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SPECIAL

150 million years of climatic stability: evidence from the Atacama Desert, northern Chile

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The sedimentary succession in the Atacama Desert records deposition under an arid to semiarid climate from the late Jurassic (150 Ma) to the present day. Palaeomagnetic data indicate no significant latitudinal movement of this area since the late Jurassic. The present-day location of the Atacama within the dry subtropical climate belt is the principal cause of aridity. This situation is likely to have prevailed since the late Jurassic, supplemented by (1) the continentality effect (enhanced by the Gondwanan landmass), and (2) the presence offshore of a cold, upwelling current (from at least the early Cenozoic onwards and possibly earlier), resulting in conditions promoting climatic stability and desert development. Rapid and extreme climatic fluctuations during the Plio-Pleistocene were not sufficient to destabilize the climate within the Atacama. Comparison with other long-lived deserts (e.g. SW USA, Namib, Sahara and Australia) suggests that the Atacama is the oldest extant desert on Earth.

Keywords: Atacama, Chile, Andes, palaeoclimatology, deserts.

Characterizing the factors responsible for controlling climate stability or instability is important for predicting present-day climate change and understanding climate change in the rock record. Arid environments are particularly sensitive to subtle climatic variation. Understanding the controls on ancient desert development is therefore important for supplying limits to global (palaeo-) climate models. To assess the controls on ancient desert development it is necessary to have a well-dated, continuous sedimentary succession from which palaeoclimatic information can be extracted, together with constraints on the causes of aridity. Here we review meteorological, sedimentological and palaeomagnetic data from the Atacama Desert that indicate that conditions have been conducive to the existence of a desert in this area since the Jurassic.

Atacama Desert climate. The Atacama Desert effectively comprises the hyperarid part of the Peru–Chile desert; the latter extends between 1°N and 37°S, incorporating the forearc area of Peru and northern Chile, and part of the Western Cordillera (Fig. 1). Aridity in western South America is induced primarily by subtropical anticyclonic atmospheric subsidence. This is reinforced by the presence of the upwelling, north-flowing, cold Humboldt Current along the west coast of South America, which prevents precipitation in the coastal regions. A further controlling factor is the rain shadow effect of the Andean Cordillera, which is illustrated by the precipitation profile shown in Figure 2. The orographic impact of the Andean Cordillera can be seen clearly, enhancing rainfall on the east slope and forming a rain shadow on the west slope. An additional cause of aridity is the continentality effect. This occurs where rain-bearing trade winds cannot penetrate continental interiors (Thompson 1975), and is clearly illustrated in Figure 2 by the westward continent-wide decrease in rainfall across South America. To determine the influence of these factors in controlling aridity in western South America through geological time, it is necessary to examine the sedimentary, stratigraphic and palaeolatitudinal history of the Atacama Desert.

Mesozoic to Cenozoic sedimentological record of the Atacama. The late Mesozoic and Cenozoic stratigraphy of northern Chile is shown in Figure 3. Jurassic to early Cretaceous strata were deposited in a back-arc basin situated in the present-day Central Depression and developed east of a volcanic arc located in the Coastal Cordillera (Fig. 3; Chong 1977; Ardill *et al*. 1998). For much of the largely marine Jurassic succession a climatic signature cannot be determined. However, a relative sea-level fall in the late Oxfordian was followed by the accumulation of 200 m of subaqueous evaporites and marginal sabkha facies under a dry climate (Ardill *et al*. 1998). This climatic regime prevailed into the latest Jurassic as indicated by deposition of lagoonal and hypersaline limestones.

An early Cretaceous to late Eocene volcanic arc was located in the present-day Central Depression. A 6000 m thick back-arc basin-fill was deposited east of the arc in the present-day Precordillera (Fig. 3). Sedimentary rocks were deposited in alluvial fan, ephemeral fluvial, aeolian, ephemeral lacustrine, evaporite and playa environments under an arid to semiarid climate (Hartley *et al*. 1992). Based on magnetostratigraphic analysis, the lower age limit is within the (late) early Cretaceous (Arriagada *et al*. 2000). Intra-arc and forearc basins were developed in what are now the Central Depression and the Coastal Cordillera, respectively. Up to 2000 m of alluvial fan and fan delta deposits of early Cretaceous age are preserved in the Coastal Cordillera (Flint & Turner 1988).

Late Eocene to early Pliocene age sedimentary rocks occur throughout northern Chile. Deposition took place in a forearc setting similar to the present-day setting with sedimentary rocks comprising alluvial fan, fluvial, sandflat, playa, evaporite, nitrate, lacustrine and marginal lacustrine deposits (Naranjo *et al*. 1994; May *et al*. 1999; Sáez *et al*. 1999; Hartley *et al*. 2000). These sedimentary rocks were deposited under a predominantly semiarid climate interspersed with periods of increased aridity (Hartley & Chong 2002).

The late Pliocene to present-day succession is represented by localized evaporites restricted to topographic lows and development of a saline crust throughout the Peru–Chile desert (Chong

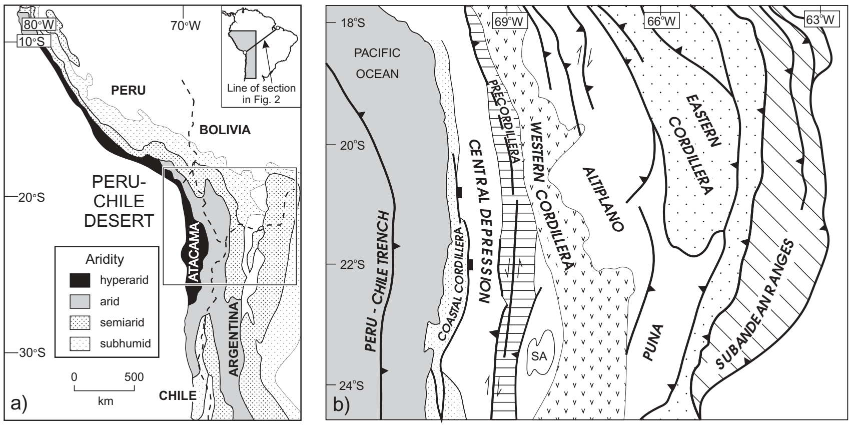

Fig. 1. (**a**) Location map showing present-day climatic zones of western South America; location of cross-section for Fig. 2 is shown. (**b**) Morphotectonic subdivisions of Central Andes. SA, Salar de Atacama.

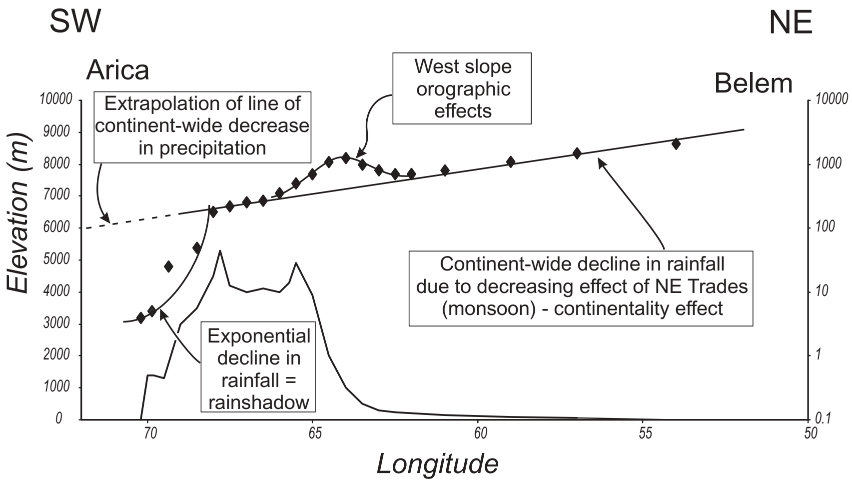

Fig. 2. Major present-day precipitation characteristics in a NE–SW topographic profile across South America from Belem (Brazil) to Arica (Chile), modified from Houston & Hartley (2003). (For line of section see Fig. 1.)

1988). This phase of deposition marked the onset of the present-day hyperaridity in the Atacama and was established between 3 and 4 Ma (Hartley & Chong 2002). The hyperarid climatic regime in the Atacama is also in line with global palaeoclimate models for this time period (e.g. Haywood *et al*. 2000, 2002). The eastern and southern margins of the Atacama have fluctuated between arid and hyperarid conditions during the Pleistocene (e.g. Betancourt *et al*. 2000; Bobst *et al*. 2001; Latorre *et al*. 2002; Rech *et al*. 2002; Grosjean *et al*. 2003). However, even the extreme changes in atmospheric circulation and sea surface temperatures during the Pleistocene were not sufficient to destabilize boundary conditions and enhance precipitation in the core of the Atacama, where thick evaporite deposits indicate hyperaridity throughout the Pleistocene.

The late Jurassic, Cretaceous and Cenozoic sedimentary record from northern Chile is dominated entirely by sediments deposited under an arid to semiarid climate. There is no record of more humid climate indicators (e.g. coals, gley sols, etc.). Northern Chile has therefore been subject to a continuous arid to semiarid climate since the late Jurassic and possibly earlier. Even the extreme climatic fluctuations of the Pleistocene had little impact on climatic stability within the Atacama.

Mesozoic and Cenozoic palaeolatitude of the Atacama. Apparent polar wander (APW) paths for the stable craton of South America during the Jurassic and Cretaceous were reviewed by Beck (1999), and reference poles have been calculated for the Cenozoic by Somoza & Tomlinson (2002). These studies indicate that the virtual geomagnetic pole for the South American craton has been located within 9.2° latitude of the present-day spin axis since at least 165 Ma. The APW of 9.2° occurred between 115 and 80 Ma and with the exception of this short time interval there has been no identifiable APW of South America relative to the present-day spin axis (Beck 1999). Palaeomagnetic data from northern Chile indicate that there has been no latitudinal translation of strata relative to the South American craton since the late Palaeozoic (Jesinkey *et al*. 1987; Hartley *et al*. 1988; Somoza & Tomlinson 2002). Northern Chile has therefore remained at approximately the same latitude since the late Jurassic, with the exception of relatively minor latitudinal movements ($<10°$) between 115 and 80 Ma.

Controls on Mesozoic and Cenozoic climate in western South America. An arid to semiarid climate has prevailed in the Atacama from the late Jurassic to the present day, which suggests that the present-day controls on climate may extend into the late Jurassic. The main influence on desert development in northern Chile is the location within an area of anticyclonic subsidence, which is controlled by the global Hadley circulation and is not strongly related to the regional distribution of land and sea (Williams 1994). In the southern hemisphere the area of atmospheric subsidence occurs at present between 15 and 30°S, and during global hothouse conditions would have been displaced slightly polewards (Scotese *et al*. 1999; Scotese 2004). Global circulation model experiments for Neogene times suggest broadening of the Hadley cell with an associated prediction of reduced

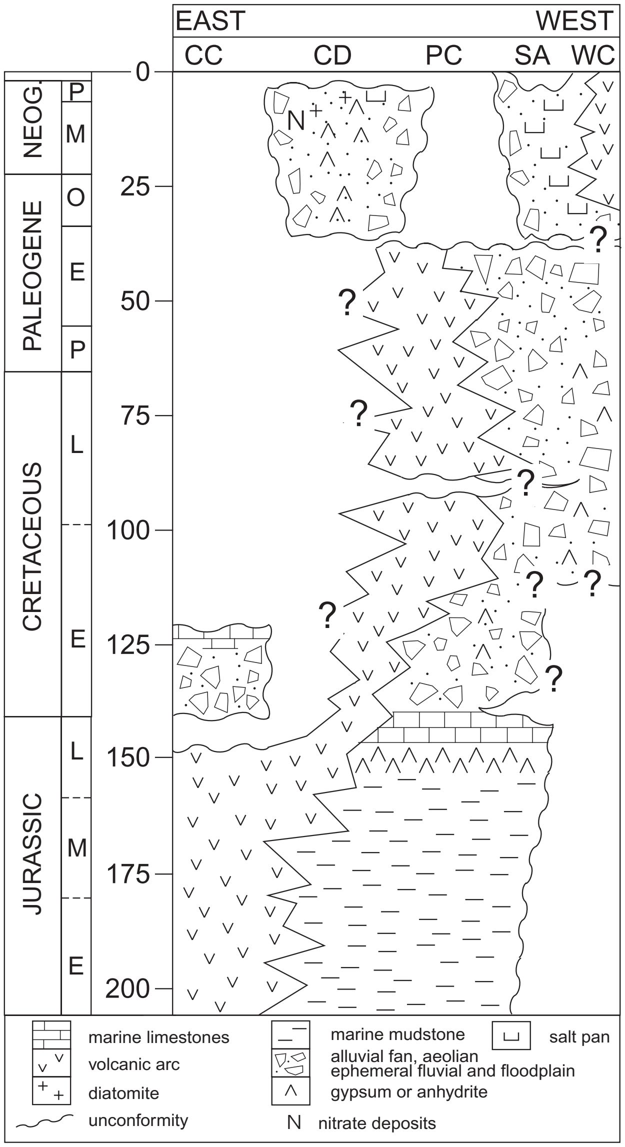

Fig. 3. Simplified Mesozoic and Cenozoic stratigraphy, northern Chile. Cenozoic from Hartley *et al*. (2000); Cretaceous from Flint & Turner (1988), Hartley *et al*. (1992) and Arriagada *et al*. (2000); Jurassic from Chong (1977) and Ardill *et al*. (1998). CC, Coastal Cordillera; CD, Central Depression; PC, Precordillera; SA, Salar de Atacama; WC, Western Cordillera. (See Fig. 1 for location of morphotectonic provinces.)

total precipitation over tropical areas, but no change in the location of the southern limit of the Hadley cell (e.g. Haywood *et al*. 2000). The lack of substantial, post-late Jurassic, latitudinal movement of northern Chile means that the Atacama has been situated between 15 and 30°S and that, despite fluctuations in the width of the Hadley cell, the Atacama has remained beneath the cool, dry limb of the descending cell for at least the last 150 Ma.

The rain shadow effect associated with the Andean Cordillera can be discounted as a climate-controlling mechanism in the Mesozoic and Palaeogene, as Andean uplift did not commence until 30 Ma (Kennan 1999; Hartley 2003). Also, if the rain shadow effect were removed through extrapolation of the line of continent-wide decrease in precipitation west of the Andes (the dashed line in Fig. 2), northern Chile would still be subject to annual precipitation of less than 500 mm. The implication from this is that even if the Andes were not present today, the continentality effect would still result in an arid to semiarid climate in western South America. Indeed, in the late Jurassic to early Cretaceous the continentality effect can only have been enhanced relative to the present day, as western South America formed the westernmost edge of the vast Gondwanan continental landmass.

An ancestral Humboldt Current may have influenced climate, as evidence for the initiation of a cold, upwelling current off the west coast of South America dates back to latest Cretaceous to earliest Cenozoic times (Keller *et al*. 1997). The development of organic-rich Cenomanian–Turonian shales along the Peruvian Pacific margin is also considered as evidence for the presence of an upwelling current along western South America extending back as far as 100 Ma (Arthur *et al*. 1987). In summary, location within the southern hemisphere trade wind belt, the continentality effect (enhanced by the Gondwanan landmass) and, to a lesser extent, the presence of an ancestral Humboldt Current controlled aridity along the western margin of South America from the late Jurassic onwards.

Age of the Atacama and comparison with other deserts. The Atacama Desert forms one of a series of west coast, subtropical deserts such as much of Australia, and the Sahara and Namib deserts. These deserts are considered to be some of the oldest in the world, although their longevity has long been debated (e.g. Ward *et al*. 1983; Glennie 1987). In the Sahara, aridity was initially established in the late Cretaceous in the northwestern Sahara and in the main Sahara during the Oligocene, as revealed by the presence of aeolian sand in Oligocene ocean cores off NW Africa (Sarnthein 1978). However, aridity was not established across North Africa and Arabia until the Oligocene (Oberlander 1994) and was not widespread until the mid-Miocene, when a xeric flora well adapted to aridity was established (Bonnefille 1983; Williams 1994; Shaw 1997). The Namib Desert in SW Africa is, based on sedimentological evidence, considered to date back to 80 Ma (Ward *et al*. 1983). Palynological evidence suggests that the Benguela Current, a key feature in controlling climate along the SW African margin, was active by at least the late Miocene (Siesser 1980).

In Australia, the earliest signs of aridity occur within the early Cenozoic (Bowler 1976; Williams 1984); however, extensive tropical forests covered much of Australia during the Miocene, giving way to abundant grassland in the Late Miocene (Tedford 1985). Widespread aridity is not considered to have prevailed across Australia until the late Miocene (Bowler 1976). The onset of desertification in Asia commenced at 22 Ma (Guo *et al*. 2002) and a similar early Miocene age is considered to reflect the onset of aridity in SW North America (Oberlander 1994). Of the present-day deserts, the Atacama therefore contains the longest continuous record of sedimentation under an arid to semiarid climate.

Conclusions. The Atacama Desert contains a virtually continuous Late Jurassic to present-day sedimentary record of deposition under an arid to semiarid climate. Palaeomagnetic data indicate that the palaeolatitude of the Atacama has been close to that of the present day since the late Jurassic. These observations, together with global climate models, suggest that the Atacama has lain within the southern hemisphere dry subtropical climate belt for the last 150 Ma. The principal causes of aridity in western South America for the last 150 Ma have been atmospheric subsidence associated with the descending limb of the Hadley cell, the continentality effect (enhanced by the Gondwanan landmass) and the presence offshore of a cold, upwelling ancestral Humboldt Current. Rain shadow effects were unimportant. The sedimentary record in the Atacama records 150 Ma of climatic stability despite extreme fluctuations in climate during the Plio-Pleistocene. As such it represents the longest extant desert on Earth. The Atacama is unusual as it is possible to attribute the causes of aridity to a combination of specific mechanisms through geological time. In cases where the causes of aridity cannot be determined reconstruction of palaeoclimate belts is likely to be much more problematic.

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