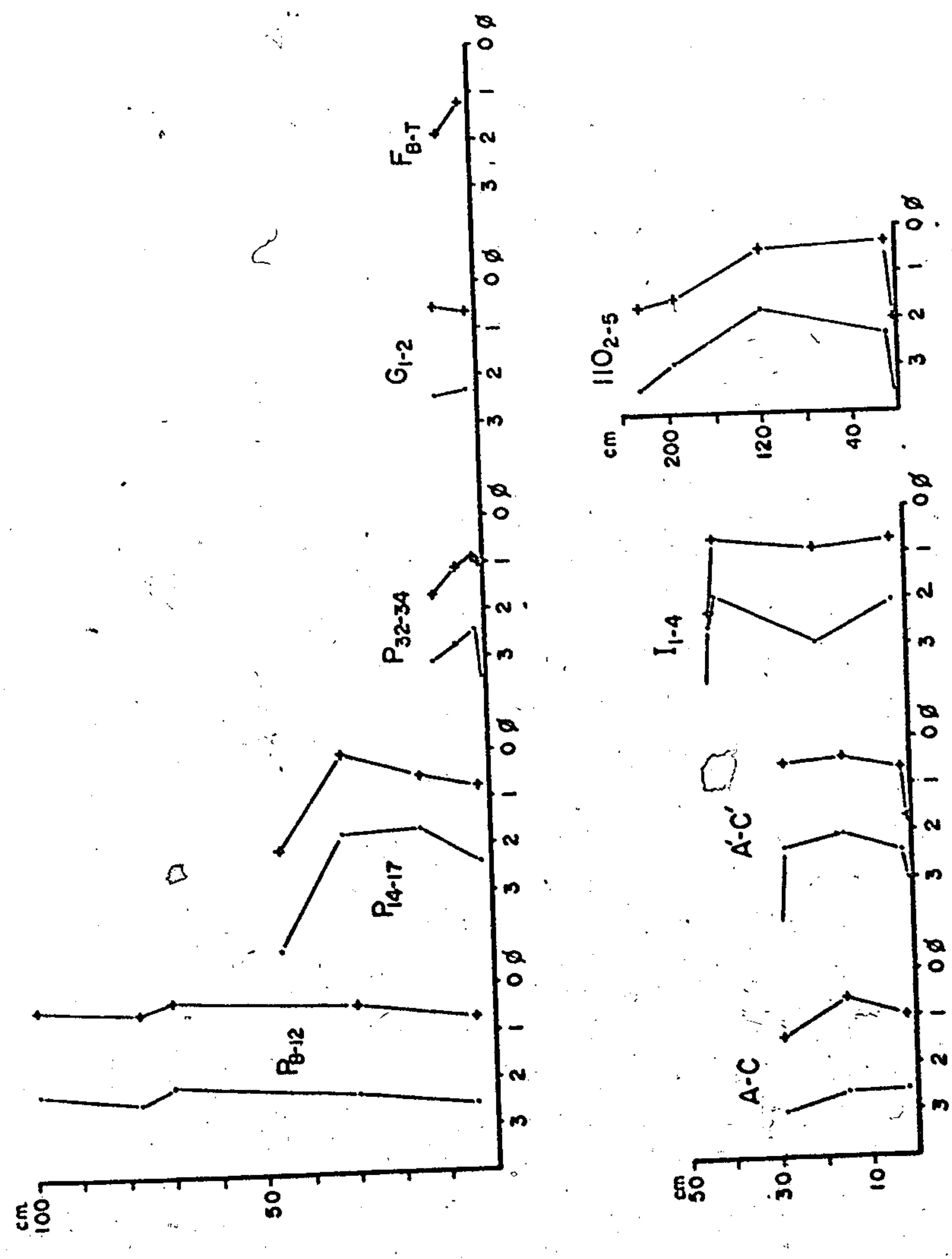

increasing
height
in bed
A'-C'
A-C

Figure 22. Plots of mean and maximum grain-size versus position in bed. Note that phi scale is reversed respect to Figure 22. Dots indicate mean size and crosses indicate maximum size (average of ten largest grains).



cm
100
50
cm
50
30
10
cm
200
120
40
F_{8-T}
G_{1-2}
P_{32-34}
P_{14-17}
R_{8-12}
I_{1-4}
A'-C'
A-C
$11O_{2-5}$
0 ø
1
2
3

cases the difference in means was found to be significant at the 5% level. The laboratory results confirmed field observations that indicated that inverse grading is very common in the Punta Negra graywackes.

Furthermore, observing closely the base of the beds one can in some cases notice a thin band - less than 1 cm thick - of distinctly finer sand, as, for example, in beds P_{32-34}, A'-C' and 110_{2-5}. In Figure 23 some of the means of the bottom samples were estimated visually because of the fine grain-size. When shale chips are present, they never occur at the very base but on top of this finer-grained band. In thin section, this band shows a fairly sharp but transitional, upper boundary (Fig. 23). The fine grained band is thought to be an integral part of the turbidite for two reasons: (i) the clear decrease in maximum grain-size rules out simple dilution with fine sand from the underlying turbidite and (ii) since silt and clay-sized particles were not considered for the size distributions, the possible incorporation of silt from the top of the underlying turbidite would not affect the mean.

In summary, the lower part of these beds show a well defined inverse grading. Furthermore, there seems to exist two different rates of inverse grading: (i) a very rapid inverse grading at the base of the beds and (ii) a slight inverse grading above.

The upper part of the massive interval in these turbidites show normal - although in some cases very rapid - grading and merge with the shale on top. There is no sharp change from inverse to normal grading as some of the plots in Figure 22 may suggest; actually the central part of the turbidite is generally structureless.

A similar grading pattern with inverse grading in the lower

Figure 23. Microphotograph showing part of samples P_{32} (above) and P_{32}(a) (below). Shows the strong rate of inverse grading present at the base of many Punta Negra graywackes. Scale in microns at bottom right corner.

part of the bed and normal grading in the upper part, has been recognized in other areas. Ksiaskiewicz (1954) called this pattern "pen-symmetrical grading". Interestingly, pen-symmetrical grading seems to occur more frequently in thick beds of the type called fluxoturbidites (Ksiaskiewicz, 1954; Ricci Lucchi, 1968). In the Punta Negra Formation, pen-symmetrical grading occurs in thick as well as thin beds and it differs from the standard pattern because the inversely graded portion of the bed is composed of two zones with different rates of grading. Double inverse grading such as this has not been explicitly described in the literature but it seems that it is not peculiar to the Punta Negra turbidites. In a study of inverse grading in turbidites of the Macigno (Oligocene formation in the Northern Appennines, Italy), Passerini (1966, Figs. 1 and 2) presents a micro-photograph from the base of an inversely graded bed which is very similar to Figure 23, and his plots of maximum grain-size show a rapid rate of increase in grain-size near the base and a slower rate of inverse grading above it, for some of the beds.

An attempt was made to find out if lateral grading was present. A wedge-shaped bed was sampled at the very extreme (sample A'''), at 8 meters from the extreme (samples A'-C') and at 10 meters from the extreme (samples A-C) (see Table III and Figs. 21 and 22). Unfortunately, there is no obvious trend; if anything, one might say that grain-size tends to increase towards the edge of the channel.

Bed 2 in Table III, illustrates the normal grading in the matrix of a thick pebbly mudstone in section V. There are no internal structures in the mudstone other than the slight normal grading from base to top. The larger clasts vary in diameter from 2 to 18 cm and occupy less than

5% by volume, of the rock. The clasts are not graded and none of them lay at the very base of the bed. That the clasts do not occur at the base of the beds is characteristic of most paraconglomerates in the Punta Negra. Whether or not normal grading is a common feature of these paraconglomerates could not be determined; most of the exposures with pebbly sandstones were poor. Normal grading was recognized in the field in two other pebbly mudstones.

An overall lateral grading was observed in the conglomerates and paraconglomerates of the Punta Negra Formation. East of the Villicum Range there are conglomerates with clasts as large at 40 cm, in a medium and coarse-grained sandstone matrix. In section III, just west of the Zonda Range along the San Juan River, there are pebbly sandstones with clasts as large as 25 cm and matrix of medium- to fine-grained wacke. Farther west, in sections IV and V, there are only pebbly mudstones with clasts smaller than 18 cm and a micaceous silty matrix. No paraconglomerates were seen in the other sections.

2.6 Petrography

The Punta Negra Formation appears in the field to be very homogeneous in colour and composition, both vertically and areally. Its three lithological components are, in order of decreasing abundance; (i) graywackes (ii) shales and (iii) conglomerates and paraconglomerates. In hand specimen, the graywackes are dark olive-green, well indurated and generally medium-grained. The shales are dark gray to almost black and mostly silt-sized. The aspect of the conglomerates and paraconglomerates depends to a large extent on the amount and grain-size of the matrix. The conglomerates may be light brown or greenish and the paraconglomerates, olive-green to dark gray.

The following discussion refers mainly to the graywackes; comments on the other lithologies will be made explicit.

Roundness and Shape

Figure 24 presents the results of the study of roundness of 150 grains from two thin sections (samples 110_4 and I2). Quartz, feldspar and lithic fragments all have modes in the subangular interval. The different asymmetries of the frequency polygons for quartz and lithic fragments should reflect their relative resistance to rounding. The feldspar polygon shows relatively low variance, this may reflect the effect of cleavage in controlling roundness.

The results of the study of shape (elongation) on 100 quartz grains from two thin sections (samples 110_4 and I2) are presented in Figure 25. The arithmetic mean of the sample is 0.55, that is, the grains are about twice as long as they are wide. Figures 26 and 27 illustrate the texture of the Punta Negra graywackes.

Fifteen pebbles from a pebbly sandstone and a pebbly mudstone were rounded to well rounded, and a sphericity of 0.7 and an oblate shape, following Zingg's method (Blatt and others, 1972, p.66). According to the data presented by Samos (1966) for quartzite pebbles the clasts were probably reworked in a beach environment before entering the basin, because of their high degree of roundness.

Mineralogy

The mineralogical composition of a few selected samples from the Punta Negra Formation is presented in Table IV. For samples

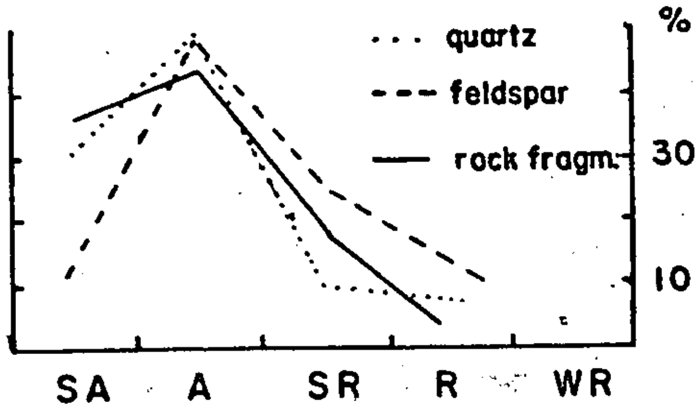


Figure 24. Frequency polygons for roundness of principal minerals of the Punta Negra graywackes. 150 grains were counted.

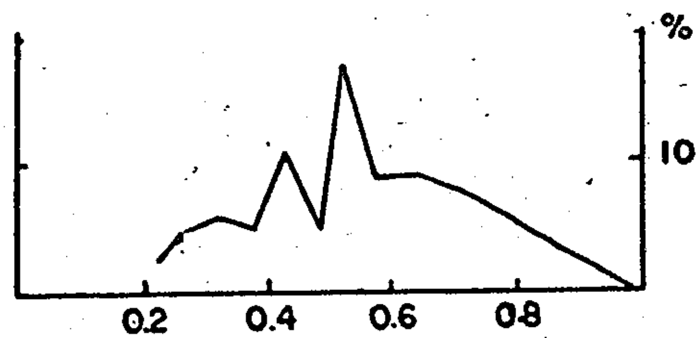


Figure 25. Frequency polygon for shape (elongation) of 100 quartz grains in the Punta Negra graywackes.

Figure 26. Typical texture of a Punta Negra graywacke. Crossed nicols. 63x.

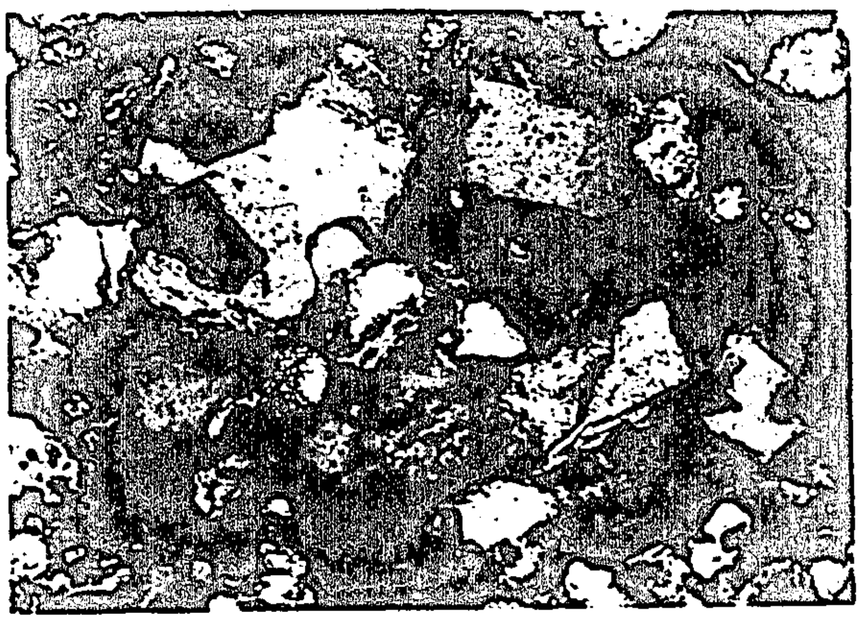


Figure 27. Detail of the central portion of Figure 26. Note some intergrowth between the matrix and the quartz overgrowths. Crossed nicols. 63x.

Mineralogic composition of selected samples

Component	110_5	110_4	110_3	$Av.110_{5-3}$	40	Aver	U_1	J_3	J_5
Quartz	35	32	28	32	32	32	34	43	31
Plagioclase	1	2	tr	1	3	2	-	-	-
K-feldspar	tr	-	-	tr	tr	tr	-	-	-
Muscovite	5	3	5	4	8	6	14	-	5
Biotite	4	1	1	2	-	1	1	-	-
Rock fragm. (quartzose	23	31	36	30	29	34	38	23	4
Rock fragm. (micaceous	10	13	4	9					
Heavy minerals	1	1	2	1	3	2	3	-	-
Calcite cement	1	-	-	tr	tr	tr	-	16	60
Matrix	20	19	20	20	24	22	9	1	-
	100	102	99		99		99	17(a)	100
								100	

(a) Detrital carbonate

110_{5-3} : Graywacke from section V; see Table V for location of samples within bed.

$Av.110_{5-3}$: Average of first three samples.

Aver. : Average of $Av.110_{5-3}$ and 40.

U_1 : Subgraywacke from near the top of section V.

J_3 : Arenite, coarse-grained turbidite east of the Villicum Range.

J_5 : Arenite, channel sandstone from east of the Villicum Range.

TABLE IV

110_{5-3}, 300 grains were counted in each thin section and for the other 4 samples, 150 grains were counted in each slide. The errors involved in the modal analysis were not calculated but because of the small number of grains counted they must be relatively large (see, for example, Griffiths, 1967, p. 193 and 198). This is why the percentages have been rounded to integers. The procedures employed in the modal analysis were explained under Methods and additional information and operational definitions are given for each mineral.

Quartz makes up about one third of the rock. Usually contains inclusions, mostly liquid but also of chlorite, muscovite or biotite. Examination of 300 grains in two thin sections from section V, revealed that 85% have undulating extinction, 10% have fragmental extinction and only 5% show normal or almost normal extinction. Polycrystalline quartz with mica flakes between crystals were counted as metamorphic rock fragments. A small amount of overgrowth seems to be common but it is generally difficult to see because original boundaries are not distinguishable. Overgrowths are never idiomorphic; they trap mica flakes of the surrounding matrix. When carbonate is present it partially replaces quartz.

Feldspar is scarce, usually not more than four or five grains in a thin section. The composition of the plagioclase was determined with a universal stage or by measuring the index of refraction in immersion liquids. The K-feldspar was distinguished by twinning or index of refraction. One thin section was stained to see whether untwinned feldspar grains were omitted from the count, but this was not so. Clear albite (An_2), neatly twinned, unzoned and without cleavage, predominates. Zoned and rather turbid oligoclase (An_{10-15}), is present in trace amounts. Potassium feldspar is mainly orthoclase with well developed cleavage and abundant solid inclusions, in some cases it is perthitic. Microcline is present. The index of refraction and staining showed that the potassium feldspar has not been albitized.

Micas occur in moderate amounts in the graywackes. They were distinguished by colour, birrefringence and the intermediate index of refraction measured with immersion liquids. The most common variety is a pale green phengitic muscovite (n_Y=1.597). Chlorite and biotite occur in small proportions. Detrital chlorite is present in two varieties: the commonest is a ferrous prochlorite with n_Y=1.642 and blue-gray interference colour, the other is a prochlorite with n_Y=1.632 and brown interference colour. The biotite is more or less bleached or altered to chlorite. When fresh it has an n_Y=1.704 (annite); the proportion of fresh biotite is slightly higher in the upper part of some beds. The mica flakes are usually deformed between more rigid grains.

Heavy minerals are represented by opaque and non-opaque minerals. They were studied in thin section, not separated. Opaque minerals predominate but their types were not distinguished. Among the non-opaque minerals the most common is sphene, then follow zircon and clinopyroxene, and last apatite and tourmaline, based on qualitative observations. The proportion of heavy minerals increases slightly in the upper part of the beds.

Rock fragments in the graywackes appear to be all low-grade metamorphic; a few doubtful granitic grains are present. The composition of the rock fragments varies between mainly quartz grains interlocked with a few parallel muscovite flakes and occasional plagioclase or biotite, and mainly muscovite surrounding a few small elongate quartz grains. Distinction between a grain of mica and a micaceous rock fragment is based on the presence of quartz between the mica flakes. The quartz-rich varieties are more abundant (see Table IV). The size distribution of the quartz grains in the rock fragments is coherent with that of the individual quartz grains found in the graywackes. The mineralogy of the rock fragments, too, is identical to that of the whole rock except for some heavy minerals and, perhaps, oligoclase.

In the arenite of sample J_3, besides the metamorphic fragments, there are fragments of micritic and bioclastic limestones, some carbonate pellets and a few fine-grained clasts that resemble shale more than a metamorphic rock.

The pebbles in the conglomerates and paraconglomerates consist mostly of metaquartzite. A few clasts of volcanic rocks such as diabase or syenitic porphyry are present, and other clasts of quartzose schists, metagraywackes, vein quartz and limestone were found.

Matrix was defined as all grains smaller than 30 microns. It is composed of the same minerals described above but muscovite and quartz predominate. X-ray analyses of the shales and bulk samples of the graywackes indicated that clay minerals are absent. The greatest difficulty when measuring the matrix content was distinguishing between the larger mica grains or very micaceous rock fragments which have been sheared by compaction, and the matrix-size muscovite and chlorite. On several occasions it was noted that higher concentrations of fine mica flakes appeared to be related to the nearby presence of a micaceous rock fragment, as if that rock fragment had been sheared and had shedded mica flakes. These flakes however, were seldom of matrix size.

Quartz grains are scanty; presumably they would be readily dissolved and contribute to overgrowths. It is probable that some recrystallization of the small micas has taken place.

Comparison with the Ordovician graywackes in the Precordillera which show diffuse quartz boundaries and, occasionally, mica growing perpendicularly between quartz grains (Fig. 35), suggests that recrystallization in the Punta Negra Formation graywackes is incipient, at most, and mimetic.

The average matrix content of the Punta Negra graywackes is about 20%. These results, obtained by point-counting under medium-power magnification, were checked on one thin section under high-power magnification; both results were similar.

Calcite cement is present in minor quantities in the graywackes. It is more abundant near the base of the beds and absent from the shales. It replaces a little quartz and feldspar. The texture is sparry.

In the arenites east of the Villicum Range calcite can be very abundant and replacement of the framework minerals is extensive in some cases. The texture is sparry.

2.7 Origin of the matrix

Cummins (1962) expressed an idea which was not totally new but had never before been presented so clearly and definitely: that the matrix in graywackes is mostly of secondary origin. A few years later, Kuenen (1966a, p. 296) went so far as to state that if a turbidite with a mean grain-size of 245 microns has 14% matrix, part of the matrix must be of secondary origin. These works have had a great influence on students of graywackes, an influence that was largely beneficial because they did point out a real problem; but in the opinion of the author, they went too far in their conclusions.

Cummins maintained that graywackes are compositionally immature and under diagenetic conditions the unstable minerals will alter to chlorite, sericite and silica, giving place to a "matrix". Supporting evidence would be: (a) that modern turbidites have little matrix, and (b) that typical graywackes occur preferentially in old orogenic belts.

Two main processes may contribute to the production of secondary "matrix": (i) mechanical breakage of micaceous rock fragments, and (ii) intrastratal solution and neoformation (diagenetic growth) of chlorite, sericite and quartz. Mechanical breakage will generally precede neoformation, and in the Punta Negra graywackes, where neoformation is negligible, mechanical breakage is the main cause for the obscure boundary between matrix and framework. In the following paragraphs, an attempt will be made to show that many graywackes may actually have a considerable amount of detrital matrix.

It is a common observation that rock fragments (usually feldspars too) are associated with the coarser size grades. Since rock fragments and feldspars constitute the unstable sand fraction, one would expect the coarser portions of turbidites to have a large proportion of secondary "matrix", and to be depleted of unstable grains. This expectation would also be supported by the fact that circulating intrastratal aqueous solutions should be bounded by the impermeable shale layers and should easily penetrate the coarser - more porous - bases of turbidites. But, in point of fact, it has been reported many times that the proportion of matrix decreases with increase in grain size. Okada (1966) found that the lower parts (coarser) of many Early Paleozoic graywackes in Wales, were relatively free of matrix. Crook (1960) maintained that the matrix of some New South Wales graywackes "shows little signs of reconstruction", and his Levy Graywacke Member is "very coarse lithic graywacke, locally rudaceous, which is very poorly sorted and has little matrix".

On the other hand, one cannot readily accept that 30% of a rock can be so easily dissolved. In lithic sandstones well within the zeolite facies, Coombs (1954, p.90) recognized several types of rock fragments and the recrystallized matrix forms 30% of the rock, which is similar to the possible original pore space. In more typical graywackes, Coombs and others (1959, p.66) define the initial stage of metamorphism by the appearance of minute chlorite crystals disseminated in the matrix; this stage precedes the appearance of prehnite and pumpeyllite. So it is the author's impression that before 20 or 30% of a sandstone is dissolved and transformed into matrix, not only would recrystallization be clearly manifest, (e.g. as "floating texture"), but probably metamorphic minerals would appear.

Rock fragments being the most important available source material for secondary "matrix", an inverse relationship would be expected between rock fragments and matrix contents. To study this relationship, the content of micaceous and volcanic lithic fragments for two suites of Early Paleozoic graywackes were plotted against matrix content (Fig. 28). Overall there is a very slight inverse correlation which can be accounted for by the relations between rock fragments and matrix contents versus grain-size, or hydrodynamical behaviour (Kuenen, 1966a). If 30-40% of the rock fragments had been destroyed to give place to "matrix" in

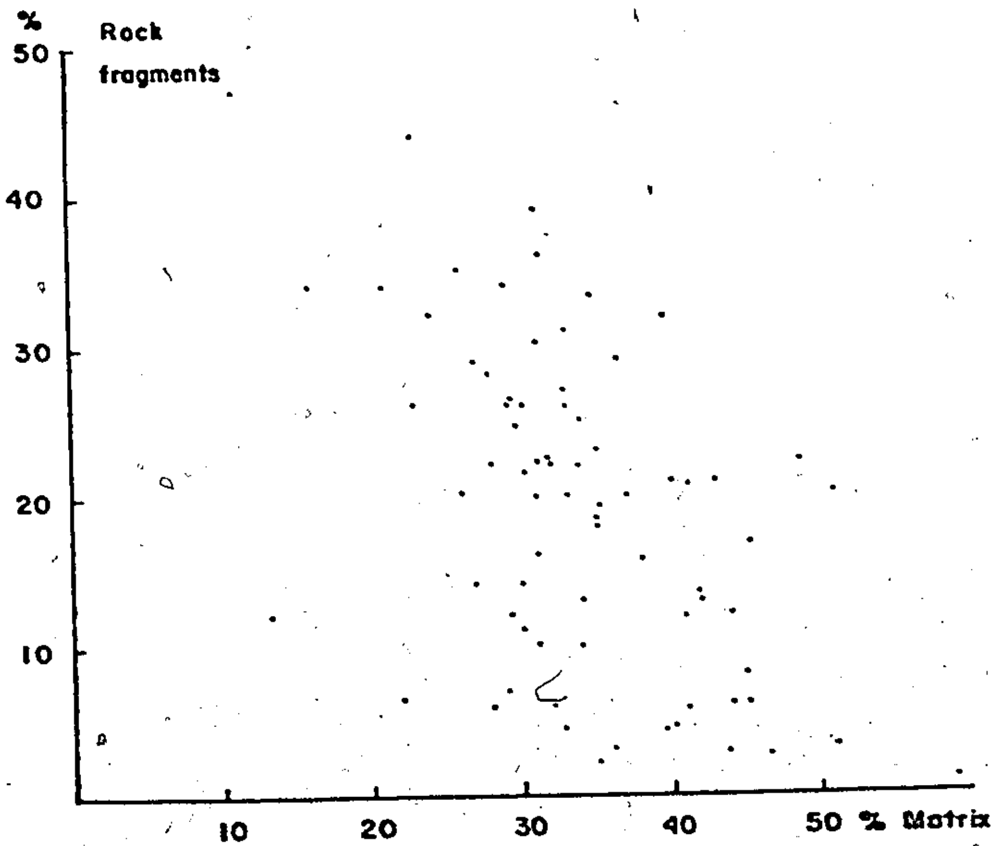


Figure 28. Plot of rock fragment versus matrix contents for two Lower Paleozoic suites of graywackes. Data from Walton (1955) and Okada (1966). If the matrix had been formed by destruction of the rock fragments, a larger angle of slope for the correlation line would be expected.

originally clean sandstones, one would expect a larger angle of slope for the correlation lime.

The second argument put forward by Cummins and Kuenen to support the idea that graywackes have a large proportion of secondary matrix, is that modern turbidites have little quantities of matrix. Some new data is available which is worth summarizing, for it modifies this long standing assertion.

Horn and others (1971a) published a large number of sieve analyses on cores from the Hatteras and Sohm abyssal plains in the North Atlantic. Most of the "not visibly graded", most of the graded sands and many other analyses by different authors have more than 10% silt + clay (this is equivalent to about 7-8% of material finer than 31 microns, or matrix) and overlap the field of ancient graywackes (Horn, and others, 1971a, Figs. 8 and 9). The same data - excluding samples with means larger than 4 phi - are plotted in Figure 29 to show the relation between matrix content and mean size. In these sands, 13% silt + clay is equivalent to about 10% material less than 31 microns in diameter, so more than half of the sandy samples are actually wackes. From the Pacific Ocean, Horn, and others (1971b, p.64) report that "of 22 samples of sand taken from the bases of coarse layers, an average of 10.4% of the sediment is smaller than 40 microns, 7.5% is smaller than 30 microns, and 2.4% is smaller than 3.9 microns."

The conclusion is that the generalization that recent turbidite sands are "clean" is not well supported. Many of them are wackes according to Gilbert's classification (in Williams and others, 1954, p.290).

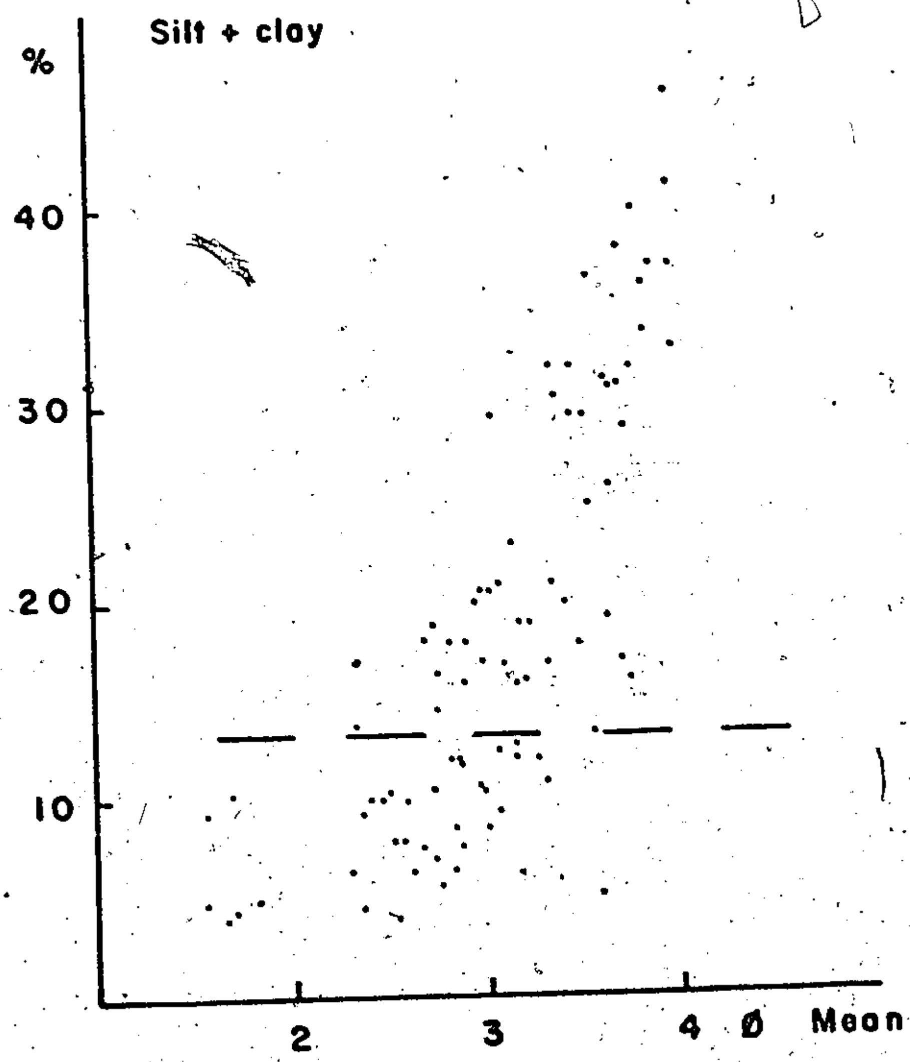


Fig. 29. Plot of silt + clay content versus mean size for recent turbidites in the North Atlantic. Data from Horn and others (1971a). Samples above the broken line have more than 10% matrix, and may be called "wackes".

As any other problem, the "graywacke problem" must be approached with an open mind. Diagenesis and hydrodynamics, undoubtedly, may influence the matrix content of a turbidite. But, for example, source lithology and the processes which accumulate sand - that eventually might form turbidites - on the shelf and submarine canyons, should also control the amount of matrix in a turbidite. A high matrix content in a graywacke cannot be discarded "a priori". Each case must be studied individually.

2.8 Mechanism of deposition

In this thesis the Punta Negra graywackes have been called turbidites, thus revealing the assumed mechanism of deposition. Nevertheless, the reader may have noticed that some characteristics such as the absence of ripples and the complex grading do not conform perfectly to the ideal turbidite. In the following, a more precise description of the stages and mode of deposition will be given and the peculiar sedimentary features will be explained. A brief discussion of relevant sedimentation mechanisms is presented first.

Following the scheme presented by Middleton and Hampton (1973), the main possible mechanisms of deposition of the Punta Negra graywackes are: (a) debris flow, (b) grain flow, (c) liquefaction and (d) turbidity currents. Only a few specific points will be discussed for each of these processes; for the general theory and more information the reader is referred to Middleton and Hampton (1973).

Debris flows have the fundamental distinguishing property of possessing yield strength (Johnson, 1970, Ch. 12). The yield strength is the sum of two components (Hampton, 1972, p. 779): (i) a frictional resistance caused by collisions among grains, and (ii) cohesion of clay or fine mica. Less than 10% clay is sufficient to develop yield strength (Hampton, 1972, p.779).

Subaerial debris flows and their deposits have been known for a long time but recently debris flows have been postulated to act in submarine conditions (Fisher, 1971; Hampton, 1972). As Johnson pointed out, a debris flow consists of a basal layer subject to shear and an undeformed upper part. The thickness of the sheared layer will increase as the yield strength of the flow decreases.

Grain flow as defined by Bagnold (1954), requires the existence of a dispersive pressure, that is, a pressure acting normal to the bottom and sustaining the grains in suspension, with no need for turbulence. The dispersive pressure, in turn, results from shearing the sediment.

It has been observed both in dry and wet sediments that shear tends to produce inverse grading. According to Bagnold (1954, p. 62) this is caused by the dispersive pressure being directly proportional to the cross-sectional area of the grains. On the contrary, Middleton (1970, p.267) maintains that it is the result of larger grains rolling over smaller grains that fill the interstices. In an ideal grain flow, movement takes place along an infinite number of shear planes parallel to the base of the flow. Consequently, given sufficient time, complete inverse grading should develop.

An important consideration is what type of sediment is more likely to move as a grain flow. As pointed out before, a relatively small percentage of fine interstitial material can give the sediment yield strength and prevent shear throughout the bed. Consequently, one expects grain flows to occur more often in clean sands than in wackes.

Horn, and others (1971b, Fig. 3, core RC 10-225) describe a core taken on the submarine fan off Vancouver Is., near shore. Three beds about 10 cm. thick show complete inverse grading. These are good examples of possible grain flows.

Liquefaction occurs when water pore pressure in a sediment equals the normal stress component, reducing to nil the shear strength. In this ideal condition the sediment behaves like a Newtonian fluid.

A liquefied flow stops when the excess water has been eliminated and this occurs rather fast (van der Knaap and Eijpe, 1969; Middleton, 1970) unless the beds are several meters thick. Fine micaceous and clayey material will produce yield strength and give the sediment debris flow properties. The best sediment for liquefaction would be poorly sorted sand but without very fine cohesive material.

Liquefaction and grain flow may be important in the initial or final stages of sediment movement but it is doubtful that they have much importance as transporting mechanisms.

Turbidity currents are divided into low- and high-density; the value of the limiting density is not known (Kuenen, 1966a, set it arbitrarily at 1.1 /cc) and probably varies with the size of the flow and the sediment used. The most characteristic unique feature of a deposit from a low-density turbidity current is good normal grading throughout; laminations and ripples are common but accessory. In deposits from high-density turbidity currents grading can be absent, poorly developed, irregular or inverse, except near the top where it should be normal; laminations and ripples are absent more often than in the low-density current turbidites. The experimental work by Kuenen (1948; 1966a) and Middleton (1966a,b and 1967) have been most enlightening in the understanding of turbidity currents.

From his experiments with high sediment concentration Middleton (1967, p. 495) described sedimentation in the following manner: "The accumulation of the bed, therefore, took place in four main phases: (1) initial deposition of sediment followed by extensive shearing of the bed, with the top of the bed not clearly defined; (2) formation of an expanded, 'quick' beds; "Helmholtz" waves at the upper surface of the bed produce shearing motion deep within the bed; (3) disappearance of waves and formation of a plane surface, and consolidation of the bed; and (4) very slow deposition of the finest sediment from the 'tail' of the current". Slight inverse grading was present in most turbidites formed from high concentration flows but not in those formed by low concentration flows (Middleton, 1967, p.489).

Let us return now to the Punta Negra graywackes and review the main sedimentary features that must be explained with any mechanism of deposition that is adopted. They are: (i) the strong inverse grading very near the base, (ii) the slight inverse grading that follows and that can occupy most of the lower half of the bed, (iii) the normal grading to shale in the upper part of the beds (in some cases with laminations), and (iv) the absence of ripples.

Middleton's phase 1 of deposition is interpreted mainly as a grain flow, during which shearing produces inverse grading. The rate of inverse grading (or change in grain-size) would depend on sorting, rate of shear and duration of this phase. If slightly larger grains were present the grading would probably be more conspicuous. The shear is produced by the entrained fluid layer (Middleton, 1967, p.495) and the rate of shear depends on the velocity of the entrained fluid. The duration of grain flow conditions, judging from Middleton's experiments, need not be long; inverse grading is developed very rapidly.

It may be worth noting that during the collective settling of the grains from the suspension, water will be expelled upwards and parts of the bed may reach a state of liquefaction. But this condition is considered to be transient and unimportant in the formation of sedimentary structures. Features such as water escape structures, for example, would be destroyed by the shearing.

As long as the shear rate is high, the whole bed will be sheared. But when the shear rate gradually decreases a time will be attained when the shear stress at some point within the bed is equalled by the yield strength of the sediment. Thus, gradually, the grain flow will give place to a debris flow. Although ideally the transition should be gradual, heterogeneities in the sediment will most probably prevent this. It is suggested that it is under these debris flow conditions that the fine-grained layer at the bottom is formed.

An attempt will be made to calculate the yield strength of the debris flow. Hampton (1972, p.778) states that sandy debris flows behave similarly to clay slurries in that the yield strength decreases with addition of water. When the debris flow stage is reached in the mechanism proposed above, the porosity of the sediment should be high. A reasonable estimate is 40 to 50% (Blatt and others, 1972, p.71). For a similar water content kaolinite has a yield strength of about 1200 dynes/cm^2

(Hampton, 1972, Fig. 1). This must be an absolute maximum because kaolinite is more cohesive than silt-sized mica; the contribution of frictional resistance due to the sand grains is not known.

Another approach to the problem of calculating the yield strength of the debris flow, is provided by Johnson (1970, p. 506) who presented an equation relating the thickness of the rigid part of a debris flow to its yield strength. The equation is valid for subaerial debris flows and has the following form:

$$y_o = \frac{k}{\gamma_f \sin \delta} \left[\left(\frac{b}{a} \right)^2 + 1 \right]$$

where

y_o is the thickness of the rigid part of the debris flow.

γ_f is the specific gravity of the flow

k is the yield strength of the debris

δ is the slope of the flow surface

a is half the width of flow

and b is the depth of flow

Adapted for subaqueous debris flows and expressed in dimensional form it changes to:

$$\frac{y_o}{b} = \frac{k}{b \gamma' \sin \delta} \left[\left(\frac{b}{a} \right)^2 + 1 \right] \quad ; \quad \gamma' = \gamma_f - \gamma_{water}$$

In the Punta Negra Formation the beds are much wider than they are thick, so $\frac{b}{a}$ is close to zero and the term in brackets is approximately equal to 1. Since the fine-grained layer at the base, which is considered to be the sheared layer, is very thin, $\frac{y_o}{b}$ is also approximately equal to 1. The formula, then, is reduced to:

$$k = b \gamma \sin \delta$$

In order to calculate the yield strength a few values must be assumed. Disregarding compaction, b will be taken as 40 cm, which is approximately the average bed thickness. For the density of the flow, a value of 1.5 g/cm^3 is taken. This is intermediate between 1.1 g/cm^3, proposed by Kuenen (1966a) as the lower limit of high density turbidity currents, and a value of 2 g/cm^3, common in natural subaerial debris flows; a density of 1.5 g/cm^3 is also compatible with a water content of 40 to 50%. Finally, a slope of 1.5 degrees is assumed (see, for examples, Nelson and Kulm, 1973, Table 1).

With these values:

$$k = 40 \text{ cm } (0.5 \text{ g/cm}^3) 970 \text{ cm/sec}^2 \ (0.026)$$

$$k = 500 \text{ dynes/cm}^2.$$

The obtained yield strength is well below the estimated maximum of 1200 dynes/cm^2. Unfortunately, no measurements of yield strength in sandy slurries could be found in the literature.

Two of the sedimentary features present in the Punta Negra graywackes remain to be discussed, namely, the normal grading and the absence of ripples. Normal grading is thought to be formed during Middleton's phase 4 of deposition, that is, sedimentation of the fine sediment from the 'tail' of the current. The thickness of the normally graded part of the bed will depend on the amount of sediment that remained in suspension; in many cases it is very thin. After the Helmholtz waves disappear and the bulk of the bed consolidates (Middleton's phase 3 of deposition) it seems that the velocity of the entrained layer should be relatively low and the amount of sediment in suspension should also be low. Recalling the discussion on ripples given above, both these factors would hinder the development of ripples. Which of the two was more important is not known.

The laminations pose a special problem. When a laminated interval is present, the normal grading is well developed and occupies a relatively thick portion of the bed (perhaps, one third or one fourth of the total thickness), although the reverse does not hold, for normal grading can be well developed without apparent laminations. No attempt will be made to explain the occurrence of laminations in these beds. An essential question remains unanswered concerning the origin of the laminated interval in turbidites, which is, whether the laminae are formed because of changes in the current velocity or by shear caused by a uniformly decelerating current (Kuenen, 1966b).

In summary, the following stages are proposed for the deposition of the Punta Negra graywackes:

Stage I. The sediment is transported almost to its final place of deposition by a high density turbidity current. A gross estimate for the velocity of the current could be 2 to 3 m/sec, depending on the thickness and density of the underflow (Middleton, 1966b). Accordingly, the duration of this stage would be in the order of 1 or 2 hours, depending also on the distance to the site of deposition.

Stage II. A relatively short time before the flow finally stops, grain flow conditions obtain (phase 1 of Middleton). A slight inverse grading develops.

Stage III. The rate of shear decreases as the current velocity diminishes. The shear stress within most of the beds is not sufficient to overcome the yield strength so shearing stops and the grain flow is transformed into a debris flow. A sharp inverse grading is formed near the base because of locallized shearing. In Middleton's experiment, there could have been no debris flow stage because there was no matrix to impart strength. So the fine-grained band should not be present.

Concerning the pebbly sandstones and mudstones little can be said because they were not sufficiently studied. The preliminary observations presented in section 2.5 (Sedimentary Structures) indicated that the matrix of these paraconglomerates shows both lateral and vertical grading. The lateral grading is evidenced by a bulk change from pebbly sandstones to pebbly mudstones downcurrent; the vertical grading was observed in pebbly mudstones and it is a slight normal grading.

The necessary yield strength to support a cobble 18 cm in diameter (maximum size found in the pebbly mudstones) is (Johnson, 1970, p. 487) about 2000 to 3000 dynes/cm^2, depending on the density of the mud. With an increase in the yield strength, the critical Reynolds number also increases and more energy is necessary to produce turbulence in the flow (Hampton, 1972, p. 789 ff.). Compared with experimental slurries (Hampton, 1972) or with natural subaerial flows (Johnson, 1970), a value of 2000 dynes/cm^2 for the yield strength is relatively high; a flow with such a yield strength would probably be mostly laminar. Consequently, if it is assumed that the clasts were transported supported by the matrix as debris flows, it is difficult to explain how the grading developed only in the matrix.

One particular pebbly sandstone merits an individual description. It is 1.3 m thick, with clastsup to 10 cm in diameter embedded in a matrix of very fine muddy sand (Fig. 30). The bed is massive but there is abundant evidence of internal shear. The clasts are concentrated near and at the base, which is abnormal. It is a unique example. No explanation for these features will be attempted. More petrographic work is needed, particularly to ascertain that the grading is a characteristic feature of the matrix of these paraconglomerates.

2.9 Paleocurrents

About 360 paleocurrent measurements were made on the Punta Negra Formation. Of these only 14% are vectorial, the rest give line of movement only. One measurement for each bed was taken; in very few cases when two distinctly different directions were present, both angles were recorded separately. The samples were taken wherever possible and the total number of measurements for each section plotted together. The degree of exposure of the soles of beds varies along sections, and sometimes the measurements are concentrated where the soles are better exposed. Consequently, the samples are far from being random. An attempt was made to study the vertical (time) variations in the paleocurrent pattern. Each section was divided into approximately equal parts and the measurements in each of those parts plotted separately. No significant changes in mean directions could be detected, perhaps because the number of measurements was too small.

Throughout the Punta Negra outcrops the strikes of the beds range between 340° and 40°; the majority of the measurements were taken on beds with strikes ranging between 350° and 10°. Strike variation within

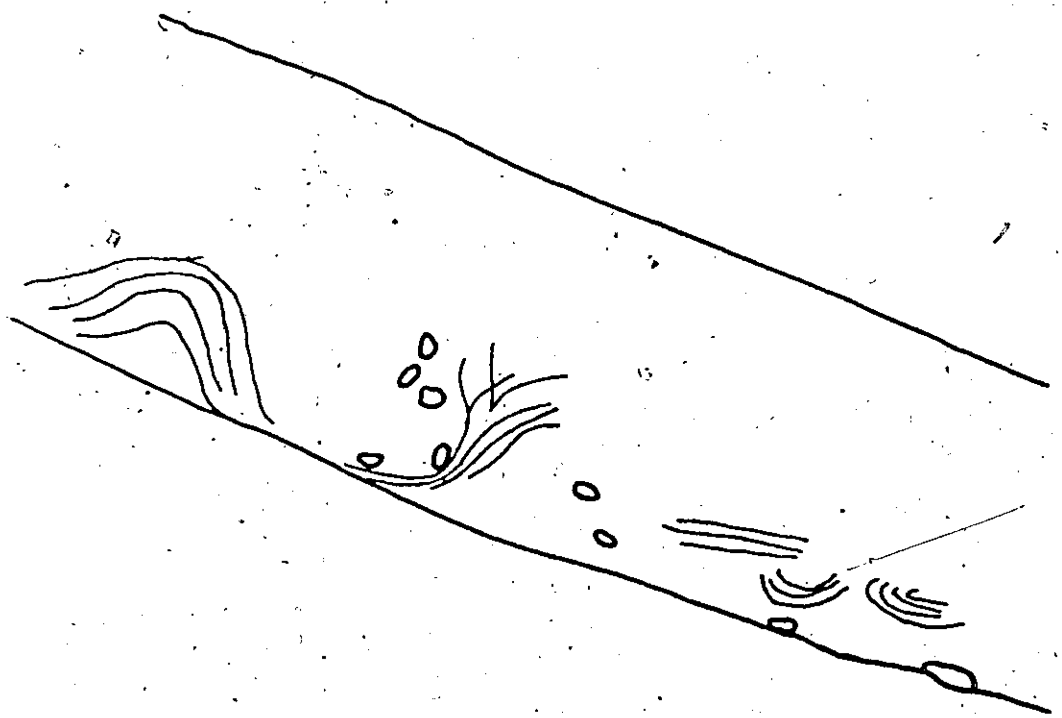


Figure 30. Pebbly sandstone 1.3 m thick, at section IV. The clasts are concentrated near the base and the clast on the right slightly deforms the shale below. The thin lines indicate a faint cleavage visible in the rock which is attributed to shearing and deformation while in a state of liquefaction.

sections is generally smaller, about 10° in range. The average measurement error is about 5-10°, determined empirically.

The paleocurrent rose diagrams are plotted in Figure 31. The numbering on the diagrams corresponds to that of the sections in Figure 5, with the exception of VIa which was measured 7 km north of section VI, along the San Juan River. Each rose diagram consists of two parts: inside the circumference the ungrouped vectorial measurements are plotted and outside the circumference are plotted all the data (both vectorial and line-of-movement). The data are grouped into 20° intervals, as percentage of the total; the zero line is the circumference.

The distributions show rather well developed trimodality (section VII), good bimodality (section III) and unimodality with very large dispersion. The main flow component is to the north in section III and gradually rotates to the west closer to the Tontal Range. Section VII, closest to the Tontal Range has a divergent flow pattern.

Figure 32 shows the suggested vector means for these distributions and their geographical location.

PUNTA NEGRA FORMATION

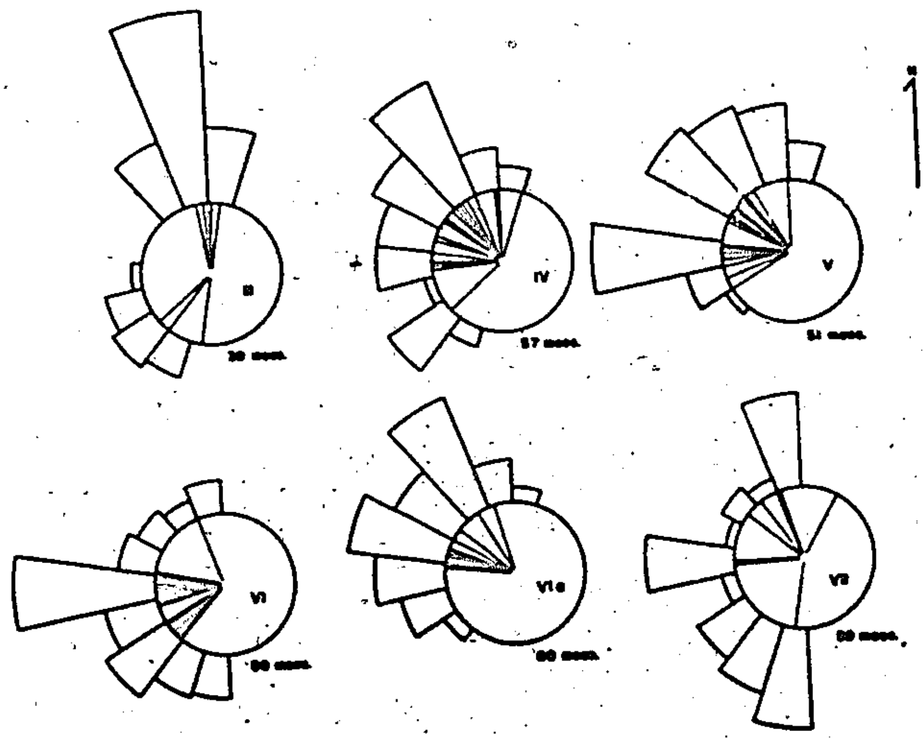


Figure 31. Paleocurrent rose diagrams for the Punta Negra Formation. Inside the circumference are plotted the individual vectorial measurements. Outside the circumference, all the data (vectorial plus non-vectorial) are plotted as percentages; the circumference is the zero value. The data is grouped in 20 degree intervals. For geographic location of the diagrams see Figure 6.

PUNTA NEGRA
FORMATION

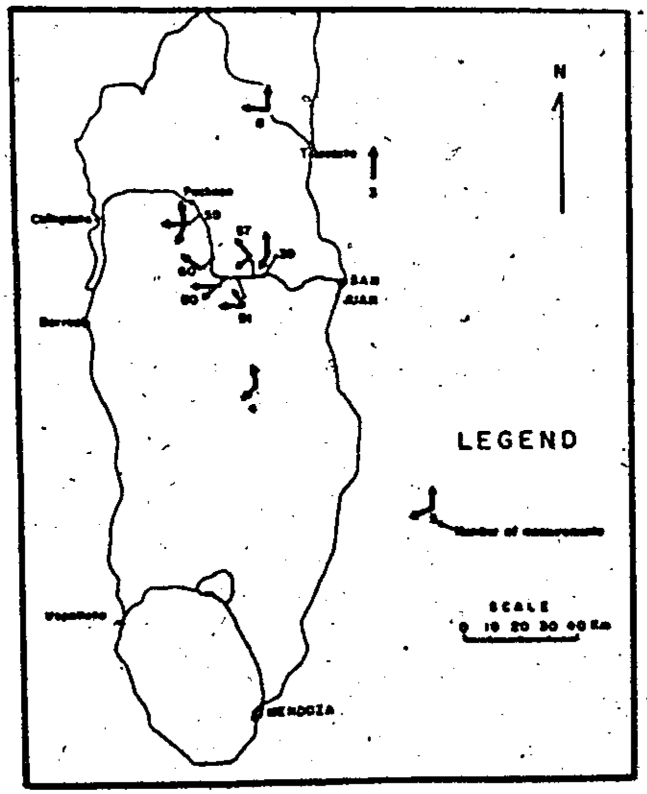


Figure 32. Paleocurrent pattern for the Punta Negra Formation. Only the estimated vector means are plotted.

2.10 Conclusions

The Punta Negra Formation can be divided into two facies, namely, (i) a conglomeratic lithofacies, on the east (facies A) and (ii) a graywacke lithofacies, including most of the Punta Negra Formation outcrops (facies B).

The association of conglomerates with shales and some slump features, and the absence of turbidites, suggests that facies A was deposited on a slope bordering the mainland. Turbidity currents crossed this slope and deposited sediment farther west, to form facies B. The adjacency of facies B to the slope sediments, the high sand/shale ratio, the thick bedding and the presence of a few paraconglomerates, suggests that facies B was deposited as a submarine fan. All the detailed work for this thesis was carried out in facies B.

The sandstones in facies B are well indurated, dark olive green, quartzose lithic wackes. The sole marks and the internal structures indicate that they were deposited from turbidity currents. The shales are composed of mica and quartz, mostly silt-size. They are laminated and occasionally show ripple cross-lamination. The shales are also considered to have been deposited from turbidity currents; no evidence for contourites was found.

Special emphasis was given to the mechanism of deposition of the sandstones in facies B. The internal sedimentary structures, in particular the grading, were carefully studied in the field and the laboratory. A typical sandstone-shale couplet in facies B of the Punta Negra Formation will show the following internal sedimentary structures, from base to top:

(i) a thin, fine-grained band which gradually, but very rapidly, passes to (ii) a coarser-grained portion with a slight inverse grading, occupying about one third of the bed, (iii) a central structureless portion, which serves as transition to (iv) a normally graded portion of the bed, which in some cases passes to (v) a laminated interval and (vi) the laminated shale on top. Ripples within the sandstone are very rare.

The main transporting mechanism is thought to have been high density turbidity currents, modified in the last stages of deposition by grain flow and debris flow conditions. Evidence for the turbidity current mechanism stems from structures iv, v and vi: evidence for grain flow comes from structure ii, and for debris flow, from structure i. The abundance of matrix is considered a rather circumstantial, that is, not unequivocal, evidence for high density turbidity currents.

The paleocurrent pattern for the Punta Negra Formation shows two main components for the paleoflow, namely, to the N or NNW, and to the west. The measurements show polymodal distributions and large dispersions, as might be expected from a submarine fan.

Several explanations concerning the facies changes, bedding characteristics and paleocurrent pattern, were deferred until the paleogeography had been described. In the next section, an attempt will be made to reconstruct the paleogeography of the Punta Negra basin.

DEVONIAN TURBIDITE BASIN IN ARGENTINA

CHAPTER THREE

REGIONAL GEOLOGY AND PALEOGEOGRAPHIC SYNTHESIS

This section presents the results of a reconnaissance study of the Regional Geology of the Precordillera. The objective of this study was to establish the prior geological history and throw some light on the paleogeography of the Devonian in the area where the Punta Negra Formation was deposited. Only the pre-Carboniferous rocks are described.

The rocks in the Precordillera are mainly sedimentary with locally abundant volcanic or metamorphic rocks, and are mostly Paleozoic in age. Figure 33 is a stratigraphic table summarizing presence or absence of the Paleozoic in the Precordillera.

3.1 Precambrian

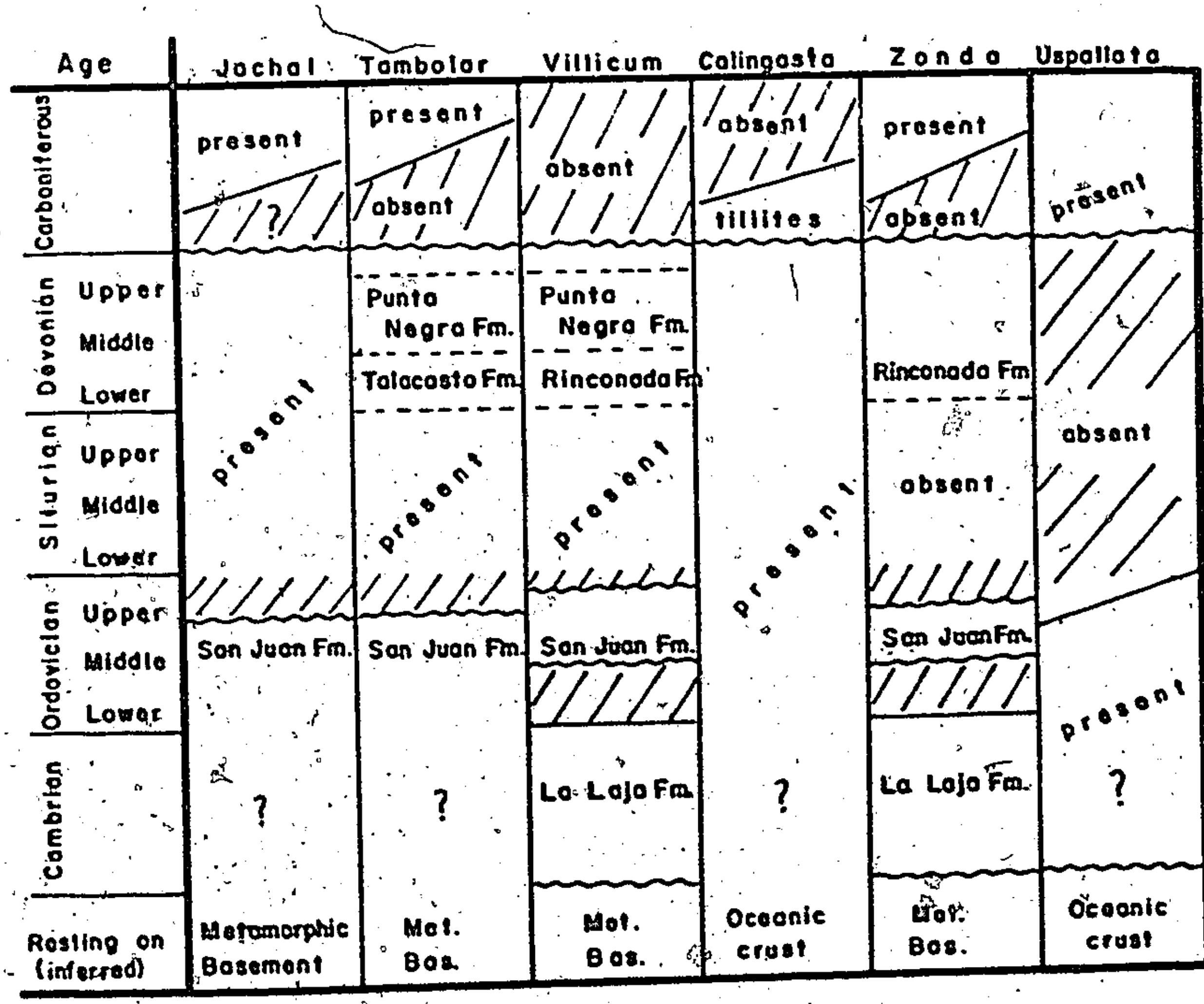
Within the Precordillera, Precambrian rocks are exposed only in a small hill some 40 km south of San Juan, along the road to Mendoza (Fig. 2). The exposure consists of quartz-muscovite and chlorite-biotite schists, metadiabases, amphibolites and metamorphosed pegmatites. The assemblages fall within the greeschist facies (Kilmurray and Dalla Salda, 1971). Evidence for the age comes from the regional geology. The oldest rocks in the surroundings are Lower Cambrian unmetamorphosed limestones.

Further east this metamorphic basement outcrops much more extensively forming ranges.

3.2 Cambrian and Ordovician

Because of their similar lithology, the separation of these two systems in the field is for the most part impossible, unless fossils are present, so they will be described together. Nevertheless, there

Fig. 33. Stratigraphic table showing correlation and areal extent of the main Paleozoic units discussed in this work, as well as the general presence or absence of the Paleozoic in the Precordillera. The hatched areas indicate that rocks of these ages are absent; the rocks may have been eroded or never deposited. The world 'present' in the blank portions of the columns, indicates that rock representatives for those time intervals were recognized but it does not mean that the sequences are complete. The queries for the Cambrian indicate that it may be present but has not yet been recognized with certainty.


Age
Jachal
Tambolar
Villicum
Calingasta
Zonda
Uspallata
Carboniferous
Devonian
Upper
Middle
Lower
Silurian
Upper
Middle
Lower
Ordovician
Upper
Middle
Lower
Cambrian
Resting on (inferred)
present
?
present
absent
absent
absent
tillites
present
absent
present
Punta Negra Fm.
Talacasta Fm.
Punta Negra Fm.
Rinconada Fm.
Rinconada Fm.
present
present
present
present
absent
absent
San Juan Fm.
San Juan Fm.
San Juan Fm.
San Juan Fm.
present
?
?
La Laja Fm.
?
La Laja Fm.
?
Metamorphic Basement
Mat. Bas.
Mat. Bas.
Oceanic crust
Mat. Bas.
Oceanic crust

are doubts as to whether they correspond to a single continuous depositional cycle. The Cambro-Ordovician deposits can be divided into two facies: limestone in the east and clastics in the west (Fig. 34).

The limestone facies extends from north of Jachal to Mendoza, and from the eastern border of the Tontal-Tigre Ranges until about the city of San Juan where it is covered by recent sediments. The best exposures are along the Zonda-Villicum Ranges. The base is never exposed but it is believed that the limestones rest on the metamorphic basement. The thickness reaches 3000 meters.

Borrello (1971) described Cambrian sediments outcropping in the Zonda and Villicum Ranges. They are limestones, dolomitic limestones and dolomites, in medium and thick regular beds; some clays and arenites are present. Chert nodules are scanty and oolites are common in the carbonates. The exposed thickness for this unit is 600 meters. The age has been well established with trilobites. In the San Juan area, ages are Early to Middle Cambrian, and the next fossils up in the carbonate sequence are Middle Ordovician, with the beds conformable. Around Mendoza, the Cambrian limestones have more sand intercalated. Here they contain Middle and Late Cambrian trilobites but there is an angular unconformity with the overlying Middle Ordovician limestones (Borrello, 1964; 1971, p.429). There is some evidence, then, for a regional unconformity between the Cambrian and Ordovician despite the similar lithology. Borrello (1971) employed the name La Laja Limestone for the Cambrian system exposed in the Zonda-Villicum Ranges. It is here proposed to change it to La Laja Formation, complying with stratigraphic terminology rules.

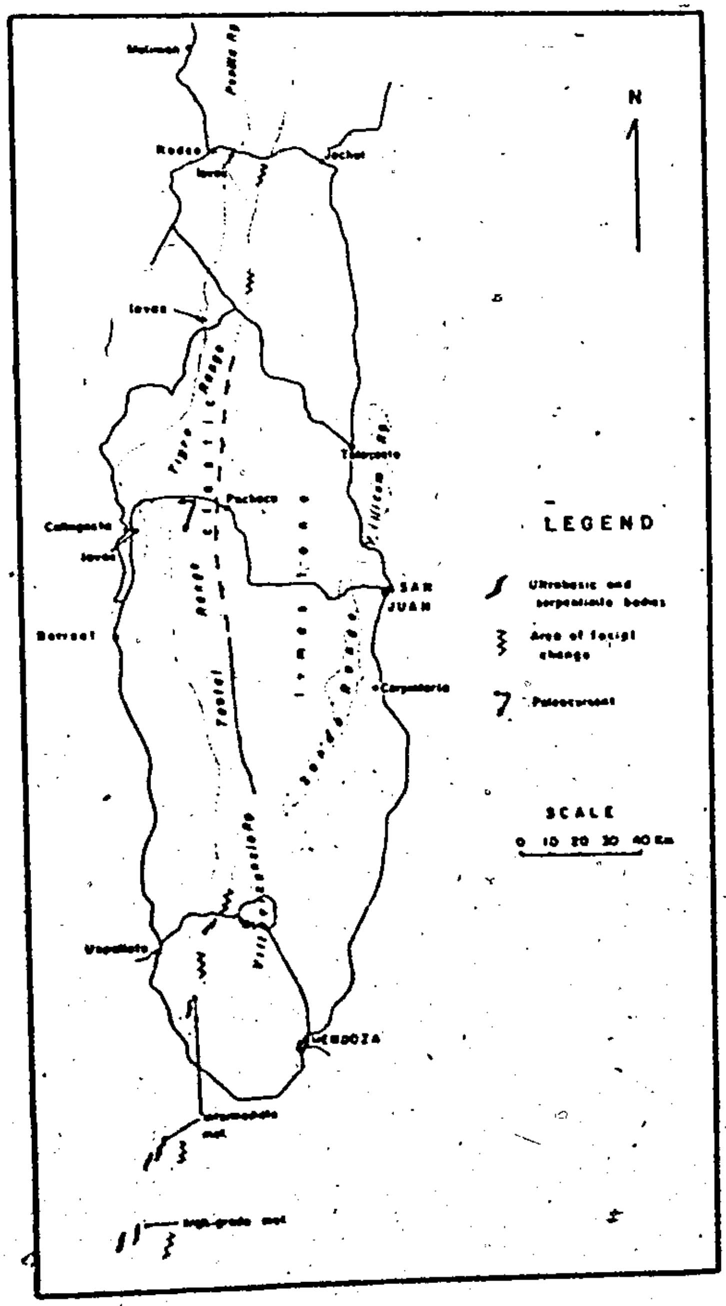


Fig. 34. Simplified geologic map of the Precordillera showing the main characteristics of the Cambro-Ordovician erathem. Description in text.

The Ordovician limestones in the eastern Precordillera comprise the greater part of the Zonda-Villicum Ranges and are exposed several times by the thrust faults over the central area. The limestones are rich in fossils which indicate Middle Ordovician age (Harrington and Leanza, 1957).

Around the city of Mendoza the Ordovician system begins with a conglomerate, followed by black laminated shales with graptolites, somewhat sandier calcareous shales, a breccia of Cambrian limestone clasts (1 to 10 cm in diameter) with a disperse texture, in a calcareous and silty matrix, and, finally, a limestone sequence. The total thickness is about 250 m, and the top is marked by an unconformity below the Silurian. Fossils indicate Llandeilian and Caradocian ages (Borrello, 1971).

Outcrops in the Zonda Range show thick and medium-bedded gray limestones where abundant stromatolites, numerous chert nodules and lenses, mudcracks and a bed of edgewise intraformational conglomerate were seen. Exposures to the west are thinner bedded bioclastic limestones, also with chert nodules. The chert does not form regular beds; it has been partially dolomitized along fractures (Espisua, 1968). Finally, the western-most exposures, around the locality of Pachaco, show thick (up to 2 meters) limestone beds with irregular bands of brownish dolomite near the base of every bed. In thin section the dolomite appears as small rhombs. Terrigenous sediments are absent. The maximum thickness for the limestone unit is 3000 meters north of Jachal (Furque, 1972).

In the northeastern Precordillera, around Jachal, there is a transition upwards within the Ordovician system, of limestones to black shales. The limestones always make up for the greater part of the sections but the shales may be as thick as 100 meters (Cuerda, 1965). The transition comes about by a gradual increase in the clay content of the limestones. The clay forms thin laminae which alternate with pure limestone beds a few centimeters thick. Chert is still present. The thickness of this transitional member varies from a few meters to several tens of meters. The shales are black, laminated, calcareous and contain graptolites which indicate Caradocian age (Baldis, 1970). These shales are interpreted as formed under euxinic conditions in stagnant or restricted shallow (?) waters.

Padula and others (1967) employed the name San Juan Formation for the Middle Ordovician limestones in the Precordillera. In the present work, this same formational name is broadened to include the black Caradocian shales - which should be distinguished as a member - because of their transitional connection to the limestones and their small thickness that would preclude mapping them as a separate formation.

Going west the limestone lithofacies passes to a clastic lithofacies (Figs. 5 and 34); the actual lateral passage was not seen. Along the Jachal River the clastics consist of phyllites and quartzites and contain Caradocian graptolites (Furque, 1972). Farther south along the nucleus of the Tontal-Tigre Ranges, west of Pachaco, the clastics consist of light gray graywackes, sometimes pebbly, a very few paraconglomerates and slates. Near Calingasta there are gray shales and sandstones containing Caradocian graptolites (Baldis, 1970).

Basic volcanics consisting of diabase sills and pillow lavas appear in the Upper Ordovician. They occur in three more or less aligned areas (volcanic centres?): (i) just east of Calingasta, (ii) west of the Gualilan Valley, and (iii) just east of Rodeo. The volcanics form massive bodies of unknown thicknesses which digitate eastwards as lava flows intercalated in shales. Whatever originally existed to the west it has been truncated by the faulting that formed the Rodeo-Uspallata valley. At Calingasta the lavas occur very close to the contact with the Silurian and at the other two outcrops they are in the upper part of the Ordovician sequences but the Silurian is absent due to erosion.

The age of the rocks forming the Tontal Range is in dispute due to the lack of fossils. Padula and others (1967) postulate a Devonian Age for these outcrops. The present author is inclined to correlate them with the Caradocian clastic sediments along the Jachal River and near Calingasta, because of their similar degree of metamorphism and relation to the Ordovician limestone. The idea of a Devonian age certainly stems from the strong resemblance of these rocks to the Punta Negra Formation to the east. However, the detailed study of the Punta Negra does not support the presence of a coarse lithofacies of this formation in the Tontal area. Based on a qualitative examination of thin sections of 4 specimens the graywackes from the Tontal Range are very similar to those of the Punta Negra formation, except for greater recrystallization of the matrix in the Tontal graywackes (Fig. 35).

For the sake of completeness, a further area with possible Cambro-Ordovician outcrops will be described which was not visited by the author. The exposures run east and south of Uspallata, and their importance lies in the higher metamorphic grade and presence of ultrabasic rocks. The sequence consists of Cambrian (?) and Ordovician limestones and clastics,

Figure 35. Thin section of a turbidite in the clastic Ordovician near Calingasta. Arrow points to recristallized matrix, perpendicular to edge of extinguished quartz grain. This texture indicates an initial stage of recrystallization of the matrix minerals. Crossed nicols. Scale by bottom right corner.

concordantly intruded by peridotites, serpentinites and diabases. The limestones are deformed and recrystallized. The clastics show several cyles of deformation and have been metamorphosed to phyllites, calcareous phyllites and schists, within the greenschist facies, or to garnet gneisses of the granulite facies, in different areas. Serpentinites are the most common intrusion and are associated with the greenschist facies of metamorphism. Dunites, wehrlites and pyroxenites are associated with the granulite facies of metamorphism (Zardini, 1960; Römer, 1964; Cosentino, 1968; Villar, 1969). These ultrabasic bodies are located near the transition from limestone to clastics but principally in the clastic lithofacies (Fig. 34).

The age of these rocks is also in dispute. Several authors maintain that they are Precambrian (Gonzalez-Diaz, 1957; Zardini, 1960) based only on the metamorphic grade and absence of fossils. On the other hand, Caminos (1972), without much evidence either, assumes that they are Lower Paleozoic. The present author correlates them with the outcrops in the Tontal-Tigre Ranges mainly because of the transition between limestone and clastics (Römer, 1964; Zardini, 1960) and their geographic position aligned with the Tontal Range (Fig. 34).

Some major lateral changes within the clastic lithofacies are apparent. Grain-size decreases from Rodeo to the south and also from the east to the west. In the area east of Rodeo there are coarse-grained to conglomeratic quartzites. Just west of Pachaco there are conglomerates and coarse-grained turbidites. Instead, to the southwest and west, shales and fine-grained sandstones are present. Paleocurrent measurements reaffirm those observations by showing bimodal distribution directed south and west with south predominant (Figs. 34 and 36).

Some highlights of the tectonic events during the Cambro-Ordovician can be pointed out. Overall it was a period of subsidence and sedimentation, interrupted during the Early Ordovician by uplift in the mainland and shelf area, which caused the deformation of the Cambrian around Mendoza and the erosion or nondeposition of the Lower Ordovician. Before Caradocian times, compression restarted producing large open folds in the limestone and along the present position of the Tontal-Tigre Ranges. These arches may have acted as sills which restricted water circulation in the interior; in these restricted basins the black euxinic shales may have been deposited. The limestone breccia by the city Mendoza would belong to this orogenic phase.

It is postulated that this orogeny metamorphosed the clastic Cambro-Ordovician sediments in the west, and metamorphism was accompanied by intrusion of ultrabasics and extrusion of pillow lavas. The evidence for a Late Ordovician Age of the metamorphism is not very abundant. The supporting observations are: (i) the regional unconformity over the shelf area between the Ordovician limestones and the Silurian, (ii) the volcanic episode just before the Silurian and (iii) sulphide mineralization around Calingasta which affects only the Ordovician sediments. Opposing evidence to this age is that the Silurian around Calingasta appears to be conformable on the Ordovician. Since the Silurian here consists mainly of shales, a slight angular unconformity may have been overlooked.

3.3 Silurian

The Silurian outcrops can be conveniently arranged in two groups:

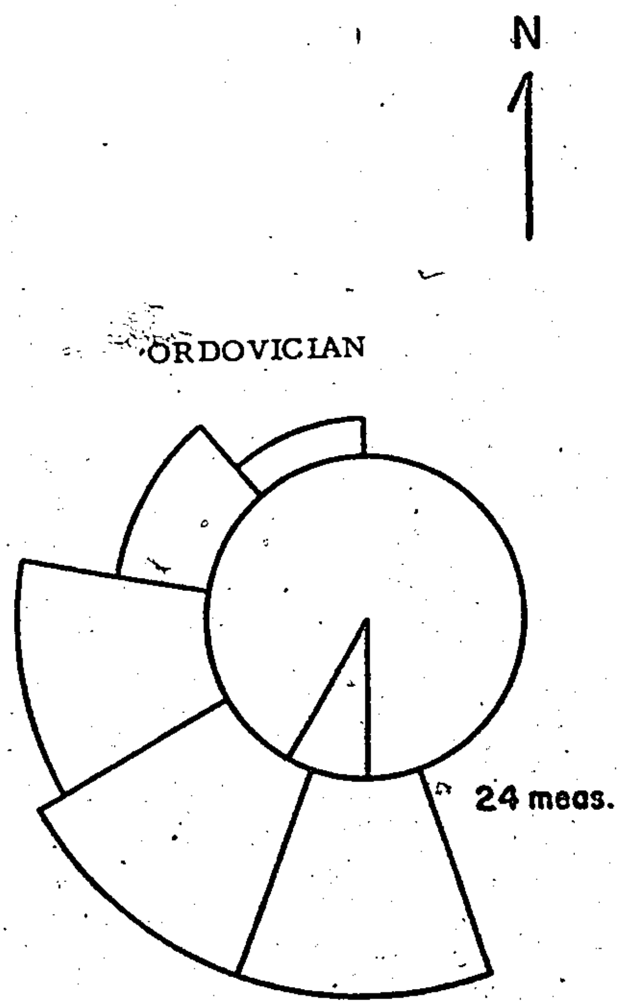


Figure 36. Paleocurrent rose diagram for the Ordovician. All measurements were made along the San Juan river between Pachaco and Calingasta. For explanation see legend to Figure 31.

(i) a narrow exposure in the eastern Precordillera, that is, east of the Zonda-Villicum Ranges and (ii) a widespread occurrence in the central Precordillera. Fossiliferous Silurian sediments are present west of the Tontal Range but they will not be described because of insufficient data. In Figure 2 the Silurian and Devonian were not separated due to the small thickness of the Silurian system. A summary of the Silurian in Argentina from the paleontological standpoint is presented by Amos (1972).

(i) eastern Precordillera. Along the eastern slope of the Villicum Range there is a narrow exposure of possible Silurian sediments containing trilobites and brachiopods, lying disconformably on the black Caradocian shales. Although fossils were found they have not been identified yet, so the proposed Silurian age is subject to doubt. The criterion is that these sediments differ in lithology from the overlying, certainly Lower Devonian, sediments.

The sequence begins with an erosional contact between the shales below and a basal polymictic conglomerate 10 m thick, and continues with green shales, bioturbated in parts, and a few turbidites. The total thickness is less than 100 m (Figure 7). Sole marks are very scanty, about half a dozen were observed trended north-south. One doubtful example of flutes with direction of movement to the south was found. The transition to the Devonian is gradual. On the eastern slope of the Zonda Range there is a small outcrop of green and purple shales and a pebbly mudstone. The thickness is only a few meters and the Devonian sediments in this area erode deeply into the Silurian shales; farther south, at the latitude of Carpinteria, the Silurian is completely absent.

One good example of flutes with direction of movement to the north was observed.

(ii) central Precordillera. In the area extending between the Zonda-Villicum and the Tontal-Tigre Ranges, the Silurian system disconformably overlies the San Juan Formation. Wherever the contact between these two units is exposed there is a thin (0.5 to 2 m thick) conglomerate with clasts of chert.

The Silurian sediments in the central Precordillera are fine-grained, in general, with shales, siltstones and fine sandstones. Paleontologic dates cover the Wenlockian and Ludlovian; the Llandoverian is either partly or totally absent. Two principal lithostratigraphic units are distinguished, following Cuerda and Baldis (1971): an older sandy unit and a younger shaly unit. Formational names are avoided because the present nomenclature is too complicated and badly needs revision. The sandy unit consists of quartzarenites, calcarenites, some thin conglomeratic lenses and lesser proportion of multi-coloured shales. The shaly unit consists mainly of green shales with calcarious nodules and thin bedded wackes and calcarenites. Fossils are abundant, mainly bivalves, and form coquinae. Bioturbation is strong in parts. Ripples both symmetrical and asymmetrical, are the most frequent sedimentary structure but a few grooves and prod casts were also seen. Half a dozen measurements on ripples around Jachal consistently gave lines of movement North-South to NE-SW with a probable direction of movement to the north and northeast. A few channel sandstones were observed but generally the sandstones are thin-bedded and regular. Some beds may be classified as turbidites but usually they lack grading and sole marks. Perhaps they are better interpreted as storm layers.

The thickness of the Silurian increases from nil south of the San Juan River to about 800 m at Jachal. The Silurian sediments were certainly deposited in shallow water. They probably include shelf and littoral deposits. The brief study does not allow a better definition.

3.4 Devonian

The Devonian rocks commonly overlie the Silurian but in some areas they rest directly on Ordovician limestones, for example, east of the Zonda Range at the latitude of Carpinteria. The contact with the Silurian seems to be conformable in most of the central Precordillera (Cuerda, 1969) and unconformable in the western Precordillera (Padula and others, 1967) and at least part of the eastern Precordillera.

Since the onset of the Devonian, the folds or arches that had begun forming in Caradocian times exerted an important control on the sedimentation. In particular, two such arches must be considered, namely, one developing along the present position of the Zonda-Villicum Ranges and the other along the present position of the Tontal-Tigre Ranges. The basic idea of the existence of these two arches is not new to this thesis. Amos (1954) postulated the presence of a mountain range in the same position as the Zonda-Villicum Ranges during the Devonian; Harrington (1967, p.656) summarizes this work. Another mountain range, this one in the position of the Tontal Tigre Ranges, was postulated by Amos and Rolleri (1965) to have existed during the Carboniferous (see Padula and others, 1967, for a summary). As a result of the present investigation the initial stage of formation of these arches has been traced back to the Caradocian and, more important, it is concluded that neither of these arches was emergent during the Devonian. They controlled sedimentation in a passive manner without shedding detritus in any noticeable amount. In other words, they were not mountain ranges.

For the purpose of organizing the description, the Devonian outcrops will be divided into three areas covering the central and eastern Precordillera: (i) the northeast Precordillera, (ii) the central Precordillera and (iii) the eastern Precordillera. These divisions reflect different source areas and the control on sedimentation by the Zonda-Villicum and Tontal-Tigre arches.

(i) northeast Precordillera. Just SW of Jachal, the Devonian - conformably overlying the Silurian - begins with a thick (600 m) marine succession of green shales and siltstones and micaceous fine sandstones (Fig. 37). The sediments are very much bioturbated with Zoophycus and other burrows. Near the top of this fine-grained unit small slump folds are present, paraconglomerates appear and bioturbation seems less important for lamination is better preserved. Above this unit but interfingered with it follow large lenses of yellowish sandstones and conglomerates. The lenses are some hundreds of meters long and tens of meters thick. The sandstones are medium-grained to conglomeratic, some thinner beds show grading into shale and may be interpreted as turbidites, but generally these sandstones are massive and structureless. The conglomerates erode into the sandstones. Maximum clast-size is about 10 to 20 cm, in general, although a few boulders more than 1 m in diameter were seen. The clasts are mainly of granite but sandstone, limestone and metequartzite clasts are also present.

Some levels of fine sandstones within these lenses show abundant

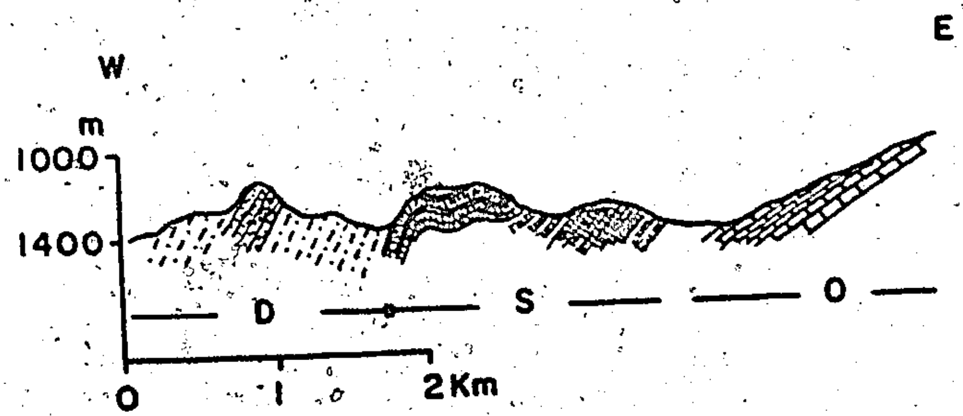


Figure 37. Cross-Section south of Jachal. See Figure 2 for general location. Description in text.

lenticular bedding and other levels of medium-grained sandstones show well developed dune-size trough cross-lamination; the sets are a few cm thick and the troughs are about 20 cm in diameter.

Above the zone with coarser-grained sediments, the green bioturbated shales and siltstones resume, but now thin beds of fine-grained turbidites are common and increase in frequency to the top. The Devonian in this area is unconformably overlain by the Carboniferous (Furque, 1972) but the contact was not visited by the author. The total thickness, measured from a 1:100,000 map (Baldis, 1970) is estimated to be about 1500 m.

Farther west, along the Jachal River, and south from this area, turbidites and shales constitute the main lithology of the Devonian. Three days were spent in studying the outcrops west of Jachal for about 20 km, and one day was employed in visiting outcrops approximately 40 km almost directly south of Jachal (Fig. 2). The generalized sedimentary sequence begins with green shales and siltstones, frequently calcareous, fossiliferous, which gradually pass upwards to medium-bedded, medium-grained turbidites in some cases micaceous and with parallel parting (Fig. 38). The lower part of the sequence, more shaly, contains an abundant brachiopod fauna which indicates an Early Devonian Age (Padula and others, 1967). The upper part is not fossiliferous. The thickness for the Devonian in this region is about 2000 m (Baldis and Cano, 1968; Espisua, 1968).

Ten paleocurrent measurements from the northeast Precordillera are plotted in Figure 39 and show a mean to the southwest. Although the data is very scanty these outcrops are tentatively interpreted as a submarine

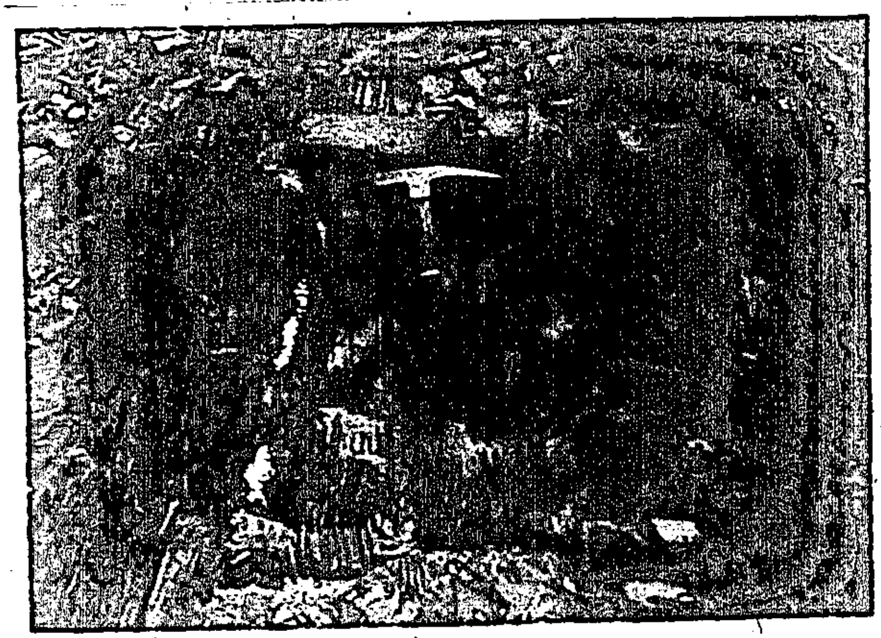


Figure 38. Parallel parting in wackes. These wackes have a plutonic and metamorphic source lithology. In thin section they show abundant muscovite and iron oxide replacements. Base to the left (East). Devonian SSW of Jachal.

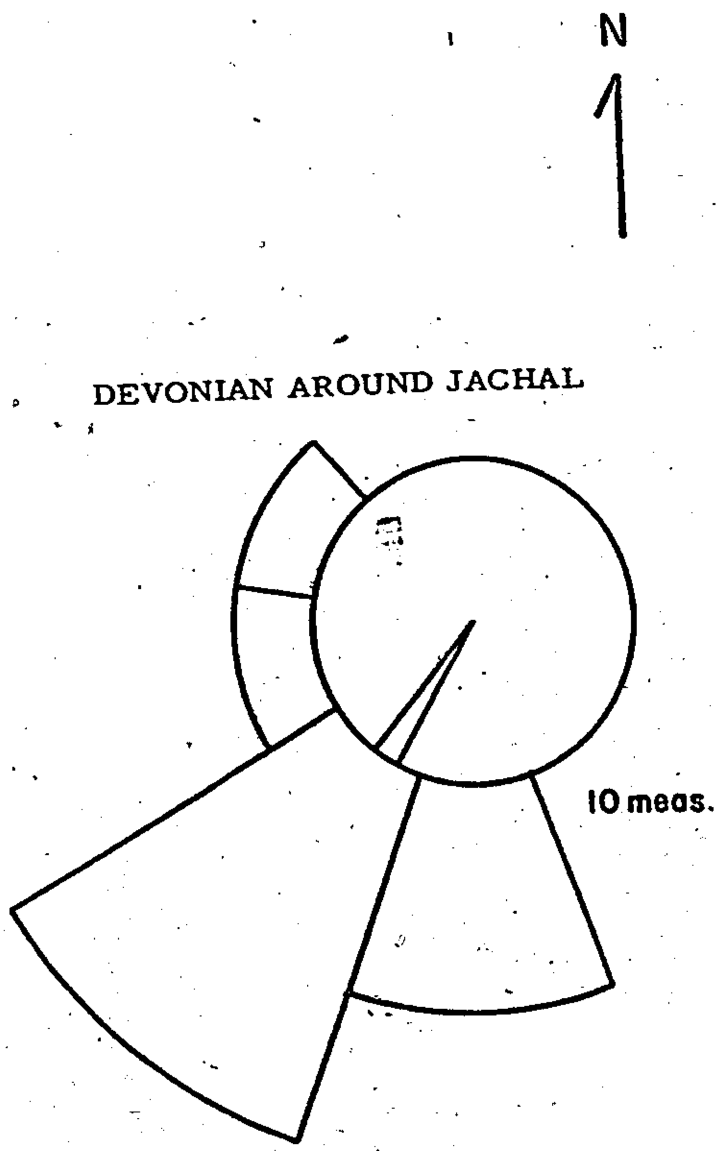


Figure 39. Paleocurrent rose diagram for the Devonian around Jachal. For explanation see legend to Figure 32.

fan with at least one feeder area near Jachal and a source lithology composed of igneous and metamorphic rocks.

(ii) central Precordillera. This outcrop area extends south of the Gualilan Valley bounded by the Tontal-Tigre and Zonda-Villicum Ranges until some 60 km south of the San Juan River. Since this is the region where the Punta Negra Formation outcrops, most of the field work is concentrated here. The tectonic structures are relatively simple and the presence of the Punta Negra Formation with its distinctive lithology makes it a simple matter to separate the Lower Devonian from the Middle and Upper Devonian in the field. The Devonian system in the central Precordillera conformably overlies the Silurian and is everywhere unconformable beneath the Carboniferous.

The Lower Devonian in this area is lithologically homogeneous and consists of fine- and medium-grained greenish sandstones and green, gray and purple shales. The purple shales always occur at the top, immediately below the Punta Negra Formation. They are laminated and contain Chondrites burrows and coral remains (Baldis, 1970). The thickness of the purple shale unit varies between about 10 and 50 m; it is thickest at section IV, and thinnest south of the San Juan River (Baldis, 1970). The sandstones are massive and structureless probably due to the extensive bioturbation; among others, Zoophycos burrows were recognized. In some cases graded bedding or lamination are visible. Brachiopods are abundant. In one outcrop, at section VI, a thin level of purple, fine-grained oolitic sandstones was found.

Overall, the Lower Devonian shows a decrease in sandstone content and grain-size to the west and northwest. At section III, it has a few conglomeratic levels (Leverato, 1968) and the purple shale unit is very silty. Farther west along the San Juan River, up to section VI, sandstone predominates over shale, there are no conglomerates and the purple shale unit is more shaly. Finally, at section VII, shales predominate over sandstone. No paleocurrents could be measured.

The thickness of the Lower Devonian is about 300 m at Talacasto; it decreases to about 200 m along the San Juan River and to about 100 m, 20 km south of the San Juan River; the minimum measured thickness is on the eastern flank of the Tontal Range, about 30 km directly south of Pachaco, and amounts to 40 m (Baldis, 1970). Consequently, the thickness of the Lower Devonian decreases sharply to the south and southwest; this is interpreted to be due to the presence of the Tontal arc. Small isolated pockets of Lower Devonian marine shales are preserved on top of the Tontal Range (Kerllenevich, 1967) evidencing at least partial submergence of the Tontal arc during this epoch.

Baldis (1970) grouped the Lower Devonian outcrops in the northern and central Precordillera as the Talacasto Formation. The type section is exposed NW of Talacasto and corresponds to section VIII of this paper. The lithology of the type section is very similar to the lithology of the outcrops south of it but differs markedly from those to the north. In the Lower Devonian outcrops just west of the Gualilan Valley, both lithologies appear interfingered. From a strictly sedimentological viewpoint it seems convenient to restrict the name Talacasto Formation to the Lower Devonian outcrops south of the Gualilan Valley. More field work is needed in order to establish the source areas and environment of deposition of the Talacasto Formation.

The Middle and Upper Devonian is represented by the Punta Negra Formation which has already been described.

(iii) eastern Precordillera. This area comprises the outcrops east of the Zonda-Villicum Ranges (Fig. 2) and is quite deformed tectonically (cf. Structural Geology). Approximately five days were spent in this area.

East of the Villicum Range (section III of Fig. 5 and Fig. 7), the Devonian seems to be conformable on the Silurian but east of the Zonda Range an erosional unconformity between both systems is evident and even farther south, the Silurian is absent (section I of Fig. 5). Recall from the discussion of the Silurian that evidence for the presence of this system is only lithological at the moment.

The Devonian sequence consists of gray-greenish shales with lenticular fine sandstone, embedded in which are boulders of limestone and lenses of coarse clastics. Shale is predominant. The fine sandstone forms lenses a few cm thick and some tens of cm long which apparently lack internal structures. The shales are generally laminated but in parts they are bioturbated. A few turbidites with granule-size quartz clasts are present. A peculiar feature of this lithofacies is the presence of small channel sandstones and channel conglomerates. The sandstones are medium grained and calcareous, and form lenses about 1 m long. They are structureless but occasionally grooves can be seen on their bases. The conglomerates form lenses several meters long and 1 or 2 m thick. The clasts are well rounded and tightly packed, in a sandy matrix.

The clasts are of metaquartzites, followed by limestones and granitic rocks. Most of the clasts are aligned but do not show imbrication. Some conglomerates have internal sandstone beds or lenses that give them a banded appearance. Boulders of Ordovician limestone several meters in diameter are very common east of the Zonda Range (Fig. 40) and seem to decrease in frequency east of the Villicum Range. Sole marks in these rocks are restricted to a few grooves which indicate a North-South line of movement. Amos (1954) included the whole Devonian sequence as the Rinconada Formation. Brachiopods present in the lower part of the sequence indicate an Early Devonian Age (Amos and Boucot, 1963).

The origin of the limestone boulders is a matter of controversy and necessitates further discussion. The description of the Devonian given above is biased because only limestone fragments a few meters in diameter were mentioned. In point of fact, the limestone bodies range in sizes from subspherical bodies a few meters in diameter to limestone ridges up to 2 km in length, oriented North-South. In most cases the limestone is surrounded by the shaly Devonian sediments. Tectonic deformation is intense, the bedding is vertical for the most part and the type of sediment does not allow the recognition of top and base of the sequence except in few occasions.

The earlier interpretations on the origin of these limestone bodies (Braccaccini, 1946; Heim, 1948) suggested that they had all been tectonically emplaced. The larger bodies, forming ridges, resulting from overthrusting the Ordovician limestone onto the Devonian and the smaller bodies having been emplaced either by faulting or by 'squeezing' and intrusion of the limestone into the Devonian sediments. Later, Amos (1954; see also Harrington, 1967) suggested that the origin of all the

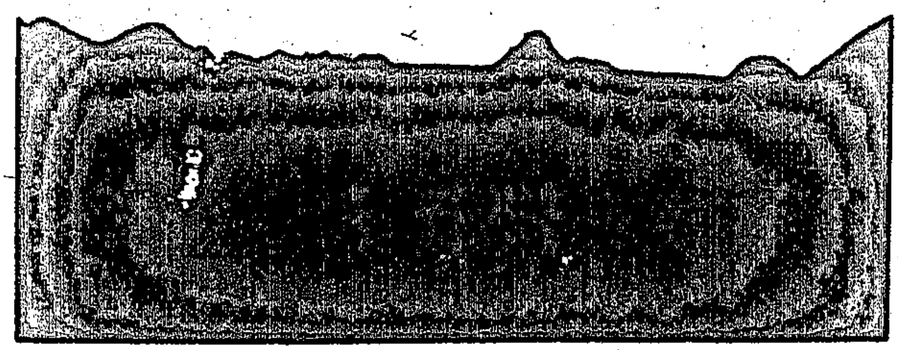


Fig. 40. Limestone boulders outcropping because of differential erosion of the shaly matrix. East of the Zonda Range at the latitude of Carpinteria. View looking north.

limestone bodies was sedimentary. He postulated the existence during the Devonian of a mountain range, along the present position of the Zonda Range, from which the limestone had been derived. The large bodies would be the result of gravitational sliding of limestone slabs into the basin and the smaller fragments, as well as the conglomerates, would have been transported by rivers flowing into the basin.

The present author believes that both hypotheses are partially correct. The larger limestone bodies were formed by faulting and the smaller ones are sedimentary. One of the supposed limestone slabs, exposed WNW of Carpinteria, was carefully examined. It forms a ridge about 1 km long, and the bedding dips strongly to the west. Along the western flank of this ridge, is exposed a clastic sequence beginning with Silurian shales followed by Devonian shales and conglomerates. There is no apparent angular unconformity between the Silurian and the Ordovician limestone. The whole sequence dips west and is right way up. Along the eastern flank of this ridge, the strata are overturned and dip west but a similar succession is exposed. Purple siltstones (no shales were found) considered Silurian, are followed by the green Devonian shales and conglomerates. These observations strongly suggest that the limestone was faulted (probably after being folded, to account for the overturning of the beds along the eastern flank). Indirect evidence against the idea of large limestone slabs sliding into the basin, is the absence of limestone breccia. The limestone clasts in the conglomerates are rounded and make up less than 50% of the total clasts (field estimate).

Against the idea of a mountain range during the Devonian is the fact that the limestone fragments occur only east of the postulated range. Furthermore, there is no evidence whatsoever that such a range could have contributed the clastic sediments because the basement is nowhere exposed along the present Zonda Range.

Nevertheless, the smaller, subspherical limestone bodies are certainly sedimentary. East of the Villicum Range, where deformation is much less, some of the fragments can be seen completely embedded in the Devonian shales. But their source area could not have been to the west, judging from the regional paleocurrent pattern. Furthermore, since the thickness of the Silurian and Devonian east of the Zonda-Villicum Ranges seems to increase to the north, it is thought that their source areas lay to the south.

From cursory field observations, there appears to be a vertical zonation shown by the proportion of limestone clasts. The limestone boulders and limestone clasts in the conglomerates, are concentrated in the lower part of the succession. In the upper part the conglomerates are less frequent and do not contain as many limestone clasts, and no limestone boulders are present. This upper part is considered to be a lateral equivalent of the Punta Negra Formation. The basis for this more or less arbitrary separation are: (a) the paleocurrent pattern for the Punta Negra Formation (Fig. 32), indicates transport from the east, (b) the mineralogy in both areas is identical, (c) the Punta Negra Formation lacks limestone clasts almost completely, so the connection between the two areas could only have taken place after the erosion of limestone had ended. Accordingly, the name Rinconada Formation is restricted to the Lower Devonian and the Middle (and Upper?) Devonian is included as part of the Punta Negra Formation.

The post-Devonian sediments over the central and eastern Precordillera are continental. West of the Tontal Range there are marine sediments of Carboniferous Age (Frakes and Crowell, 1969)

3.5 Paleogeography

The main paleogeographic elements that controlled the deposition of the Punta Negra Formation were the Zonda-Villicum and Tontal-Tigre arches, (Fig. 41). Both arches were submerged. The existence of the Zonda-Villicum arc is evidenced by the abrupt facies change of the Silurian and Devonian from one side to the other of the Zonda-Villicum Ranges, and the north-south paleocurrent directions for the Devonian east of these ranges. The Tontal arc, in turn, is evidenced by the absence of the Punta Negra Formation on, or west of, the Tontal Range, and by the divergent paleocurrent pattern of the Punta Negra at section VII (Fig. 31).

The source area for the Punta Negra Formation is thought to have been to the southeast, based on the paleocurrent pattern. The source lithology was the Precambrian metamorphic rocks. Figure 41 also shows the area thought to have been occupied by the Punta Negra submarine fan and the postulated submarine fan, to the north, which interfingered with the Punta Negra submarine fan. The source area for the northern fan is tentatively located east of Jachal but more paleocurrent data is needed.

Figure 42 is a schematic cross-section along the present San Juan River showing the paleogeography at the end of the Early Devonian, that is, before deposition of the Punta Negra Formation. The future areas of deposition of the facies A and B of the Punta Negra are indicated.

The change in the position of the shoreline during the Devonian is indicated in Figure 41. The location of the lines indicate a trend

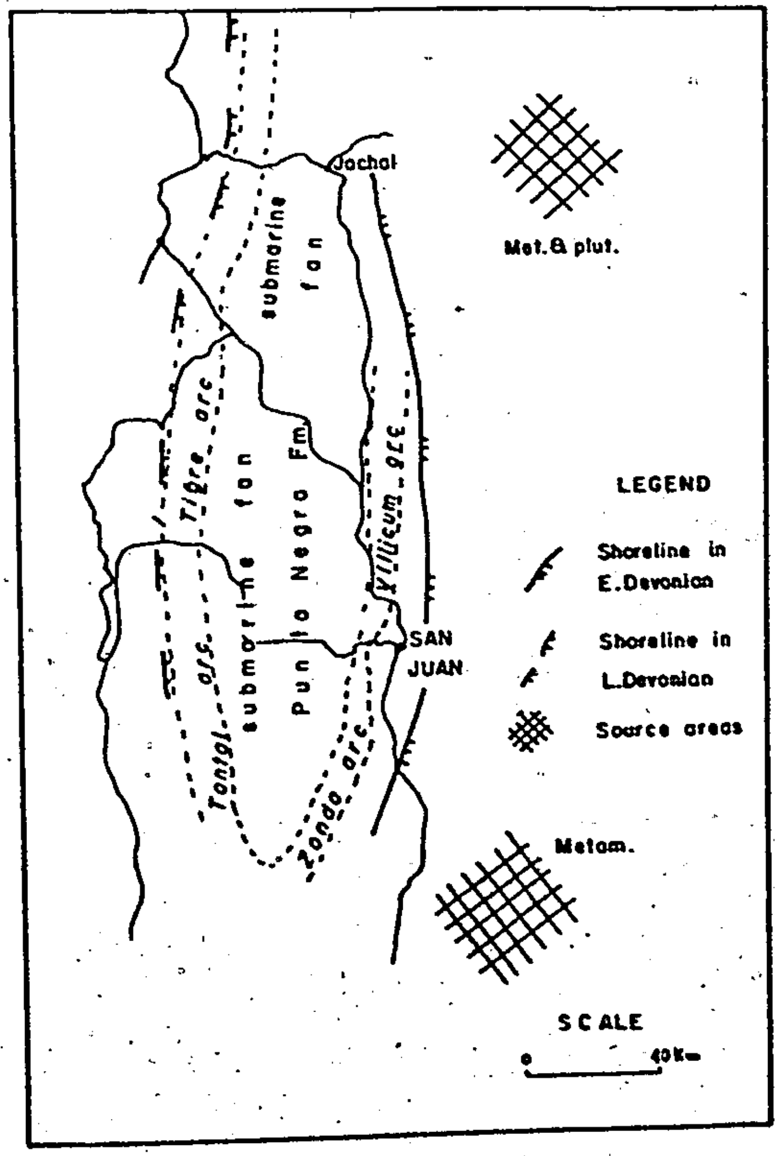


Fig. 4I. Main paleogeographic elements controlling sedimentation in the Precordillera during the Devonian.

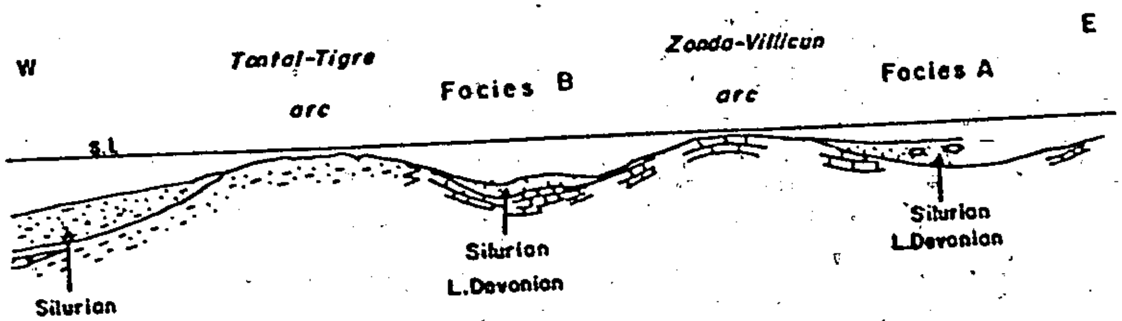


Figure 42. Schematic cross-section of the Precordillera along the San Juan River. It depicts the geologic and topographic conditions just before the sedimentation of the Punta Negra Formation.

and not the actual position of the shoreline, which is not known. By the end of the Devonian, the miogeoclinal region would have been filled in by the Punta Negra and the shoreline had regressed to the west flank of the Tontal-Tigre arc. Evidence for this is the presence of marine Carboniferous west of the Tontal Range, while only continental Carboniferous is present to the east. Also, the upper part of the Punta Negra Formation at sections IV and V, show some evidence of reworking of the graywackes and some interference ripples that may have been formed by wave action.

3.6. Development of the Punta Negra submarine fan and comparison with other submarine fans

During the Early Devonian, a strong uplift occurred on the mainland, in the northeast Precordillera. The Cambro-Ordovician limestones covering the Precambrian were rapidly eroded, as shown by the boulders in the Rinconada Formation. The sediments were funnelled to the north (present geography) along the sub-basin formed by the Zonda-Villicum arc. By the end of the Early Devonian the limestone cover had been completely eroded.

During the Middle and Upper Devonian, the Precambrian yielded large amounts of sediment which was transported into the basin by turbidity currents. The clastics rapidly filled in the sub-basin to the east of the Zonda-Villicum arc and flowed into the central Precordillera. Thus, the sedimentation of the Punta Negra submarine fan began. In the initial stage, small depressions west of the Zonda arc may have been filled with sediment. But the correlation of the lower thicker-bedded level (Fig. 18) would suggest that during this time deposition occurred more or less simultaneously over the whole basin area. From then on, accretion of the fan would have been mainly vertical, because the Tontal arc impeded its extension to the west.

The Punta Negra submarine fan measures about 100 km in width and 50 km in length; in areal extent it ranks among the small modern fans (see Nelson and Kulm, 1973, Table 1). Considering the period of deposition as 20 m.y. (Middle and partly Lower Devonian), an average thickness of 900 meters disregarding compaction and the average number of turbidites as 1500, one obtains a sedimentation rate of 1 meter of sediment every 22,000 years and 1 turbidite every 13,000 years. Since many thin silty turbidites were not counted the last figure can be considerably smaller.

Facies A of the Punta Negra Formation is considered to have been deposited on a slope adjacent to the mainland. The absence of turbidites does not allow to include it as part of the fan itself. Facies B is characterized by the absence of deep channels and coarse material, the horizontal bedding, little signs of erosion and its great areal extent. In Normark's (1970) classification facies B would correspond well with outer fan or lower part of the suprafan morphology. Using Mutti and Ricci Lucchi's (1972) classification, which is based on the study of ancient sediments, facies B would correspond to the intermediate fan region because of the presence of thinning-upwards cycles, although the resemblance is not very good due to the lack of conspicuous channelling in facies B. Consequently, the upper fan and most of the suprafan (or intermediate fan) are not developed in the Punta Negra Formation.

An interesting characteristic of the Punta Negra fan is the lack of downcurrent changes in grain-size, sedimentary structures, etc. except for the paraconglomerates. The La Jolla canyon and fan (Shepard, 1960), which is smaller but is also restricted in its development by topographic highs, does not show any downcurrent trend either. On the contrary, the Astoria fan (Nelson and Kulm, 1973) shows clear downcurrent changes in texture, sedimentary structures and bed-thicknesses. The Astoria fan is about as wide as the Punta Negra but it is several times longer; it is not severely restricted by topographic highs.

One obvious explanation for the absence of down-current variations in the Punta Negra Formation is that due to the presence of the Tontal arc, it did not have sufficient space to develop fully. Or, again, that a distal facies is present but was not observed during field work; a good part of the outcrops remain to be visited. If the sediments were coarser, some changes in texture would probably become evident.

3.7 General conclusions

The Punta Negra Formation was deposited in a continental borderland during the Middle and Upper Devonian. It comprises two sedimentary facies, namely slope deposits on the east and submarine fan deposits in the west. The greater part of the outcrops correspond to the submarine fan facies.

The submarine fan developed in a small basin restricted by topographic rises or arches. One of these rises, the Tontal-Tigre arc, impeded the extension of the fan to the west and influenced the bedding characteristics and the paleocurrent pattern.

The main transporting mechanism for the graywackes that form the

Punta Negra Formation were high density turbidity currents. In the last stages of deposition, however, grain flow and debris flow mechanisms acted on the sediment and produced a complex inverse grading pattern. The necessary condition for the formation of high density turbidity currents seems to be high sediment concentration, with or without fine cohesive material, judging from Middleton's experiments in which he used only glass beads. The presence of cohesive material such as clay or fine mica might help in maintaining the high concentration by increasing the viscosity and dampening the turbulence.

The grain flow stage should be present in all high density turbidity currents so inverse grading should be a common feature in deposits from this type of sediment gravity flows. But debris flow conditions are probably determined by the presence and amount of cohesive material that may impart yield strength to the sediment. Consequently, the fine-grained band at the base of the bed should be more common in turbidites with a high matrix content.

The reconnaissance work on the Regional Geology yielded a few important results: (i) the geographical distribution of the clastic lithofacies of the Ordovician was extended to include the outcrops in the Tontal-Tigre Ranges and the metamorphic and ultrabasic rocks near Uspallata; (ii) the existence of rises along the present position of the Zonda-Villicum and Tontal-Tigre Ranges was confirmed but the present author maintains that these two rises were submerged during the Devonian and did not contribute sediment; (iii) by the end of the Devonian or beginning of the Carboniferous, the basin to the east of the Tontal-Tigre arc was filled in and continental conditions were established over the continental borderland region.

The main sedimentological aspects of the Punta Negra Formation that would require further field work are: (i) the outcrops south of the San Juan River should represent the southern margin of the fan and might provide more information on how the basin was filled; (ii) the lithology of facies A should be better studied in order to ascertain whether it was connected to facies B or developed in a separate sub-basin; (iii) there should be an attempt to find the distal facies of the fan, and (iv) the interfingering of the main fan with the submarine fan to the north should also be better studied.

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