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Permian and Quaternary playas, a discussion based on climatic, tectonic and palaeogeographic settings

Playas del Pérmico y del Cuaternario: una discusión basada en los marcos climático, tectónico y paleogeográfico

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Abstract

Playas represent evaporitic environments, which are mainly controlled by precipitation, evapotranspiration and elevation. They are well represented on the current Earth and were widely developed on the Permian Pangaea as well, although their geographic distribution was different. First, the present paper deals with a clarification in the definition of the relatively confused notion of playa or *alkali flat* including both geomorphological and geological aspects illustrated by field experience carried out in Tunisia, Tibet and Oman. Then, we discuss the link between playas, climate and tectonics, with its palaeogeographical implications, using a comparison between the current belts (Alps, Himalaya, etc.) and the Appalachian-Variscan-Uralian-Mongolian belt, the development of which lasted until the Late Permian for the younger segments. Some tectonic problems are put into light such as the role of orogen as climatic barrier and the importance of large-scale strike-slip faulting.

Keywords: Permian, Climate, Tectonics, Playa, Mountains belts, Escape tectonics

Resumen

Las playas representan ambientes evaporíticos que están controlados básicamente por la evaporación, evapotranspiración y la elevación. Están bien representados en la actualidad en la Tierra y también lo estuvieron en Pangea, durante el Pérmico, aunque su distribución geográfica era diferente. La primera intención del presente trabajo está en la clarificación del relativamente confuso término de playa o *alkali flat*, incluyendo los aspectos geomorfológicos y geológicos basándonos en la experiencia llevada a cabo en Túnez, Tíbet y Omán. Seguidamente discutimos la relación entre playas, clima y tectónica, con sus implicaciones paleogeográficas, utilizando comparaciones entre los cinturones tectónicos actuales (Alpes, Himalaya, etc.) y el cinturón de los Apalaches-Varisco-Urales-Mongol, cuyo desarrollo se prolongó hasta el final del Pérmico en sus segmentos más jóvenes. Se sacan a la luz algunos problemas tectónicos tales como la barrera climática producida por el propio orógeno y la importancia de la fracturación de tipo desgarre a gran escala.

Palabras clave: Pérmico, Clima, Tectónica, Playa, Cadenas Montañosas, Tectónica de escape

1. Introduction

A major effort is under way to reconstruct past climatic changes to help predict physical and biologic responses to climate. The planet Earth is already experiencing the impacts of these changes on biodiversity, freshwater resources and local livelihoods. Glacier melting, sea-level rise and desertification in the tropical regions (Fig. 1) are the major problems to be solved. For the study of global climate, the interest of the Late Carboniferous to Permian time-span (Ludwig, 1988; Fluteau *et al*., 2001; Chumakov and Zharkov, 2003) and this from the latest Permian to Early Triassic as well (Kiehl and Shields, 2005; Woods, 2005) has been emphasised. The tectonic influence on climate has been evidenced either during Carboniferous to Triassic times (Oyarzun *et al*., 1999) or simply for the Late Carboniferous to Early Permian interval (Glover and Powell, 1996). Fluteau (2003) provided with an extended synthesis for the Phanerozoic. More recently, Roscher and Schneider (2006) synthetized the climate setting of the Late Carboniferous and Permian, considering some major geodynamic aspects such as the closure of the Rheic ocean. Moreover, they proposed for the Variscan orogen a lower elevation (about 2000 m) than previously assumed (Becq-Giraudon and Van den Driessche, 1994).

The Late Carboniferous-Permian-Early Triassic times record the transition from a cold interval, approximately ending during the Early Permian (Table 1), characterised by repeated periods of extensive glaciation and deglaciation affecting the southern Gondwana, to a warm-climate interval, prolonged during the whole Mesozoic and a major part of the Cenozoic until the Quaternary cold events. The most extensive Phanerozoic glaciation lasted about 90 My and its termination occurred during the Sakmarian on the southern border of the Gondwana supercontinent (Visser, 1993).

Consequently, Late Carboniferous to Early Permian has been considered as the best available analogue to the Recent (DiMichele *et al*., 2001). During that period, Laurasia and Gondwana became welded together to constitute the supercontinent Pangaea rimmed by a broad and unique watermass, the Panthalassic ocean or Panthalassa (Fig. 2). Recent advances in palaeogeographic reconstructions ask for reconsidering the global tectonic evolution (Scotese, 2001; Stampfli and Borel, 2002; Torsvik and Cocks, 2004). A major worldwide geodynamic event, the Variscan orogeny *sensu lato*, culminated during the Permian. From the Visean onward, mantle-derived activity indicated lithosphere thinning and post-orogenic crustal extension (Lorenz and Nicholls, 1984; Matte, 1986; Bonin, 1998; Stampfli *et al*., 2002). The European segment, the so-called Variscan belt *sensu stricto* or Hercynian belt, was formed by the collision of Gondwana and Laurasia. This sketch is complicated by the subduction of the north-western Palaeotethys along an active margin. The major collisional effects ceased during the Late Carbonif-

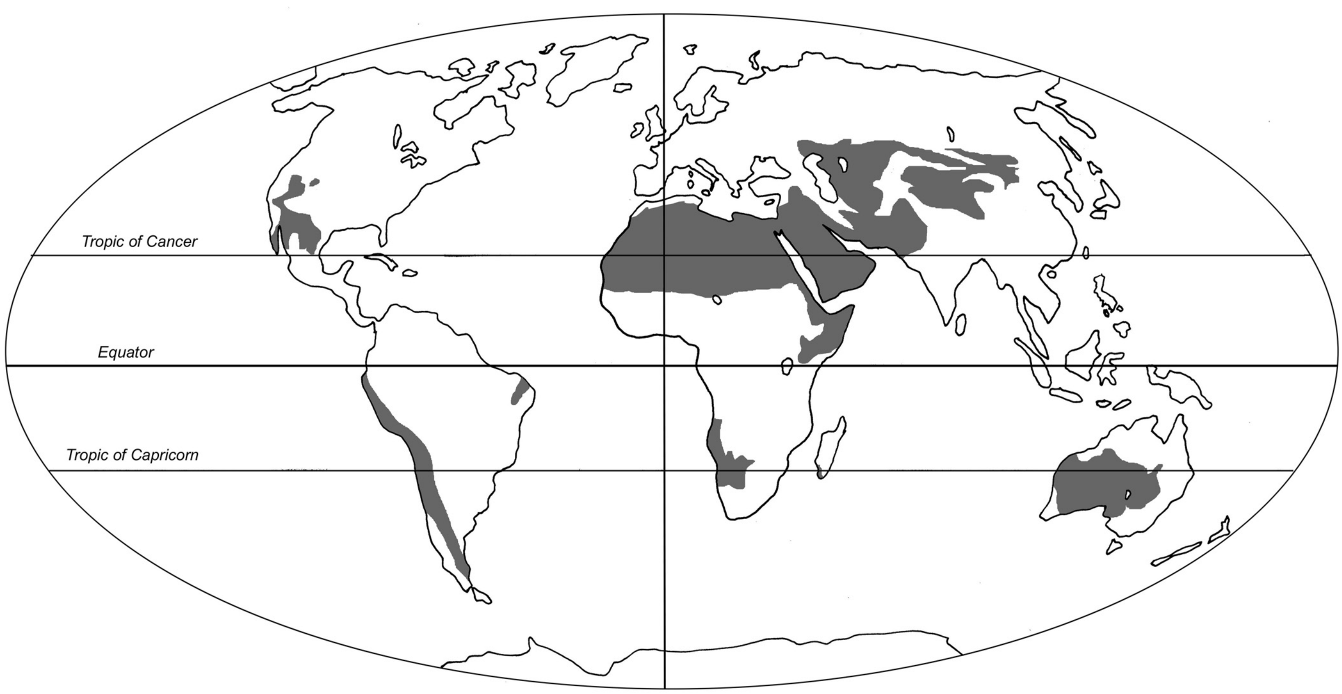

Fig. 1.- Current arid regions of the world (rainfalls less than 200mm/year).
Fig, 1.- Zonas áridas en la actualidad en la Tierra (con precipitaciones inferiors a 200mm/año).

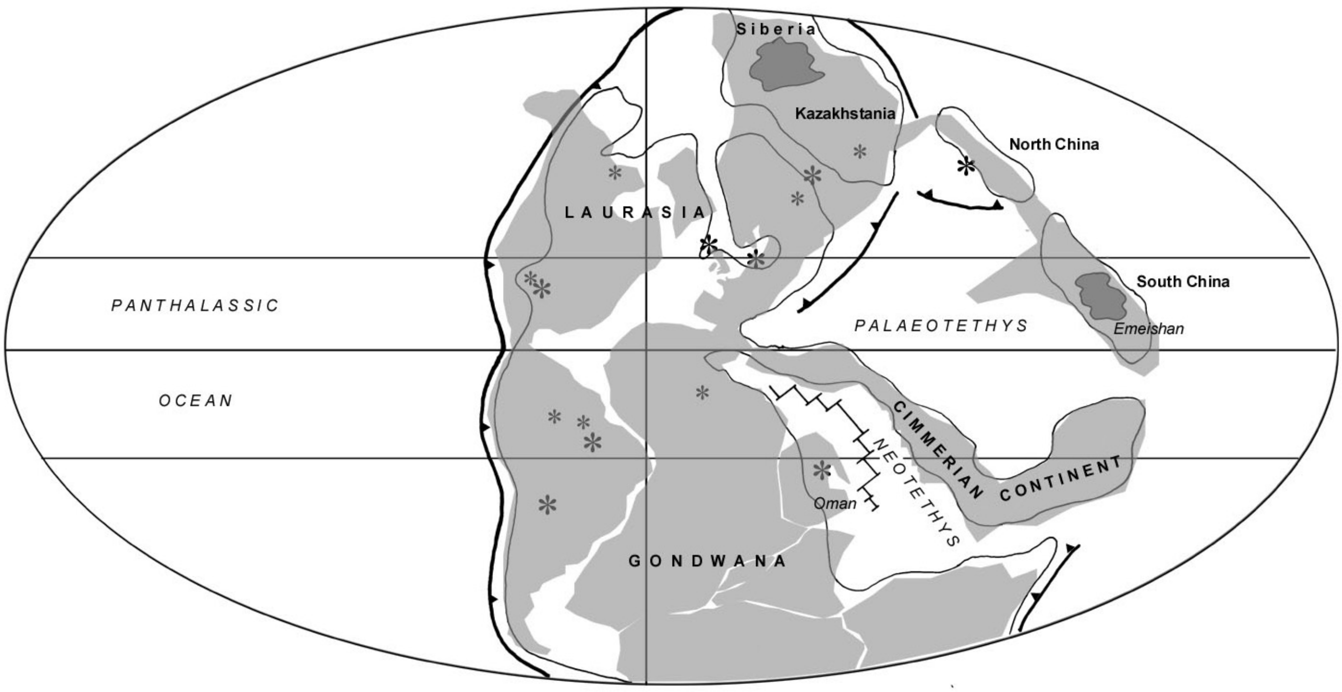

Fig. 2.- Late Permian palaeogeography. Siberia and Emeishan traps are represented in dark grey. * (small stars) Early Permian evaporites. ∗ (large stars) Late Permian evaporites. The Permian palaeogeography is consistent with Pangaea A.

Fig. 2.- Paleogeografía del Pérmico Superior. Los vulcanismos de Siberia y Emeishan están representados en gris. * (asteriscos pequeños) evaporitas del Pérmico Inferior. ∗ (asteriscos grandes) evaporitas del Pérmico Superior. La paleogeografía es consistente con el modelo de Pangea A.

erous. During the Permian, the Scythian belt was formed (Natal'in and Şengör, 2005), Laurasia-Kazakhstan collision produced the Uralian belt (Matte, 2002), whereas Kazakhstan and Eastern Siberia led to the Central Asian belt (Nikishin *et al*., 2002; Van der Voo *et al*., 2006), also named Altaids or Mongolian belt. These events culminated during the Middle Permian. Some tectonic movements occurred also during the Late Permian, particularly in eastern Eurasia. In the Alleghanian orogeny (Hatcher, 2002), the major tectonic activity occurred first in the Early Carboniferous (Mississipian) with the closure of the eastern Rheic ocean due to the collision of Gondwana and part of North America and, second, between the Late Carboniferous (Pennsylvanian) and the Early Permian, more precisely the Late Sakmarian, with the collision of South America and southern North America, forming the Ouachitas. The Gondwanan segment or 'Mauritanides' is less known and time-constrained. One other problem is the place of North Gondwana (current Africa) and the transition from the Alleghanides to the Eurasian Variscides. Indeed, in northern Africa the chronology of the Late Palaeozoic tectonics is not well established such as in the Moroccan Meseta and also in the Anti-Atlas where there is a lack of Late Carboniferous and Permian deposits (Burkhard *et al*., 2006).

Therefore, during the Middle Permian, there is probably a worldwide culmination of the orogenic deformations for the Phanerozoic (Khain and Seslavinsky, 1992; see also Table 1). Granitization appears as a major geodynamic marker for the Middle and Late Permian, particularly in America and Asia. The opening of the Neotethys initiated also during the Early Permian (Fig. 2), characterised by the drift of the Cimmerian blocks (Cimmerian continent?) from the Gondwana toward the northern margin of the Palaeotethys (Ziegler and Stampfli, 2001; Stampfli and Borel, 2002).

The global aridity of the Permian and Triassic Pangaea, including some high latitude areas, could be explained by the particular distribution of land- and watermasses. Geochemical variations of unusual amplitudes occurred during the Permian (Scheffler *et al.*, 2003) and particularly at the Permian-Triassic boundary interval (PTBI) (Baud, 2005). Geochemical elements, such as oxygen or sulphur, show extreme negative or positive excursions, revealing major changes on the continent and in the ocean where the general circulation should be affected (Winguth and Maier-Reimer, 2005). This unique Phanerozoic setting ended with the major biological crisis close to the PTBI.

The present paper focuses on playas. This typical landform could be easily defined in the present-day arid and

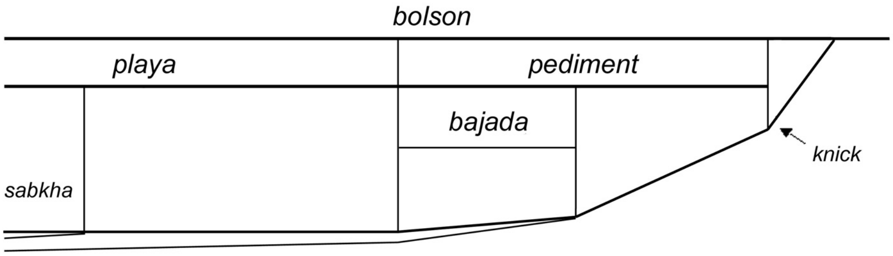

Fig. 3. Morphology of the bolson landform including both playa and pediment (after Demangeot and Bernus, 2001, modified).

Fig. 3.- Morfología de "bolson landform" incluyendo tanto la playa como el pedimento. (Modificado de Demangeot y Bernus, 2001).

semi-arid landscapes. Ancient playa environments are more difficult to decipher, although they have been documented in a number of places of different stratigraphic ages. One of the oldest playa is probably that identified by Simpson *et al*. (2004) in the Palaeoproterozoic of South Africa. Playa facies have been proposed for Uppermost Neoproterozoic (Vendian) deposits of Svalbard (Fairchild and Hambrey, 1995). Generally, a few examples of saline pan deposits has been described in the Precambrian. On the contrary, playa mudflats, perennial lakes and ephemeral stream environments are very common in the 'Old Red Sandstones' (Devonian) (*e.g*., Clarke and Parnell, 1999). After the Carboniferous, a stratigraphic system poor in playas, the Permian and Triassic are conversely the richest in that kind of environment. However, playas still remain relatively rare in the Early Permian, for example in the Salagou Fm of the Lodève basin, Nahe Subgroup of the Saar basin or the Hornburg Fm of the Saale basin (Schneider and Gebhardt, 1993; Schneider *et al*., 2006), and in the Orobic Alps (Cassinis *et al*., 1986; Cadel *et al*., 1996). Permian playas develop in the middle Early Permian (Schneider and Gebhardt, 1993; Roscher and Schneider, 2006) and become more and more common in the Middle and Late Permian (Gand *et al*., 1997; Freytet *et al*., 1999) and in the Triassic (*e.g*. Paul and Peryt, 2000). More generally, during the Permian the widening of closed drainage areas on land reduced the transport of organic and mineral nutrients to seas (Chumakhov and Zharkov, 2003). Playa environments are also very common from the Jurassic (Spalletti and Piñol, 2005) to the Present, a period characterised by global temperate climate conditions. Since the amalgamation of almost all continental terranes into the Pangaea supercontinent, plate tectonics radically altered the distribution of landmasses. Regional climates developed, and current arid conditions prevail in tropical areas but also close to the equatorial regions, such as in Peru, NE Brazil, Somalia, Kenya etc. (Fig. 1).

As a result of their low density and high solubility, evaporites play key roles in some geological processes and particularly in the crustal deformation. Sometimes, thick Permian evaporitic sequences could be recognised, such as in the Zechstein sea (Langbein, 1987; Hryniv and Peryt, 2003), but their marine origin is clear and only some paralic facies could be considered as actual playas such as in the Late Permian of NE England (Turner and Smith, 1997). Using the example of Chott el Djerid, Tunisia, Bryant *et al*. (1994) have shown that as an ephemeral lake shrank, brine produced could be similar to modern sea water. Thus, evaporites alone can not be considered as the evidence of playa, as illustrated by the evaporites of the Messinian crisis, which are linked with evaporation in a deep basin-shallow water model (Rouchy and Caruso, 2006) and do not indicate playa environments.

2. The playa environment

2.1 The current playas and their setting

The Spanish name *playa*, which literally means 'beach', was initially used in Mexico and U.S. Southwest (*e.g*. Hamilton, 1951). This morphology, also named 'alkali flat' or 'salt pan', describes a flat-bottom depression periodically covered by water (Fig. 3). This water could either slowly filtrate into the ground water system or evaporate into the atmosphere, both causing the deposition of evaporites, sand, and mud as well. Briere (2000) stipulates that a playa, as a discharging intracontinental basin, remains dry at least 75% of the year. Typical sites of playa environments are known at Black Rock Desert in Nevada and the Bonneville Salt Flats in Utah. Nevertheless, alkali flats are very common, particularly in the driest regions of Asia such as the Qaidam Pendi or Qaidam desert in Western China (Fig. 4B), in Southern America and particularly in the Atacama desert (Flint, 1985; Hartley and Chong, 2002; Hartley, 2003), in the arid regions

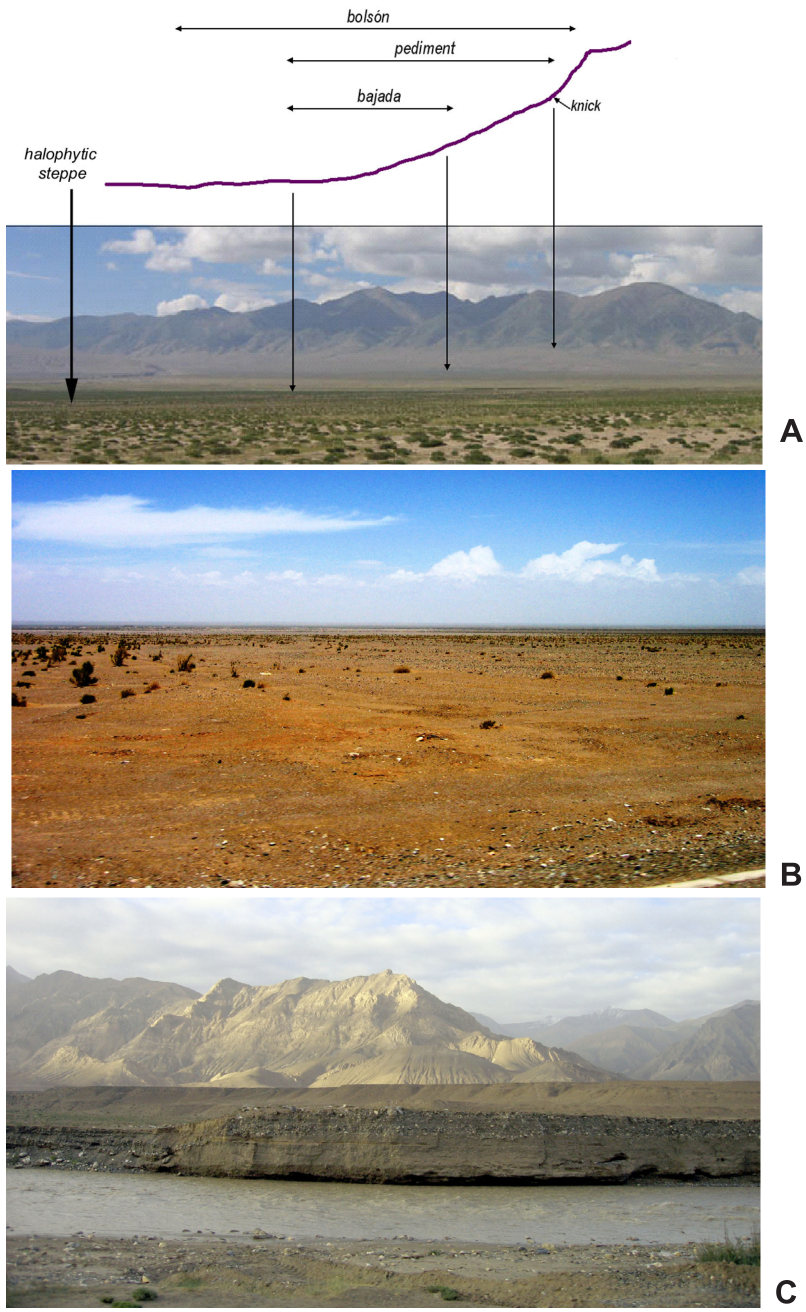

Fig. 4.- Photographs of the Qinhai Province (China). A. Playa landform. Example near Ngola Shan between Qaka and Gaxun (Qinhai Province, China). B. Playa with sabkha in the background. Eastern Qaidam Pendi (Qinhai, China), region of Dulan (Qaganus).C. Alluvial deposits (mainly conglomerates) in front of the Kunlun belt (Naij River), region of Golmud (Kerno).

Fig. 4.- Fotografías de la Provincia de Qinhai (China). A. Extensión de playa. Ejemplo cerca de Ngola Shan, entre Qaka y Gaxun (Provincia de Qinhai, China). B. Playa con sabkha al fondo. Al este de Qaidam Pendi (Qinhai, China), región de Dulan (Qaganus). C. Depósitos aluviales (principalmente conglomerados) frente al cinturón de Kunlun (río Naij), región de Golmud (Kerno).

of Australia – the Lake Eyre Basin, including much of the landmass of arid inland Australia drains into it, is the largest modern endorheic system in the world (Magee *et al*., 2004) – in the Middle East and in northern Africa. They also exist in temperate zone, for example at Laguna de Playa in the central Ebro basin, NE Spain.

Therefore, playas or alkali flats constitute large zones of aggradation in semiarid or arid regions. The flat-floored desert depression, usually centred on the playa and surrounded by mountains, is named bolson, from the Spanish *bolsón,* which means 'large purse' (Fig. 3). Basically, it is necessary to consider the playa as a whole, including the bolson (Fig. 4A). This type of basin characterises *Basin-and-Range* structures. If developed under certain conditions of aridity, the centre of the playa could be occupied by a shallow intermittent endorheic lake, the so-called sabkha lake, sometimes but inadequately named playa lake. Some authors consider that sabkha – or sebkha – would be marine influenced, whereas playa would be only continental (*e.g*., Bates and Jackson, 1987; Briere, 2000). For us, this definition is inappropriate because some typical current sabkhas, such as the 'Sebkha Mekerrhane', Algeria, are far away from the sea (see also Fig. 6). According to seminal works (*e.g*., Coque, 1962) we consider here the sabkha as the centre of the endorheic system. Some evaporite-free coastal playas, the so-called khabras, are linked with variations of the sea level, in Eastern Oman for example. Others are related to the dissolution of continental salts, such as the Zone of Chotts in Tunisia (chott meaning 'shore' in arabic).

In the salt pan, evaporites are deposited due to the concentration by evaporation of natural solutions of salts (Warren, 1999). Such areas consist of fine-grained sediments including colloids and clays infused with alkali salts. The least soluble salts (calcium and magnesium carbonates) precipitate first, on the outside of the pan, followed by sodium and potassium sulphates. Finally, in the centre of the playa, sodium chlorides, potassium chlorides, and magnesium sulphates are deposited. Associated to sodium chlorides, sodium and potassium carbonates could be concentrated in alkali sabkha lake, such as the current Lake Magadi in the Eastern Rift Valley, Kenya. The most common minerals are halite, gypsum (or its water-depleted form, the so-called bassanite), anhydrite, primary dolomite, and sodium sulphates. While the alkali flat itself will be devoid of vegetation, flats are commonly ringed by salt-tolerant plants, forming a halophytic steppe, the famous 'chott' *stricto sensu*. Therefore, the vegetation-free character indicated by Bates and Jackson (1987) is not relevant for defining a playa.

Some of the present-day playas obviously suffer a tectonic influence. For example, the Zone of Chotts, region of the Presaharian Tunisia, is situated in a series of tectonically controlled depressions that lie between the Atlas Mountains and the Saharan Platform, along a structural line, the so-called *Sillon Tunisien* or Tunisian trough, linking the Tripolitania trough, Libya, to the East, to the Chott Merouane-Chott Melrhir, Algeria, to the West (Burollet, 1991). In such areas, subsidence phenomena are superimposed to the evaporation and deflation processes. Nevertheless, evaporite deposits are not necessarily linked with tectonics (Rouchy *et al*., 2001). For example, elevation and strong evaporation could explain the presence of the famous Salar of Uyuni in the Bolivian Altiplano. *Salar* means salt pan in Spanish and, therefore, is equivalent to sabkha. In addition, hypersaline systems are known in current polar regions.

Finally, it should be emphasised the interest of the playa as a palaeoenvironmental marker. This landform characterises the aridity of the area under investigation, any extrapolation in terms of palaeolatitudes being more difficult.

2.2. The Permian playas

2.2.1. Evidences and location of the Permian playas

Permian times represent not only a key period for understanding the Late Variscan tectonic evolution (*e.g*. Khain and Seslavinsky, 1992; Nikishin *et al*., 2002; Deroin and Bonin, 2003), but also for studying palaeoclimates (*e.g*. Fluteau *et al*., 2001; Roscher and Schneider, 2006). During the Permian and the Triassic as well, a worldwide development of deserts could be emphasised in a number of Pangaean places. But, whereas arid facies should be inferred, real playa environment are sometimes difficult to evidence. If evaporites are used as markers for the Permian playas, the following regions should be cited: Southern America, South-West north America, Central Asia, etc. (Fig. 2).

2.2.2. America

Some authors have depicted the North American equatorial region as predominantly everwet. Nevertheless, as early as 1964, Briden and Irving recognised eolian sandstones and evaporites in the western equatorial Pangaea. Equatorial aridity during Early Permian has been specifically dealt with by Kessler *et al*. (2001) and shifts in Late Palaeozoic atmospheric circulation in that region have been documented by Tabor and Montañez (2002). A synthesis of the Permian facies of the USA has been done by Mazzullo (1995). In Texas, coastal sabkha and salt pan deposits have been inferred by Handford (1981). More recently, Dickson *et al*. (2001) working in West Texas examined Late Permian continental calcite and saddle dolomite cement. This cement has $^{87}Sr/^{86}Sr$ values lower than those known for contemporaneous marine carbonates. This is interpreted by the authors as the evidence of the presence of hypersaline brine during diagenesis. Anderson and Dean (1995) and Kirkland *et al*. (2000) detailed some aspects of the evaporitic series in the Late Permian of the Delaware Basin. Benison and Goldstein (2000) studied the sedimentology of ancient Permian saline pans in North Dakota. Acid saline lake deposits have even been proposed as analog of the Martian strata (Benison, 2006). In Arctic North America, Beauchamp (1995) has also emphasised the importance of evaporitic deposits.

In Southern America, part of Gondwana, Permian evaporites are frequent, particularly at the top of the Late Paleozoic, for example in the Upper section of the Paganzo Group, Argentina (Limarino *et al*., 2006). The Permian-Triassic sedimentary facies have been correlated with both tectonics (Zerfass *et al*., 2004) and palaeoenvironment (Zhang *et al*., 1998).

2.2.3. Eurasia

In Europe, there is a considerable amount of references concerning Permian geology (*e.g*., Cassinis *et al*., 1995; Cassinis, 2001; Virgili *et al*., 2006). These numerous references include the seminal works using the French (Autunian, Saxonian, Thuringian) and German termi-

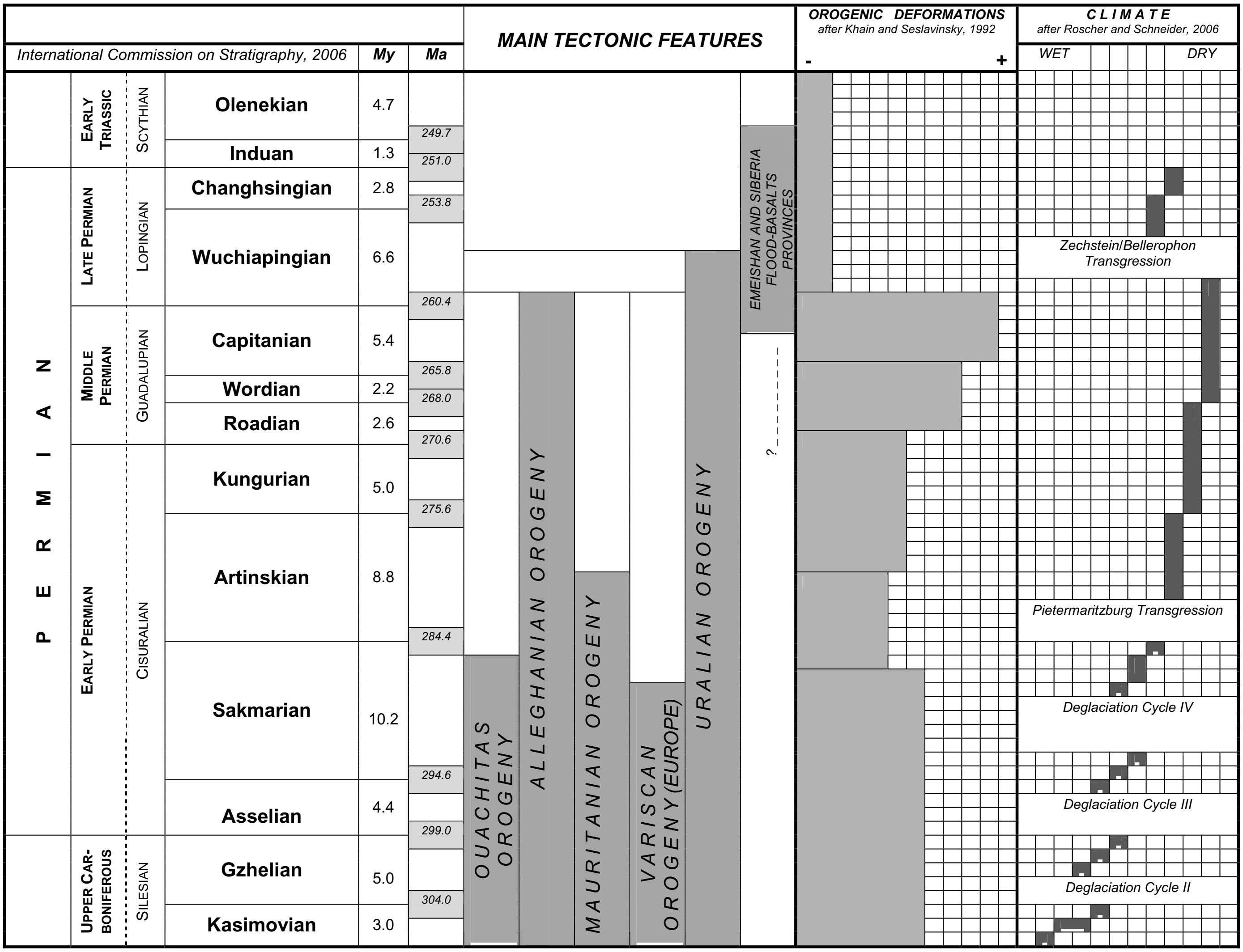

Table 1. Stratigraphy of the Permian (according to the Subcommission on Permian Stratigraphy, 2006) and main tectonic and climatic events.
Tabla 1. Estratigrafía del Pérmico (según la Subcomisión Estratigráfica del Pérmico, 2006) y los principales eventos tectónicos y climáticos.

nology (Rotliegende, Zechstein). Facies such as the so-called 'Saxonian' and 'Zechstein' characterise the continental and marine shallow-water facies, respectively. In the same areas, Late Triassic is the realm of large-scale evaporites (Keuper). It exists an old and general consensus about the existence of wet conditions during the very Early Permian continuing palaeoenvironments developed during the uppermost Carboniferous. With the north oriented drift of Laurasia, Europe suffered tropical conditions as early as the Guadalupian and until the PTBI. Driest facies appeared in the Middle (Guadalupian) and Late Permian (Lopingian). For example, the Uppermost Dethlingen and Hannover Formations (Capitanian-Wuchiapingian according to Schneider *et al*., 2006) represent an evaporitic playa mud flat environment with associated perennial playa lake and salt flats. The facies distribution is the result of a complex interplay of climate and tectonism. The recent synthesis by Schneider *et al*. (2006) also precises that several short phases of increased humidity could temporarily interrupt the general trend, especially during the Wuchiapingian (lower part of the Lopingian) as well (Table I). These phases could correspond to the last pulses of the major Permo-Carboniferous glaciation.

The Early and Middle Permian are uniquely represented by continental deposits. In France for instance, most of the Permian basins show evidence of arid environments (Chateauneuf and Farjanel, 1989, Deroin *et al*., 2001). Nevertheless, in Europe evaporites are rare. It is possible to mention the Eisenach Formation (Kungurian-Roadian) of the Thuringian Forest Basin, Germany, or the Chotěvice Formation (Kungurian) of the Krkonoše-piedmont Basin, Czech Republic (Schneider *et al*., 2006). The same trend could be described in Spain (Arche and López-Gómez, 2005), British Islands, Germany (Roscher and Schneider, 2006), Italy (Cassinis, 2001) and particularly Sardinia (Pittau and Del Rio, 2004), North Sea (Martin *et al*., 2002), the Czech Republic, Poland, Bulgaria (Yanev, 2000), Russia, Ukraine, etc., where "New Red Sandstones" characterised Late Palaeozoic intracratonic basins.

Playa facies are generally devoid of any biostratigraphical indicative fossils, but tetrapod footprints, and also insects, concostracans, plant remains, etc. appear in places very common. Such a sedimentology and palaeontology as well are consistent with dry conditions during the Middle Permian (Guadalupian). Playa environment dominates and is associated with aeolianites and rare evaporites. Thus, no large-scale evaporitic deposits are known in the Cisuralian and in the Roadian as well. On the contrary, Wordian and Capitanian (Upper Rotliegend II) and Zechstein present a great amount of marine evaporites especially in the Southern Permian Basin, which extended from England to North Germany and Poland, and in the Zechstein Sea. Legler *et al*. (2005) have shown that the mega-playa system of the central Southern Permian Basin has been temporary flooded by marine ingressions. Evaporites are also frequent in central Eurasia (Chuvashov, 1995) and largely developed in the eastern regions such as the Kungurian deposits of the Precaspian basin, Kazakhstan (Barde *et al*., 2002).

In the higher latitudes of Eurasia, the same sketch as been reported from the Norwegian-Greenland sea area (Stemmerik, 1995) and in the Barents shelf area as well (Stemmerik and Worsley, 1995). Therefore, from the Middle Permian onward, arid conditions prevail. These conditions characterised also the Triassic times as illustrated in the Early Triassic of the Thuringian sub-basin of the Germanic basin, where carbonate sedimentation took place in a playa lake environment with variable salinities (Paul and Peryt, 2000).

Rotliegend sequence stratigraphy in the Southern Permian Basin suggests climatically forced fluctuations in the level of an expanding playa lake system (Gast, 1991, Kiersnowski *et al*., 1995). The associated facies changes define essentially isochronous sequence boundaries. Spectral analyses of gamma ray logs have indicated that individual sequences display internal cyclicity consistent with orbital (Milankovitch) forcing. Confirmatory results have been reported from the spectral analysis of field logs from the continental Permian Brodick Beds of the Isle of Arran, England (Bailey, 2001).

2.2.4. Africa

In Northern Africa, the situation is very similar to that encountered in Spain or France (Medina, 1996; Hofman *et al*., 2000). Elsewhere in the North African craton, the same type of environment prevailed (Sidor *et al*., 2005). No Permian evaporites are known in southern Africa. Nevertheless, the Karoo supergroup perfectly illustrates the changes between a cold and semi-arid climate during the Late Carboniferous-earliest Permian interval to warmer and eventually hot with fluctuating precipitation during the most of Permian times (Stollhofen *et al*., 2000; Burgoyne *et al*., 2005).

3. Geochemical particularities of the Permian times

A number of studies evidence extreme geochemical conditions during Permian times and particularly at the Permian-Triassic boundary interval (PTBI). These geochemical variations could be related to major global changes leading from icehouse to hothouse conditions, probably mainly caused by a drop in atmospheric CO_2 to about five times present levels (Berner, 2006a), even if some authors argue that low atmospheric levels prevailed (Beerling, 2002). This Late Permian drop was brought about mainly by a decrease in the burial of terrestrial derived organic matter, but also with a possible contribution from the weathering of older organic matter on land (Berner, 2006b). The Early Triassic time is characterised by a quite different biological activity, and particularly the absence of large metazoan reefs. More generally, carbon isotopes provide interesting information for the continent landmass and for the marine environment as well (Krull *et al*., 2004).

Although a major attention has been placed on the PTBI where rapid environmental changes may occur, a longer period spanning at least 4 My also experienced a series of evolutionary events as evidenced by numerous extinctions and recoveries of terrestrial animals or plants (McAllister Rees, 2002; McAllister Rees *et al*., 2002; Burgoyne *et al*., 2005). In the meantime, multiple extinctions of marine organisms occurred and a sustained oceanic anoxia prevailed. In the aftermath of the major extinction, the fossils are characterised by an incredibly small size (Twitchett, 2006). It is noteworthy to consider the development of halotolerant bacteria at about 250 Ma (Satterfield *et al*., 2005).

The dramatic negative excursion of the rate in $\delta^{34}S$ in the Late Permian is probably related to the extent of evaporites. High O_2 environment could have altered canopy transpiration rates and thefore water-use efficiency during the Permo-Carboniferous (Beerling and Berner, 2000). More generally, decreased $\delta^{18}O$ revealed as early as the Early Permian is generally interpreted as a decrease in rainfalls. Nevertheless, increased CO_2 seemed to be the

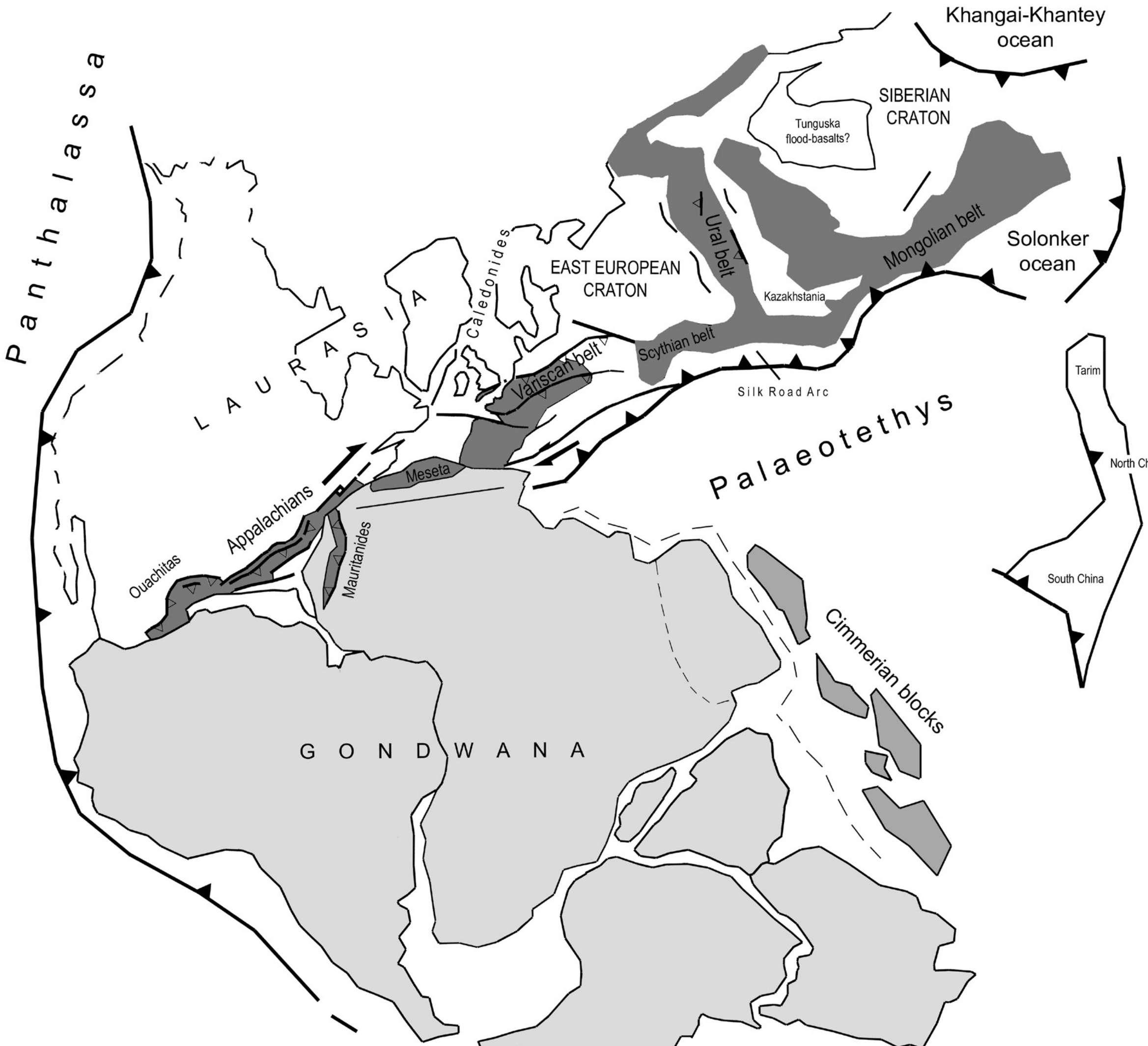

Fig. 5. The Appalachian-Variscan-Uralian-Mongolian belt during the Early Permian (about 275 Ma). Note that Tunguska flood-basalt Province should appear as early as the Early Permian. Permo-Triassic Silk Road Arc, Khangai-Khantey and Solonker oceans are indicated according to Natal'in and Şengör (2005).

Fig. 5.- El cinturón de los Apalaches-Varisco-Urales-Mongolia durante el comienzo del Pérmico (275 m.a. aprox.). Tener en cuenta que los basaltos de la provincia de Tunguska aparecerían con el comienzo del Pérmico. El Arco permo-triásico de *Silke Road* y los océanos de Khangai-Khantey y Solonker están localizados basados en datos de Natal'in y Şengör (2005).

main parameter and evidenced the rapid episode of plant die-off (Smith, 1995). To explain such an increase in Permian atmospheric CO_2 different hypotheses have been proposed. The role of the volcanic activity (flood basalts), particularly that of the Siberian (Tunguska) and Emeishan traps, has been emphasised (Fig. 2) (Bin He *et al*., 2007). If this hypothesis is correct, it should be noticed that the CO_2 increase appeared as early as the Early Permian. In fact, there is few Early Permian datings for this volcanic activity and if developed from the Cisuralian onward, the traps were probably limited. A more general influence of the extensional tectonics as outgassing and CO_2-releasing source should be taken into account.

4. Comparison between the Appalachian-Variscan-Uralian-Mongolian belt and the Alpine-Himalayan belt

4.1. Palaeogeography

A consensus exists regarding the presence of a mainly Palaeozoic ocean North of the Cimmerian continent, the Palaeotethys (Fig. 5), a younger late Palaeozoic-Mesozoic ocean located South of this continent, the Neotethys, and finally a middle Jurassic ocean, the Alpine Tethys, an extension of the central Atlantic ocean in the western Tethyan regions. Additional Late Palaeozoic to Mesozoic oceans complicate somewhat this relatively simple picture. Therefore, there are still some confusions about what Tethys existed at what time. The classical Pangaea A is consistent with field data and also with the supposed plate arrangement of the Jurassic prior to the onset of the Atlantic ocean (Scotese, 2001; Stampfli and Borel, 2002). Palaeomagnetic measures have led to the Pangaea B hypothesis, Gondwana landmass being in an about 3000 km more eastward position with respect to Laurasia (Irving, 1977). As a contribution to solve that problem, Muttoni *et al*. (1996, 2003) proposed an evolution from an Early Permian Pangaea B to a Late Permian Pangaea A. From the geodynamic point of view, a large westward displacement of Gondwana could be explained by the dextral strike-slip régime during the Late Palaeozoic (Arthaud and Matte, 1975, 1977; Shelley and Bossière, 2002). As an illustration for France, this large-scale dextral shearing brought together, from the one hand the Ligerian (French Massif Central) and Aquitaine terranes and, from the other hand the Armorican (Brittany) terrane (Stampfli *et al*., 2002). The dextral strike-slip is indicated by arrows in Figure 5. During post-Early Permian to Triassic this movement is more difficult to advocate. In the Variscan belt of Western Europe, for example, the dominant strike-slip regime along west-east faults is mainly sinistral and the strike-slip is probably slower than during the previous period. This movement appears later, during the Triassic, in the Russian platform (Ruban and Yoshioka, 2005). However, the problem of relating the movement along the Palaeotethyan major shear zone (active margin) and the deformations along the other shear zones has already been addressed (Lawver *et al.*, 2002). It remains difficult to consider a 3000 km-displacement during the Late Carboniferous-Permian? having no other field marker than palaeomagnetism.

4.2. Analogies

First studies in the 1970's have quoted resemblance between the Variscan and the Himalayan belts, particularly concerning the type of thrusting (Mattauer and Etchecopar, 1977). Whereas early stages of an orogen's exhumation history are generally obscured in the belt itself by later tectonics and erosion, late events are theoretically simpler to illustrate. In that way, the comparison between the geometry of the Variscan belt of Western Europe and the Himalayas (Burg, 1983) or the Basin and Range Province (Malavieille, 1993) has been envisaged. Thus, some similarities between the pattern of strike-slip faults and thrusts in the Ibero-Armorican and West-Himalayan virgations have been emphasised (Matte, 1986). Some attempts have been made to compare the orographic setting of the Tibet Plateau and the French Massif Central (Becq-Giraudon and Van den Driessche, 1994). It seems interesting to extent the comparison between the orogenies using the location of the playas, actually observed for the current ones, simply suggested by the geological records for the Permian ones.

At the current Earth surface, it exists a more or less continuous belt line from the Atlantic ocean to the Far East (Fig. 6). Around the Mediterranean sea, the Alps, Apennin, Dinarides, Hellenides, Taurides and Pontides are linked to the Tethyan Cenozoic tectonics. To the East, the major event is the continent-continent collision between India, one part of the former Gondwana, and the south-eastern margin of Eurasia. This collision is in progress since about 55 My and produced the major current orogen, the Himalayas. Nevertheless, other belts have been laterally produced by the collision, for example the Hindu Kush and Pamir. One particular aspect of the India-Eurasia collision is the presence of a large plateau, the so-called Tibet Plateau, the mean elevation of which is about 4500 m. The Tibet Plateau suffered a polyphased evolution. It is bordered on its north-western edge by a large sinistral strike-slip fault, the Altyn Tagh fault, which is still very active (Fig. 7B).

'Tectonic escape', 'extrusion tectonics' or 'lateral extrusion' have been proposed for the last tectonic developments either in Tibet (Tapponnier *et al*., 1986) or in the Alps (Ratschbacher *et al*., 1991). The identification of such a tectonics in the Variscan belt is still debated and represents a challenge for a better understanding of the orogen. Nevertheless, escape tectonics has been proposed by Vauchez *et al*. (1987) to explain the dextral strike-slip in the southeastern Appalachian and the sinistral strike-slip in the western Senegal-Mauritania (Mauritanides) provinces. In the European Variscan belt (Fig. 7A) some major faults could be related to escape tectonics such as the Bray Fault, the Cévennes Fault, a number of faults in southern Iberia, etc. The role of the Tornquist Suture, possibly reactivated during the Late Palaeozoic movements, is not clear. In Figure 7A, dextral late strike-slip movements are clearly put into light by the displacement of the Armorica terrane bordered to the north by the Avalonia terrane and, to the south, by the Galicia-South Brittany suture.

Currently, typical playas could be observed in the Qinhai Province of western China between the Kuku Nor (Lake Kuku) and the northern border of the Altyn Tagh sinistral strike-slip fault. These correspond to the Qaidam Pendi (Fig. 4B) with other occurrences in the Taklamakan (Fig. 7B). This latter is China's largest and driest desert. In Qaidam Pendi and Taklamakan as well, basins lack drainage and salt has accumulated over large areas. The

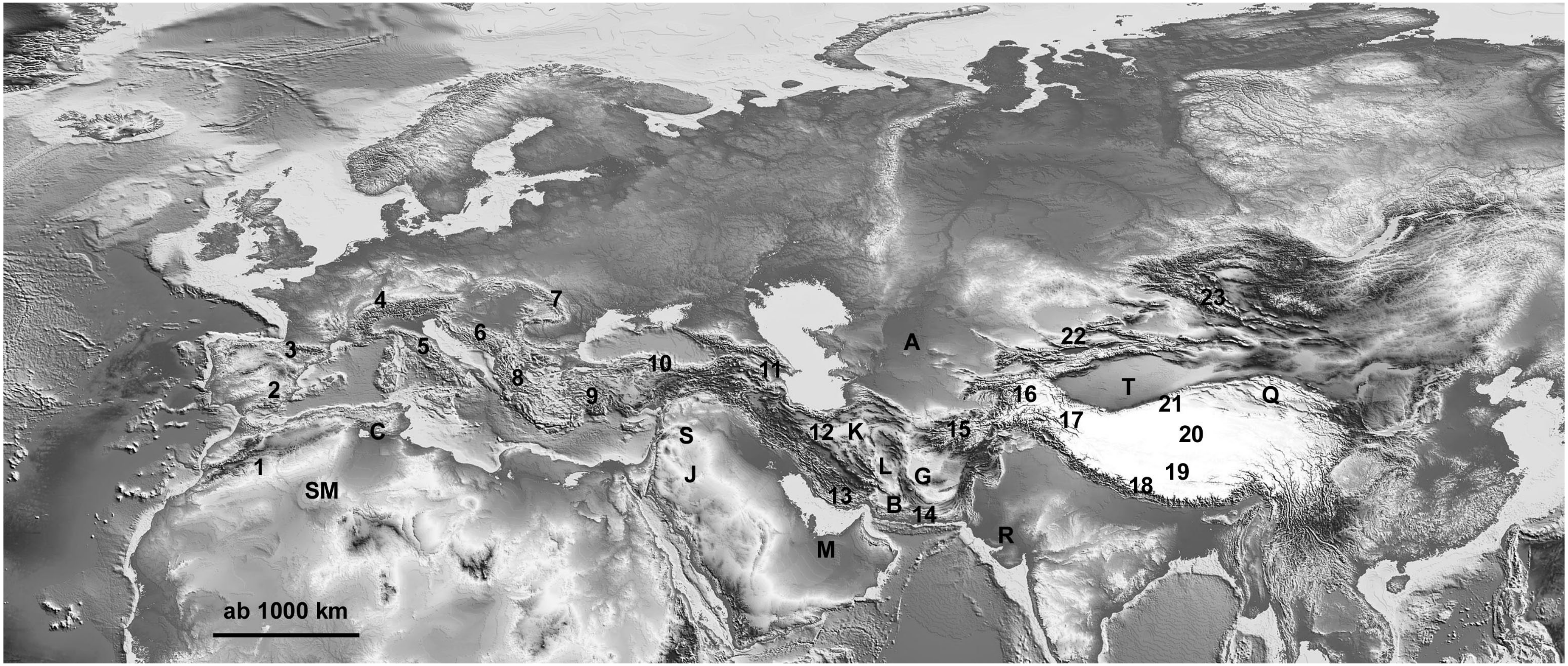

Fig. 6. The current tectonic belts from the Atlantic ocean to Asia. The background is a synthesis of the worldwide digital elevation model realized by the Shuttle Radar Topography Mission (SRTM, NASA). Numbers refer to the main belts: 1. Anti-Atlas, 2 Betics, 3. Pyrenees, 4. Alps, 5. Apennin, 6. Dinarides, 7. Carpathians, 8. Hellenides, 9. Taurides, 10. Pontides, 11. Caucasus, 12. Elburz, 13. Zagros, 14. Makran, 15. Hindu Kush, 16. Pamir, 17. Karakorum, 18. Himalaya (Great Himalaya Range), 19. Nyainqentanghla, 20. Tanggula, 21. Kun Lun, 22. Tien Shan, 23. Altai. The Tibet Plateau extends between no18 and no21; the 'Roof of the World' appears in white. Letters refer to the main present-day salt flats and endorheic systems: A. Aral Sea (Kazakhstan and Uzbekistan), B. Baluchistan (Pakistan), C. Zone of Chotts (Tunisia and Algeria), G. Gowd-e-Zereh (Afghanistan), J. Qâ-al-Jafr (Jordan), K. Dasht-e-Kevir (Iran), L. Dasht-e-Lut (Iran), M. Sabkhat Matti (United Arab Emirates), Q. Qaidam Pendi (Qinhai, China), R. Rann of Kutch (Great Indian Desert, Gujarat, India), S. Syria, SM. Sebkha Mekerrhane (Algeria), T. Taklamakan (Xinjiang, China).

Fig. 6.- Los cinturones tectónicos actuales desde el Atlántico hasta Asia. La información es una síntesis realizada del modelo digital de toda la Tierra llevada a cabo por *Shuttle Radar Topography Mission (SRTM, NASA)*. Los números se refieren a los principales cinturones y las letras a las principales llanuras de sal y sistemas enorreicos actuales.

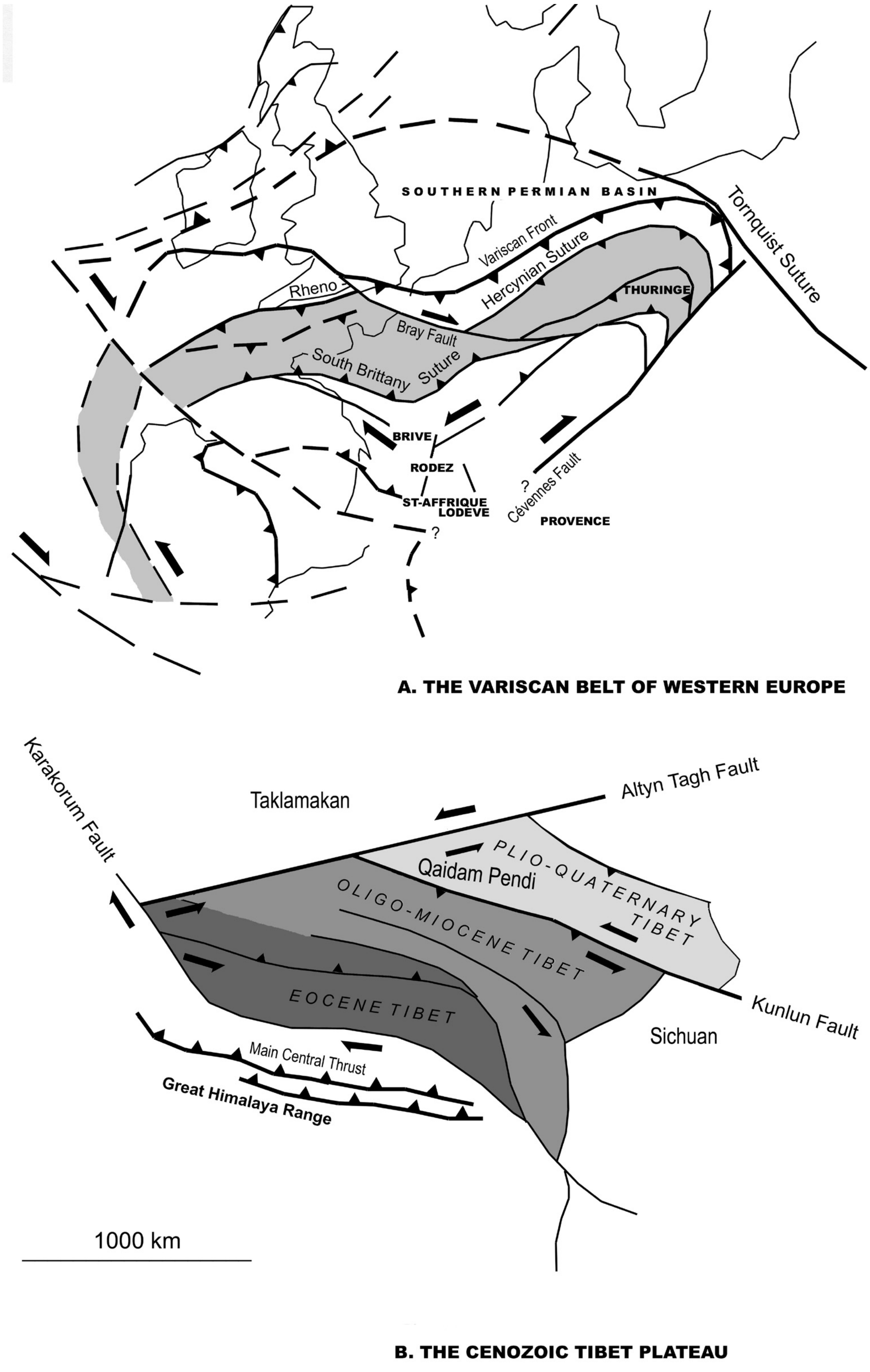

Fig. 7. Comparison between A: The Variscan belt of Western Europe (after Matte, 2002, modified) and B: The Cenozoic Tibet plateau (after Tapponnier *et al.*, 2002, modified). In Figure 7A, grey tones represent the extent of the Armorica terrane.

Fig. 7.- Comparación entre A: El Cinturón Varisco del Oeste de Europa (modificado de Matte, 2002), y B: La Plataforma Tibetano cenozoica (modificado de Tapponnier *et al.*, 2002). En la Figura 7, los tonos grises indican la extensión del área de Armórica.

Qaidam basin has been undergoing continuous shortening since the beginning of the Cenozoic and show good synchroneity with uplifting history of the Qinhai-Tibet Plateau (Wenchen *et al.*, 2001). It has a rhombic shape, largely due to the strike-slip tectonics, and an area of about 120 000 km² with a mean elevation of 3000 to 3500 m a.s.l. It suffered a relatively weaker Cenozoic deformation than that of the deformed surrounding area in the northeastern edge of the Qinhai-Tibet Plateau (Zhou et al., 2006). Due to their setting, Taklamakan and Qaidam Pendi are cut off from the effects of the Asian monsoon. In such areas, playas rich in evaporites are common. In addition, between the Qaidam Pendi and the Kunlun piedmont, a complex system of playas, endorheic basins, and braided rivers surprisingly recalls what should have occurred during the erosion of the Variscan belt associated to coarse sediments such as sandstones and conglomerates (Fig 4C).

5. Discussion

Playas are relatively rare at the current Earth surface. They are concentrated in isolated areas where arid conditions prevail, principally in Qinhai-Tibet, Central Asia, the Middle East and northern Africa (Fig. 6). From the tectonic point of view, it is necessary to take into account the bolson, which is a better marker than the playa itself. The bolson delineates large and elongated zones of aggradation such as the current Qaidam Pendi. Such areas could be linked with escape tectonics. Moreover, evaporites could characterise the central part of the morphological system, the so-called sabkha, but they are not necessarily present in the current systems and preserved in the old ones. Such morphologies were developed in the Valley and Ridge Province of the Appalachians and in the Ouachitas as well. Due to the Alpine deformation, the view is not so clear in the Asian segments of the Variscan orogeny where evaporites are common.

The current dispersion of the landmass results in a great number of local climatic barriers and, therefore, to different playa types: elevated in the Andes, close to the sea – and possibly below the sea level such as in Algeria – in the Zone of Chotts, linked with endorheic basin in Lake Eyre, etc. Playas from the US Southwest and those from China are closely linked to present-day belts. They are probably closer analogues to the Permian playas than others.

In southern stable Europe (Fig. 7A), *i.e.* southern France, the Provence, Lodève, Saint-Affrique, Rodez and Brive Permian basins contain the most developed playas with a special emphasis on the Lodève basin. All these basins are separated from the Variscan Front by the Massif Central. It is interesting to note that in the current Tibet Plateau the younger unit, Plio-Quaternary in age, the so-called Qaidam Pendi rich in playa environments, is in the same structural position with respect to the Main Central Thrust of the Himalayas (note that the vergence of the Variscan and Himalayan main thrusting is opposite). There is a centrifugal zonation of the Tibetan units lasted since about 55 My (Fig. 7B). This time period could more or less represent the latest stages of the orogeny, *i.e.* Late Carboniferous-Early Permian for the Variscan one. For the Tibetan Plateau this sketch is complicated by large-scale strike-slip faults and the link with other further tectonic features (Baikal rift, Altai, etc.). Moreover, the Tibet plateau is still uplifting, whereas the Variscan orogen's uplift probably stopped during the Late Carboniferous. Therefore, the situation during the Late Variscan time with the amalgamation of all the landmasses into the Pangaea was clearly different. Nevertheless, it is possible to suggest that the basins of southern France were parts of an isolated area forming a structural unit at the southwestern edge of the Massif Central and bordered by large-scale strike-slip faults. The largest Permian playa system, the Southern Permian Basin, was in a quite different tectonic setting characterized by thermal subsidence.

A question arises: was the Late Variscan belt more or less continuous? The large Appalachian-Variscan-Uralian-Mongolian belt comprised some dependencies: Ouachitas, Mauritanides, Moroccan Meseta, Scythian belt, Altaids (Fig. 5). The entire belt was comparable to the present 'Alpine' belt starting from the north African Atlas, and joining the Alps, Dinarides, Taurides, Causasus, Penjab, Himalayas, etc. (Fig. 6). Clearly, these are the results of diachronous and different types of collision: continent/continent (Himalayas), progressive shortening collapse of narrow oceans (Alps, Dinarides), etc. Between the different segments, it exists large corridors of lowlands or sea. The timing of each orogeny could be very variable and short as recently illustrated by Dewey (2006), particularly if arc/continent collisions are concerned – this is probably the case for the Scythian belt and also for the Permian far eastern orogenies affecting the southeastern margin of Eurasia and exotic blocks (Tarim, North China, etc.).

The study of the Permian and Triassic times, particularly the tectonic setting of a number of intramountainous basins, indicates a transition from plate tectonics to continental tectonics (Molnar, 1988). There are only rare occurrences of Permian oceanic deposits such as in Oman Mountains. Therefore, the palinspastic reconstructions should be elaborated only with isolated pieces. Some of the pieces of this gigantic jigsaw considerably derived, such as the Cache Creek terrane of the Canadian Cordillera recently interpreted as accreted seamounts that originated close to the eastern Tethys ocean (Johnston and Borel, 2007). The major problem is to consider the transition from the crustal thickening as a syn-collisional effect, and the gravitary collapse clearly post-collision and possibly related to basin and range extensional structures. It should be noticed that the valleys and ridges of the Appalachians present some affinities with the basin and range structures.

The problem of gravitationary collapse has been discussed for the Tibet Plateau and the Variscan orogeny as well (Becq-Giraudon and Van den Driessche, 1994). But as already mentioned, the European Variscides are probably formed as early as the Late Carboniferous and are not representative of the entire Late Palaeozoic belt, the maximum development of which is situated in the late Early Permian and, most probably, in the Guadalupian (Khain and Seslavinsky, 2002).

6. Conclusions

The Late Carboniferous and earliest Permian is represented by worldwide coal basins – even at high latitudes. Progressively, arid conditions appeared and dominated in the Middle Permian (Guadalupian), with a large development of playas even close to the equator. From a palaeoenvironmental viewpoint, during the Late Permian (Lopingian) and the Early Triassic as well the most important feature is a major carbon lack, with no more reefs in the ocean and no more coal deposits in the continental basins. The entire planet Earth has been dramatically altered: atmospheric composition, general water circulation, chemistry of the oceans, etc. This is mainly due to the geodynamic setting, the existence of the large Appalachian-Variscan-Uralian-Mongolian belt modifying a lot of parameters. Low $^{87}Sr/^{86}Sr$ values observed until the PTBI illustrate the fact that erosion is a continuing phenomenon during the entire Permian and the Triassic as well. Moreover, the widening of closed drainage areas on land reduced the transportation of organic and mineral nutrients to seas. A dramatic negative excursion of the rate in $\delta^{34}S$ during the Late Permian could be related to the extent of evaporites, particularly in the Southern Permian Basin. This resulted in a great climate change and finally by the major biological crisis of the Phanerozoic, which is not necessary concentrated at the PTBI boundary but begins a few My before.

The understanding of the evaporites and, more generally, of the Permian and Triassic playa environments with respect to the geodynamic evolution would require a better knowledge of the palaeogeography from the one hand, and of the geometry of the orogens, particularly their elevation, from the other hand.

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