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1-49 MINERALOGY AND PROVENANCE OF CHILE TRENCH SANDS

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RESUMEN

El área estudiada se extiende a lo largo de los 2.000 km de la fosa que enfrentan al margen continental Andino comprendido entre los 23° y 42°de Latitud Sur. En el diagrama QFL, las arenas de la Fosa Chilena definen un campo de composición que incluye al promedio de las arenas modernas provenientes de margenes continentales activos de tipo transcurrente, arco continental, trasarco oceánico, y antearco oceánico (Valloni y Maynard, 1981), y representan toda la gama de denudación de los arcos continentales, desde los profundamente erosionados hasta los no erosionados (Dickinson *et al*., 1983).

El alto contenido de cuarzo y feldespato alcalino, y el anormalmente bajo contenido de líticos y plagioclasa calcica que se ha detectado en las arenas de la fosa mediante los diagramas QFL y QmPK sugieren una fuente de origen más bien plutónica o un arco magmático profundamente erosionado para las arenas del Norte y Centro de Chile y para el sector englaciado del archipiélago en el Sur de Chile.

En Chile Central, la naturaleza plutonica del orígen se correlaciona con la ausencia de volcanismo cuaternario. En el sector costero del archipiélago chileno, la glaciación pleistocénica ha erosionado profundamente hasta las raices magmáticas de los Andes, produciendo un arco continental erosionado a pesar de la presencia de un volcanismo activo. En el norte de Chile, los detritos volcánicos de la alta cordillera quedan atrapados en la cuenca longitudinal de antearco, lo que favorece el exagerado aporte hacia el fondo del mar de las rocas cristalinas de la cordillera de la Costa.

El conjunto de los minerales pesados varía desde extremadamente inestable y químicamente inmaduro (Olivina-Piroxena derivada del volcanismo cuaternario en el Sur de Chile), hasta relativamente estable y maduro (Hornblenda-Biotita-Andalusita-Granate, derivada de antiguos terrenos pre-Andinos en el norte de Chile).

ABSTRACT

The Chile Trench study area extends over 2,000 kilómeter along the Andean continental margin, from 23° S to 42° S latitude. On the QFL diagram, the compositional field defined by the suite of Chile Trench sands encompasses the average compositions of modern sands from strike-slip, continental arc, oceanic backarc, and oceanic forearc types of active margins (Valloni and Maynard, 1981), and ranges over the complete spectrum from dissected to undissected continental arc settings (Dickinson et al.,1983). Trench sands along North Chile, Central Chile, and the glaciated archipelago of South Chile are derived from a more plutonic source region, or "dissected" magmatic arc, as shown by abnormally low lithic and calcic plagioclase content, but high quartz and alkali feldspar on QFL and QmPK plots.

In Central Chile, the plutonic nature of the provenance is correlated with an absence of Quaternary volcanism. Ashore from the Chilean archipelago, Pleistocene glaciation has carved deep into the magmatic roots of the Andes, effecting arc dissection in spite of active volcanism. In arid North Chile, the volcanic debris of the High Cordillera is trapped in the longitudinal forearc basin, allowing an exaggerated contribution to the deep-sea from the crystalline rocks of the Coast Range.

Heavy mineral assemblages range from extremely unstable and chemically immature (i.e. and olivine/pyroxene assemblage derived from the Quaternary volcanism of southern Chile) to the relatively stable and mature (i.e. a hornblende/biotite/andalusite/garnet assemblage derived from the ancient pre-Andean terranes of northern Chile).

INTRODUCTION

The Chile Trench provides an outstanding opportunity to study petrofacies within a linear tectonic basin adjacent to an active magmatic arc. Several physiographic gradients exist along this portion of the Andean margin that are expected to influence the petrologic composition of deep-sea sands (Fig. 1). These gradients include: (a) abrupt terminations and a spatial gap in the distribution of Quaternary volcanism in the arc, which define a geomorphologic segmentation in the overriding plate (Muñoz Cristi, 1956; Lomnitz, 1962), (b) an extreme climatic gradient that ranges from one of the world's most severe deserts in northern Chile to the glacially-dissected terranes of the southern Chile archipelago (Galli-Oliver, 1969; Scholl et al., 1970), and (c) a thinning of the continental crust from 70 km in the north to 40 km in the south (Couch et al., 1982; Ocola et al., 1971), accompanied by a trend toward a more "oceanic" composition of the

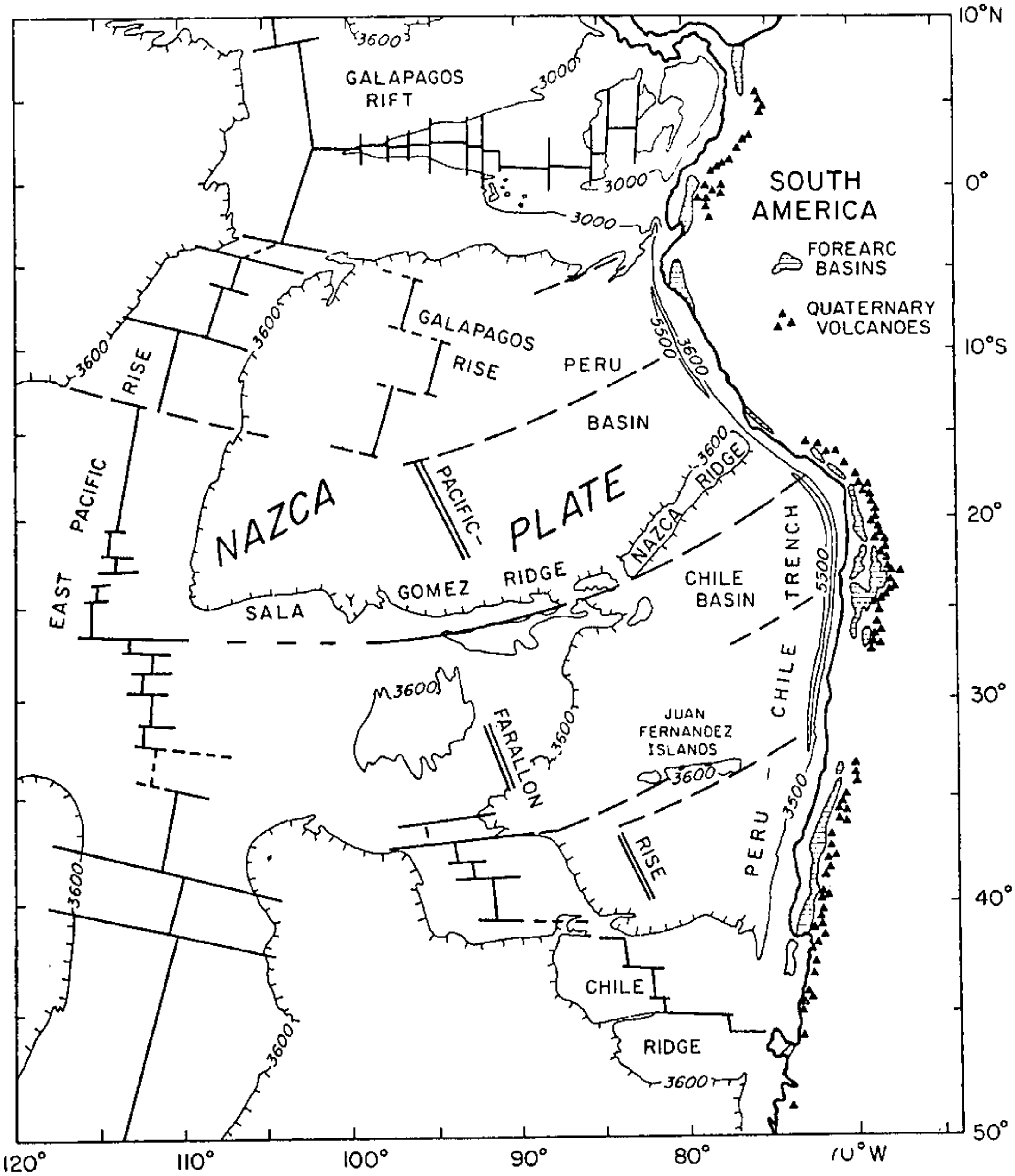

Fig. 1. Physiography of the Nazca Plate and Andean continental margin. Bathymetry contours after Mammerickx and Smith, 1978. Offshore features include postulated segments of the Pacific-Farallon Rise (Mammerickx *et al.*, 1980); onshore features include Pliocene-Quaternary strato-volcanoes (Simkin *et al.*, 1981; Paskoff, 1977), and forearc basins as outlined by the distribution of Quaternary alluvium (after Ruiz and Corvalan, 1968).

pre-Andean basement toward the south (Hervé _et al._, 1974, 1976; Coira _et al._, 1982).

The objetives of this study are to characterize the light and heavy mineral and lithic composition of late Quaternary sands from the Chile Trench, to relate the observed petrologic assemblages to their provenance in the Coast Range and High Cordilleras of Chile, and to establish the influence of volcanism, geology, climate, and the morphology of the continental margin on the petrologic signal.

BACKGROUND

The Chile Trench study area extends from 18°S to 45°S latitude, from a prominent bend in the strike of the Andean cordilleran system to the intersection of the Chile Rise (Fig. 1). Although the volume of sediment in the trench axis parallels the onshore climatic gradient (i.e., increased precipitation and erosional denudation toward the south), the structure and morphology of the trench is obviously segmented by tectonic discontinuities near 27.5°S and 33°S latitude (Figs. 2, 3). The segments are referred to as (a) North Chile province (20°S to 27.5°S lat)-- isolated sediment basins are ponded within depressions of a broken basaltic basement; (b) Central Chile province (27.5°S to 33°S lat.)-- the trench sediment fill is continous but thin (10 km wide) and shallow (several hundred meters thick); and (c) South Chile province (33°S to 45°S lat.) -- the trench fill swells in volume to greater than 30 km in width and up to 2 km in thickness, and completely buries the structural trench south of about 38° S (Schweller _et al._, 1981).

An identical segmentation is apparent in the physiography of the overriding continental plate, and in the configuration of the dipping seismic zone (Fig. 3; Stauder, 1973; Barazangi and Isacks, 1976); evidently the margin segmentation is genetically related to the subduction process. In both the North and South Chile provinces, a trench-parallel forearc basin separates the Coast Range from the High Cordillera, which is formed by a chain of active stratovolcanoes (Fig. 1). In the Central Chile province, both the longitudinal depression and Quaternary arc volcanism are absent.

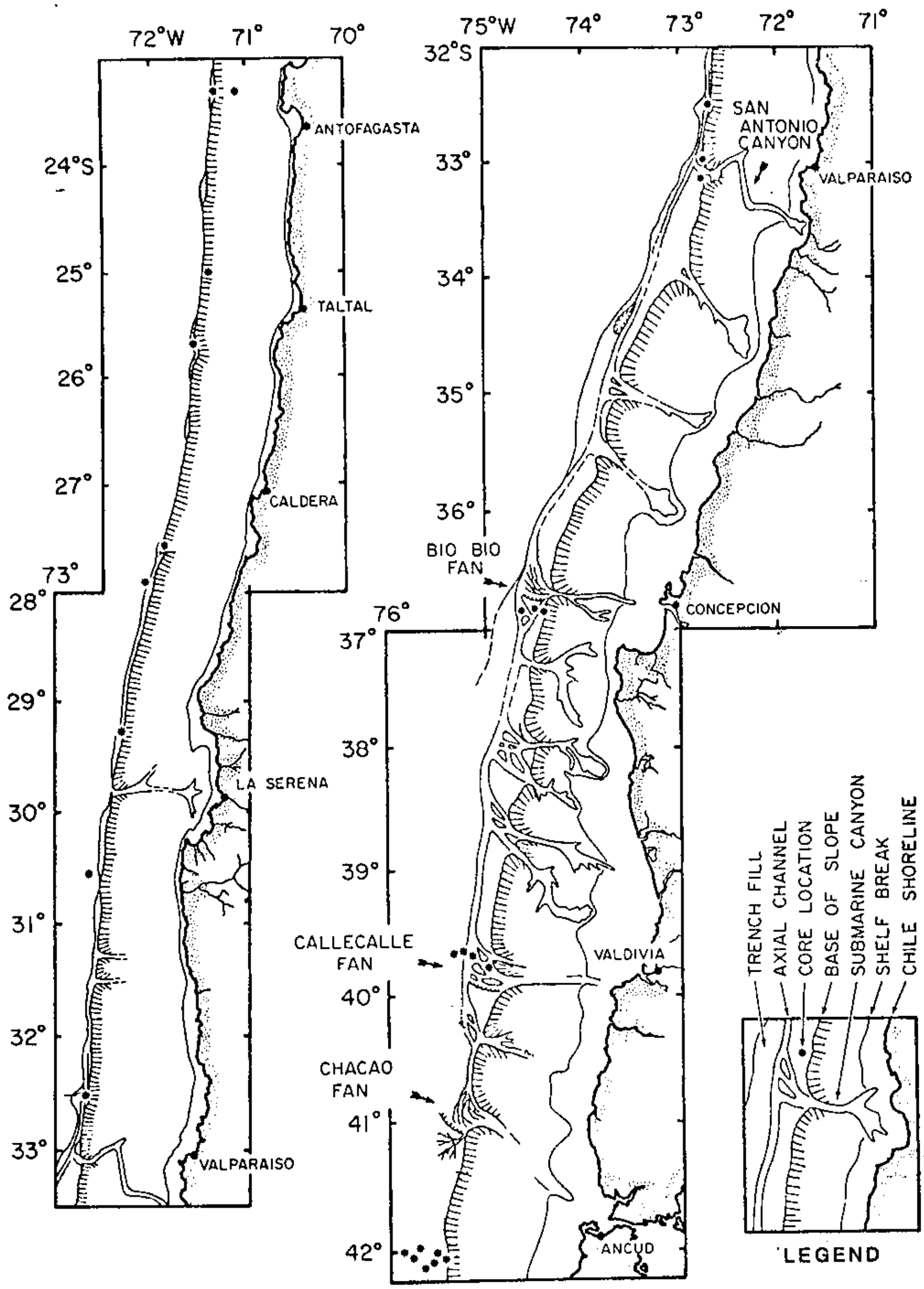

Fig. 2. Map view of the Chile Trench sediment fill. The distribution of axial sediments is shown in stippled pattern; fan distributary and trench axial channels are unshaded. Asterisks denote core control. The shelf break is represented by the 200-m bathymetry contour. Submarine canyon morphology is from Prince et al. (1980), and from data collected on the R/V MELVILLE in 1980.

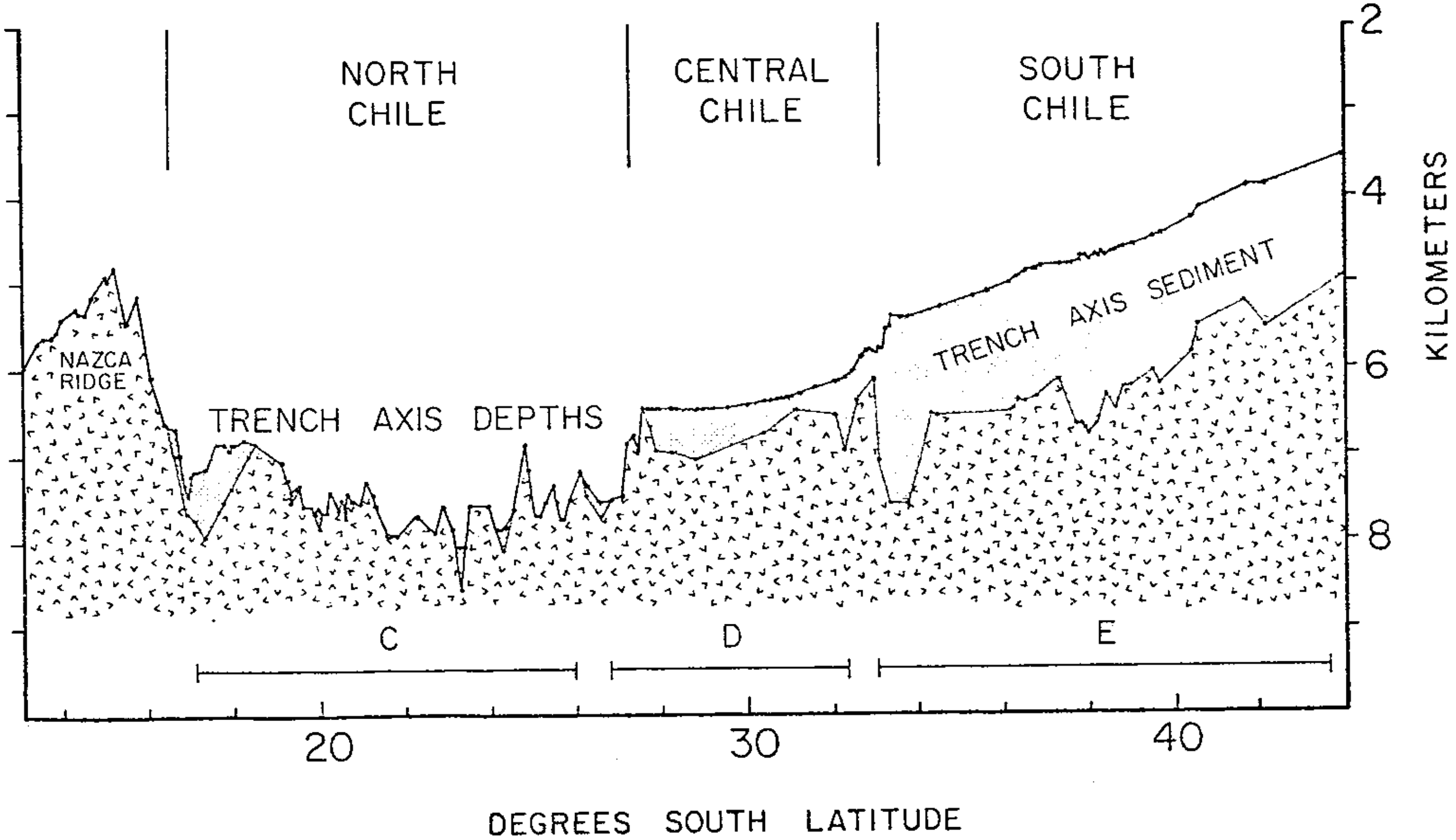

Fig. 3: Axial cross-section of the Chile Trench. Bathymetric thalweg depths, depth to oceanic basement (checked pattern) from seismic reflection, and the thickness of the axial sediment fill (stip - pled pattern) are plotted according to latitude (after Schweller et al., 1981). Segmets in the subducting oceanic plate, as determined from hypocenter location in the inclined seismic zo ne, are shown below (C, D, and E, after Barazangi and Isacks, 1976).

South of 41°S the trench is filled by a sequence of flatlying, conformable, sheet flow turbidites (Figs. 2, 4). Two turbidites can be correlated across the 30-km-wide trench wedge in seven cores near 42°S, based on stratigraphic position, sedimentology, radiocarbon dating, ash content and mineralogy (Fig. 4). The youngest sheet turbidite--the Black Ash unit--is composed of nearly pure (70%), fresh, basaltic andesite lithic grains with a scoriaceous texture. The older turbidite--the Sand Lens unit--is composed of quartz and feldspar mineral grains and reworked volcanoclastics. The coarsest and thickest sands are centralized in the Sand Lens unit (Fig. 4, cores M-09 and M-07) and grade both landward and seaward into finer, siltier deposits, reflecting a cross-trench gradient in flow velocity during deposition. Much of the Sand Lens unit was deposited under upper flow regime conditions, while the Black Ash unit was deposited under lower flow regime conditions.

At 41°S, the trench's axial channel emanates from the mouth of the Chacao submarine canyon and trends northward down the gravitational gradient, integrating and centralizing the longitudinal sediment dispersal system for many hundreds of kilometers (Figs. 2). The channel provides a major avenue for long-distance, along-margin transport of material. Numerous submarine canyons in South Chile deliver sediment across the margin from subaerial drainages. Trench fans are built at the mouth of these canyons (i.e. the Bio-Bio and Calle-Calle fans), and the fan channels become tributary to the axial channel. The axial channel continues across the tectonic discontinuity at 33°S (the San Antonio Discontinuity) and partway into the Central Chile province, where the axial gradient eventually disappears and sedimentation becomes truly ponded.

METHODS

Twenty-six cores were utilized to characterize the mineralogy of the trench axis and trench wall environments in the Chile Trench, the bulk of these being piston cores obtained on the R/V MELVILLE during an Oregon State University cruise in November 1980. Sand samples were extracted from these cores for processing, taken mainly from the basal portions of coarse

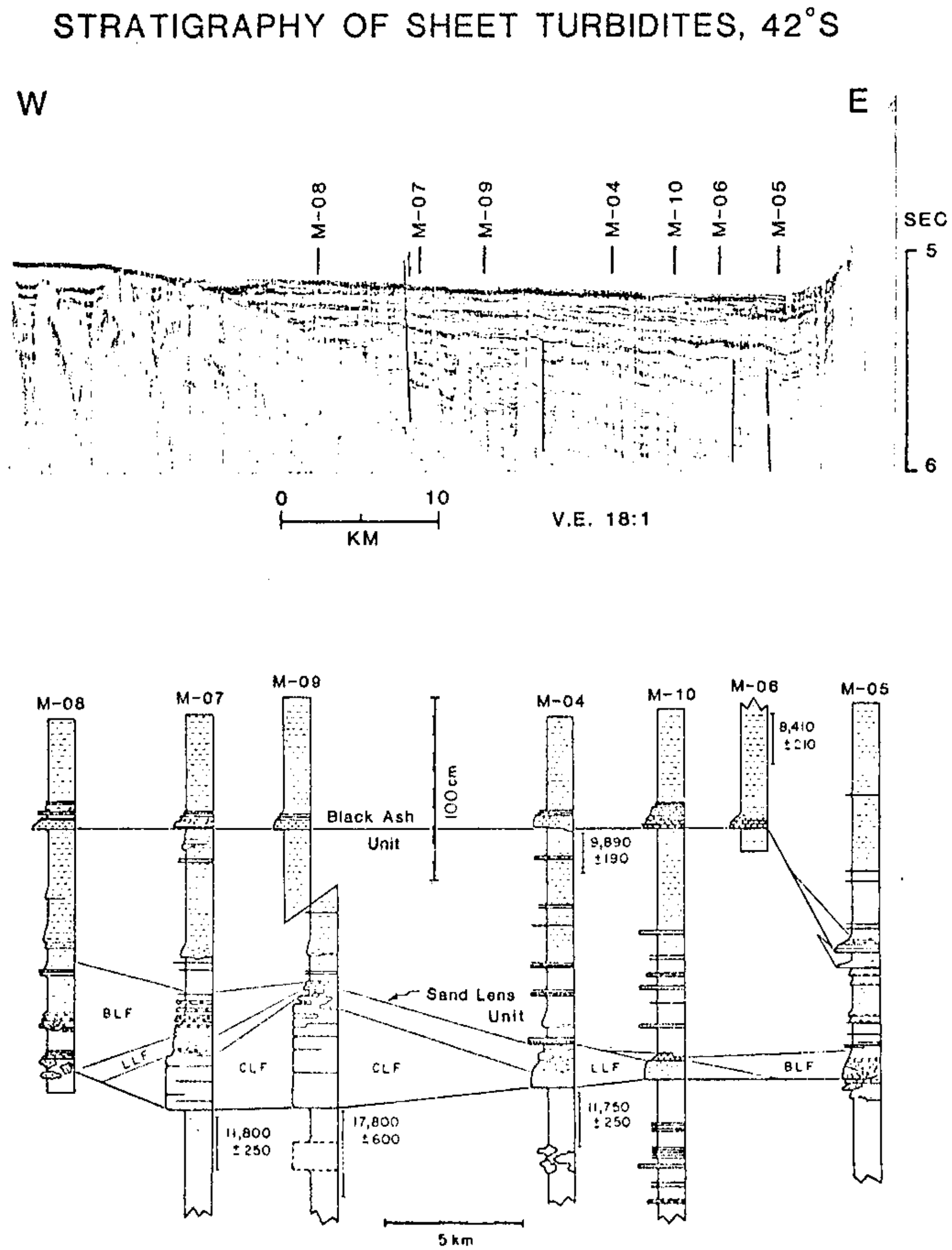

Fig. 4. Sheet flow turbidites near 42°S. (A) Seismic reflection profile showing extensional faulting and mild deformation of the conformable sequence, with location of coring transect. (B) Lithologic correlation of individual sheet flow units (the Black Ash and Sand Lens units) in piston cores across the 30-km-wide wedge. Carbon-14 age control is shown. Note the lateral lithofacies changes in the Sand Lens unit, reflecting a channelization of velocity during turbidity current deposition (CLF = Channel lithofacies, LLF = Levee lithofacies, BLF = Basin Lithofacies). The less disturbed section in the gravity core trigger weight is spliced on top of the piston core section of core M-09.

-grained turbidites. Carbon-14 dates indicate that our samples are younger than 50,000 years old.

The sands were disaggregated with H_2O_2, then sieved to isolate the fine to very fine sand fraction (62-250 microns). This fraction was then split into light and heavy mineral separates using tetrabromoethane (specific gravity of 2.97 g/cc). A portion of each heavy mineral split was crushed to powder, mounted and X-rayed from 15 to 40 degrees 2θ at 0.20°/3 sec, using copper radiation. A total of 36 samples were selected for petrographic quantification.

The light mineral split was mounted on microscope slides with epoxy resin, and stained for plagioclase and potassium feldspar according to the method of Laniz et al. (1964). For each slide, at least 400 mineral grains were identified under reflected light. The counting method of Dickinson (1970) was followed. The heavy minerals were mounted in Canada balsam, and more than 20 species were identified petrographically by counting 250 or more translucent grains per slide.

RESULTS

Light Mineralogy

The range of QFL values (quarz-feldspar-lithic composition) for the Chile Trench samples is basically coincident with values obtained from continental slope and abysal plain environments along the Andean margin (Fig. 5; Yerino and Maynard, 1984). The Chile Trench data encompass the average compositions of modern sands from strike-slip, continental arc, oceanic back-arc, and oceanic forearc types of active margins (Valloni and Maynard, 1981). The data also span the entire compositional range within the magmatic arc field, from undissected arc (supracrustal volcanic cover) to dissected arc (unroofed plutonic roots) tectonic settings, as defined by Dickinson et al. (1983) for ancient Phanerozoic sandstone. The Q/F ratio is consistently less than unity, but nearly the entire range of lithic composition is represented, implying that immature, quartzofeldspathic sands suffer varying amounts of dilution by volcanoclastic grains. It is clear that diverse geotectonic environments and sedimentary provenances may

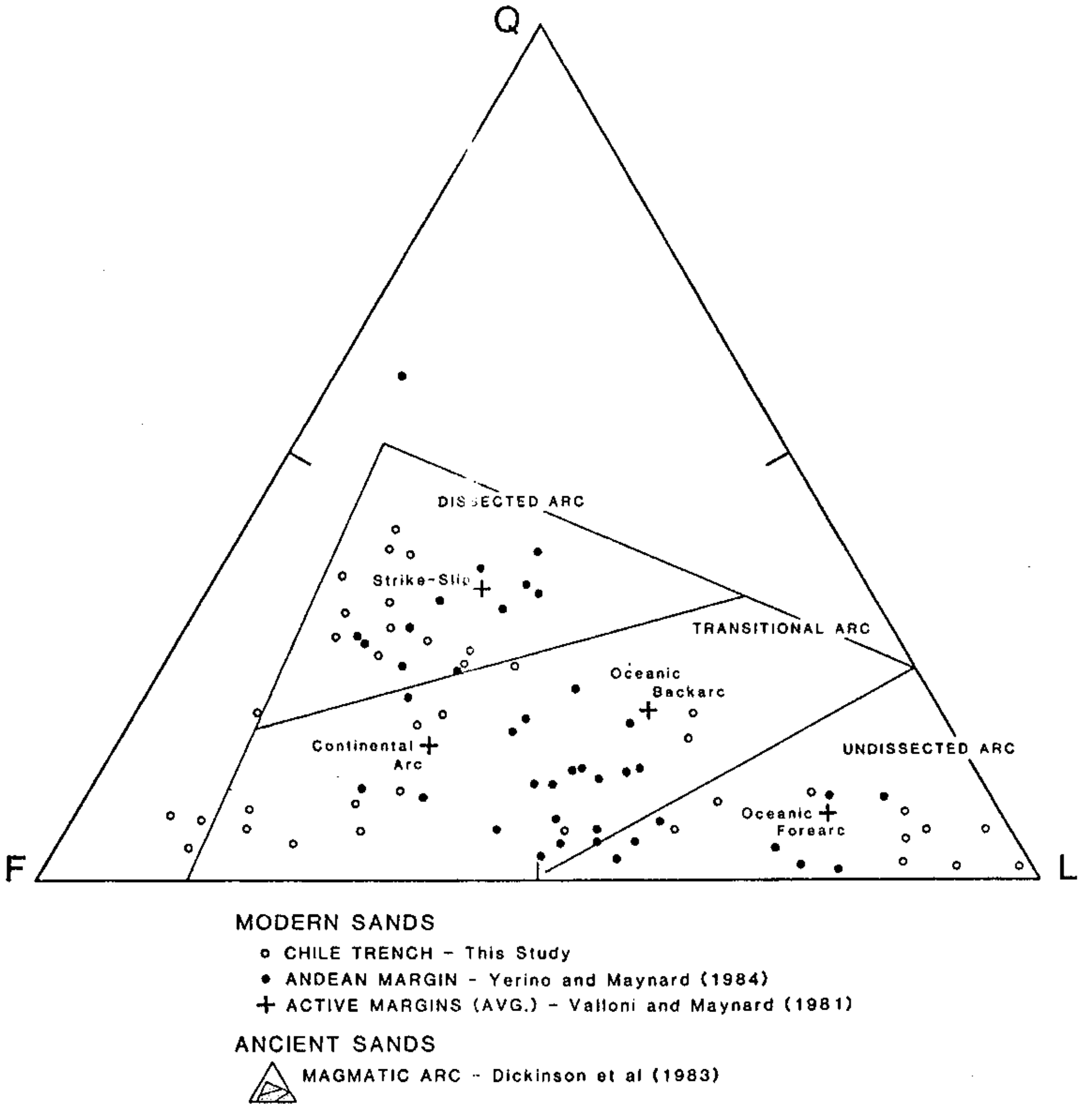

Fig. 5. QFL composition (quartz-feldspar-lithic) of modern sands from the Andean continental margin. Chile Trench samples (solid circle)and Andean margin samples from continental slope and abyssal plain settings (open circle) are plotted. Also shown are the average compositions of modern deep-sea sands from several different active margin settings (crosses), and the magmatic arc compositional field for ancient Phanerozoic sandstones.

exist along a single continental arc, and that the QFL composition of the sand fraction is a poor discriminator between different types of active margin settings.

In Figure 6a, we consider the distribution of samples on the QFL diagram according to their geographic position along the Chile Trench. Samples from the sheet flow basin at 42° S show a bi-modal distribution. The compositional split reflects the difference between two sheet turbidites that were deposited under contrasting flow regime conditions, and which represent different hydrodynamic facies (see Background). Samples that are rich in volcanic lithic grains represent the composition of the Black Ash unit, while the more quartzofeldspathic mode represents the coarser, higher energy deposits of the Sand Lens unit. Apparently, vessicular volcanic scoria is concentrated in the low-energy portions of a turbidity current due to its low density and irregular shape; quartzofeldspathic grains are largely diluted by this lithic component in the black Ash unit.

Most samples from the South Chile province contain subequal amounts of feldspar and lithic grains, and less than 20% quartz. Sands from the North Chile province (aside from a single ash-rich sample), the Central Chile province, and from the high-energy lithofacies of the sheet flow basin at 42°S exhibit markedly higher quartz content and lower lithic content (Fig. 6A); these samples plot within the "Dissected Arc" field of Dickinson et al. (1983). The quartzofeldspathic nature of the Central Chile sands is not surprising since Plio-Quaternary volcanism is absent along this semgent of the Andean margin (Fig. 1). Erosion has cut through the Mesozoic and Cenozoic volcanic carapace and exposed the crystalline rocks of the underlying batholith.

The relatively low lithic content of North Chile and some 42°S sample is anomalous since both regions lie adjacent to active volcanic arcs. In the North Chile province, the aridity is so extreme that many rivers do not discharge into the ocean, but evaporate on the plains of the longitudinal depression in ephemeral lakes and salt flats. Much of the debris from the volcanic High Cordillera is thus trapped as alluvium in ponded interior basins (Mortimer and Saric, 1975). The crystalline lithologies of

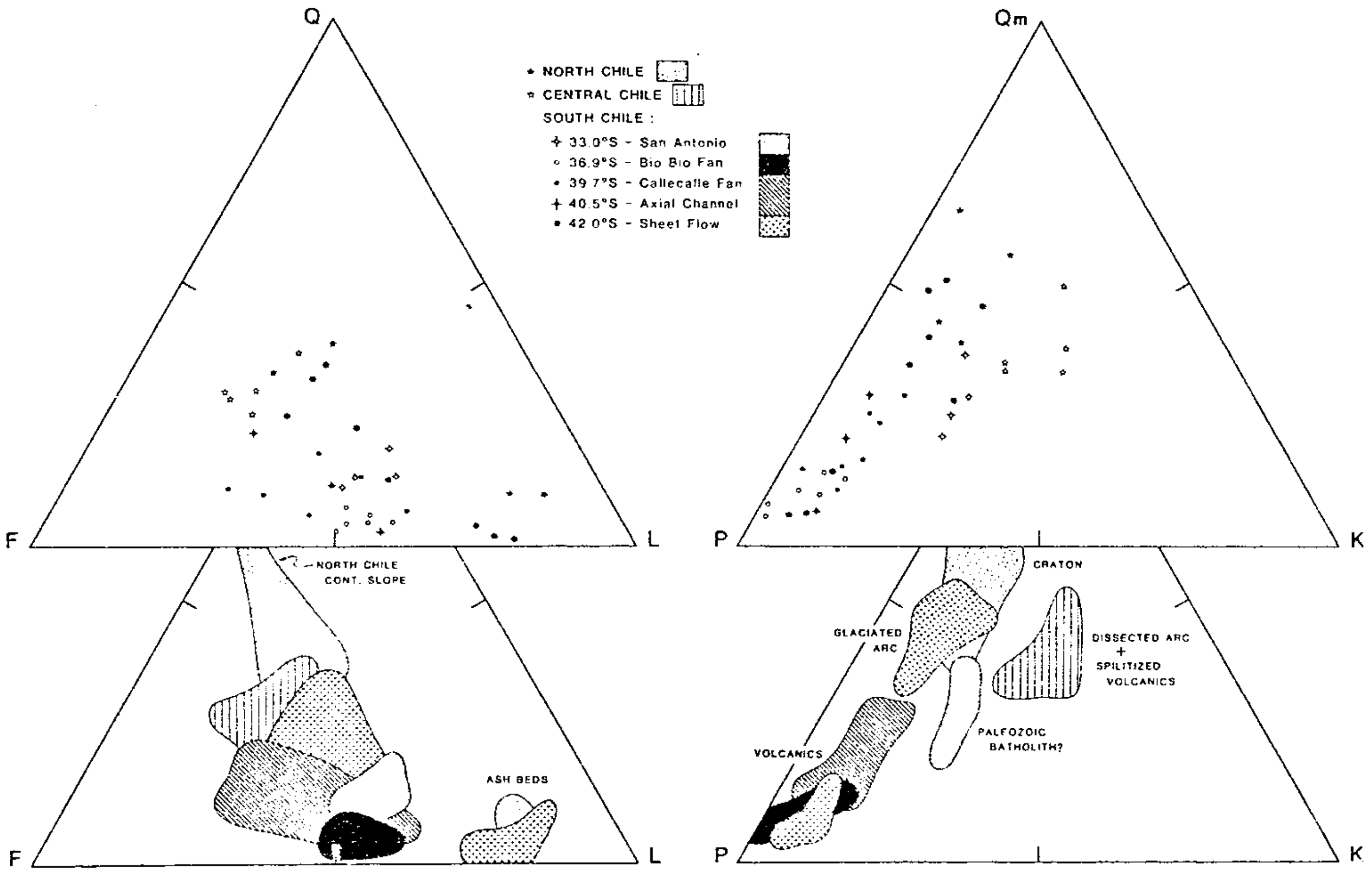

Fig. 6. QFL and QmPK composition of Chile Trench sands: petrologic variations along the strike of the margin. Note that samples from the North Chile and Central Chile provinces, and from the sheet flow basin at 42°S in the South Chile province, are enriched in quartz and alkali feldspar, and depleted in lithics and plagioclase feldspar, reflecting a derivation from more plutonic source terranes.

the Coast Range may provide an exaggerated contribution of quartz and feldspar minerals to the offshore under these harsh desert conditions.

At 42°S, dissection of the volcanic arc is probably enhanced because Pleistocene glaciation was severe at these southerly latitudes (Paskoff, 1977). Mechanical erosion beneath a moving ice mass will reduce plutonic rock much more effectively than river processes, especially in an area of steep relief and high maritime precipitation, such as southern Chile (Flint, 1971). The Andean batholith crops out extensively on the western flank of the High Cordillera in the high latitudes of the South Chile province, and the Quaternary stratovolcanoes of the arc are built directly upon it (Ruiz and Corvalan, 1968).

The monocrystalline mineral grains of quartz, plagioclase, and alkali feldspar were normalized to 100% and displayed on the ternary QmPK diagram (Dickinson and Suczek, 1979) (Fig. 6B). The majority of samples from the South Chile province are very plagioclase-rich, with $<$ 30% quartz and $<$15% alkali feldspar, reflecting their derivation from the contemporary volcanic arc. This includes samples from the low-energy, ash-rich deposits of the sheet flow region, since many of the glassy volcanic lithics contain sand-sized plagioclase phenocrysts. The influence of a plutonic provenance in samples from North Chile, Central Chile, and from the high-energy deposits of the sheet flow basin at 42°S is more clearly indicated by the monocrystalline population. Sands from North Chile and the 42°S region are characterized mainly by a significant increase in the quartz component over plagioclase.

The Central Chile samples show not only an elevated quartz contribution but, above all, the greatest enrichment of alkali feldspar. The anomalous alkali-enrichment can be attributed, at least in part, to a volcanic provenance rather than a strictly plutonic one. In the basal section of the Andean eugeosyncline (pre-middle Cretaceous), volcanic sequences were laid down in a submarine environment, metamorphosed during burial under greenschist facies conditions, and altered to spilitic/keratophyric compositions (Aubouin _et al._, 1973; Aguirre _et al._, 1974; Levi, 1970). This has caused the in situ replacement of much calcic plagioclase by pure to microperthitic albite. These older volcanic strata crop out extensively along the Central Chile province. Apparently, the erosional dissection of the Andean Cordillera that is associated with volcanic inactivity in Central Chile has also cut deeply into the eugeosynclinal sequence and exposed the basal, alkali-enriched strata.

A group of samples near the San Antonio Discontinuity at 33°S is displaced toward the "K" pole as well (Fig. 6B). The drainage in this region cuts through the Paleozoic batholith of the Coast Range, and the Paleozoic plutons are generally more alkaline in composition than the Andean intrusions (Berg et al., 1983).

Heavy Mineralogy

The heavy mineral content of the trench sands can be determined qualitatively by analyzing the X-ray diffractograms of this density fraction for major mineral peaks (Figs. 7a, 7b).

Samples from the sheet flow basin at 42°S plot as two distinct fields on the QFL and QmPK diagrams, each light mineral field defining the composition of a particular sheet turbidite--the low-energy Black Ash unit, and the high-energy Sand Lens unit (Figs. 4, 6A, 6B). However, the heavy mineral assemblages from both the quartzo-feldspathic and ash-rich turbidites are markedly similar, and represent a mixed igneous/metamorphic provenance (Fig. 7a). Olivine, both ortho- and clinopyroxene, and hornblende are indicative of basic to acidic extrusive, and intermediate to acidic intrusive igneous rocks. Epidote, chlorite, and hornblende suggest a metamorphic contribution of low to medium grade (Gonzalez-Bonorino and Aguirre, 1970).

The heavy mineral assemblage appears relatively insensitive to changes in the energy of the depositional environment. The only consistent difference between the two turbidites at 42°S is that the Black Ash unit contains substantially more biotite (Fig. 7a); this probably represents an effect of hydraulic sorting during deposition, and not a change in provenance. Both platy mica and vessicular volcanic scoria are easily entrained, and likely become concentrated in the low-energy portions of the turbidity

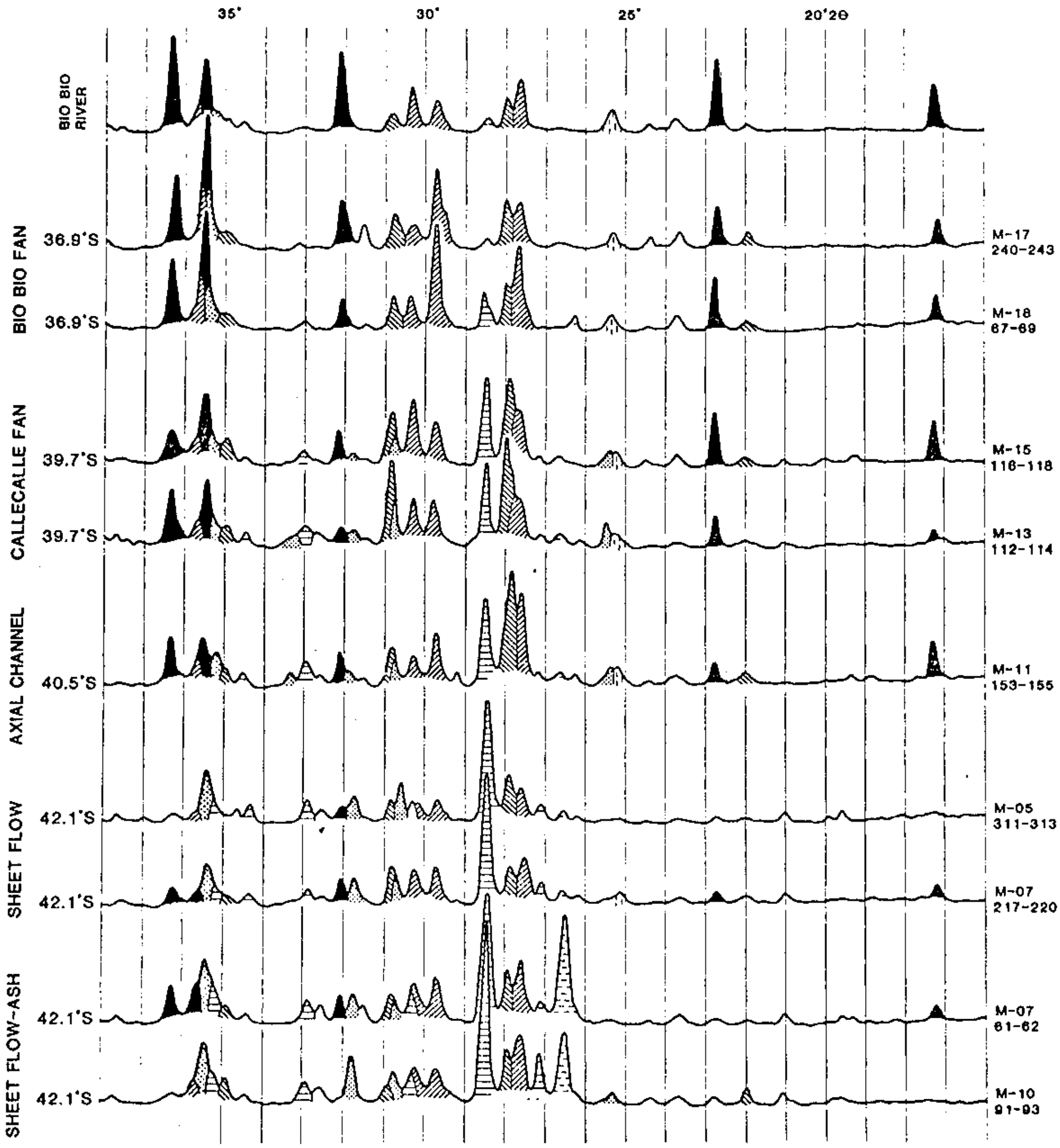

Fig. 7a. X-ray diffractograms of Chile Trench heavy mineral separates. Diffractograms are stacked according to latitudinal position along the trench. Major mineral peak occurrences are located in the legend on the following page, and scaled by their relative peak intensities. Core numbers and sample intervals are noted.

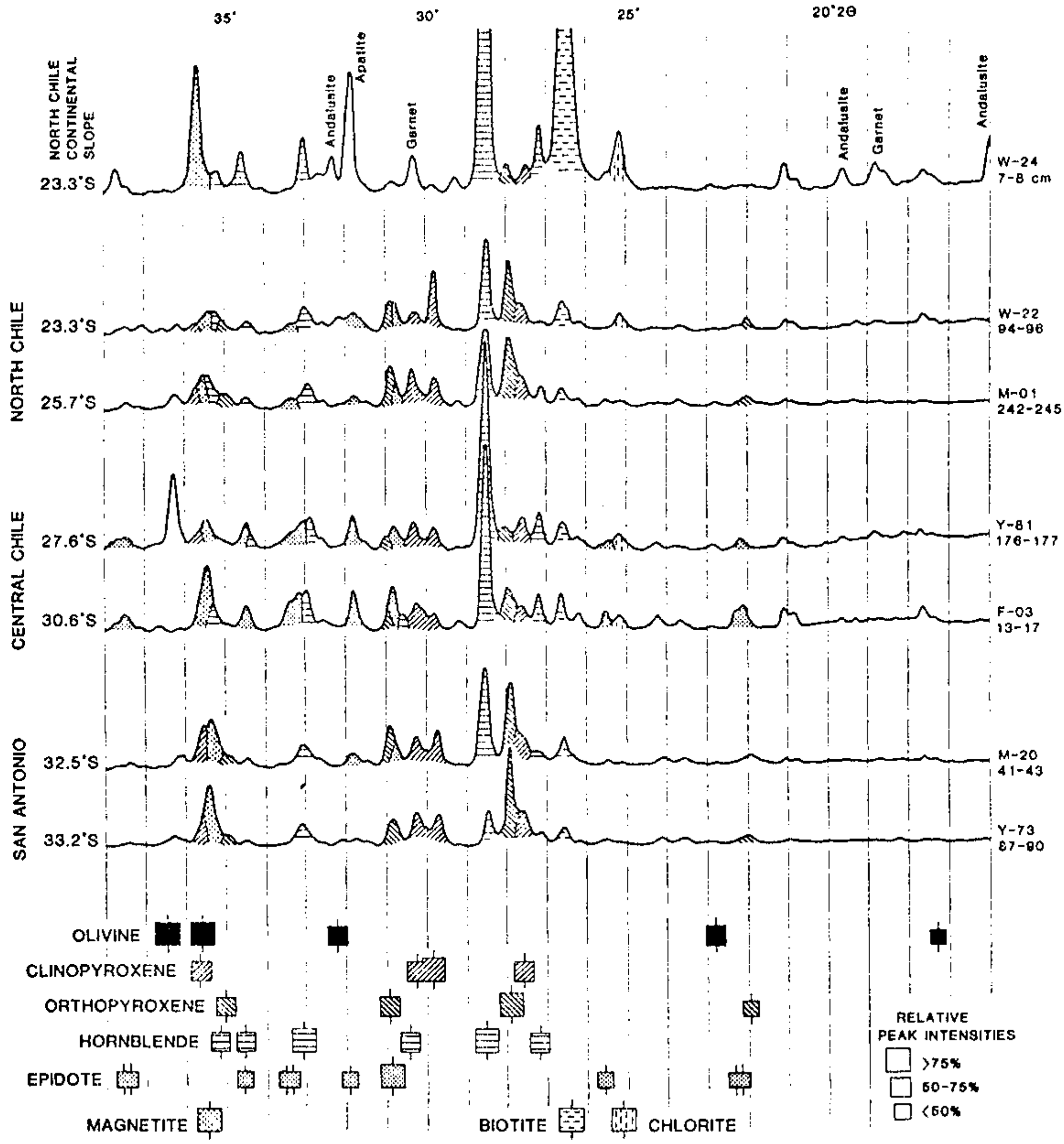

Fig. 7b. X-ray difractograms of Chile Trench heavy mineral separates. See Figure 7a for caption.

current. Evidently, minerals from a broad geographic provenance, including both the Coastal and High Cordilleras, become mixed in the fluvial, littoral, and shelf environments before progressing to the deep-sea at 42° S. These sands are then diluted by a fluctuatig content of volcanic lithics that may represent (a) lithofacies changes imposed within the basin of deposition during the evolution of turbidity currents, or (b) actual changes in the intensity of arc volcanism.

The mineralogy of sands taken near the axial channel at 40.5° S, and from the Calle-calle submarine fan off Valdivia at 39.7°S, contains a mixed provenance assemblage similar to that of the sheet flow basin at 42° S (Figs. 2, 7a). However, one notices a gradual increase in olivine content relative to hornblende in progressing north along this part of the margin. Presumably this reflects a northward decrease in the intensity of glaciation, and in the extent to which mechanical erosion has carved into the plutonic roots of the arc, olivine being a typical phenocryst phase of the southern Chile Volcanics (Deruelle, 1982).

Diffractograms from the Bio Bio fan at 39.7° S show exceptionally well-defined peaks for olivine and both pyroxenes, with clinopyroxene apparently dominant over orthopyroxene (Figs. 2, 7a). The contribution of hornblende, a common to abundant heavy mineral in almost all other Chile Trench environments, is minor or insignificant on this particular submarine fan. The composition of these sands is the most chemically immature and least differentiated of the entire trench; the source of this unstable sediment can be traced onshore to the Bio Bio River (Fig. 7b; Baba and Scheidegger, in press).

Several core samples straddle the San Antonio Discontinuity near 33°S, and all are apparently derived from the structurally-controlled San Antonio submarine canyon system (Fig. 2). These sands share a mineralogy that is characterized by abundant hornblende, orthopyroxene, and magnetite components, reflecting an intermediate to acidic igneous provenance (Fig. 7b; López-Escobar *et al.*, 1977).

For hundreds of kilometers along the Central Chile province--from at least 27.6°to 30.6°S latitude--the heavy mineral assemblage is quite homogeneous,and dominated by hornblende and epidote of plutonic/metamorphic provenance (Figs. 2, 7b). Secondary pyroxene minerals attest to intermediate volcanics in the source region,necessarily reworked from and older stratigraphic sequence because Plio-Quaternary volcanism is absent along this segment of the Andean Cordillera.

Sands from the North Chile province exhibit a similar assembalge, but pyroxene minerals have gained importance relative to the hornblende-epidote association in conjunction with the reappearance of active volcanism onshore (Fig. 7b). It is interesting to compare a core sample from a ponded basin in the trench axis at 8080 m (W-22) with one taken 20 km directly upslope, on the lower continental slope at 5100 m (W-24). The diffractograms from these two samples are exceptionally dissimilar. The trench axis core contains a heavy mineral assemblage that compares well with sands recovered from the trench axis farther south, but in a different ponded basin (core M-01). The lower slope core contains significant quantities of hornblende, biotite, andalusite, and garnet, suggesting derivation from an intermediate -grade metamorphic provenance. Core W-24 represents the most chemically mature, compositionally differentiated, craton-like assemblage recovered from the Chile Trench, and is likely derived from the pre-Andean terranes of northern Chile.

The remarkable contrast between the mineralogy of samples W-22 and W-24 suggests that the trench axis sands may have been derived from a longitudinal, axially-removed source (along-margin transport), while the lower continental slope sands represent local submarine weathering and recycling of slope deposits, through upslope gravitational failure (across-margin transport). In support of this hypothesis, Neogene quartz feldespathic sandstones were dredged at this latitude between 4,000 and 5,000 m water depth, and their heavy mineral fraction is rich in biotite and hornblende (Kulm et al., 1981). A strong apatite reflection in W-24 is also consistent with a continental slope derivation, since authigenic precipitation of this mineral (as phosphorite) is common in the upper slope environment (Veeh et al., 1973).

CONCLUSIONS

The composition of the Chile Trench sands ranges from that characteristic of a dissected magmatic arc setting (derivation from exposed batholithic roots) to that of an undissected magmatic arc setting (derivation from supracrustal volcanic cover). Compositions typical of "dissected" magmatic arcs or plutonic source terranes -- rich in quartz and alkali feldspar, poor in volcanic lithics -- are found in the Central Chile and North Chile provinces, and in the sheet flow basins of the South Chile province, for a variety of reasons. In Central Chile, the plutonic nature of the provenance is correlated with an absence of Quaternary volcanism. Ashore from the sheet flow basins of South Chile, Pleistocene glaciation has carved deep into the batholithic roots of the magmatic arc in spite of active volcanism. In arid North Chile, the volcanic debris of the High Cordillera is trapped in the longitudinal forearc basin, allowing an exaggerated contribution to the deep-sea from the crystalline rocks of the Coast Range.

Several heavy mineral associations are evident in the trench which can be related to source rocks onshore. The most compositionally inmature and least differentiated assemblage is composed of olivine and pyroxene components, derived from the Quaternary volcanism of southern Chile. A hornblende-pyroxene-magnetite suite represents an intermediate to acidic igneous provenance, and a hornblende-epidote-chlorite suite represents a low-grade metamorphic provenance of the greenschist facies. Finally, the most mature and compositionally differentiated assemblage is characterized by the heavy minerals hornblende, biotite, andalusite, and garnet, probably derived from the pre-Andean terranes of northern Chile where this suite is most strongly represented.

The petrologic composition of trench sands should be a sensitive indicator of the contemporary configuration of the adjacent magmatic arc (its volcanism, geology, climate, and morphology) because the residence time of sediments in the undeformed trench basin is only a few hundred thousand years (Schweller y Kulm, 1978). Chemical wathering in the source area is apparently insignificant because olivine forms a major component of the heavy mineral fraction even where the climate is humid and the cordilleran relief is relatively low. However, hydraulic sorting in the depositional basin may modify the assemblage by concentrating minerals of anomalous density or shape, such as vessicular volcanic scoria and platy mica.

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