Journal of the Geological Society

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Journal of the Geological Society 1987; v. 144; p. 599-610
doi:10.1144/gsjgs.144.4.0599

Journal of the Geological Society, London, Vol. **144,** 1987, pp. 599–610, 12 figs. Printed in Northern Ireland

The origin of the Upper Palaeozoic Chañaral mélange of N Chile

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Abstract: The fragmented and mixed strata of the Chañaral mélange extend for some 220 km from N to S in the coastal ranges of N Chile (26°20′ to 28°20′S). The mélange was produced in an accretionary wedge resulting from the NE subduction of the ancestral Pacific oceanic plate beneath the Gondwanaland margin during Carboniferous times. The mélange consists essentially of blocks of sandstone in a pelitic matrix. These sediments were deposited as deep-sea basin–plain turbidites prior to their fragmentation. Other blocks in the mélange include mafic volcanic rocks, with the geochemical characteristics of oceanic island basalts, and rare shallow-marine limestones.

Structures in the mélange suggest an origin by two distinct deformation processes involving unlithified sediments. Initial boudinage and break-up of the strata was apparently accomplished by intrastratal movement resulting from imbricate thrusting within the accretionary wedge. The second process produced cross-cutting zones of breccia which are interpreted as fluid escape conduits resulting from the high pore pressures produced during underthrusting.

Much of the present-day western coast of South America was an active continental margin during mid to late Palaeozoic times. Accretionary complexes of this age have been identified in Colombia (McCourt *et al.* 1984); between 25° and 29°S in N Chile (Bell 1984); in southern Chile around 40°S (Gonzalez-Bonorino 1971; Hervé *et al.* 1981) and S of 49°S (Nelson *et al.* 1980; Mpodozis & Forsythe 1983).

The first detailed investigation of the Palaeozoic metasedimentary and volcanic rocks in the coastal region between 25° and 27 °S in northern Chile was undertaken by the author, in collaboration with the Servicio Nacional de Geología y Minería of Chile, in 1981. The intensely deformed rocks were interpreted as an accretionary wedge produced by NE-directed subduction (Bell 1982, 1984). During this investigation a large-scale mélange was identified in the area S of the town of Chañaral. The present paper records the results of a subsequent, more detailed study of the mélange between 26°20′ and 28°20′S. The objectives of this investigation were to record the distribution, relationship with the country rocks, lithology and structures of the mélange. Large-scale mélanges are commonly associated with accretionary wedges but their origin remains a subject of debate (Raymond 1984; Cowan 1985). The structures of the Chañaral mélange, together with the relationship with the adjacent sedimentary rocks, suggest that the mélange was produced by two distinct deformation processes incorporating unlithified sediments within an accretionary wedge.

Geological setting of the Chañaral mélange

Palaeozoic sedimentary, volcanic and plutonic rocks crop out extensively between 25° and 29°S in northern Chile (Fig. 1). The rocks form two NNE to SSW elongated strips separated by a 100 km wide graben infilled with younger strata (Levi & Aguirre 1981). The western margin of this graben is the N–S-trending Atacama strike-slip fault system which has an as yet undetermined sense of movement and which was active mainly during the Cretaceous (Naranjo 1978). To the E of the graben is the early Carboniferous Chinches Formation, a little-deformed lacustrine succession (Bell 1985) intruded by late Palaeozoic granitoids and unconformably overlain by volcanic rocks of late Carboniferous to early Permian age (Mercado 1982; Sepulveda & Naranjo 1982). To the W of the graben is the Las Tórtolas Formation, a thick turbidite sequence with minor alkali basalts (Bell 1982) and the fragmented and chaotically mixed rocks of the Chañaral mélange.

The Las Tórtolas Formation

Rocks of the Las Tórtolas Formation extend for at least 400 km from N to S (Fig. 1). The basement of these strata is unknown, although at Isla Gaviota the formation is faulted against quartzites and garnet–actinolite–epidote schists of probable early Palaeozoic age (Godoy 1976). The Las Tórtolas Formation was tectonically deformed and subjected to greenschist facies metamorphism (Miller 1970; Aguirre *et al.* 1972) during the late Carboniferous or early Permian (280 ± 15 Ma; radiometric age of phyllite ESE of Chañaral) (M. Brook & R. J. Pankhurst pers. comm.), prior to the intrusion of Lower Permian monzogranites (267 ± 8 Ma). The deformed strata are unconformably overlain by Triassic and Jurassic volcanic and sedimentary rocks (Mercado 1980; Naranjo 1978).

The thickness of the Las Tórtolas Formation is unknown due to the lack of distinctive stratigraphic markers and to the intense deformation. The widespread distribution of the turbidites does, however, suggest a thickness of at least several kilometres. An estimate of more than 3 km (Berg & Breitkreuz 1983) to the E of Chañaral took no account of the very tight folding.

The strata consist essentially of thinly-bedded arenaceous and pelitic turbidites. Rare pebbly sandstones and conglomerates have been recorded between Chañaral and Punta Obispo. Palaeocurrents, indicated by current scour marks, were directed towards the SSE in the region N of Chañaral (Bell 1982). The only two palaeocurrent indicators recorded S of Chañaral were directed towards the S and the SE. Sandstones and conglomerates had a predominantly metasedimentary provenance of greywacke, feldspathic arenite, siltstone and vein quartz, together with andesitic and felsic volcanic rocks and rare diorite and granodiorite.

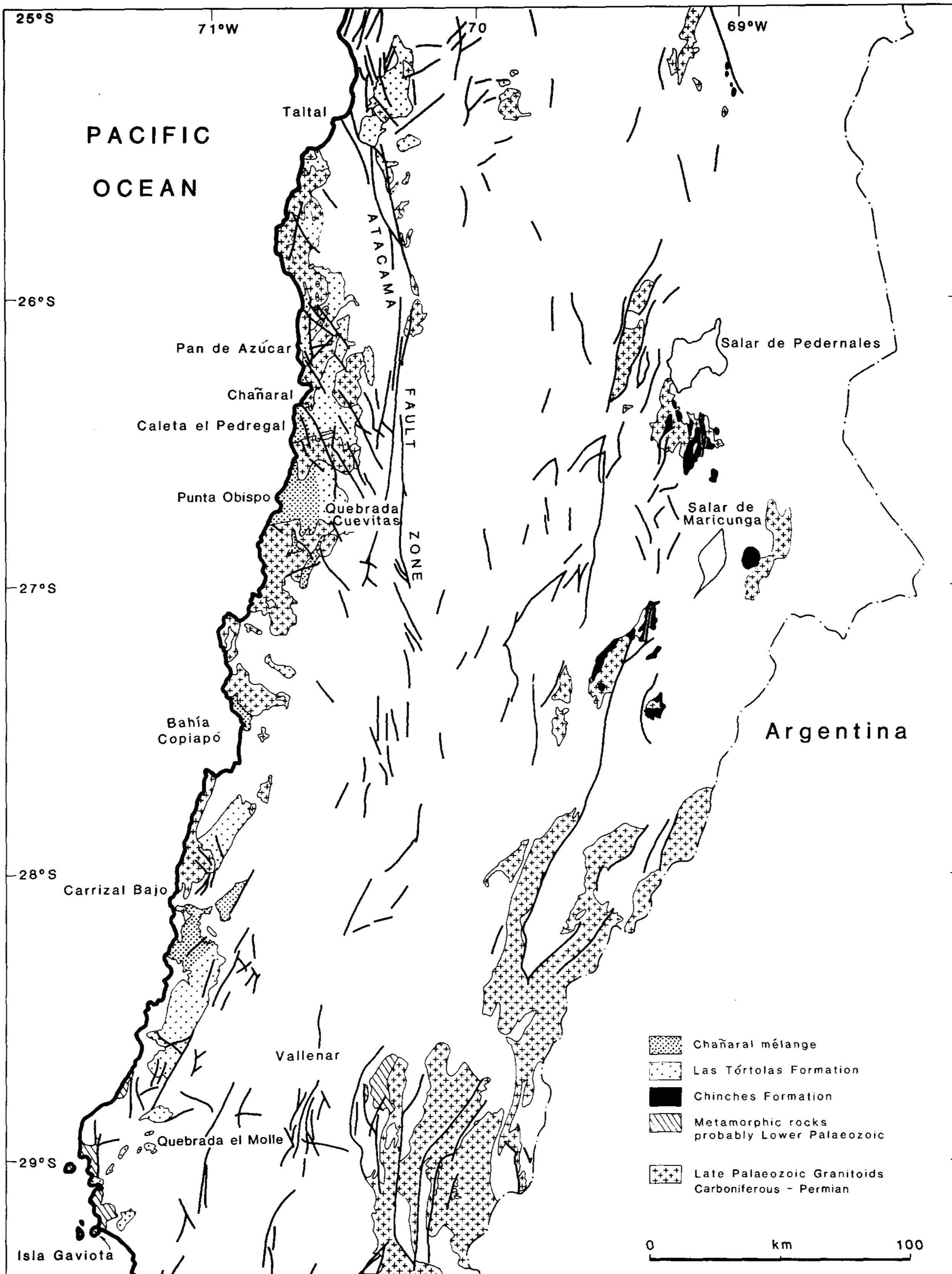

Fig. 1. Geological map showing the distribution of Palaeozoic strata in the region between 25° and 29°S in northern Chile. The mélange is found in the coastal region S of Chañaral.

A few limestones up to several metres thick, interstratified with the siliciclastic turbidites in the area between 26° and 28 °S, consist of broken fragments of calcareous red algae (Bell 1982).

Mafic alkali volcanic rocks, including pillow lavas and hyaloclastite breccias, are interstratified with the turbidites at Pan de Azúcar (Bell 1982). A 200 m thick sequence of dacitic tuffs and agglomerates at Quebrada el Molle probably also forms part of the Upper Palaeozoic sequence but its stratigraphic relationship with the Las Tórtolas Formation is unknown.

The Chañaral mélange

The Chañaral mélange extends for some 200 km from N to S and 30 km from W to E (Fig. 1). The fragmented strata are continuous for the 70 km S of Chañaral, with other occurrences at Bahía Copiapó and Carrizal Bajo. The mélange was produced essentially by the fragmentation of strata of the Las Tórtolas Formation, but it is readily distinguishable in the field and therefore forms a distinct mappable unit. The definition of mélange adopted here (Silver & Beutner 1980) is those rocks where stratigraphic continuity has been completely lost on a scale of metres to tens of metres. The mélange contains only a very few exotic blocks (Hsü 1968) of rock types not recorded in the Las Tórtolas Formation. One of these blocks, at Aguada de la Changa (Fig. 3), is a conglomeratic limestone with spiriferaceans of a probably late Palaeozoic age, and bryozoa of possible Carboniferous or Permian age (P. D. Taylor pers. comm.). Bell (1982) suggested an Ordovician to Devonian age for the Las Tórtolas Formation on the basis of a trace fossil assemblage. However, the newly discovered fossils in the mélange, together with considerations of the regional stratigraphy (Coira *et al.* 1982; Davidson *et al.* 1981*a, b*), now indicate a Devonian to early Carboniferous age.

Sedimentary rocks in the mélange

Most of the mélange consists of fragmented and mixed sandstone, siltstone and shale derived from the Las Tórtolas Formation. Minor components include conglomerate, mafic volcanic rock, limestone and marble. The mélange typically comprises blocks (or phacoids) of sandstone in a mudstone matrix (Fig. 2). The proportion of sandstone to mudstone is very variable, ranging from about 20% sandstone SE of Bahía Las Animas (Fig. 3) up to 90% E of Caleta el Pedregal. The sandstones are texturally and mineralogically immature medium- to fine-grained feldspathic and lithic arenites and greywackes.

Matrix-supported conglomerate and pebbly sandstone have been recorded in the mélange at Quebrada Los Infieles, Caleta el Pedregal and Aguada de la Changa (Fig. 3). Clasts are well-rounded and discoidal to spheroidal in shape. They are normally granule or pebble-sized, with a few up to 200 mm in diameter. Some of the conglomerates and pebbly sandstones form distinct bands and irregularly-shaped masses or blocks within the mélange, but in most places the boundary between conglomerate and mélange is diffuse and poorly defined. Most of the conglomerates have been completely disaggregated, with individual well-rounded clasts intermixed with other blocks in the mélange.

A 30 m diameter block of interstratified bioclastic limestone, sandstone and conglomerate at Aguada de la Changa is unlike any other sequence recorded either in the mélange or in the Las Tórtolas Formation. The conglomerate is matrix supported with very poorly-sorted clasts up to 5 cm in diameter. Most clasts are intraformational mudstone together with a few well-rounded fragments of chert, sandstone, vein quartz and felsic volcanic rock. Poorly preserved fossils include crinoids, rugose corals and bivalves in addition to the previously mentioned spiriferaceans and bryozoa.

Blocks of marble in the mélange, 30 km SE of Punta Obispo (Fig. 1), consist of a pale-coloured breccia of small angular and slightly flattened fragments up to 20 mm in diameter. The rock comprises 97% equi-dimensional calcite crystals, up to 2% of randomly oriented euhedral tremolite needles and scattered grains of quartz and pyrite. The only fossils identified are small silicified echinoid fragments.

Magmatic rocks in the mélange

Mafic volcanic rocks form a minor proportion of the mélange but are locally abundant S of Bahía Las Animas

Fig. 2. Mélange comprising sandstone blocks in a pelitic matrix. South of Punta Obispo.

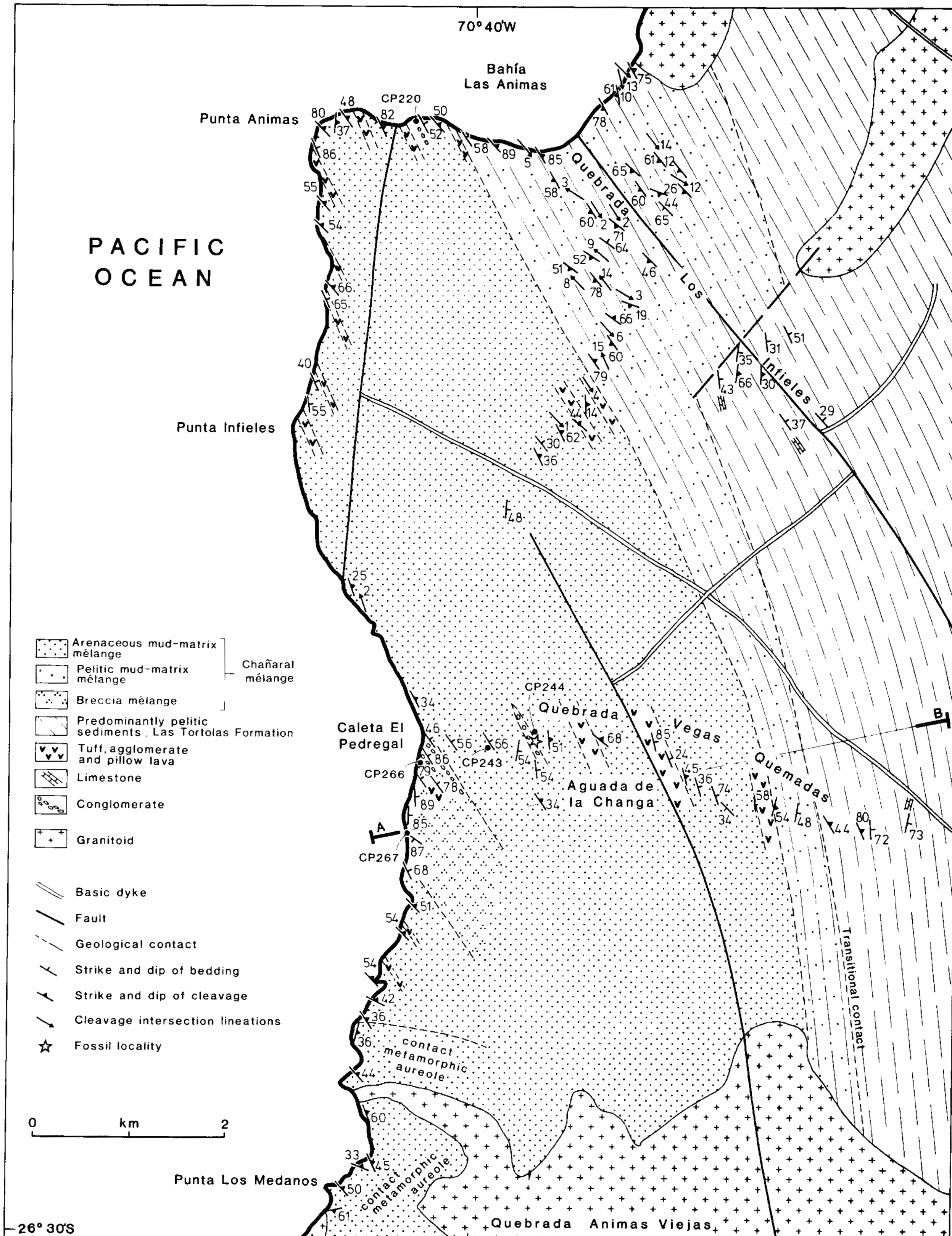

Fig. 3. Geological map showing the distribution of the main rock types in the mélange S of Bahiá Las Animas.

(Fig. 3) and at Bahía Copiapó (Fig. 1). At least 10 sequences of mafic tuffs and lavas up to 200 m thick are interlayered with the mélange at Báhia Las Animas (Fig. 3). Much of the volcanic material is disaggregated and mixed in the mélange, but a 20 m thick sequence of pillow lava and tuff, interbedded with sandstone and shale in Quebrada Vegas Quemadas, indicates that the volcanic rocks were interstratified with clastic sediments of the Las Tórtolas Formation prior to their disaggregation.

The mélange at Bahía Copiapó consists of intermixed masses of volcaniclastic sediment, tuff and agglomerate. Enclosed within the pyroclastic rocks are lenses of pillow lava and porphyritic lava up to 20 m thick. The pillows are up to 1 m in diameter with little interstitial material. Most of the lavas have a variolitic texture of plagioclase laths (An_6 to An_{22}). A 10 m block of coarse-grained pyroxenite in the mélange at Bahía Copiapó consists of about 10% oligoclase (An_{29}) and 85% clinopyroxene (extensively altered to actinolite) together with some sphene, a skeletal opaque mineral and clinozoisite. This pyroxenite has the same geochemical characteristics as the lavas but contacts with the surrounding tuffaceous mélange are tectonic.

Metamorphic minerals in the mafic volcanic rocks, including actinolite, epidote, biotite, chlorite and zoisite, indicate a greenschist facies.

Major and trace elements in 24 of the volcanic rocks were analysed by XRF at Bedford College, University of London. Preliminary results show that on the Ti-Y-Zr diagrams of Pearce & Cann (1971, 1973) the specimens plot in the field of within-plate basalts. Low Zr/Nb ratios and high Sr, Ni and Cr indicate that these rocks resemble alkali rather than normally depleted mid-ocean ridge basalts (Bell 1982). Incompatible element diagrams using the mantle normalized values of Wood *et al.* (1979) show affinity to ocean island basalts.

Origin of rock types in the mélange

The sandstone and shale which comprises the bulk of the Chañaral mélange was produced by the fragmentation of deep-sea turbidites (Bell 1982). The matrix-supported conglomerates and pebbly sandstones probably originated as channelized mass-flow deposits, possibly associated with a deep-sea fan. The provenance of these sedimentary rocks consisted predominantly of andesitic volcanic and low-grade metasedimentary rocks, together with rare diorite and granodiorite. These rock types suggest a continental magmatic arc terrane, comparable with the present-day Andes.

The fossiliferous limestone, sandstone and conglomerate sequence at Aguada de la Changa was deposited in a shallow, high-energy, warm-water marine environment. Similarly the brecciated marble SE of Punta Obispo contains echinoids of probable shallow-water marine origin.

Volcanic rocks in the mélange have the geochemical characteristics of mid-plate, oceanic island alkali basalts (Bell 1982). In common with the geochemically and geologically similar mafic volcanic rocks in the Dunnage mélange of Newfoundland (Wasowski & Jacobi 1985), these rocks probably originated on a submarine volcano or an oceanic island rather than at a mid-ocean ridge or associated with a subduction complex. The interstratification of mafic volcanic rocks with turbidites indicates contemporaneous eruption and deposition, close to the source of the sediments. A similar field relationship has been reported in the Ghost Rocks Formation mélange of Alaska (Byrne 1984).

Contacts between the Chañaral mélange and the Las Tórtolas Formation

Gradational or transitional contacts between the Las Tórtolas Formation and the mélange have been recorded at several localities S of Chañaral. The turbidites become progressively more disrupted and mixed to form the mélange over distances ranging from centimetres to several kilometres across the strike. In most exposures a contact between the mélange and the turbidites is impossible to define. Similar gradational contacts have been recorded in other mélanges (Fox 1976; Moore & Wheeler 1978).

In Quebrada Los Infieles and Quebrada Vegas Quemadas (Fig. 3) the contact between the turbidites in the E and the mélange in the W extends in a NNW to SSE direction, slightly oblique to the stratification over a distance of about 10 km. This contact is transitional, with the turbidites becoming progressively more broken up towards the W (Fig. 4). In Quebrada Vegas Quemadas, 4 km E of Caleta el Pedregal (Fig. 3), the first signs of fragmentation are apparent only in mudstones and thinly interbedded sandstones, with the more thickly-bedded sandstones showing no signs of deformation. Towards the W, over a distance of about 1.5 km, the thicker sandstones become progressively more disrupted until stratification is quite unrecognizable.

Farther S, in Quebrada Cuevitas (Fig. 1), the complex transitional zone is about 10 km wide with zones of mélange up to 1 km wide between relatively undisturbed sedimentary rocks. South and E of Carrizal Bajo (Fig. 1) the mélange

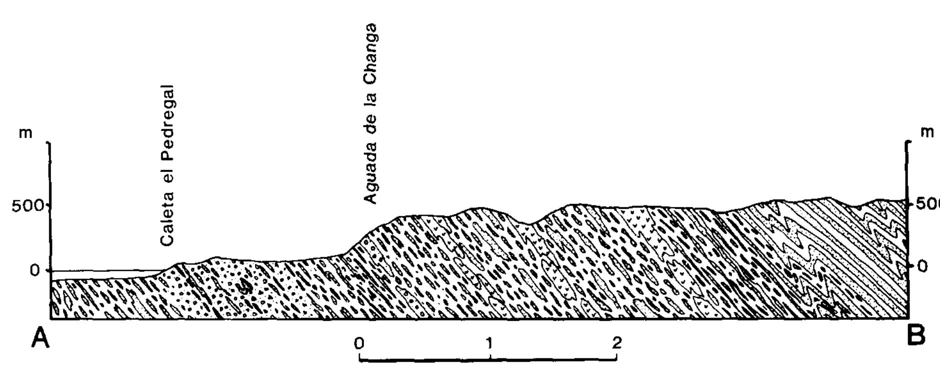

Fig. 4. Sketch cross-section along Quebrada Vegas Quemadas (A to B on Fig. 3) showing the gradational contact zone between the Chañaral mélange in the W and the Las Tórtolas Formation in the E.

forms layers between 0.5 and 10 m thick within the turbidites. At Pan de Azúcar (Fig. 1) fragmented horizons up to several metres wide cut the turbidites at a distance of up to 25 km from the main occurrence of mélange.

Although most bands of mélange in the transition zones are parallel or near-parallel to the stratification, there are no distinct erosional or depositional contacts between the mélange and the undisturbed strata. Similarly, no stratigraphic truncation of the fragmented sequences has been recorded.

Deformation in the Chañaral mélange

The mélange is characterized by intense and complex deformation which has produced a bewildering mixture of rock types and structures, exposed over a huge area of at least 4000 km^2. The mélange has been subjected to three phases of deformation; the earliest of these (D_1) resulted in the stratal disruption and mixing which produced the mélange. Structures produced during the first phase of deformation are well preserved in the relatively competent arenaceous strata in coastal exposures S of Bahía Las Animas (Fig. 3). Subsequent phases of deformation (D_2 and D_3) produced structures which are recognizable in both the Las Tórtolas Formation (Bell 1984) and the Chañaral mélange. In many localities this subsequent deformation has masked the D_1 structures.

D_1 structures

The most obvious structural feature of the mélange is the fabric of poorly-sorted blocks surrounded by matrix (Fig. 2). The mélange typically consists of blocks of sandstone (or less commonly mafic volcanic rocks, conglomerate, limestone and marble) in a pelitic matrix. This rock type is referred to here as mud-matrix mélange (Fig. 3). Most blocks are less than 0.5 m in diameter, but they range from millimetres up to hundreds of metres. They are normally very poorly sorted with respect to size, and the proportion of blocks to matrix ranges from masses of sandstone with little matrix (Fig. 5) to wisps of sandstone in a pelitic mass. In places the contacts between blocks and matrix are sharply defined but elsewhere the boundaries are ill-defined. In thin sections the blocks and matrix are commonly seen to grade into one another (Fig. 6).

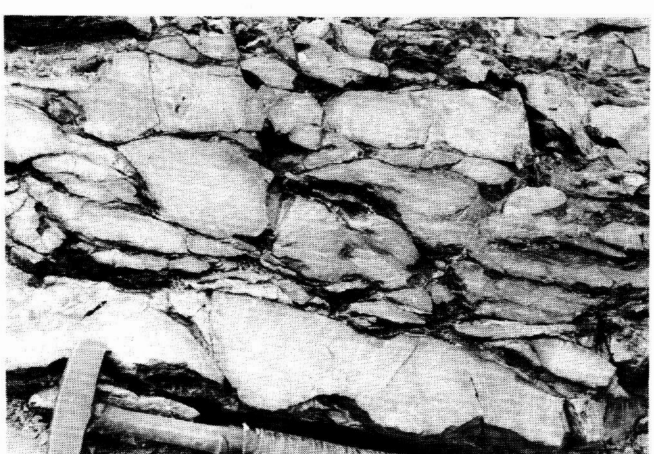

Fig. 5. Mélange of interlocking sandstone blocks showing pinch-and-swell structures and boudinage. Quebrada Vegas Quemadas.

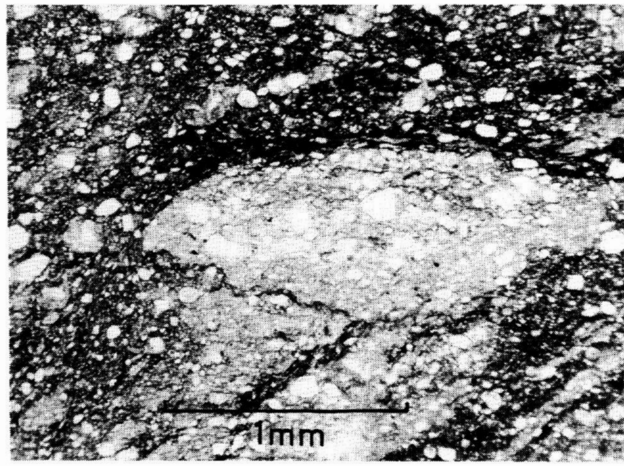

Fig. 6. Thin-section showing the gradational relationship between blocks and matrix in mélange S of Punta Obispo.

Most blocks are irregularly subrounded to angular. Many approximate to oblate spheroids but in a few locations they are distinctly prolate. In Quebrada Vegas Quemadas a lineation (L_1), defined by elongation of these prolate spheroids, plunges at a low angle towards the NE. In most places the blocks are separated from one another by the matrix but more rarely they are attached in sheets (defining a planar fabric S_1) resembling irregular 'chocolate tablet' boudins. In places where the mélange is interlayered with undisturbed strata, for example at Quebrada Vegas Quemadas (CP 244), these sheets of blocks are parallel to the bedding (Fig. 7). The ellipsoidal shape of the blocks, and their arrangement in sheets, is therefore a product of the disruption of bedding. This disruption grades from slight necking or pinch-and-swell of sandstone beds to the complete disaggregation of the sediment into individual

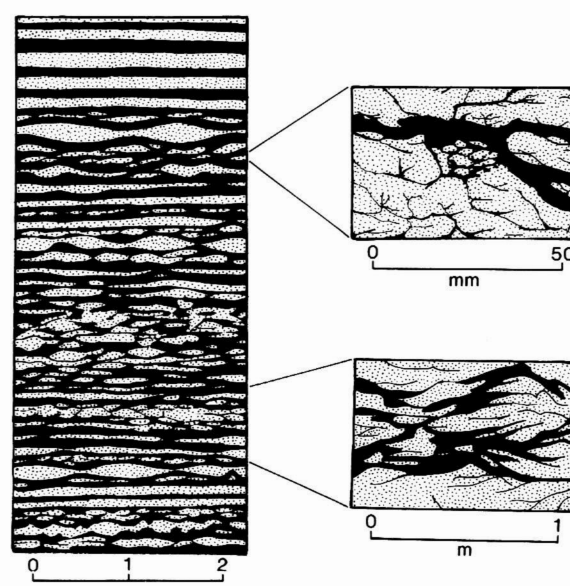

Fig. 7. Diagram showing the fabric in the mélange and its relationship with undisturbed strata. Location CP 244, Quebrada Vegas Quemadas.

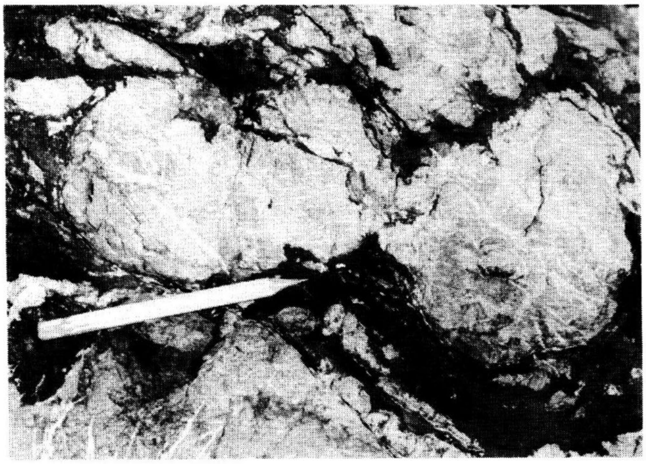

Fig. 8. Mélange with irregular cusp and flame-like contacts between sandstone blocks and pelitic matrix. Punta Los Medanos.

clasts. At location CP 244 a transitional sequence, from undeformed bedding to pinch-and-swell structures and boudins and finally to discrete blocks was observed both across (Fig. 7) and along the strike. The boudins are very irregular in shape with abundant bulbous protrusions, and they commonly form stacked or interlocking masses. Although in most exposures the whole mass of the rock is fragmented, in a few localities some of the boudinaged and disaggregated layers are constrained between apparently unstrained beds (Fig. 7), indicating that the deformation was limited to specific horizons rather than being penetrative. Contacts between sandstone blocks and the more ductile pelitic matrix commonly exhibit irregular cusp and flame-like structures (Fig. 8), with the matrix intruding the blocks as anastomosing veins, wisps and irregular masses. Although much of the deformation appears to have been accomplished in a ductile manner, some blocks of tuff and sandstone show parallel but irregularly orientated sets of small-scale normal faults which resemble the three-dimensional web structures (Cowan 1982), ascribed by Byrne (1984) to shear-zone cataclasis. No cataclastic comminution of grains associated with D_1 has been recognized in the Chañaral mélange. This could, however, be the result of masking of cataclastic structures by subsequent deformation and metamorphism. Mineral-filled extensional fractures similar to those described by Byrne (1984) are very abundant, particularly in sandstone blocks (Figs 5 & 8), but their orientations were not recorded and hence their dynamic significance is not known.

Despite the appearance of chaotic fragmentation and mixing (Fig. 2), and an apparently irregular distribution of rock types at a scale of metres to tens of metres, mapping of the mélange between Bahía Las Animas and Quebrada Animas Viejas (Figs 3 & 4) has shown that the mélange retains elements of its original stratigraphy on a scale of hundreds of metres. Bands of arenaceous, pelitic and volcanic-rich strata form persistent horizons or trains of blocks in individual outcrops and over distances of up to 10 km along strike. A distinctive example of this is the train of six large blocks of brecciated marble (up to 150 m in diameter) which extend over a distance of 5 km from N to S, SE of Punta Obispo. The blocks have sharp tectonic contacts with the country rocks and consequently their depositional relationship with the turbidites is not known. They are rounded to slightly elongated and are distributed parallel to the regional strike. A similar preservation of 'ghost' stratigraphy has been recorded in other mélanges (Barnes 1984).

A distinctive type of mélange found at Caleta el Pedregal and Punta Obispo (Fig. 1) comprises a breccia of sandstone and mudstone fragments, in places with no interstitial matrix but elsewhere with a sandy or silty matrix (Fig. 9). This rock type is referred to here as breccia mélange (Fig. 3). The fragments are irregularly shaped and angular to poorly rounded. They range in diameter from 1 to 500 mm with an average of about 10 mm. In places the breccia forms a matrix between sandstone blocks and masses of mélange, pillow lava and irregularly-folded turbidite; elsewhere it forms irregular bands between 10 and 100 m wide which cross-cut, and therefore post-date, the mud-matrix mélange at Caleta el Pedregal (CP 267). A gradation from partial to complete brecciation indicates that in places the fragmentation occurred *in situ* or with relatively little movement of the clasts. A small proportion (less than 1%) of well-rounded pebbles and cobbles within the breccia were produced by the disaggregation of pebbly sandstone and conglomerate. In most localities the mud-matrix and breccia mélanges cannot be distinguished clearly and they are therefore grouped together as D_1.

In thin section the fragments in both the mud-matrix and the breccia mélanges have irregular and diffuse boundaries (Fig. 6). No evidence of strain associated with the origin of the mélange (Byrne 1984) has been observed in individual grains. Similarly, on a larger scale, there is no definite

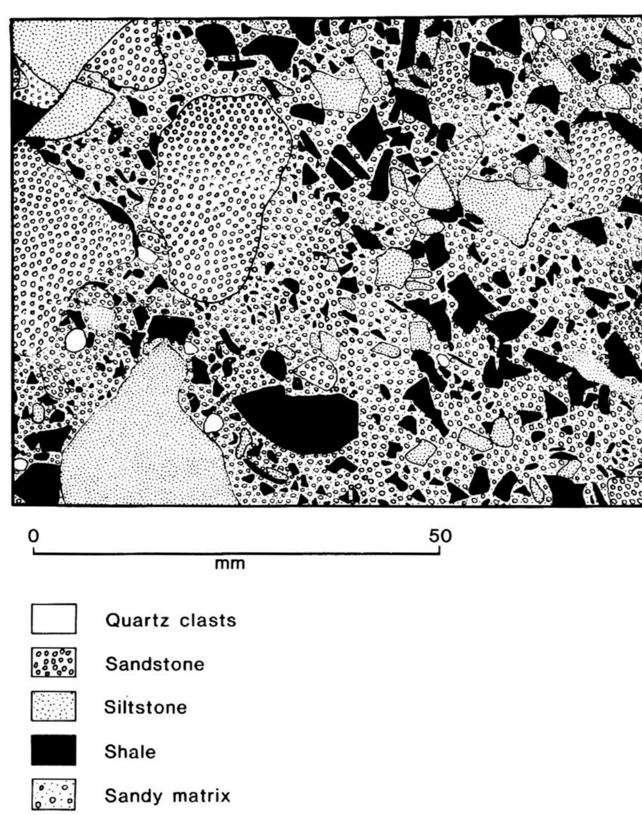

Fig. 9. Diagram showing fragments of sandstone, siltstone and shale in a sandy matrix forming the breccia mélange at Caleta El Pedregal.

Fig. 10. Irregular D_1 folding of boudinaged sandstone beds S of Punta Obispo.

evidence of slickensides, mylonites or mineral-filled veins produced during the development of the mélange (D_1).

One of the most striking features of the mélange is the paucity (and in most places absence) of folds. A few poorly-defined irregular F_1 folds, with a wavelength of up to 1 m, deform the previously boudinaged bedding. Abundant rootless, tight to isoclinal folds have been observed only in Quebrada Vegas Quemadas (CP 243) (Fig. 10). The orientation of fold axes and axial planes is irregular and difficult to measure and no preferred orientations have been recorded. Although these folds deform S_1, they are cut by the D_2 tectonic fabric, and they are therefore believed to be part of the complex D_1 deformation.

D_2 structures

At most localities the primary fabric (D_1) of elongated and flattened blocks produced during the formation of the mud-matrix mélange has been overprinted by a strong tectonic fabric or fabrics. The pelitic matrix commonly exhibits evidence for at least two phases of deformation (D_2 and D_3), whereas many of the more competent sandstone and volcanic blocks have been little deformed. These two later episodes of deformation were first identified (and described as the first and second phases) in the Las Tórtolas Formation N of Chañaral (Bell 1984).

Fig. 11. S_2 cleavage fabric oblique to sheets of blocks (S_1) at Punta Animas.

D_2 in the Las Tórtolas Formation is characterized by tight chevron folds with a wavelength of tens to hundreds of metres. The F_2 folds are associated with a strong axial-planar slaty cleavage (S_2) which is normally sub-parallel to the bedding and dips towards the NE (Bell 1984). No definite F_2 folds have been recorded in the mélange, probably due to the destruction of most planar surfaces during D_1, but S_2 is represented by a slaty cleavage or schistosity in the pelitic matrix. At some localities S_2 is associated with a significant flattening or elongation of the arenaceous blocks. The S_2 fabric varies from sub-parallel to oblique to the sheets of blocks (S_1) in the mélange (Fig. 11). This relationship can be seen on stereographic plots of the two fabrics (Fig. 12, Area A) where S_1 and S_2 are near parallel but S_2 has a slightly more northerly strike.

D_3 structures

D_3 structures are locally well developed but elsewhere virtually absent in the Las Tórtolas Formation (Bell 1984). The folds vary in wavelength from millimetres up to 20 m and are characterized by an open and commonly asymmetrical style. The folding is accompanied by a crenulation cleavage (S_3) which usually forms an irregularly cross-cutting conjugate pattern. S_3 cleavage is generally more steeply dipping than S_2 but both sets dip persistently towards the N and NE (Bell 1984).

S_3 is represented in the pelitic matrix of the mélange by a crenulation cleavage (or conjugate set of crenulation cleavages) deforming the S_2 slaty cleavage. It forms a spaced fracture or solution cleavage in some sandstone blocks but elsewhere is strongly deflected around the more competent blocks. In most localities S_3 is more strongly developed than S_2. The intersection of near-perpendicular S_2 and S_3 has produced a strong linear fabric at a few localities but in most places the two planar fabrics are near parallel, with their intersection producing only a weak linear fabric. South of Chañaral S_2 has a lower angle of dip towards the N than S_3. Poles to S_2 form a girdle about horizontal NW–SE-trending F_3 fold axes (Fig. 12, Area A).

Two thin andesitic dykes which cut both the S_1 and S_2 structures 0.5 km E of Punta Animas (CP 220) are themselves folded by F_3. The folds have a zig-zag style associated with a conjugate set of fracture or solution cleavage planes (S_3). Shortening is estimated at 50%. These folded dykes indicate that, despite their near parallelism (Fig. 12), the S_2 and S_3 fabrics were produced by distinct tectonic events separated by a phase of magmatic activity.

Origin of D_2 and D_3 structures

Slaty and crenulation cleavages, schistosity and flattening of blocks in the mélange were produced tectonically as the result of two episodes of deformation associated with low-grade regional metamorphism. The orientation and asymmetry of these structures suggest that they were the product of underthrusting towards the NE within an accretionary wedge (Bell 1984).

Origin of the Chañaral mélange

The chaotic mixing and subsequent deformation and metamorphism of the rocks of the Chañaral mélange has

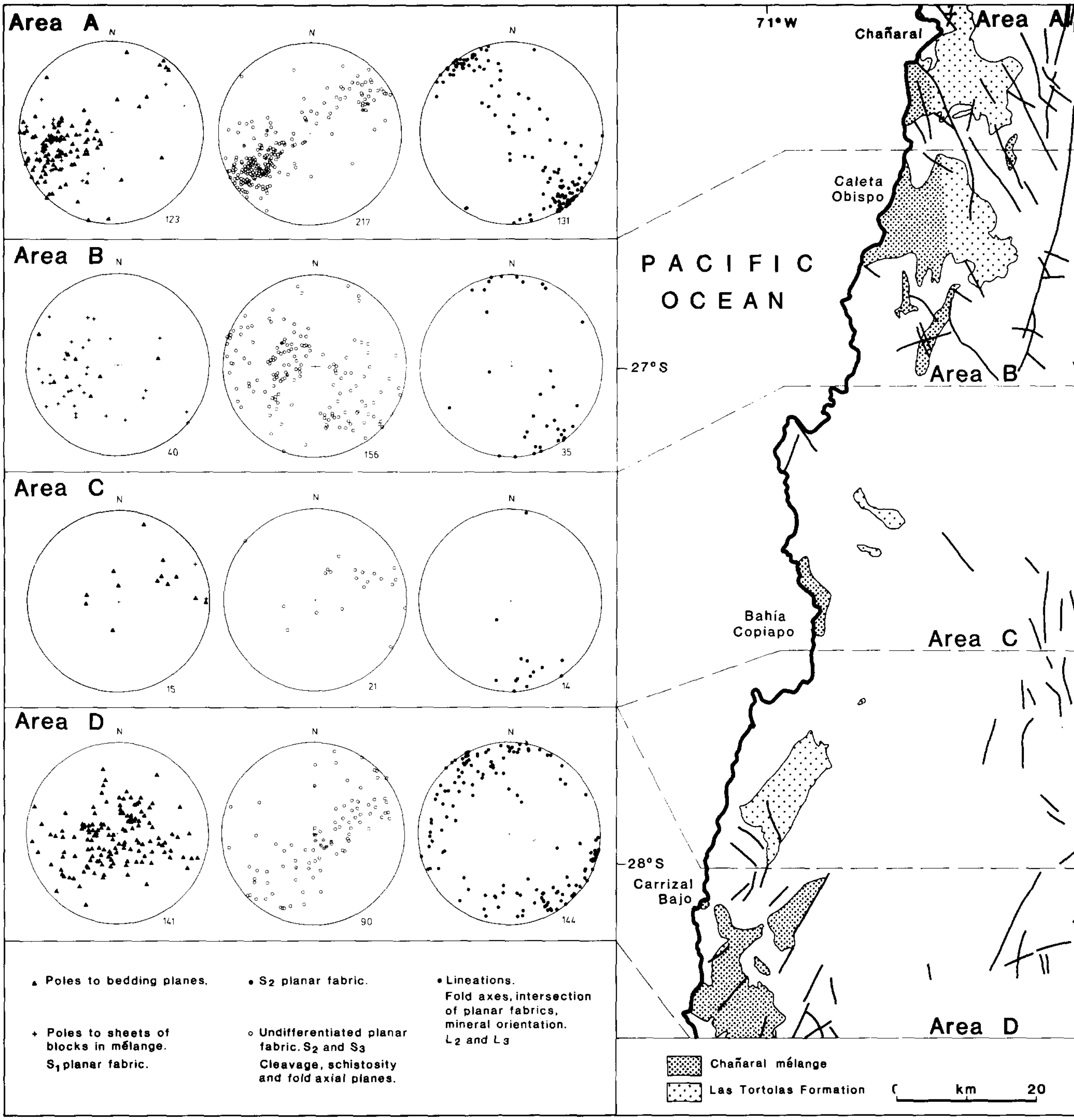

Fig. 12. Equal area lower hemisphere stereographic projections showing the orientation of bedding and tectonic fabrics in the mélange. Note the parallelism of bedding and sheets of blocks (S_1) in Area A.

prevented a detailed interpretation of their depositional environment. The majority of the sedimentary rocks were derived from a continental magmatic arc and were deposited in a deep-sea turbidite environment. The interstratified mafic volcanic rocks originated by within-plate eruptions close to the continental source of the siliciclastic sediments. These deep-sea sediments and lavas were probably accreted by the underthrusting of an oceanic plate towards the NE, beneath the Gondwanaland continental margin (Bell 1982, 1984 and in press). Isolated blocks of limestone and marble in the mélange, deposited in a high-energy, shallow-water marine environment possibly originated either on an oceanic island or on the outer high of the accretionary wedge (Seely *et al.* 1974).

Mélanges are large-scale masses of chaotically fragmented and mixed strata. Their origin has been ascribed to slumping (olistrostromes) (Page 1978; Cowan 1982); to tectonic deformation, particularly by imbricate thrusting within an accretionary wedge (Hsü 1968, 1973, 1974; Jones *et al.* 1978; Blake & Jones 1974); to diapirism (Pudsey & Reading 1982; Williams *et al.* 1984) or to combinations of these processes (Raymond 1984).

When seen in both hand specimen and thin section all D_1 deformation structures in the Chañaral mélange appear to have originated from movement between grains, rather than involving the strain of individual grains. Evidence for soft-sediment deformation is also provided by the often poorly defined and wispy nature of the contacts between blocks and matrix, by the highly irregular nature of the deformation and by the presence of disaggregated conglomerates. These rocks were therefore either unlithified or poorly lithified at the time of deformation. Evidence for a soft-sediment origin for other mélanges has been presented by many workers including Page (1978), Naylor (1981) and Cowan (1982). The distinction between soft-sediment and tectonic deformation is probably unrealistic in a developing accretionary wedge where sediments may become scraped-off and accreted in an unlithified or partly lithified state (Moore & Karig 1980).

Although the disaggregation of unconsolidated sediment is commonly ascribed to superficial debris flows and slumps (Woodcock 1976, 1979; Cowan 1982) the Chañaral mélange exhibits evidence for intrastratal movement rather than superficial slumping. It occurs between, but grading into, undeformed strata, in zones ranging from centimetres to kilometres in width. The contacts show none of the conformable depositional features of olistrostomes (Boles & Landis 1984) and some contacts are oblique to the stratification over large areas. Much of the soft-sediment deformation in the Chañaral mélange therefore resulted not from superficial slumping but from intrastratal movement between and within packages of unconsolidated or partly-consolidated sediment.

Origin of the mud-matrix mélange

Pinch-and-swell structures, boudins and cusp structures in the mud-matrix mélange are suggestive of ductile extension of the more competent sandstone layers, accompanied by plastic flow of the less-competent pelitic layers (Ramsay 1982). The boudins and small-scale normal faults are indicative of layer-parallel extension. A similar dominance of extensional structures has been recorded in many mélanges (Hsü 1973; Hibbard & Williams 1979; Cowan 1982) and although some mélanges exhibit abundant folds (Kay 1972; Moore & Wheeler 1978), many, like the Chañaral mélange, are characterized by a paucity of folds and other evidence for layer-parallel shortening (Moore & Karig 1980; Hsü 1974; Cowan 1974, 1982).

The boudins in the Chañaral mélange typically have the form of flattened oblate rather than prolate ellipsoids. The simplest explanation for this is that the deformation resulted from symmetrical layer-parallel extension (Cowan 1982). However, the location of sheets of boudins between apparently unstrained beds with a similar lithology suggests that little symmetrical extension can have taken place. An alternative mechanism, provided by the strain partition model of Platt & Vissers (1980) and Platt (1984), indicates that extension can result from simple as well as pure shear. Brodzikowski & van Loon (1985) have also explained the origin of interlayered fragmented and non-fragmented strata by sliding between layers.

The structures and lithology of the mud-matrix mélange resemble those described as Type I by Cowan (1985), with incipient to thorough fragmentation of interbedded sandstone and mudstone. This fragmentation was ascribed by Cowan (1982) to gravitationally driven slumping of incompletely consolidated sediment on the inner trench slope of an accretionary wedge. The most commonly accepted alternative to this model is the imbricate underthrusting, offscraping and underplating of sediment within the accretionary wedge (Seely *et al.* 1974; Moore & Karig 1980; Moore *et al.* 1982; Cowan 1985). This second model is preferred as an explanation for the origin of the Chañaral mélange because of the predominance of trench floor and abyssal plain rather than trench slope sediments (Underwood 1984), and the huge scale of the disrupted strata.

Origin of the breccia mélange

The breccia mélange cross-cuts, and therefore post-dates, the more abundant mud-matrix mélange. The breccia apparently originated by the breakdown of the pre-existing mud-matrix mélange into angular fragments. Most of the sediments were coherent yet incompletely lithified, and some coarser-grained rocks such as pebbly sandstones and conglomerates became disaggregated into individual detrital clasts. Becker & Cloos (1985) have interpreted similar breccias in the Franciscan mélange as the accumulation of talus along the front of an intrabasinal scarp. However, the breccia in the Chañaral mélange originated by *in situ* fragmentation of the strata and an alternative explanation is therefore required. The brecciation with no associated mineralization or cataclasis suggests an origin by fluid fracturing of the sediment. The movement of fluids produced by abnormal pore pressures has been proposed as a mechanism for the dilation and brecciation of unconsolidated sediment by Ritger (1985), Brodzikowski & van Loon (1985) and van Loon *et al.* (1985). Partial liquefaction of the sediment into a slurry of angular fragments (Tobisch 1984) may have been the result of high pore pressures produced by compaction of the unconsolidated sediment.

The breccia mélanges may therefore be fluid-escape structures resulting from high pore pressures produced during underthrusting in the accretionary wedge. Hydraulic fracturing to relieve high pore pressures results in brecciation and up to 30% dilation (Pickering 1983; Plint 1983). High pore-water pressures have been used to explain vein structures and other evidence of brittle failure of unconsolidated sediments in accretionary wedges (Ritger 1985; Cowan 1983; Carson *et al.* 1982). Abundant evidence for high pore pressures and for the venting of pore water has been recorded in modern accretionary wedges (Westbrook & Smith 1983; Moore *et al.* 1982; Suess & Massoth 1984; Kulm *et al.* 1984).

Mud diapirism has been proposed as a mechanism for the origin of mélanges (Higgins & Saunders 1967; Westbrook & Smith 1983; Larue & Speed 1984; Wang & Shi 1984; Williams *et al.* 1984; Cowan 1985; Becker & Cloos 1985). However, the breccias in the Chañaral mélange do not have a muddy matrix and are not associated with bodies of mobilized mud. They differ lithologically from the mud-matrix lithology mélange of Cowan's Type III, which has been interpreted as associated with mud diapirism.

If the breccias originated as fluid-escape structures they may have moved upwards as diapiric piercement structures (Plint 1983; Fowler *et al.* 1985) or obliquely upwards along the landward-dipping seismic reflectors characteristic of accretionary wedges (Shipley 1984; Underwood 1984). High pore pressures have been used to explain the long décollements and other evidence for imbricate thrusting in accretionary wedges (Westbrook & Smith 1983; Moore *et al.* 1982; Underwood 1984). Cloos (1984) suggested that some of the landward-dipping seismic reflectors may be the porous, laterally extensive fractureways (metres to tens of metres in width) filled with dewatering fluids derived from deeper underthrust water-rich sediments. The form and dimensions of these proposed conduits bear a close resemblance to those deduced for the breccias in the Chañaral mélange.

If the breccias resulted from fluid escape then a massive volume of fluid must have been involved to produce zones up to 100 m wide. Such large volumes of fluid may be present in an accretionary wedge, Shipley (1984) has estimated a 40% porosity reduction beneath 375 m of oceanic sediment at the base of the trench slope, probably resulting from fast sediment loading produced by underthrusting of sediment (Wang & Shi 1984).

Conclusions

The Carboniferous Chañaral mélange was formed in an accretionary wedge resulting from the subduction of an oceanic plate towards the NE beneath the Gondwanaland continental margin. The deformation which formed the mélange was the product of two distinct processes involving unlithified sediments. The first process of stratal breakup was probably accomplished by intrastratal movement resulting from imbricate thrusting. This was followed by brecciation apparently produced by hydraulic fracturing resulting from the escape of water under high pore pressures. Superimposed on the mélange are two phases of tectonic deformation apparently also produced within the accretionary wedge.

The assistance of members of the Servicio Nacional de Geología y Minería, and in particular M. Suarez, is gratefully acknowledged. A. D. Saunders and G. F. Marriner kindly provided facilities for geochemical analysis and H. R. Rollinson interpreted the results. B. C. Storey, J. L. Smellie and J. R. Harpum gave advice on an early version of the manuscript. Fossils were identified by M. R. A. Thomson, R. Riding and P. D. Taylor. Financial assistance was provided by research grants from the Natural Environment Research Council and the Royal Society. Field assistance and transport were kindly provided by the Servicio Nacional de Geología y Minería.

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Received 20 December 1985; revised typescript accepted 19 September 1986.