# 2 Metamorphic and plutonic basement complexes

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The present-day Andes have formed in response to subduction-related processes operating continuously along the western margin of South America since the Jurassic period. When these processes started, the continental margin was mainly formed of metamorphic complexes and associated magmatic rocks which evolved during Proterozoic (?), Palaeozoic and Triassic times, and which now constitute the basement to the Mesozoic and Cenozoic Andean sequences. These older units are commonly referred to in the Chilean geological literature as the 'basement' or the 'crystalline basement'.

The basement rocks crop out discontinuously (Fig. 2.1) in northern Chile, both in the coastal areas and in the main cordillera. In contrast, from latitude 34°S southwards, they form an almost continuous belt within the Coastal Cordillera extending to the Strait of Magellan. In addition, sparse outcrops occur both in the main Andean cordillera as well as further east in the Aysen and Magallanes regions. In the first maps and syntheses of the geology of Chile (e.g. Ruiz 1965) these rocks were generally considered to be of Precambrian age, forming a western continuation of the Brasilian craton. Later work has demonstrated that rocks first described as metamorphic basement units show a wide range of metamorphic grades and ages extending from possible Late Proterozoic through Palaeozoic and even, in some cases, to Jurassic–Cretaceous.

With regard to previous works that have attempted to synthesize data on Chilean basement geology, the reader is referred to those by González-Bonorino (1970, 1971), González-Bonorino & Aguirre (1970), Aguirre *et al*. (1972), Muñoz Cristi (1973), Hervé *et al.* (1981*a*), Hervé (1988), Breitkreuz *et al.* (1988), Damm *et al.* (1990), Bahlburg & Hervé (1997), Hervé *et al.* (2000, 2003*a*) and Willner *et al.*(2005). These accounts reflect increasing progress in our understanding of the basement based on recent field studies, the application of radiometric dating techniques, and new ideas concerning the evolution of accretionary prisms and terrane geology.

A description of the different units that constitute the Chilean basement geology is presented below, including information about their age, metamorphic characteristics and geological settings, largely based on the above-mentioned publications as well as on more specific studies that will be cited appropriately. Particular emphasis will be on recent studies that have attempted to determine P–T–t paths of metamorphism through mineralogical observations and thermodynamic calculations which were developed in the last two decades, although studies of some of the units are still in an immature state.

As a general framework, the description of the units will be based on the terrane model as established by Bahlburg & Hervé (1997) for northern Chile and northwestern Argentina, depicted in Figure 2.1. The older metamorphic complexes of northern Chile will be treated first, the Late Palaeozoic accretionary complexes of the coastal areas of central Chile next, and finally the Late Palaeozoic to Mesozoic complexes of the Patagonian Andes.

## North Chile (Norte Grande): Arequipa–Antofalla and Mejillones terrane areas

In the main Andes and in the Coastal Cordillera of northern Chile, scattered outcrops of basement rocks occur sporadically under the Meso-Cenozoic cover (Fig. 2.1). The isolation of these units has hindered detailed interpretation of their geological significance and correlations between them. Interpretations can be assigned to two main types: (a) that they reflect terrane tectonics, related to the collision of Laurentia and Gondwana in Early Palaeozoic times; and (b) that these rocks represent *in situ* evolution of old cratonic units of the western margin of Gondwana.

Metamorphic rocks cropping out in northern Chile are grouped within the Belén, Sierra de Morena-Chojas, and Limon Verde complexes (all placed within the Arequipa–Antofalla Terrane: Fig. 2.1), and the Mejillones Metamorphic Complex, which may be a separate terrane. In addition to these metamorphic complexes, a volcanic and sedimentary sequence known as the Cordón de Lila Complex (CLC) crops out on the west side of the Andes in northern Chile.

Bahlburg & Hervé (1997) and Bahlburg *et al.* (2000) have observed that during the Palaeozoic era in northern Chile and northwestern Argentina, a magmatic and metamorphic lull of *c*. 100 million years, from the Lower Silurian to the early Late Carboniferous, allows separation of the rock units into two orogenic groups: (a) Cambrian to Early Silurian rocks deformed during Lower Palaeozoic orogenic cycles in an active margin setting; (b) rocks formed after Lower Palaeozoic orogenies but affected by the Late Carboniferous to Permian Toco event, in which active margin conditions resumed after a lull during which the area evolved as a passive margin (Silurian–Early Carboniferous).

The more detailed account that follows presents lithological and geochronological data from both published and unpublished work, organizing the data within the framework of the models provided by Bahlburg & Hervé (1997) and Bahlburg *et al.* (2000). The detailed data available from Argentina, Bolivia and Peru are beyond the scope of this chapter (see Bahlburg & Hervé 1997; Loewy *et al*. 2004). The descriptions given below are organized to deal initially with the general geology, then metamorphic grade, and finally geochronology. The geotectonic setting is discussed under a separate heading at the end of this chapter.

### *Belén Metamorphic Complex*

The Belén Metamorphic Complex (BMC) (Basei *et al.* 1996) forms a narrow outcrop of metamorphic and igneous rocks along a high-angle west-vergent thrust system located on the western slope of the Chilean Altiplano plateau between Chapiquiña and Tignamar (Muñoz & Charrier 1996). Along

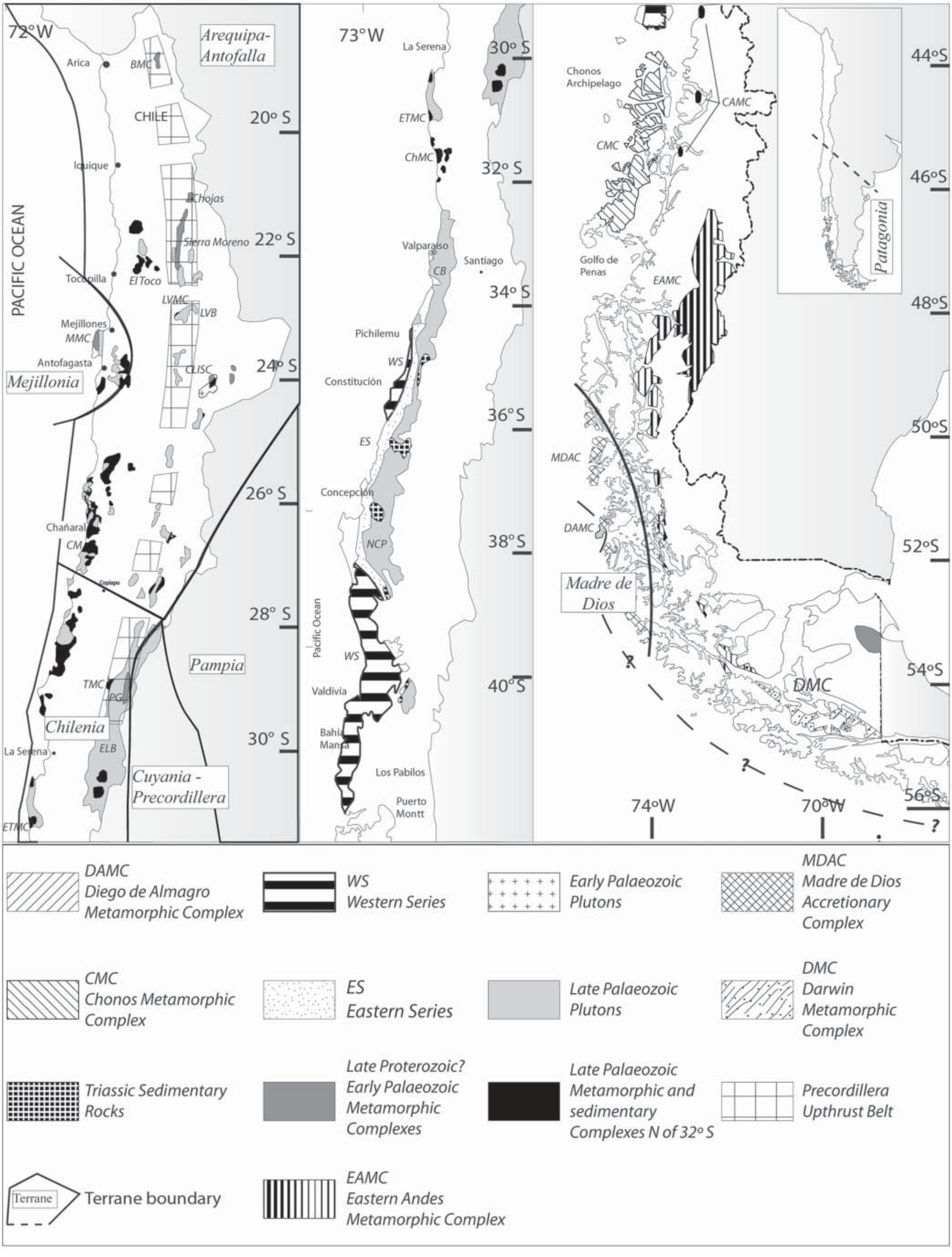


**Fig. 2.1.** Geological map showing the distribution of outcrops of the metamorphic complexes, the Palaeozoic and some Triassic sedimentary units, and associated plutonic belts in Chile.

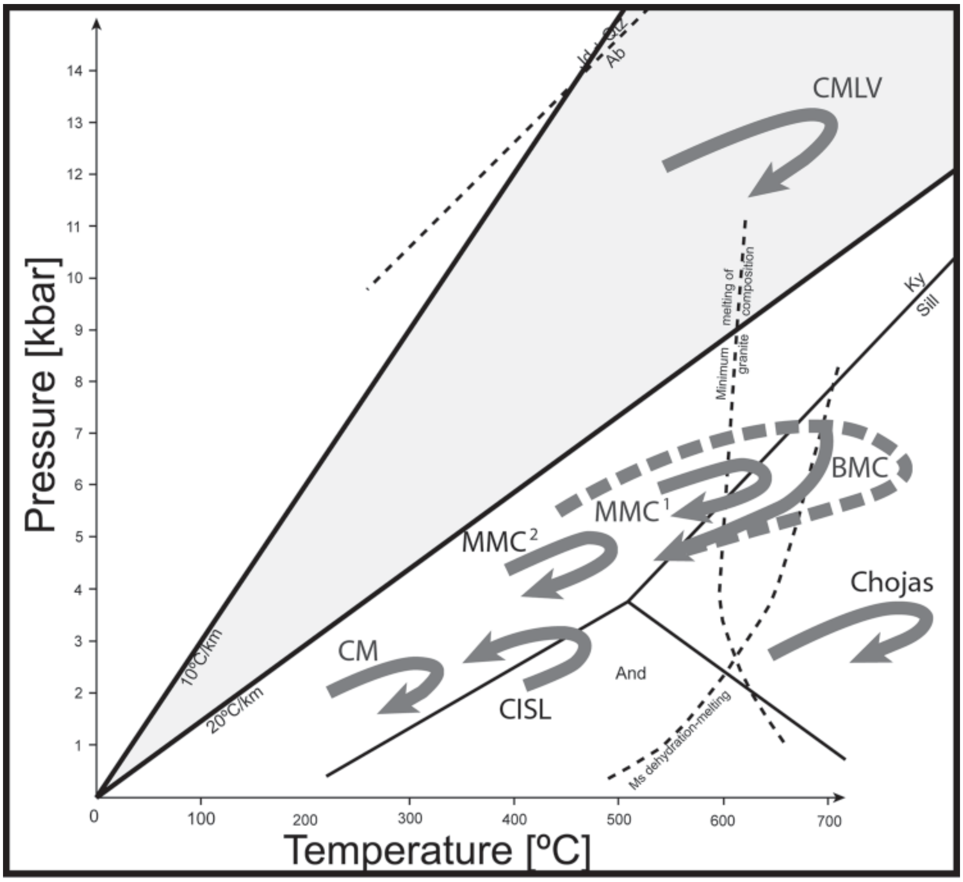


**Fig. 2.2.** A compilation of P–T–t trajectories for the different units of the 'metamorphic basement' complexes of northern Chile. Sources of data: Limón Verde Metamorphic Complex (CMLV), Lucassen *et al.* (1999); Belén Metamorphic Complex (BMC), Damm *et al.* 1990; Mejillones Metamorphic Complex (MMC1), Damm *et al* (1990); (MMC2), Baeza (1984); Lila Igneous and Sedimentary Complex (CISL), Damm *et al.* (1990); Chojas, Damm *et al.* (1990); Chañaral Mélange (CM), Marioth & Bahlburg (2003).

these faults the BMC is thrust westward over late Cenozoic deposits. Uncomformably covering the BMC are Jurassic marine deposits, and Cenozoic volcaniclastic and continental sedimentary rocks (Pacci *et al.* 1980; Muñoz *et al.* 1988*a*; García 1996). The BMC mainly comprises foliated amphibolites and subordinate quartz micaschists, orthogneisses and serpentinites. It is intruded by a small gabbro stock and by mafic, aplitic and felsic dykes.

Peak metamorphic conditions for the Belén Metamorphic Complex have been determined by Wörner *et al.* (2000*a*) at *c.* 700°C and 7 kbar. The prograde metamorphic path is reflected in zoning patterns of garnets which indicate a simple, single-stage metamorphic event. Retrograde stages are marked by lower grade overprinting in amphibolite and greenschist facies. The resulting P–T–t curve is shown in Figure 2.2.

The first geochronological determination of the age of the BMC was by Pacci *et al.* (1980) who produced a Rb–Sr reference isochron of 1000 Ma which has since been later recalculated to 500 Ma (Damm *et al.* 1990). These authors determined a $1460 \pm 448$ Ma Nd–Sm whole-rock isochron for metabasites which was considered as the crystallization age of the protoliths. Basei *et al.* (1996) obtained U–Pb zircon upper intercept ages (conventional method) of $509 \pm 46$ Ma for the Quebrada Achacagua orthogneiss and $486 \pm 32$ Ma on granitic veins at Quebrada Saxamar which they interpreted as crystallization ages of the igneous precursors. These authors also reported model Sm–Nd model ages of 1746 Ma and 1543 Ma on the Quebrada Saxamar schists testifying an ancient crustal residency for the protoliths. Wörner *et al.* (2000*a*) considered that higher intercept ages of $1877 \pm 139$ Ma and $1745 \pm 27$ Ma obtained on zircons (U–Pb, conventional method) from Belén reflect crystallization ages and that lower intercepts of $366 \pm 3$ Ma and $456 \pm 4$ Ma suggest severe Palaeozoic lead loss. Loewy *et al.* (2004) presented a U–Pb zircon age of $473 \pm 2$ Ma for the Saitoco granodiorite, and revealed the presence of 1.8 to 1.9 Ga old zircons on a cross-cutting dyke in the micaschists.

In addition, Basei *et al.* (1996) have presented a $344 \pm 22$ Ma Rb–Sr whole-rock isochron, with a $^{87}Sr/^{86}Sr$ initial ratio of 0.708 for the quartz micaschists of Quebrada Saxamar. K–Ar dating on different minerals yielded ages of 536 Ma to 516 Ma (hb) in the Quebrada Saxamar schists, of 417Ma (Ms) to 365 Ma (bt) on the Saitoco orthogneiss (Basei *et al.* 1996), and $358 \pm 10$ Ma to $457 \pm 7$ Ma (hb) (Lucassen *et al.* 2000) at Belén.

All these data point towards the involvement of the BMC in Early Palaeozoic orogenies, time-equivalents to the Early Cambrian Pampian and Ordovician Ocloyic/Famatinian orogenies, both of which are more extensively represented in northwestern Argentina. The age of the protoliths seems to be Early Palaeozoic, as no undisputed evidence of Proterozoic ages has been produced (Damm *et al*. 1990; Wörner *et al.* 2000*a*; Loewy *et al.* 2004).

### *Sierra de Moreno – Chojas metamorphic complexes*

Basement exposures of quartz micaschists, greenschists, migmatites, granites and mylonites in the Sierra de Moreno crop out as a $70 \times 20$ km belt orientated NNE–SSW (Skarmeta 1983). The western side of the outcrop comprises a 3-km-wide mylonite zone produced during the thrusting of the metamorphic complex over Jurassic rocks (Quinchamale Formation) after four superimposed deformation phases that affected these basement rocks. An additional smaller outcrop of basement micaschists, gneisses, amphibolites, migmatites and alkali syenogranites occurs in the higher reaches of Quebrada Chojas, north of Sierra de Moreno (Damm *et al.* 1990).

The high grade metamorphism indicated by Damm *et al.* (1990) at Quebrada Chojas, where schists have undergone migmatization, has been deduced to have achieved a peak of 850°C at a relatively low pressure (*c.* 4 kbar). Part of the metamorphic pathway recorded by these rocks is illustrated in Figure 2.2.

A Proterozoic age for the Chojas complex has been suggested by Damm *et al.* (1990) on the basis of upper intercepts in U–Pb zircon diagrams, which indicate 1254 + 97/–94 Ma and 1213 + 28/–25 Ma for a migmatite and an orthogneiss respectively, which have lower intercepts at 466+8/–7 and 415+36/–38 Ma, interpreted as reset ages due to the high grade metamorphism.

Loewy *et al.* (2004) have presented conventional U–Pb data on zircons from migmatite and foliated megacrystic granite which have yielded upper intercept ages of $1067 \pm 4$ Ma and $1024 \pm 5$ Ma, which they interpret as the age of crystallization of the protoliths. The lower intercepts of the former, and the concordant ages of a granitic neosome in the migmatites, yielded ages in the range of $497 \pm 16$ Ma and $470 \pm 2$ Ma. In contrast, isotopic ages at Sierra de Moreno, obtained in a much earlier study by Skarmeta (1983), give only Palaeozoic ages: $511 \pm 9$ Ma and $485 \pm 12$ Ma Rb–Sr whole-rock isochrons in migmatites and schists, respectively. These values are closer to the K–Ar ages in the range $452 \pm 11$ Ma (hb) to $372 \pm 3$ Ma (ms) for minerals in the migmatites and schists. The granites yielded K–Ar mineral ages in the range 295–225 Ma. The age pattern was further corroborated by Lucassen *et al.* (2000) with a Nd–Sm isochron of $505 \pm 6$ Ma and K–Ar ages (hb) ranging from $382 \pm 11$ to $478 \pm 15$ Ma as well as K–Ar ages (bt) in the range of $284 \pm 6$ to $311 \pm 7$ Ma.

### *The Mejillones Metamorphic Complex: an independent terrane?*

The Mejillones Metamorphic Complex (MMC) is an isolated $60 \times 10$ km outcrop of basement rocks exposed along the Mejillones Peninsula (Fig. 2.1). There is also a smaller outcrop of similar lithologies at Caleta Coloso, a few kilometres to the south. Baeza (1984) has described the metamorphic rocks as consisting of orthogneiss, paragneiss, amphibolites and micaschists, intruded by mafic to silicic plutonic rocks and dykes. The MMC consists of two metamorphic areas, one with a regional metamorphic imprint and the other with a contact metamorphic aureole developed in the lower-grade parts of the former.

Baeza & Pichowiak (1988) divided the MMC into two 'formations' (although given the lack of lithostratigraphic control, the term 'complex' is more appropriate): the Punta Angamos Formation (PAF) and the Jorgino Formation (JF). The latter exhibits a metamorphic zoning including biotite, garnet and kyanite zones, which they estimate to have reached metamorphic peak P–T conditions of 4–6 kbar and 400–600°C. The PAF developed as a contact aureole with biotite, andalusite-sillimanite, and K-feldspar–sillimanite zones, on previously metamorphosed chlorite zone rocks (Fig. 2.2)

The oldest radiometric ages obtained directly from the MMC are Rb–Sr wr data of *c.* 530 Ma (Diaz *et al.* 1985), a $521 \pm 55$ Ma Nd–Sm wr isochron (Damm *et al.* 1986) and a $525 \pm 10$ Ma Nd–Sm mineral isochron (Lucassen *et al.* 2000). The igneous complex that generated the contact aureole has been dated by U–Pb zircon upper intercept as $561 \pm 12$ Ma (Damm *et al.* 1986) which contrasts with mainly Mesozoic ages of 200 Ma (Rb–Sr wr isochron age; Díaz *et al.* 1985), 152 to 143 Ma (K–Ar ages in ms and bt) and $144 \pm 1$ Ma (U–Pb, zircon) of Basei *et al.* (1996). The influence of this Jurassic intrusive event on the metamorphic rocks is reflected by K–Ar ages of 147–162 Ma (bt) and 159 Ma (hb) from Basei *et al.* (1996), and of $151 \pm 3$ to $189 \pm 4$ Ma (bt) and $152 \pm 5$ Ma (hb) from Lucassen *et al.* (2000).

### *Cordón de Lila Complex*

In Ordovician times, the volcanic products of a magmatic arc were deposited in a marine basin located above the Arequipa–Antofalla terrane, in the present western flank of the Andes. The resulting sequences are basaltic, andesitic and dacitic to rhyodacitic lavas interbedded with hemipelagic to shallow marine sedimentary rocks, which together constitute the Cordón de Lila Complex (CLC) (Niemeyer 1989; Damm *et al.* 1990) and a thick silicic volcaniclastic apron, known as the Aguada de la Perdiz Formation (Breitkreuz *et al.* 1988). Palaeozoic, subduction-related plutons intrude the CLC, and are at least partly coeval with the volcanism.

The rocks of this succession record only very low levels of metamorphism. Damm *et al.* (1990) described the presence of mineral assemblages of the pumpellyite–actinolite–chlorite zone at the base of the succession, with the metamorphic grade decreasing to higher stratigraphic levels. This burial-type metamorphism reached peak metamorphic conditions of 3 kbar and 370°C (Fig. 2.2).

A whole-rock Nd–Sm isochron from 11 basalts and andesites of the CLC yields an age of $448 \pm 145$ Ma (Damm *et al.* 1986), which is consistent with the palaeontologically derived Llanvirnian age for the CLC (Cecioni 1982). With regard to the Palaeozoic intrusives, Mpodozis *et al.* (1983) reported Rb–Sr whole-rock isochrons of $441 \pm 8$ Ma (Tucúcaro pluton), $452 \pm 4$ Ma (Tilopozo pluton) and a $288 \pm 15$ Ma errorchron for the Pingo Pingo pluton, which, however, yielded K–Ar ages of $425 \pm 11$ (bt) and $429 \pm 12$ Ma (hb). Damm *et al.* (1990) presented U–Pb zircon ages of $502 \pm 7$ Ma (conventional, discordant) for the Choschas pluton, and lower intercept ages of $434 \pm 2$ Ma for the Cerro Lila pluton, and of 338 + 14/–18 Ma for the Pingo Pingo pluton. All ages were interpreted as crystallization ages.

### *Late Palaeozoic sedimentation and volcanism*

*Devonian–Carboniferous passive margin sedimentation*

Thick successions of shale, sandstone and rare conglomerate and limestone crop out in the Coastal Cordillera. These sequences have been given different lithostratigraphic names in different areas: El Toco Fm (TF), Sierra del Tigre Fm, Las Tortolas Fm (LTF), and the Chañaral Melange (CM: Fig. 2.1). Coeval siliciclastic shallower marine platform successions were deposited further east, in the main Andean cordillera (Zorritas Fm). The turbiditic rocks have abundantly preserved sedimentary features, such as cross- and graded bedding, obscured locally by deformation and low grade metamorphism. They have been interpreted by Bahlburg & Breitkreuz (1991) as a turbidite system representing environments ranging from a proximal depositional lobe (TF) in the north, and a distal depositional lobe to basin plain (TF and LTF) environments to the south.

Progressive synsedimentary deformation and metamorphism of these marine units took place during the Carboniferous period (El Toco event of Bahlburg & Breitkreuz 1991). The culmination of this process produced the Chañaral Melange (Bell 1982), a dismembered portion of the turbiditic complex.

The fossil record in the turbidite complex is poor but indicates a Devonian to Early Carboniferous depositional age. Late Devonian plant remains occur in the El Toco Fm (Bobenrieth 1980; Boric 1980), Devonian brachiopods in the Sierra del Tigre Fm (Niemeyer *et al.* 1985, 1997*b*) and Lower Carboniferous conodonts (Bahlburg 1987) and brachiopods (Bell 1987*b*) in the Las Tortolas Fm have all contributed to the palaeontological database. The only radiometric age determination available is a 280 Ma Rb–Sr whole-rock isochron (Brook *et al.* 1986) for the Las Tortolas Fm and Chañaral Melange which is in concordance with the radiometric ages of the plutonic rocks that intruded the already folded turbidite succession. Finally, the metamorphic grade of the turbidite succession is invariably low to very low grade, and little is known of the P–T conditions except in the Chañaral melange, with Marioth & Bahlburg (2003) establishing 2.2–2.8 kbar and 300–350°C for the metamorphic peak (Fig. 2.2).

*Permian subaerial volcanism*

Thick subaerial volcaniclastic rocks, known as the Peine Group, crop out in the Precordillera and in the high Andes in a north–south elongated discontinuous belt (Breitkreuz *et al.* 1989). The successions consist of felsic volcaniclastic rocks and andesitic–basaltic volcanic rocks, interbedded with limnic and shallow marine sediments. They lie with angular unconformity on the Devonian–Carboniferous turbidites, and interfinger to the east and west with the Early Permian marine carbonates of the Cerros de Cuevitas (Breitkreuz 1986*b*) and Arizaro formations, in Chile and Argentina, respectively. These rocks are weakly folded and have been subjected to extensive sericitization and chloritization, particularly near plutonic intrusions.

*Late Palaeozoic to Triassic batholiths*

These intrusions occur in two belts, one in the high Andes and one in the Coastal Cordillera. Brown (1990) studied these plutonic belts at latitude 26°S and concluded that they were part of the same subduction-related magmatic arc, later affected by crustal extensional processes. The presence of subvolcanic domes and high level intrusive bodies led Davidson *et al.* (1985) to recognize the existence of former caldera systems in the Imilac area dated at 290 to 217 Ma, some of which have copper mineralization. Camus (2003) has presented a synthesis of the mineralized intrusive bodies north of 24°S in the Precordillera and High Andes, indicating that they range in age from 190 to 307 Ma (K-Ar).

The Coastal Cordillera plutons have given Rb–Sr wr isochron ages (Brook *et al.* 1986) in the range of $278 \pm 16$ Ma and $221 \pm 14$ Ma. In addition, U–Pb determinations on zircon have yielded $292 \pm 14$ Ma, $230 \pm 6$ Ma and $217 \pm 12$ Ma (Damm & Pichowiak 1981). Thus, these rocks span Early Permian to Late Triassic times, similar to those of the High Andes belt which ranges in age from $270 \pm 10$ Ma to $209 \pm 19$ Ma (Brook *et al.* 1986; wr Rb–Sr isochrons). A $268 + 5/{-3}$ Ma age (Damm *et al.* 1990; U–Pb zircon, lower intercept) was obtained for the Cordón Chinquilchorro pluton, located further north, in the Cordón de Lila area. In both belts, the age groupings suggest there is a natural break in the ages during Early Triassic times.

### *Limón Verde Metamorphic Complex*

A 12 km long and 2 km wide outcrop of metamorphic rocks is exposed on the western flank of the Sierra de Limón Verde (Baeza 1984), where it is intruded by a Late Palaeozoic batholith and unconformably overlain by Triassic sedimentary and volcanic rocks. The Limón Verde Metamorphic Complex (LVMC) comprises metabasites and metapelites with metamorphic grade varying from greenschist to amphibolite facies.

Lucassen *et al.* (1999), using conventional geothermobarometry and multi-equilibria calculations, established that the peak conditions of metamorphism attained by the LVMC were *c*. 14 kbar and 660 to 720°C, conditions unique in the Central Andes for metamorphic complexes of this age (Fig. 2.2). These data, combined with the age and stratigraphic data, point towards a very rapid exhumation of the LVMC during Late Permian–Early Triassic times. The tectonic environment for the attainment of these conditions is not well understood. Lucassen *et al.* (1999) suggested a transpressional strike-slip environment whereas a collisional or subduction zone setting was previously suggested by Hervé *et al.* (1985) and Bahlburg & Hervé (1997).

Radiometric dating has not supported previous suggestions that the unit might be of Precambrian age (Baeza 1984; Rogers 1985). Hervé *et al.* (1985), Cordani *et al.* (1988) and Lucassen *et al.* (1999) established that the metamorphism took place in Late Palaeozoic times. Calculations of residence times using Rb–Sr isotopic data suggest that the protoliths could not have been older than 405 Ma (Silurian). Three Nd–Sm mineral isochrons indicate a range between 287 and 255 Ma (Lucassen *et al.* 1999). These ages are younger than the $309 \pm 11$ Ma and $300 \pm 20$ Ma ages obtained using Rb–Sr whole-rock isochrons (Hervé *et al.* 1985; Cordani *et al.* 1988). All these authors interpreted the ages as indicative of the metamorphism. Decreasing K–Ar mineral ages in hornblende, muscovite and biotite in the range 310–229 Ma indicate cooling through Permian and Early Triassic times.

## North-central Chile (Norte Chico)

The basement rocks of Norte Chico comprise the Pampa Gneisses (PG), the Tránsito Metamorphic Complex (TMC) and the coastal El Teniente (ETMC) and Choapa (ChMC) metamorphic complexes. The Pampa Gneisses have been placed within the Chilenia Terrane (Ramos *et al.* 1986), which would have docked to South America in the Devonian, and the rest lie west of it. In addition, Mpodozis & Kay (1990, 1992) have suggested the existence of an Equis Terrane (not exposed), lying west of Chilenia, in order to explain a westerly jump in subduction-related magmatic foci from Permo-Triassic to Jurassic times (Fig. 2.1).

### *Pampa Gneiss*

Ribba (1985) first described the presence of banded orthogneisses in a small outcrop in the upper reaches of Rio Tránsito (Fig. 2.1). They are intruded by Late Palaeozoic–Permian plutons, and thrust to the west over the TMC to produce a shear zone referred to as the El Portillo mylonites.

The metamorphic grade of the Pampa Gneiss reaches migmatitic conditions, and the mineral paragenesis suggests a high T–low P metamorphic environment. Ribba (1985) and Ribba *et al.* (1988) presented a Rb–Sr whole-rock isochron of $415 \pm 14$ Ma on the PG, as well as a Rb–Sr mineral isochron of $246 \pm 18$ Ma. These ages were interpreted as indicative of a Silurian metamorphic event and a Permo-Triassic resetting by a thermal event, further supported by $236 \pm 6$ Ma (bt) and $239 \pm 10$ Ma (ms) K–Ar mineral ages. The Portillo mylonites were dated at $250 \pm 26$ Ma (Rb–Sr, wr), a further indication of the Permo-Triassic tectonothermal event.

### *The Tránsito Metamorphic Complex*

Along El Tránsito Valley, east of Vallenar, large exposures of quartz micaschists, metabasites, quartzites and marbles, which crop out below or are in tectonic contact with the Mesozoic cover, constitute the Tránsito Metamorphic Complex (TMC; Ribba 1985; Ribba *et al.* 1988). It is intruded by Late Carboniferous tonalites and is unconformably covered by sedimentary and volcanic rocks of Middle Triassic age (Reutter 1974).

The metamorphic facies of the TMC is transitional between greenschist and amphibolite facies. Hervé (1982) used amphibole mineral compositions to suggest that the TMC had been metamorphosed under an intermediate P–T regime, with a metamorphic peak at about 5 kbar and $500 \pm 50$°C (Fig. 2.3). Whole-rock Rb–Sr 'errorchrons' of $303 \pm 40$, $303 \pm 35$ and $335 \pm 20$ Ma suggest a Late Carboniferous metamorphic event, with this isotope system having been perturbated by later

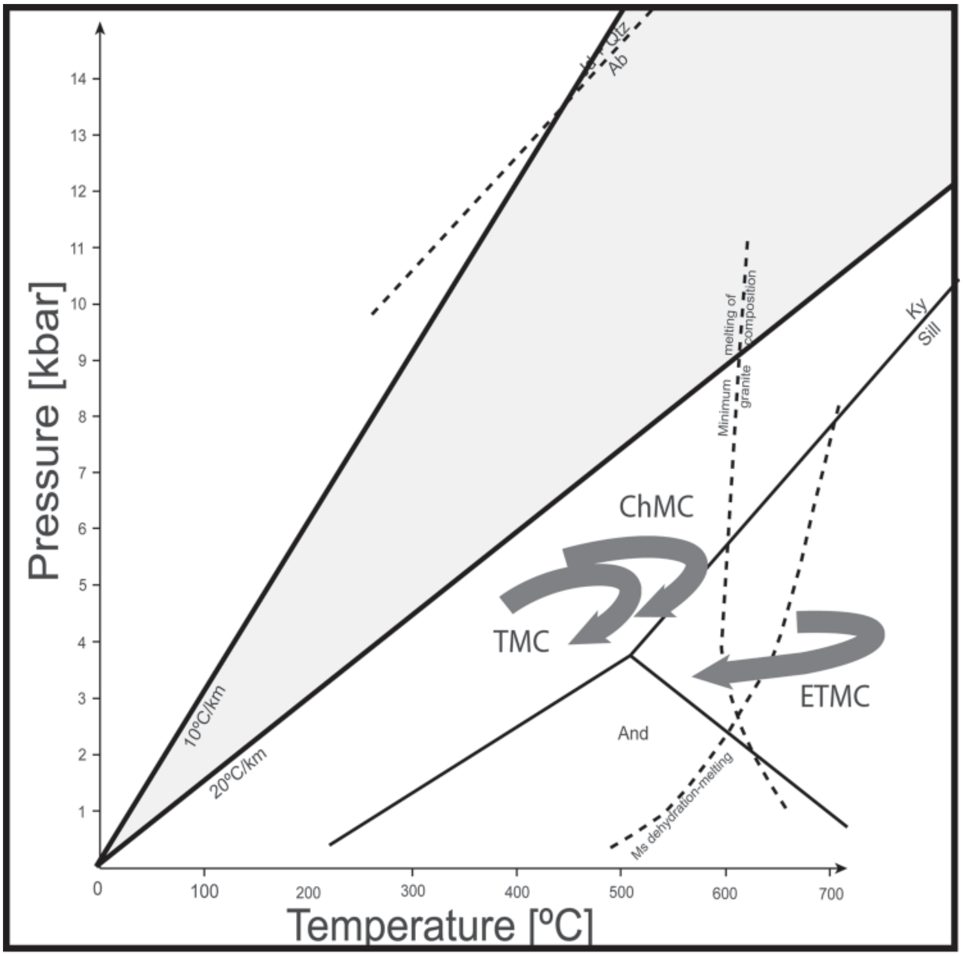


**Fig. 2.3.** A compilation of P–T–t trajectories for the different units of the 'metamorphic basement' complexes of the Norte Chico area. Sources of data: Tránsito Metamorphic Complex (TMC), Ribba *et al* (1988); El Teniente Metamorphic Complex (ETMC), Irwin *et al* (1988); Choapa Metamorphic Complex (ChMC), Godoy & Charrier (1991).

thermal episodes related to plutonic intrusions into the TMC. K–Ar mineral ages of $238 \pm 10$, $229 \pm 6$ and $231 \pm 6$ Ma on muscovite testify to Triassic isotopic resetting or cooling.

### *El Teniente Metamorphic Complex*

Discontinuous outcrops of metamorphic rocks occur in the Coastal Cordillera between Huasco (27°S) and Los Vilos (32°S). At around 31°S, Irwin *et al.* (1988) described the presence of a complex composed of ultrabasic and basaltic metabasites, metacherts, metasandstones and metaconglomerates which bear witness to a prolonged history of deformation and metamorphism in Late Palaeozoic through Early Mesozoic times. As used here, the El Teniente Metamorphic Complex (ETMC) encompasses the Cerro Negro and La Totora complexes of Thiele and Hervé (1984).

On the basis of the presence of staurolite, garnet, clinopyroxene, calcic plagioclase and albite, the $F_1$ episode of metamorphism is assigned to the upper greenschist–amphibolite facies transition. It is possible that an earlier higher grade metamorphism was partially overprinted by this event. Hervé (1982) used amphibole compositions to suggest that the metamorphic pressure was lower than in the ETMC and did not reach 5 kbar. Calculation of metamorphic temperature from plagioclase–hornblende pairs from Irwin *et al.* (1988) suggest it evolved from 700–800°C in the amphibole cores (pre-$F_1$?) to 500–550°C in the amphibole rims ($F_1$) (Fig. 2.3).

The metabasites have yielded a $311 \pm 89$ Ma Rb–Sr errorchron (Irwin *et al*. 1988) interpreted as representing the time of extrusion or an early metamorphic episode. The metabasites and metasediments were assembled before the 220–200 Ma metamorphic episode $F_1$, as suggested by a $201 \pm 61$ Ma Rb–Sr whole-rock isochron in the metaconglomerates and radiometric ages of the plutons emplaced into the metamorphic complex. Rb–Sr whole-rock isochrons of $220 \pm 20$ Ma (gabbro) and $200 \pm 10$ Ma (monzogranite) are comparable to six K–Ar ages (Hb) from the metabasites which range from $220 \pm 20$ Ma to $188 \pm 17$ Ma. Further deformational episodes $F_2$ (160–150 Ma) and $F_3$ (140–121 Ma) are recorded by the ETMC and in the associated intrusive bodies.

### *The Choapa Metamorphic Complex*

This complex comprises intensely deformed quartz micaschists, phyllites and amphibolitic schists (Rebolledo & Charrier 1994) affected by a polyphase deformation in which up to seven deformational events have been identified. They have been interpreted by Rebolledo & Charrier (1994) as the metamorphosed equivalent of the Late Devonian–Early Carboniferous Puerto Manso Formation.

The metamorphic conditions of the Choapa Metamorphic Complex (ChMC) were considered by Rebolledo & Charrier (1994) as belonging to the greenschist facies in a low to medium P–T environment, although peak conditions of metamorphism obtained from zoned actinolitic hornblende (Godoy & Charrier 1991) suggest a pressure not lower than 5 kbar in the greenschist–amphibolite facies transition (Fig. 2.3). Except for a K–Ar age of $359 \pm 36$ Ma (Am), the K–Ar ages obtained in the complex yield Jurassic ages and were probably reset by nearby Jurassic plutons.

### *Batholithic intrusions*

The Norte Chico region is characterized both by the presence of the huge composite Elqui–Limari Batholith (ELB), which extends from 28°30′ to 31°S′ in the High Andes, and by a Coastal Belt of intrusions. Following Mpodozis & Kay (1990, 1992) the ELB is viewed as comprising the subduction-related Late Carboniferous–Early Permian Elqui Superunit (ES) and the Permo-Triassic Ingaguas Superunit (IS), which resulted from crustal anatexis in a thickened continental crust generated during the San Rafael orogenic phase (Llambías & Sato 1990). Pankhurst *et al.* (1996) presented a zircon U–Pb age of $285.7 \pm 1.5$ Ma and a $256 \pm 10$ Ma Rb–Sr wr isochron for two of the main plutons of the ES and a map showing all the previous age determinations by different authors. Radiometric ages in the IS are generally in the range 200–230 Ma (Brook *et al.* 1986; Rex 1987; Parada *et al.* 1988) although some older K–Ar ages have been obtained as well. This allowed Parada *et al.* (1991) to define a Triassic–Jurassic plutonic event, the products of which are distributed in the High Andes Belt (HAB), the Ingaguas Superunit of the Elqui Limari Batholith, and in the Coastal Belt (CB). The Triassic to Lower Jurassic magmas would have formed on an extensional setting, which was replaced by subduction-related magmatism from the Middle Jurassic onwards.

## Late Palaeozoic accretionary complexes of the Coastal Cordillera of central Chile

Between latitudes 32°S and 42°S, continuous exposures of the basement occur in the Coastal Cordillera of central Chile (Fig. 2.1). This basement comprises a metamorphic complex which is exposed continuously south of 34°S, flanked to the east by the Coastal Batholith, which reaches the coast between 32°S and 34°S, and turns east south of 38°S to reappear in the Main Andean Range at 40°S and then into Argentina (Fig. 2.1).

González-Bonorino (1970, 1971) and González-Bonorino & Aguirre (1970) distinguished three metamorphic belts or ‘series’ – the Curepto, Nirivilo and Pichilemu series – which differ in metamorphic grade and direction of increasing metamorphism. Godoy (1970) and Aguirre *et al.* (1972) modified this subdivision into a Western and an Eastern series which is still widely used. The two series have been interpreted as representing a paired metamorphic belt, in the sense of Miyashiro (1961), with the Western Series being the higher P–T unit. Hervé (1977) suggested that the Western Series included accreted oceanic lithologies, and the whole was interpreted as a subduction complex by Hervé *et al.* (1976*b*, 1981*a*) and Forsythe (1982), and an accretionary wedge dominated by basal accretion by Glodny *et al.* (2005) and Willner *et al.* (2005). Hervé (1988) presented a synthesis of the knowledge of this subduction complex, which has increased greatly in recent years, particularly with regard to geochronology and P–T regimes of metamorphism.

### *The Western Series*

The Western Series (WS) comprises highly deformed metagreywackes with intercalations of metabasite (sometimes with relict pillow structures), meta-exhalites (spessartine–quartzite, stilpnomelane quartzite, massive sulphide, tourmalinite) and serpentinites; that is, it represents a mixture of continent-derived siliciclastics and slices of dismembered upper oceanic crust. A flat-lying east-dipping transposition foliation predominates. The WS shows a transitional contact with the Eastern Series at 35°30′S, and is in fault contact in other localities. These faults are associated with later destruction of the subduction complex. The fault contact at Pichilemu (35°S) was interpreted by Ernst (1975) as a ‘coastal suture zone’, but newly interpreted by Willner *et al.* (2005) to represent a Cretaceous brittle fault.

The occasional occurrence of glaucophanic amphibole along the belt and of lawsonite in Chiloe (Saliot 1968) suggested to Aguirre *et al.* (1972) that the Western Series constituted the high P–low T belt of the paired Late Palaeozoic metamorphic belts in central Chile, an interpretation confirmed by later studies. Munizaga *et al.* (1973) roughly limited the metamorphism of the basement of central Chile to the interval between 273 and 342 Ma (266–334 Ma with new decay constants) on the basis of Rb–Sr whole-rock systematics over a wide area. More specific data for exposures at different latitudes follow.

*34–36°S*

Willner (2005) determined the metamorphic peak at $350 \pm 50$°C and 7–11 kbar, followed by static recrystallization during a pressure release of 3–4 kbar and slight cooling. Hervé *et al.* (1974) presented a $329 \pm 22$ Ma K–Ar age on glaucophane from Pichilemu, thus establishing a Late Carboniferous age for the high P–T event in this area. Willner *et al.* (2005) dated the metamorphic peak (Ar–Ar plateau ages, phengite) in the interval $319 \pm 1$ to $292 \pm 1$ Ma, whereas Ar/Ar laser ablation ages in phengite in the range $322 \pm 2$ to $257 \pm 3$ Ma indicate mineral growth during retrograde pressure release. The further cooling/exhumation of the WS was monitored through fission track zircon ($206 \pm 11$ to $232 \pm 14$ Ma) and apatite ($80 \pm 4$ to $113 \pm 8$ Ma) ages. The end of accretion is marked by a late intrusion into the WS at Constitución at $224 \pm 1$ Ma (U–Pb, zircon). Average exhumation velocities were *c.* 0.2–0.6 mm/a indicating that erosion most probably was the prime exhumation factor.

*38–43°S*

In this section of the WS, which has also been called the Bahía Mansa Metamorphic Complex, Massonne *et al.* (1998*b*) recorded the second known occurrence worldwide of the high pressure mineral zussmanite in an outcrop of the WS at Ninhue. The sulphide compositions in rare massive sulphide lenses indicate metamorphic pressures of 5–7 kbar (Collao *et al.* 1986). Willner *et al.* (2001) used multivariant equilibria calculations to establish a metamorphic peak at 270–370°C and 6–8 kbar at Bahía Mansa. Glodny *et al.* (2005) determined 420°C, 8–9 kbar in the Valdivia area. Exotic tectonic blocks within the WS at Los Pabilos (Willner *et al.* 2005) exhibit a counterclockwise P–T–t path with a metamorphic culmination at 11–16.5 kbar and 600–760°C, overprinted by an epidote–blueschist re-equilibration event at 350–400°C, 10–14 kbar, not recorded in the country rocks, and a further common re-equilibration for the blocks and the country rocks at *c.* 300°C and 5 kbar (Fig. 2.4). These rocks are considered to represent the earliest accreted rocks beneath a still-hot mantle. Maximum P–T conditions of 7–10 kbar, 350–450°C were derived from metapelitic rocks of the Western Series in Chiloe (Massonne *et al.* 1999; Hufmann 2002). This range matches those conditions abundantly derived from phengites in greenschists and metapelites in central Chile (Massonne *et al.* 1998*a*).

Herve *et al.* (1990) deduced the possible presence of ages in the range 300–330 Ma, based on Rb–Sr wr dating on rocks from five localities which bear massive sulphide mineralization. Söllner *et al.* (2000*a*) presented a $293 \pm 23$ Ma U–Pb zircon age on a meta-ignimbrite at Caleta Parga (41°30′S), and Duhart *et al.* (2001) a $396 \pm 1$ Ma age on a trachyte body emplaced in mafic schists, a similar age range to the previously reported U–Pb conventional ages obtained on detrital zircon (between 388 and 278 Ma) in different metasedimentary rocks. These data suggest that the protoliths of the WS accumulated from Early Devonian to Early Permian times and are in part contemporaneous with the cooling of other parts of the complex.

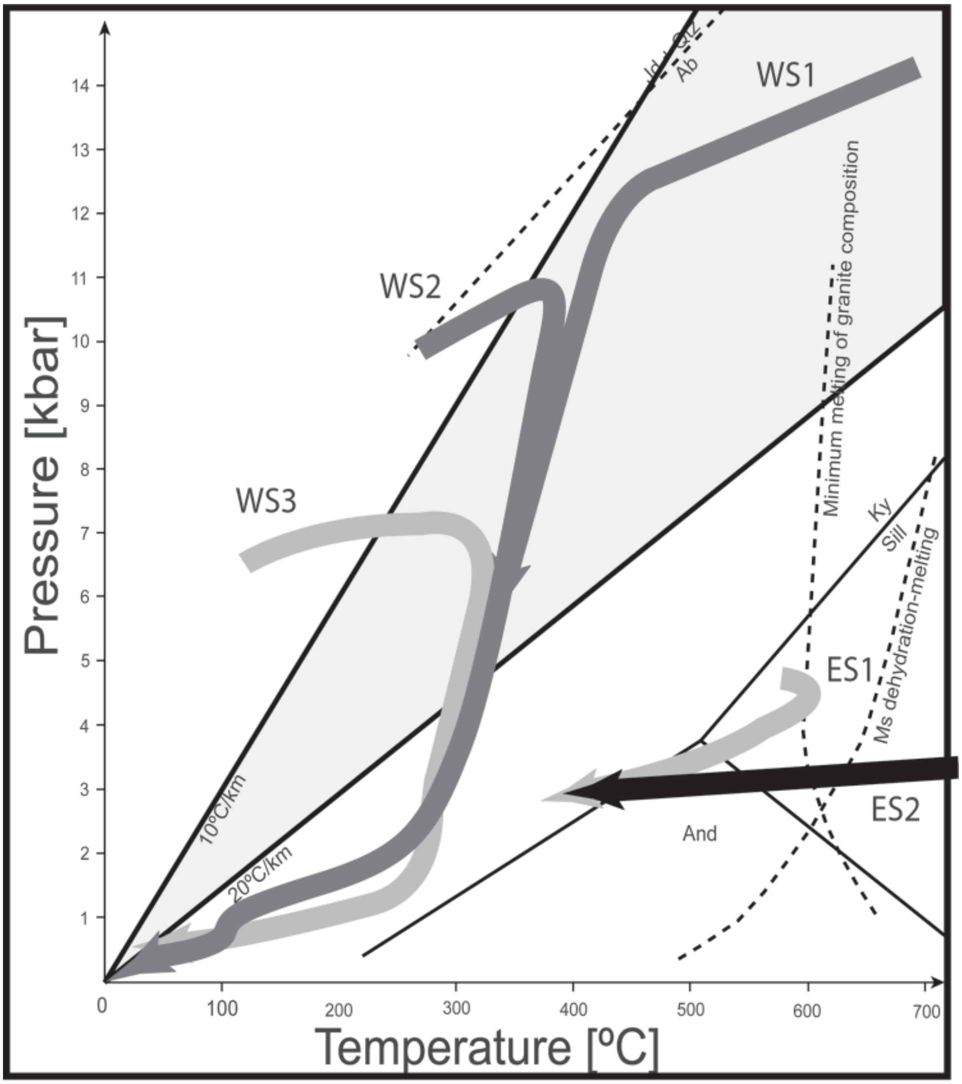


**Fig. 2.4.** A compilation of P–T–t trajectories for the different units of the 'metamorphic basement' complexes of central Chile. Sources of data: Western Series 1 (WS1 = exotic blocks), Willner *et al.* (2004*b*); Western Series 2 (WS2 = greenschist) and WS3 (blueschist), Willner *et al.* (2005); Eastern Series 1 (ES1), Willner *et al.* (2005); Eastern Series 2 (ES2), Hervé (1977).

Phengites of the oldest accreted rocks at Los Pabilos were dated by Kato & Godoy (1995: $304 \pm 9$ Ma) and Kato *et al.* (1997: $323 \pm 2$ Ma), whereas Willner *et al.* (2004*b*) produced Rb–Sr mineral isochrons of $305 \pm 3$ and $297 \pm 5$ Ma intending to date a second retrograde stage of re-equilibration. Duhart *et al.* (2001) produced Ar/Ar ages of white mica in the entire area in the range 260–220 Ma believed to be cooling ages, and Glodny *et al.* (2002) obtained a Rb–Sr mineral isochron of 285 Ma at Quidico. Younger Rb–Sr mineral isochron ages (*c.* 250–245 Ma) have been presented by Glodny *et al.* (2005) for the Valdivia area that are interpreted as dating the deformation associated with basal accretion. Rb–Sr mineral isochrons dating younger deformations during exhumation at *c.* 235 Ma and *c.* 210 Ma limit the mean exhumation rate to 0.6 +/–0.2 mm/a. Zircon fission track ages are in the range $176 \pm 49$ to $212 \pm 46$ in the Valdivia area (Glodny *et al.* 2005), whereas apatite fission track ages are between $53 \pm 7$ Ma and $65 \pm 8$ Ma.

In summary, these data allow us to deduce that basal accretion in the WS of central Chile was active for *c.* 100 Ma from Late Carboniferous to Early Triassic times.

### *The Eastern Series*

The Eastern Series (ES) is mainly composed of metagreywackes of turbiditic origin accompanied by minor but ubiquitous calcsilicate pods and lenses. They show stratigraphic continuity at outcrop scale as well as a non-transposed first folding of bedding planes, and represent a weakly deformed retro-wedge area (Hervé *et al.* 1988; Willner *et al.* 2001). The predominant deformation style with upright tight chevron folds folding the bedding planes points to frontal accretion of sediments of a former stable continental margin as inferred by Glodny *et al.* (2005). In central Chile the ES is mostly overprinted by a post-kinematic high T – low P metamorphic event. Mapped north–south trending metamorphic zones display an increasing metamorphic grade towards the batholith of the Late Palaeozoic arc which intrudes the Eastern Series in its eastern part (González Bonorino 1971; Hervé 1977). The ES has been considered the low P – high T component of the paired metamorphic belts of central Chile, and its metamorphic grade locally attains the amphibolite–granulite facies transition. Peak P–T conditions of this high T metamorphism range from

c. 400°C to 720°C at 3 ± 0.5 kbar, indicating a regional metamorphic event causing a thermal dome with the batholith in its core (Willner 2005). Hervé (1977) suggested a P–T culmination at 4–5 kbar and 600°C for the metamorphic series in the Nahuelbuta Mountains.

Hervé *et al.* (1984) presented Rb–Sr whole-rock isochrons of 347 ± 32 Ma (andalusite zone) and of 368 ± 42 Ma (sillimanite zone) with corresponding K–Ar ages of 299 ± 10 Ma and 278 ± 7 Ma. Muscovite Ar/Ar plateau ages between 301 ± 1 Ma and 296 ± 2 Ma were obtained by Willner *et al.* (2005) on a broader area in the region, indicating a short-term thermal overprint during the emplacement of the 305 Ma old coastal batholith (Fig. 2.4). The cooling/exhumation of the ES was monitored through zircon fission track ages of 221 ± 12 Ma and 215 ± 14 Ma and apatite fission track ages of 98 ± 6 Ma to 113 ± 8 Ma.

### *The Coastal Batholith*

The Coastal Batholith (CB) of central Chile (Fig. 2.1) is mainly composed of calcalkaline granitoids of Late Carboniferous to Permian ages. The granitoids were intruded into the Eastern Series of the metamorphic basement, which was subject to contemporaneous deformation and metamorphism. Triassic high level plutons of limited areal extent occur as post-tectonic bodies in the high P–T Western Series north of 38°S, and similar Cretaceous plutons occur around 40°S. Jurassic plutons, in many places difficult to distinguish from the Palaeozoic ones, increase in volume towards the northern limit of the area and beyond it, and were emplaced when the tectonic and metamorphic activity had ceased in the accretionary complex to the west. Later Mesozoic and Cenozoic plutonism migrated eastward to the Main Range cross-cutting the NW–SE trend of the southern end of the Late Palaeozoic plutonic belt at 40°S.

Stratigraphic evidence for the Late Palaeozoic age of the CB is scarce, although Carnian to Rhaetian sedimentary successions lie unconformably over the CB and the ES (but not the WS) in several localities in the Coast Ranges between 34 and 37°S, and also in the Main Range exposures at 40°S. This stratigraphical relationship limits the age of the unroofing of the batholith.

Near the northern end of the Coastal Batholith, Gana & Tosdal (1996) determined a U–Pb zircon age of 299 ± 10 Ma for the Mirasol unit, and 214 ± 1 Ma for a gneissic tonalite at Cartagena. The late Carboniferous age is similar to previously reported Rb–Sr, U–Pb and K–Ar ages in the same area, and the Late Triassic pluton has equivalents north and south of it. Further dating of the CB in this area by Gana & Tosdal (1996) shows that Middle Jurassic plutons in the age range of 156–161 Ma are widespread in this northern portion of the CB. Finally, for the Nahuelbuta Central Pluton Rb–Sr whole-rock isochrons were presented by Hervé *et al.* (1988) (294 ± 24 Ma) and Lucassen *et al.* (2004) (306 ± 5 Ma), which are concordant with the 305 ± 1 Ma U–Pb age on zircon in the Pichilemu area (Willner *et al.* 2005). Similar U–Pb zircon ages in the range 300 ± 2 Ma to 305 ± 2 Ma were obtained by Martin *et al.* (1999) at 40°S.

## The metamorphic complexes of the Patagonian and Fuegan Andes

In the Patagonian and Fuegan Andes, metamorphic rock units crop out quite extensively. They have been referred to as a 'metamorphic basement' to the Mesozoic and Cenozoic sedimentary and volcanic units. In the latter, it is possible to investigate the age and geological evolution by means of classic stratigraphic and palaeontological methods. The 'metamorphic basement', on the contrary, is for the most part composed of polydeformed rocks, where no stratigraphic controls can be established, and which contain very little or no fossil evidence for their depositional age.

The application of new methods, such as SHRIMP U–Pb determination of the detrital zircon age spectra, geochemical provenance analysis, and determination of metamorphic P–T conditions, have allowed researchers over the past decade to acquire new insights on the geological evolution of the 'metamorphic basement' of the Patagonian Andes. As a consequence, units differing in depositional and metamorphic ages, geodynamic setting and metamorphic characteristics have been identified. A description of their lithologies, metamorphic characteristics and geodynamic significance is given below.

### *The Patagonian Andes*

The Patagonian Andes consist of a rather topographically subdued mountain belt that has had a prolonged evolution going back to Late Palaeozoic times. The backbone of these mountains is provided by the Mesozoic to Cenozoic Patagonian Batholith, whose earliest (*c.* 150 Ma) components intrude low grade metamorphic complexes, which at present crop out both west and east of the continuous batholithic belt. These complexes were classically considered to be time equivalents, and are represented as such on the 1:1 000 000 Geological Map of Chile (Escobar *et al.* 1980). Research work in the last decade, however, has modified this view and allowed a subdivision of these units, the whereabouts and extent of which are presented in Figures 2.1 and 2.5. A summary of P–T–t trajectories is given in Figure 2.6.

#### *Eastern Andes Metamorphic Complex*

This unit consists mainly of polydeformed turbidite successions, with minor bodies of limestones and metabasites. It includes the previously defined Cochrane and Lago General Carrera units (Lagally 1975), Bahia de la Lancha and Rio Lacteo formations, as well as the Staines Complex (Allen 1982). The regional metamorphic grade is in the greenschist facies or lower, with higher grade rocks appearing only in the contact aureoles of Mesozoic to Cenozoic intrusions (Calderón 2000). Hervé *et al.* (2003*a*) concluded that this unit has sedimentary components deposited during Late Devonian–Early Carboniferous times, as well as younger deposits in their western outcrop areas, ranging in age up into the Permian period. Hervé *et al.* (1998), Faúndez *et al.* (2002), Ramírez (2002), Augustsson & Bahlburg (2003) and Lacassie (2003) have suggested that the turbidites represent deposition in a passive continental margin environment. This interpretation was based mainly on provenance considerations from petrographic and geochemical data. The turbidites were derived from a cratonic source, which possibly had undergone a complex and extended sedimentary recycling history. A combination of U–Pb detrital zircon ages and fission track age data on the same zircons allowed Thomson & Hervé (2002) to conclude that these sediments were metamorphosed before Late Permian times under lower P–T metamorphic conditions than those that are typical of accretionary complexes (Ramirez 2002), as shown in Table 2.1.

#### *Puerto Edén Igneous and Metamorphic Complex*

This complex consists of medium to high grade metamorphic rocks, migmatites and plutonic rocks, which crop out east of the South Patagonian batholith (49°S). Geothermobarometric constraints indicate a nearly isobaric high T – low P metamorphic and partial melting event superimposed on earlier greenschist-facies metamorphic rocks (Calderón 2000). Metamorphic overgrowths on zircons in sillimanite paragneisses record a Late Jurassic (*c.* 150 Ma) age taken as evidence of local gneiss formation under *in situ* anatectic conditions during the emplacement of the Jurassic components of the batholith (Hervé *et al.* 2003*a*).

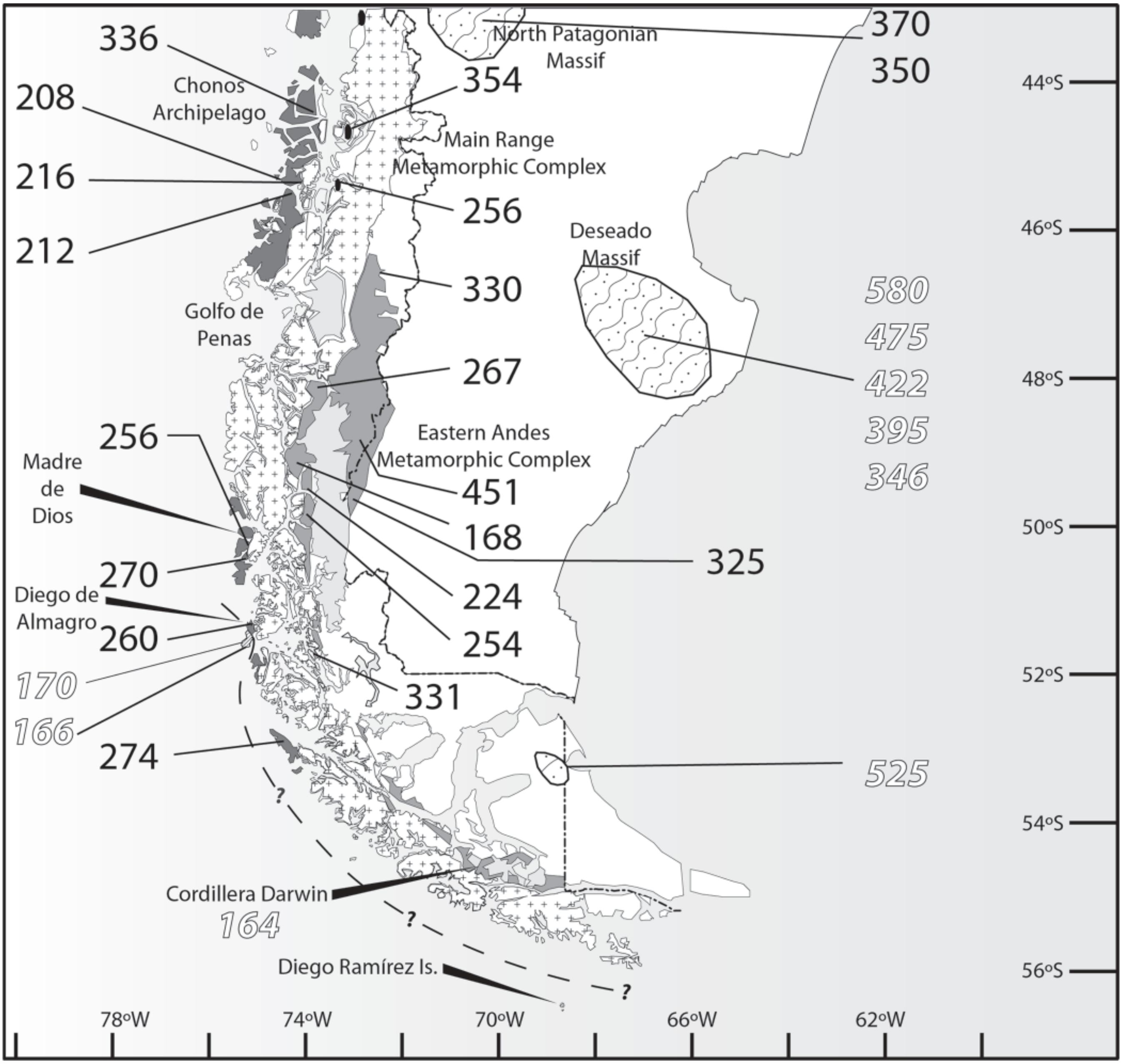


**Fig. 2.5.** Distribution of the metamorphic complexes in the Patagonian and Fuegan Andes (Hervé *et al*, 2003*a*). The bold numbers indicate the youngest detrital zircon U–Pb SHRIMP ages in metasedimentary rocks. The white italic numbers indicate U–Pb crystallization ages of igneous rocks which were later involved in the metamorphism. The ages from the North Patagonian Massif and the Deseado Massif are from Pankhurst *et al.* (2003), at from Tierra del Fuego is from Söllner *et al.* (2000*b*). Key: darker grey = coastal accretionary complexes and Cordillera Darwin metamorphic complex; intermediate grey = Eastern Andes Metamorphic Complex; lightest grey = ice and sea. Segmented line indicates the supposed eastern limit of the Diego de Almagro Complex drawn to include the Diego Ramírez Islands where Mesozoic blueschists were described by Wilson *et al.* (1989).

*Coastal accretionary complexes*

These comprise, from north to south, the Chonos Metamorphic Complex (CMC), the Madre de Dios Accretionary Complex (MDAC) and the Diego de Almagro Metamorphic Complex (DAMC), all of which crop out west of the Patagonian Batholith (PB) (Fig. 2.5).

The CMC consists predominantly of metaturbidites (Pimpirev *et al*. 1999) with restricted occurrences of mafic schists and metacherts, and broken formations are conspicuous. It has a Late Triassic depositional age, as indicated by fossil fauna (Fang *et al*. 1998) and by U–Pb age determinations on detrital zircon using SHRIMP (Hervé & Fanning 2001). The complex has been divided into two belts by Hervé *et al.* (1981*b*) similar to central Chile, with an Eastern Belt having well preserved primary sedimentary and volcanic structures that become progressively obliterated when passing into the more pervasively deformed and recrystallized rocks of the Western Belt. They were metamorphosed under high P–T metamorphic conditions (Willner *et al.* 2002) as shown in Table 2.1, before or during Early Jurassic times (Thomson & Hervé 2002).

The MDAC is composed of three tectonically interleaved lithostratigraphic units: the Tarlton limestone, the Denaro (DC) and the Duque de York (DYC) complexes (Forsythe & Mpodozis 1979, 1983). The Tarlton limestone (TL), a massive pelagic limestone body, was deposited in an intra-oceanic carbonate platform during Late Carboniferous–Early Permian

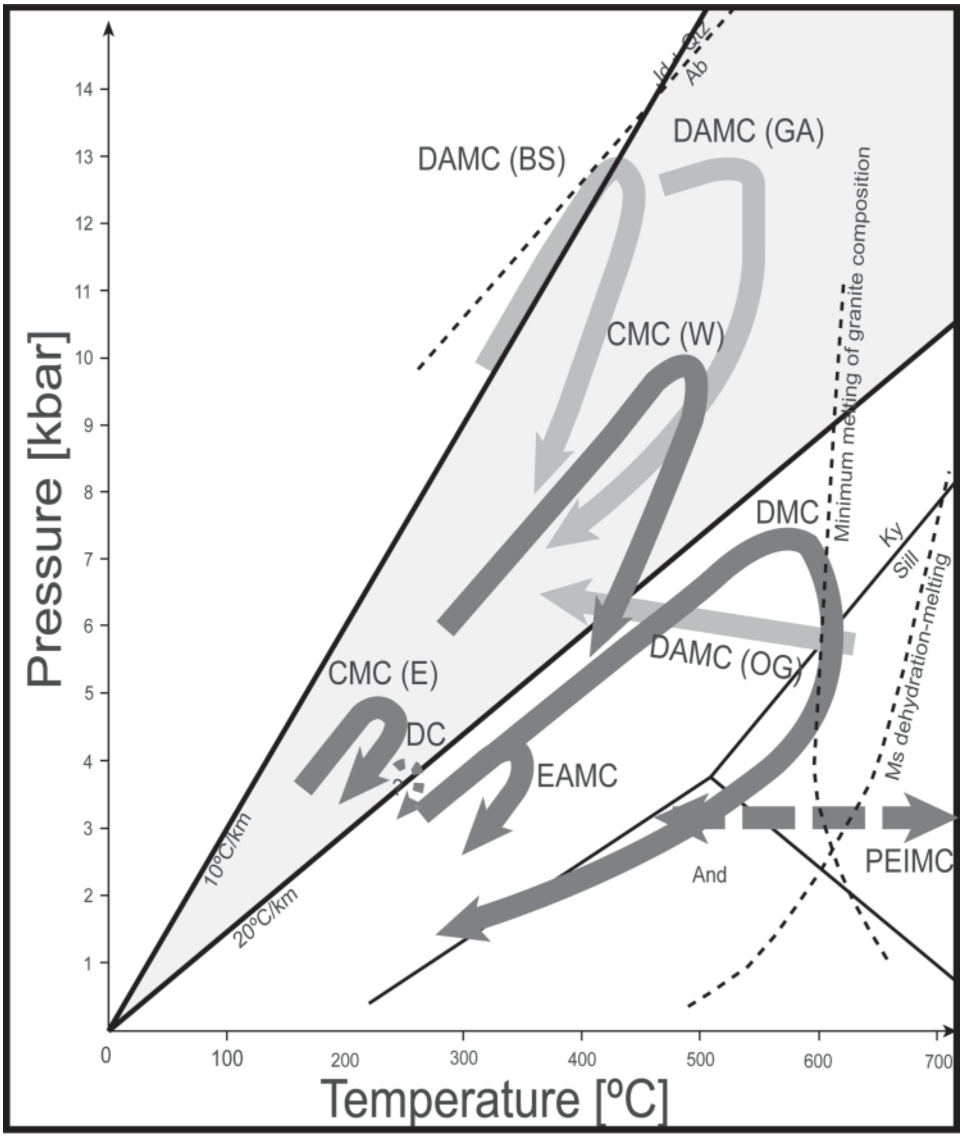


**Fig. 2.6.** A compilation of P–T–t trajectories for the different units of the 'metamorphic basement' complexes of the Patagonian and Fuegan Andes. Sources of data Chonos Metamorphic Complex (CMC), Willner *et al* (2001); Eastern Andes Metamorphic Complex (EAMC), Ramirez (2002); Puerto Edén Igneous and Metamorphic Complex (PEIMC), Calderon *et al.* 2007; Denaro Complex (DC), Sepúlveda (2004); Diego de Almagro Metamorphic Complex (DAMC), Willner *et al* (2004*b*); Cordillera Darwin Metamorphic Complex (DMC), Kohn *et al.* (1995). The curves GA, BS and OG refer to different units within the Diego de Almagro Metamorphic Complex. Aluminium silicate invariant point, minimum melting of granite (MMG) and muscovite dehydration-melting reactions are taken from Spear *et al* (1999). The MMG is displaced to lower temperatures due to involvement boron released during the prograde breakdown of tourmaline.

times (Douglass & Nestell 1976), over a penecontemporaneous (Ling *et al*. 1985) oceanic substrate (the DC) composed of pillow basalts, metalliferous and radiolarian cherts, probably in an oceanic ridge environment away from the continental influence of Gondwana. This exotic terrane was later accreted to the continental margin. Large upright chevron folds of bedding planes combined with steep reverse thrusts resemble accretionary prisms formed by frontal accretion (Forsythe & Mpodozis 1979, 1983). The DYC is a turbiditic succession which was deposited uncomformably over the TL and the DC, when they reached the vicinity of the continental margin (Forsythe & Mpodozis 1979, 1983). The DYC has radiolarian cherts at Desolación Island, which indicate an Early Permian age of deposition (Yoshiaki, written communication, 2002), and detrital zircons of late Early Permian age in all main outcrops of the unit. The Duque de York Complex, and probably the underlying TL and DC, were metamorphosed before or within the earliest Jurassic (Thomson & Hervé 2002). The very low grade metamorphism (pumpellyite–actinolite facies) of the three units of the MDAC has been sparsely studied: only the metamorphic characteristics of the Denaro Complex are shown in Table 2.1, and these suggest that the MDAC was metamorphosed under a relatively high geotherm of 15–20°C/km, similar to the Eastern Belt of the CMC. Combined petrographic and geochemical analyses (Lacassie 2003) indicate that the greywackes of the DYC were derived from an intermediate (granodioritic) composition igneous source within a dissected magmatic arc tectonic setting, where erosion had enough time to expose its plutonic roots. The DYC basin was probably adjacent to the continental crust of Gondwana, in an active margin tectonic setting (Faúndez *et al.* 2002; Lacassie 2003).

Palaeo-magnetic data on the Tarlton limestone and the Denaro complex (Rapalini *et al.* 2001) indicate that these

**Table 2.1** *A compilation of depositional ages, metamorphic ages and metamorphic peak P–T conditions for the complexes of the Patagonian and Fuegan Andes*

| Metamorphic complex | Maximum pressure (kbar) | Maximum temperature (°C) | Ages of emplacement and metamorphism (Ma) | Reference for peak P–T conditions |
|---|---|---|---|---|
| Chonos | (EB) 4.5–5.5 | 250–280 | 213–198* | Willner *et al.* 2002 |
| | (WB) 8.0–10.0 | 380–500 | | |
| Denaro | 4.1–5.5 | 260–300 | 234–195* | Sepulveda (2004), Willner (unpubl. data) |
| Diego de Almagro | (BS) 9.5–13.5 | 380–450 | 157–110 | Willner *et al.* (2004*a*) |
| | (GA) 11.2–13.2 | 460–565 | | |
| | (GM) 4.9–6.5 | 580–690 | | |
| Eastern Andes | $4.0 \pm 1.2$ | 320–380 | 364–250* | Ramírez (2002) |
| Cordillera Darwin | 6.5–7.5 | 575–625 | 164–86 | Kohn *et al.* (1995) |

For the Diego de Almagro Complex: BS, blueschists; GA, garnet amphibolites; GM, garnet–mica schists. The age column indicates first the depositional/emplacement ages and then the maximum metamorphic age as obtained through fission tracts zircon or Ar/Ar data. Ages marked with an asterisk are from Thomson & Hervé (2002). The age indicated for the Denaro Complex is at obtained for the Duque de York Complex. The authors cited in the last column have determined the peak P–T conditions of metamorphism.

units have undergone a very large counterclockwise rotation ($117 \pm 29.9°$), with negligible palaeo-latitude anomaly, after Early Cretaceous remagnetization by the thermal influence of the South Patagonian Batholith. This evidence allowed the above-cited authors to conclude that the rock units involved had been accreted to the Gondwana margin from the NW rather than from the SW as had been previously suggested by Forsythe & Mpodozis (1979, 1983) on the basis of structural studies.

The DAMC is composed of two subunits of differing metamorphic imprint, one composed of garnet amphibolites and blueschists, the other of quartz–mica schists and an orthogneiss. The contact between them has not been observed in the field. SHRIMP U–Pb ages in zircons in both the orthogneiss and a quartz-rich spessartine-bearing schist interleaved in the blueschists (Herve & Fanning 2003), have yielded Middle Jurassic ages interpreted as the age of crystallization of their igneous protoliths: a muscovite–garnet-bearing granite, and a rhyolitic rock respectively contemporaneous with the generation of the silicic Large Igneous Province (LIP) on mainland Patagonia (Pankhurst & Rapela 1995). The subsequent high P–T metamorphism occurred during Cretaceous times (Hervé *et al.* 1999). This complex is in tectonic contact (Forsythe 1981, 1982) with the DYC along the mid-crustal sinistral strike-slip Seno Arcabuz shear zone (Olivares *et al.* 2003).

In the Diego Ramirez islands, pillow basalts and metasediments form a crush mélange (Wilson *et al.* 1989), with glaucophane-bearing metamorphic assemblages. A Middle Jurassic Rb–Sr whole-rock errorchron from the metasediments (Davidson *et al.* 1989) suggests that these rocks can be correlated with those of the DAMC. Within this context it is relevant to note that non-basement rocks, such as recently studied metarhyolites of the Jurassic Tobífera Formation in the Magellanes fold and thrust belt (Hervé *et al.* 2004), have also been affected by contemporaneous metamorphic events also characterized by high P–T conditions.

*Extra-Andean Patagonia*

The pre-Mesozoic metasedimentary and plutonic units of 'extra-Andean' Patagonia which crop out in the Deseado massif, have been studied recently by Pankhurst *et al.* (2003) and Rapela *et al.* (2003*a*). The latter authors have dated metasedimentary rocks of probable latest Neoproterozoic depositional age, and plutonic bodies of Cambrian, Ordovician and Late Silurian to Early Carboniferous age (Fig. 2.5). Söllner *et al.* (2000*b*) dated 530 Ma old orthogneisses recovered from the bottom of oil wells in northern Tierra de Fuego, suggesting that early Palaeozoic rocks may extend over large tracts of southern Patagonia under the Mesozoic–Cenozoic cover.

***The Fuegan Andes***

*The Darwin Cordillera Metamorphic Complex*

The basement rocks of the Darwin Cordillera (DCMC) consist of metasedimentary and metavolcanic units, of supposedly late Palaeozoic to early Mesozoic age, which have a Mesozoic metamorphic imprint peculiar to that area (Kohn *et al.* 1995). This metamorphism is characterized by the generation of biotite, staurolite, kyanite and sillimanite zones, which are unique among the metamorphic basement complexes of the Patagonian and Fuegan Andes. Several authors (Dalziel & Cortes 1972; Nelson *et al.* 1980; Dalziel 1981, 1986) have suggested that their protoliths formed as an accretionary wedge on the pre-Middle Jurassic Pacific margin of South America. However, it is not known at present if these metamorphic rocks of the Darwin Cordillera were originally part of the Eastern Andes Metamorphic Complex, which is probably not a Late Palaeozoic accretionary complex but served as a backstop during the generation of the accretionary wedge (Augustsson & Bahlburg 2003), or if they were part of the coastal accretionary complexes of the Patagonian Andes. An orthogneiss within the DCMC showed a Middle Jurassic Rb–Sr whole-rock isochron ($157 \pm 7$ Ma; Hervé *et al.* 1979*b*, 1981*c*) and U–Pb zircon ($164 \pm 1$ Ma; Mukasa & Dalziel 1996) ages affected by the main metamorphic event. Nelson *et al.* (1980) have suggested that part of the protolith of the complex might be the Middle to Late Jurassic Tobífera Formation silicic volcanic rocks.

## Geodynamic considerations

The study of basement metamorphic rocks in Chile, and related complexes in neighbouring Argentina, provides indications about the changing tectonic environments that have existed in the area. It is clear that these metamorphic complexes have different ages and that their metamorphic evolution, though poorly known in some areas, varies widely in space and time.

Probably the best known and most readily interpreted event recorded by these rocks is the Late Palaeozoic development of an accretionary prism over an east-dipping subduction zone below the southwestern Gondwana margin in central Chile. This process generated an elongated high P–low T metamorphic belt which includes accreted oceanic lithologies and a contemporaneous parallel magmatic belt in the upper plate, both of which are well recorded and exposed.

The existence of tectonostratigraphic terranes has been identified mainly by the presence of oceanic rocks flanked on both sides by blocks of older continental crust. This interpretation is less straightforward, as it depends heavily on the evaluation of structural, geochemical and geochronological data, which can be imprecise and incomplete. Also, the sudden displacement of magmatic arcs in time has been considered to imply the docking of terranes to the continental margin. In contrast, a paucity or absence of magmatic and tectonic activity, together with developing sedimentary provenance analysis, has been used as an indicator of passive margin conditions. The subduction of upstanding oceanic features such as ridges and plateaux can bring subduction to a stop, or flatten the subducting slab to prevent magmatic activity near the trench. Finally, margin-parallel strike-slip environments have also been considered in some interpretations, and the process of tectonic erosion of the leading edge of the overriding plate (Stern 1991*b*) may destroy the continuity, or even the entire evidence for the generation of subduction complexes in a particular place and time.

### *Northern Chile*

This is the only portion of the Andean basement in Chile where significant bodies of Early (pre-Devonian) Palaeozoic rocks exist, including latest Proterozoic (?)–Early Cambrian igneous and metamorphic suites. Dalziel (1991) and Moores (1991) suggested that the Laurentian craton was located close to Antarctica and South America in Neoproterozoic and Early Palaeozoic times. The clockwise movement of Laurentia around South America would have resulted in repeated collisional tectonic interaction between the two continents, giving rise to the Famatinian orogen in southern South America and to the Taconic orogen in Laurentia (Dalla Salda *et al*. 1992). The collision included two major events, resulting in the Early Cambrian Pampean Orogeny, and later the late Ordovician Famatinian orogeny. A sliver of Laurentia detached to constitute the Arequipa–Antofalla terrane, with the Belén and Chojas metamorphic complexes near its eastern margin providing a record of the Pampean orogeny. The Ocloyic orogen could have been caused by the collision of this detached sliver – the Arequipa–Antofalla terrane – and not of the whole of Laurentia, if the Cordón de Lila Complex is interpreted as the product of a magmatic arc caused by eastward subduction of oceanic crust (Bahlburg & Hervé 1997) from the west (Fig. 2.7a). Alternatively, Forsythe (1982) have suggested that the Arequipa–Antofalla terrane was a sliver of the Gondwana continent, and rotated clockwise to generate the oceanic area in the Ordovician, and then counterclockwise to collide with its continent of origin, producing the Ocloyic orogen. Lucassen *et al.* (2000) questioned the entire terrane concept and show that Lower Palaeozoic metamorphic crystallization ages, peak P–T data (high temperatures, low to moderate pressures, Fig. 2.2) and whole-rock Nd–Sm systematics rather favour a continuous mobile belt in northern Chile and NW Argentina, i.e. south of the Arequipa Massif at 18°S and north of the Argentine Precordillera at 28°S. This basement would have originated at a convergent margin at mid-crustal levels under a very high geothermal gradient involving intensive magmatic underplating over wide areas. In the northernmost exposures the Arequipa craton would have been partly reworked within the mobile belt.

After the Silurian–Devonian lull in subduction activity, the margin of Gondwana resumed as an active margin facing and consuming an extensive oceanic plate. As a result of this, the metamorphism of the Chañaral Melange (Fig. 2.7b) took place during Late Carboniferous times within what Marioth & Bahlburg (2003) describe as a particular type of subduction zone in which the P–T regime was not high. Around this time, the Limón Verde high pressure metamorphism occurred. As this unit crops out far from the present-day coastline and the Chañaral melange, the interpretation of its tectonic setting has been difficult. Hervé *et al.* (1985) and Bahlburg & Hervé (1997) favoured a subduction zone environment whereas Lucassen *et al.* (1999) preferred a strike-slip environment for its development.

The way in which the Limón Verde Metamorphic Complex was exhumed remains questionable, but it was broadly contemporaneous with the development of mylonitic rocks at Sierra de Moreno and in the Tránsito Metamorphic Complex, north and south respectively of Limón Verde, which exhumed the Belén and Sierra de Moreno complexes and the Pampa Gneiss, then part of the backstop of the accretionary prism. It is possible that this rapid exhumation might be related to tectonic erosion of the oceanward portions of the backstop, or by subduction of an oceanic ridge, favouring the exhumation process which brought these units to the surface in mid-Triassic times. In Figure 2.1, these units are seen aligned in what has been referred to as the Precordillera upthrust belt, after Bahlburg & Breitkreuz (1991).

### *Norte Chico*

As a whole this region is characterized by the presence of the (hardly exposed) Chilenia Terrane, which was amalgamated to Gondwana in Devonian times (Ramos *et al.* 1986). As seen further north, the Late Carboniferous Tránsito Metamorphic Complex crops out in a much more easterly position than the Choapa and El Teniente complexes (Fig. 2.7c), which both have a lower metamorphic grade. The El Teniente rocks additionally record a late Triassic metamorphic event, not recognized in those of El Tránsito, which at that time had already been exhumed and exposed at the surface. It is possible that this exhumation was contemporaneous with that of the Limón Verde rocks mentioned above, thus representing a wide-scale exhumation of the backstop and of the deeper parts of the accretionary wedge which continued to develop further west. A westward jump of magmatic activity in this area from Carboniferous to Triassic times, could be interpreted as caused by a roll-back of the subduction zone by the collision of a small terrane (Fig. 2.7d) that could have contributed to the exhumation of the early subducted rocks of the El Teniente Metamorphic Complex ('Terrane Equis'; Mpodozis & Kay 1990, 1992). Finally, it is interesting to note the existence of the late Triassic metamorphic event in the coastal El Teniente exposures, contemporaneous with the Chonos event in Patagonia, which has no counterpart in central Chile.

### *Central Chile*

The geological development of central Chile in Late Palaeozoic times can be best described in terms of processes occurring along a continental margin. These processes can be related to subduction of oceanic crust leading to an accretionary prism and a magmatic arc (Fig. 2.7e). The Western Series includes lithologies of oceanic parentage, mixed with detrital sediments of continental derivation, and exhibits the imprint of a high P – low T metamorphic regime. The history of metamorphism and exhumation and the ductile deformation shown by the WS can best be explained if the outcropping rocks were initially subjected to basal accretion in the accretionary complex, followed by exhumation from 25–40 km depth during ongoing accretion.

The Eastern Series, mainly composed of a metamorphosed turbidite succession, was probably deposited in a forearc setting over the continental shelf. The deposition may have taken place during passive margin conditions in Devonian and Early Carboniferous times. Thus, the rocks of the ES were probably part of the uppermost accretionary wedge formed by frontal accretion as well as part of the retrowedge. Deformation took place mainly under very low-grade conditions and intermediate pressure, but the ES was later metamorphosed under low P – high T conditions close to the site where the magmatic arc developed.

### *Patagonian Andes*

The protoliths to the eastern Andes Metamorphic Complex were deposited in a passive margin environment from Early

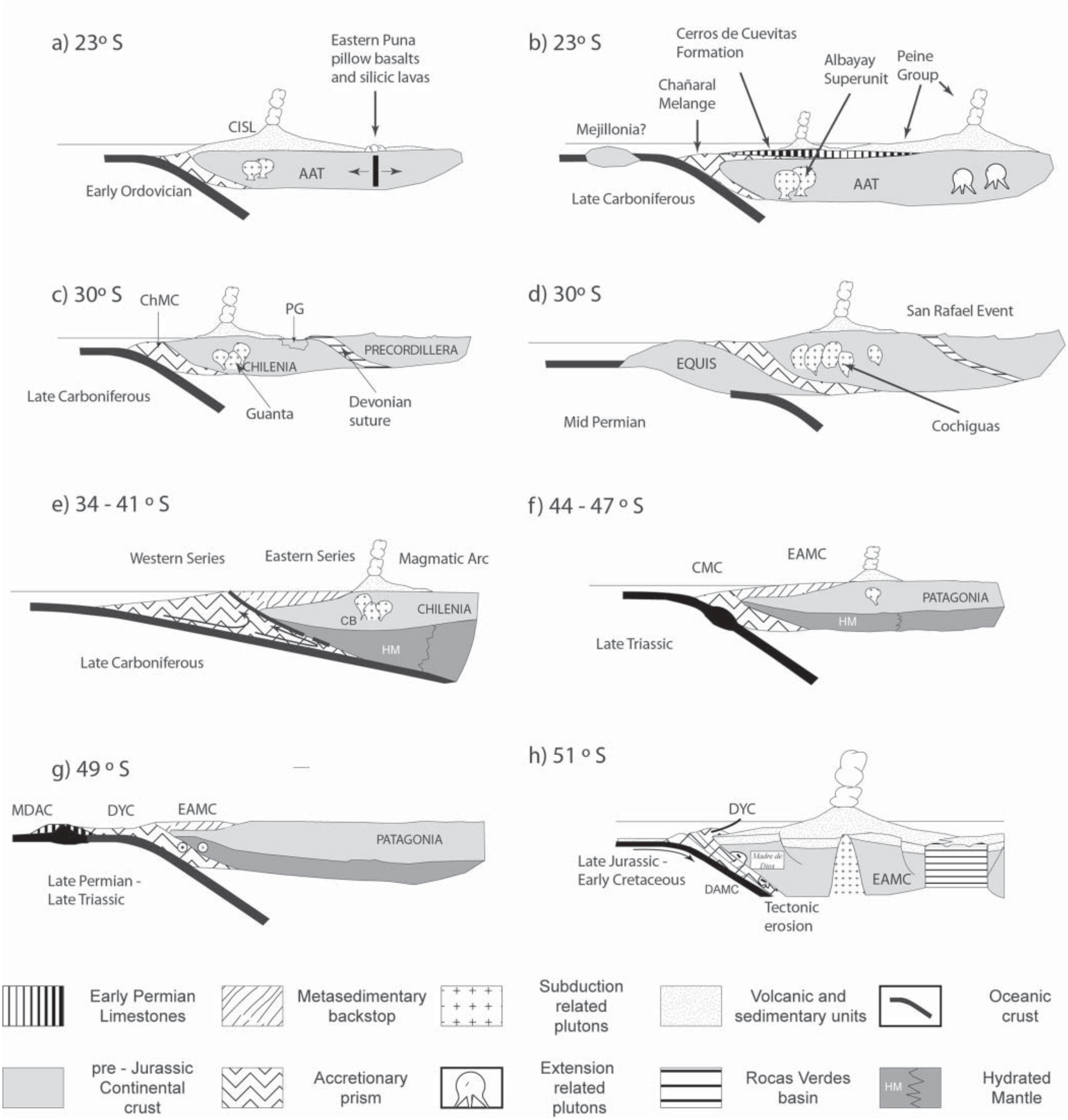


**Fig. 2.7.** Schematic cross-sections at different latitudes and time slots during the main subduction-related metamorphic and plutonic events as described in the text. Scales are not uniform.

Devonian to Early(?) Permian times. The detrital zircon age spectra on these rocks have Gondwanan affinities. The source areas could have been located in older rocks of the Atlantic margin of Patagonia, such as the Deseado massif, or in South Africa and Antarctica (Hervé *et al.* 2003*a*). It is not known if it is in place with respect to the older continental blocks, or if it has been displaced (*c.* Mpodozis, personal communication).

The western accretionary complexes, on the contrary, have evolved in subduction zone environments, where accretion of ocean floor basaltic material is recorded. However, in contrast to previous assumptions, there are no indications of Late Palaeozoic subduction in the Patagonian Andes. The Chonos Metamorphic Complex reveals a subduction event near the Triassic–Jurassic boundary (Fig. 2.7f), in which the corresponding arc might have been the largely coeval Sub-Cordilleran Batholith (Rapela *et al.* 2003*b*) in Argentina. The Madre de Dios Accretionary Complex appears to involve a composite exotic terrane, probably frontally accreted to the Gondwana margin during the same Late Triassic–Early Jurassic event as the CMC. The provenance of the Duque de York Complex, characterized by a major Early Permian zircon component, is not easily attached to a contemporaneous magmatic arc in Patagonia, where Permian igneous rocks do not crop out extensively. Lacassie (2003) suggests a far-sited origin for the MDAC, which would have collided with the Gondwana margin in the southeastern Pacific area (present coordinates) and then transported along the margin to its present position, following a model proposed by Cawood *et al.* (2002). Alternatively, as the accretion of the MDAC was from the NW, a possibility remains that the limestones originated in an oceanic environment at the latitude of northern Chile, where thick limestone deposits of Early Permian age were deposited over continental crust, mainly in Bolivia (Copacabana Formation) but also in Chile.

Hervé & Fanning (2003) have suggested that the Late Jurassic–Cretaceous evolution of the Diego de Almagro Metamorphic Complex in a subduction zone along the western margin of Gondwana only occurred after the Antarctic Peninsula, which could have been located outboard of the present continental margin (Lawver *et al.* 1998), started to drift south allowing subduction to occur near the present-day continental margin.

The P–T evolution of the metamorphic complexes (Figs 2.2, 2.3, 2.4 & 2.6) varied widely in time and space. The differences between the coastal accretionary complexes, which evolved in P–T regimes characterized by geothermal gradients between 10 and 20°C/km, and the Puerto Edén and Cordillera Darwin metamorphic complexes are evident. Only the former are considered to be typical of subduction zone environments due to the derived metamorphic P–T conditions. These conditions suggest that the subduction was slow, or that the subducting oceanic lithosphere was rather young and, thus, relatively hot.

## Concluding remarks

The metamorphic and plutonic basement complexes of Chile thus reveal the following history (sketched in Fig. 2.7) for a part of the southwestern Gondwana margin.

1. Early Palaeozoic metamorphic and plutonic events occurred, which can be assigned to the Pampean and Famatinian orogenic phases. The products of these events seem to be restricted to northernmost and southernmost Chile as there are no outcrops in between.
2. Conditions of a passive margin prevailed in the region during Silurian and Devonian times, when the collision of Chilenia is recorded in western Argentina.
3. A Late Carboniferous metamorphic and plutonic event, related to subduction of the Palaeopacific or Panthalassian ocean, is recorded in areas between latitudes 42°S and 23°S. This event has been called the Toco Orogeny in northern Chile. A chain of accretionary prisms is preserved with ages decreasing from north to south
4. Late Triassic–Early Jurassic metamorphic and plutonic activities are recorded in the Norte Chico (30–33°S) and in the northern Patagonian archipelagos (43–46°S). Plutonic rocks of the same age were emplaced in the Western Series. It is not known if these two outcrop areas represent two ends of a previously continuous accretionary complex located west of the present-day continental margin that was subducted by tectonic erosion or displaced south along the Jurassic to Cretaceous left-lateral strike-slip faults.
5. Evidence for deep seated Jurassic–Cretaceous tectonometamorphism related to an Andean setting has been found only south of 48°S. This includes the Diego de Almagro (subduction) and the Darwin (metamorphic core) complexes.

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