About the origin of the northern hemisphere Pacific arcs

Bernadí GELABERT, Francesc SÀBAT, Antonio RODRÍGUEZ-PEREA and Joan J. FORNÓS

SHNB

SOCIETAT D'HISTÒRIA NATURAL DE LES BALEARS

Gelabert, B., Sàbat, F., Rodríguez-Perea, A. and Fornós, J.J. 2001. About the origin of the northern hemisphere Pacific arcs. *Boll. Soc. Hist. Nat. Balears,* 44: 119-128. ISSN 0212-260X . Palma de Mallorca.

We present here a new hypothesis that relates the timing of global plate tectonics and the formation of the marginal basins, island arcs, spreading ridges and arc-shaped mountain belts located at the northern hemisphere Pacific ocean. According to our model, the ellipsoidal-shaped Paleogene basins of South China Sea, Parece-Vela, Shikoku, Japan, Kuril and even North American Cordillera (the Paleogene extensional phase) formed due to the termination of oceanic subduction beneath the India-Eurasia collision zone. This "lock-up" produced a net increase in horizontal stress trasmitted throughout the entire northern hemisphere Pacific ocean, which resulted in widespread extension adjacent to the eastern margin of Eurasia and western margin of North America. Both margins are linked by a maximum circle parallel to the Indian-Eurasian direction of convergence.
Keywords: *marginal basins, island arcs, Pacific, plate convergence, extension-compression.*

SOBRE L'ORIGEN DELS ARCS A L'HEMISFERI NORD DEL PACÍFIC. Es presenta una nova hipòtesi que explica la formació de les conques marginals i els arcs d'illes existents a l'hemisferi nord de l'oceà Pacífc. D'acord amb el nou model les conques paleògenes del Mar de Xina, Parece-Vela, Japó, Kuril i també la Serralada dels EUA, es varen formar degut a l'acabament de la subducció oceànica a la zona de col·lisió India-Euràsia. Aquest "tancament" va donar lloc a un increment en l'esforç horitzontal que va ser transmés al llarg de tot l'hemisferi nord de l'oceà Pacífic, produint extensió al marge oriental d'Euràsia i a l'occidental de Nord Amèrica. Ambdós marges es poden unir mitjançant un cercle màxim paral·lel a la direcció de convergència entre Índia i Euràsia.
Paraules clau: *conques marginals, arcs d'illes, Pacific, convergència de plaques, extensió-compressió.*

Bernadí GELABERT, Antonio RODRÍGUEZ-PEREA and Joan J. FORNÓS; Departament de Ciències de la Terra, Universitat de les Illes Balears, Balears, Spain, 07007; Francesc SÀBAT; Departament de Geodinàmica i Geofísica, Universitat de Barcelona, Barcelona, Spain, 08028.

Recepció del manuscrit: 29-oct-01; revisió acceptada: 24-des-01.

Introduction

Despite the origin of back-arc basins has been widely debated (Royden, 1993; Doglioni, 1993; among others) it is unclear why some subduction zones should remain static over long periods of geological time, forming relatively simple linear mountain chains, and others such as those of the western Mediterranean and the western Pacific are very mobile, become arcuate, and lead to the formation of complex orogens.

The aim of this paper is to answer that question proposing a new model of back-arc basin and arcuate folded belt formation and apply the model to the geodynamic evolution of the northern Pacific ocean. Our basic model (Fig. 1) is based in the nucleation of two opposite subductions along deep, parallel and almost vertical faults, with an extend to at least the brittle-ductile transition zone, which separates lithospheric units with different density. These steep faults are tipically normal or strike-slip faults; at passive margins the main extensional faults are parallel to the boundary between the continental and oceanic crust, forming long and narrow crustal "pieces" (Fig. 1a). At convergent plate boundaries (Fig. 1b), the orogenic belts are also very long and narrow in the horizontal dimension and research during the past two decades has shown that synorogenic normal faults are common in the hinterlands of contractional orogenic belts. Examples include the Quaternary normal faults in southern Tibet (Armijo *et al.,* 1986), the High Andes (Suarez *et al.,* 1983), Taiwan (Crespi *et al.,* 1996) and the Miocene detachment system in the Higher Himalaya (Burchfiel and Royden, 1985). Also at the hinterland of the orogenic belts, steep thrust faults usually exists. Then, at the continental margins or close to the margins, long, thin, flexible, plastic/elastic units, bounded by steep faults, exists.

If the plate convergence is parallel to this faults (Fig. 1 3a), the plastic/elastic fault bounded units, open at right angles to the convergence vector adopting an arcuate shape, with thrusting in front of the bowed-out units and the extensional (oceanic or continental attenuated crust) basin opening between the separating parts. Initially, extension is due to upper crustal collapse to fill the void caused by arc migration. Arc migration produces a horizontal push at the subducting (and denser) plates, which is responsible for the roll-back of the subducting plates. Asymmetric extension in the central basin and asymmetric subduction (usually only the subduction at the oceanic side of the former margin develops) appears controlled by the physical properties (e.g. density, thickness, length, elasticity) of the former fault-bounded lithospheric units.

The deformation of the margin can be more complex (Fig. 1 3b & 3c): in an intermediate elastic unit adopts a sigmoidal shape, two marginal basins with two new spreading centers formed obliquely to the main shortening direction. Two island arcs formed at the outer part of the arcs and a central sigmoidal island arc is located in between the two marginal basins. The subduction zones are dipping in a direction opposite to the direction of propagation of the compression out of the arcs.

This new proposed mechanism can be thought of as a case in which horizontal stresses acting on the short edges of long, thin, elastic blocks cause buckling of the blocks in the x-y plane and a "space problem" that must be accommodated by formation of ellipsoidal-shaped (marginal or back-arc) basins. Some sort of quantitative analysis will eventually be required, not in the context of this paper, to determine whether such "stiff pieces" of plate can be buckled in the manner we discuss.

The Western Pacific and the Cordilleran Foreland Fold and Thrust Belt: India versus Eurasia and North America

In an equatorial Mercator projection, the northern Pacific ocean seems to have two independent margins: the Asiatic and the north American margins (Fig. 2). But if we look at the earth globe (orthographic projection), both margins can be linked with a maximum circle oriented SSW-NNE (Fig. 3), parallel to the convergence direction, since Late Eocene times (42 M.a.), of the Indian and Eurasian plates.

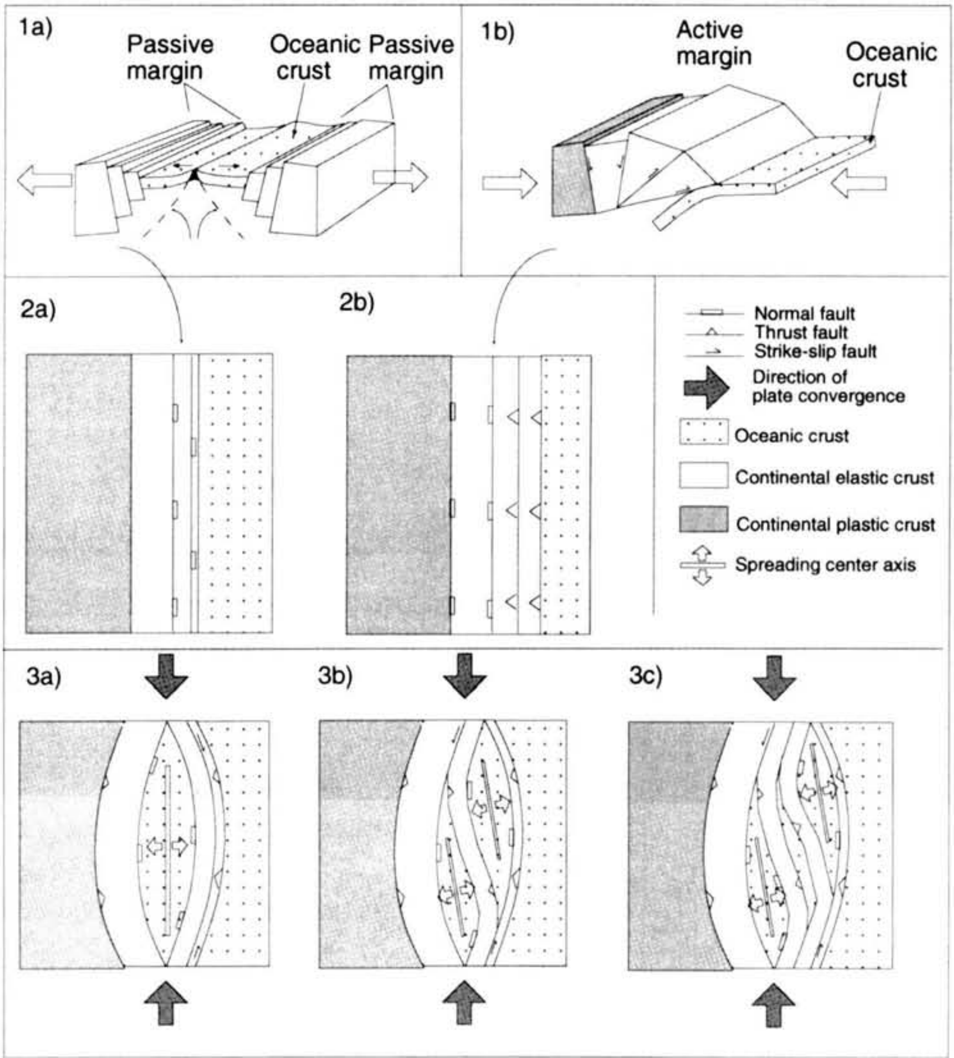

Fig. 1. 1a and 1b) Simple models of passive and active margins. 2a and 2b) Top view of the passive and active margins. 3a, b and c) If the direction of plates convergence is parallel to the fault-bounded units of the previous margin, these will bow-out at right angles to the convergence direction, producing arc-shaped belts and ellipsoidal extensional basins. More explanation in the text.

Fig. 1. 1a i 1b) Models esquemàtics de marge passiu i marge actiu. 2a i 2b) Vista aèria dels marges passiu i actiu. 3a, b i c) Si la direcció de convergència de les plaques és paral·lela a les unitats limitades per falla del marge previ, aquestes s'obriran formant un arc en una direcció perpendicular a la direcció de convergència, produint cinturons de muntanyes en forma d'arc i conques extensional de forma el·lipsoidal.

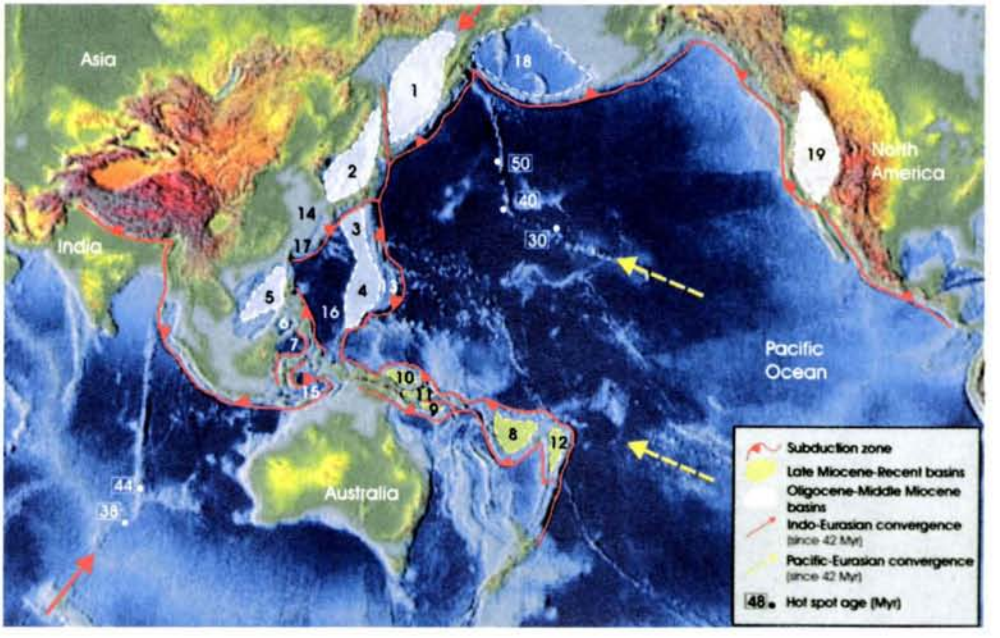

Fig. 2. Present day tectonic features of SE Asia and SW Pacific. 1. Kuril basin, 2. Japan Sea, 3. Shikoku basin, 4. Parece-Vela basin, 5. South-China sea, 6. Sulu basin, 7. Celebes basin, 8. North Fiji basin, 9. Woodlark basin, 10.Bismarck Sea, 11. Solomon Sea, 12. Lau basin, 13. Mariana trough 14. East China Sea, 15. Banda basin, 16. West Philippine basin, 17. Okinawa trough, 18. Aleutian basin, 19. American Cordillera

Fig. 2. Trets tectonics més importants del SE d'Àsia i del SW del Pacífic. 1. Conca Kuril, 2. Mar del Japó, 3. Conca Shikoku, 4. Conca Parece-Vela, 5. Mar del S de Xina, 6. Conca Sulu, 7. Conca Celebes, 8. Conca North Fiji, 9. Conca Woodlark, 10. Mar de Bismarck, 11. Mar de Solomon, 12. Conca Lau, 13. Fosa Mariana 14. Mar de l'E de Xina, 15. Conca Banda, 16. Conca de l'oest de les Filipines, 17. Fosa d'Okinawa, 18. Conca Aleutiana, 19. Serralada Americana.

The boundary between the Pacific and the Eurasian and North American plates is composed of a series of ellipsoidal basins and arcuate mountain belts or island arcs, with a roughly N-S or NNE-SSW orientation formed during the Oligocene-middle Miocene times: Kuril (Burk and Gnibidenko, 1975), Sea of Japan (Isezaki, 1975), Shikoku (Watts and Weissel, 1975), Parece-Vela (Mrozowski and Hayes, 1979), South China (Taylor and Hayes, 1980) and Sulu (Hamilton, 1979) basins. Even at the Cordilleran foreland fold and thrust belt, located at the boundary between Pacific and North-American plates, with a NNW-SSE main orientation (parallel to the eastern margin of Asia- Fig. 3), a complex ellipsoidal basin develop during Oligocene-Middle Miocene times: according to Constenius (1996), the Cordilleran fold and thrust belt collapsed and spread to the west during a middle Eocene to early Miocene (ca. 49-20 Ma) episode of crustal extension (Constenius, 1996), with growth of metamorphic core complexes and regional magmatism (McQuarrie and Chase, 2000).

We think that this Oligocene-Early Miocene episode of ellipsoidal-shaped basin formation was propably triggered by the termination of oceanic subduction beneath the India-Eurasia collision zone 43 M.a. ago (Longley, 1997). This "lock up" the spreading system in the Indian

Ocean and caused a major plate reorganization not only in the Indian Ocean but also in the Southern and Pacific Oceans (Patriat and Achache, 1984). Dewey *et al.* (1989) and Packham (1996) divide the India-Eurasia collision into three major phases: these authors proposed that between 42 Myr and 30 Myr, India-Eurasia convergence was taken up by the commencement of stacking of northern Himalayan thrust sheets and thickening of the Tibet crust to 70 km elevating it to 3 km by 30 Myr. In the second phase, after 30 Myr when the Tibetan

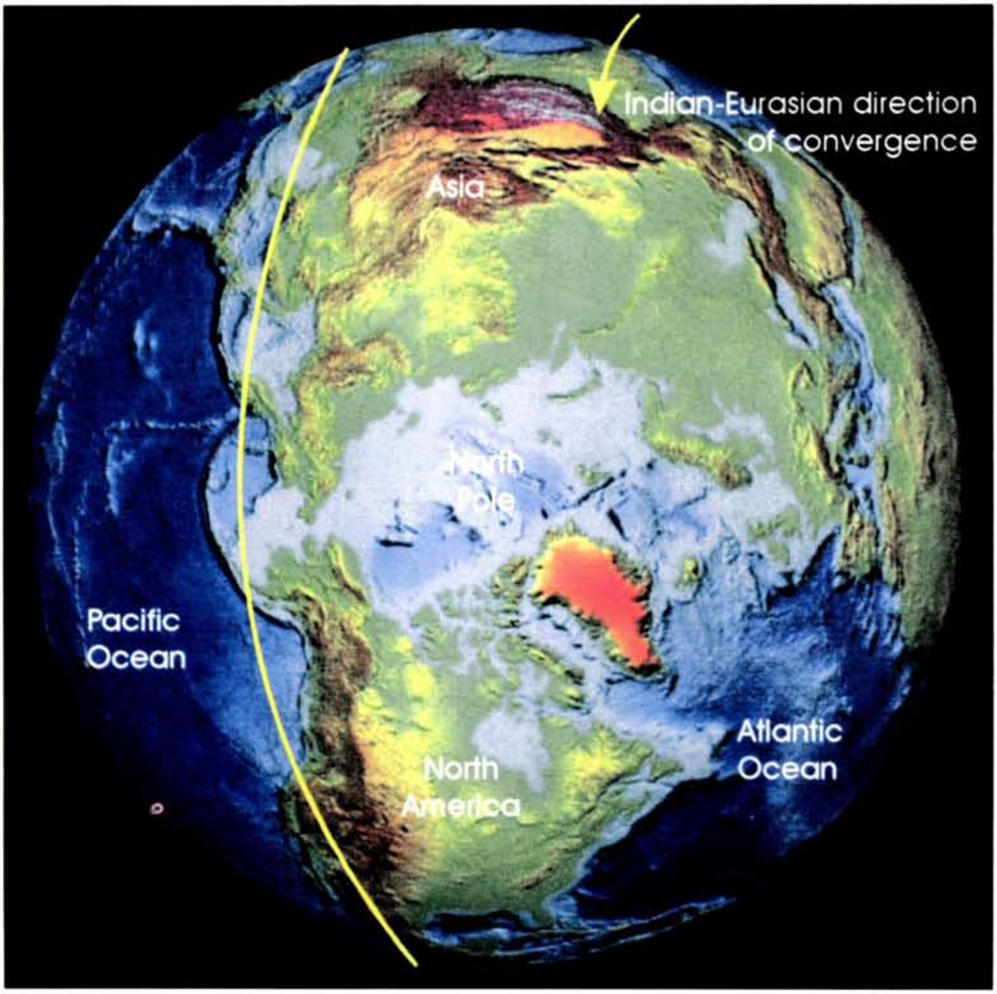

Fig. 3. In an orthographic projection the Asiatic and North American margins of the Pacific ocean can be linked with a maximum circle oriented parallel to the convergence direction, since Late Eocene time (42 Myr) of the Indian an Eurasian plates.

Fig. 3. A una projecció ortogràfica els marges asiàtic i americà de l'oceà Pacífic es poden unir mitjançant un cercle màxim orientat paral·lelament a la direcció de convergència, des de l'Eocè (42 M.a.), entre les plaques India i Euroasiàtica.

Plateau had achieved considerably buoyancy, India began to indent Asia, deflecting the Asian sutures and commencing block rotation. The present tectonic regime (or third phase) commenced in middle (15 Myr, aprox.) to late Miocene time; during it some of the convergence was transfered to eastward movement of Tibet relative to the Himalayas and in part to South China as indicated by the early Pliocene commencement of right lateral movement on the Red River fault (Packham, 1996). Elevation of the Tibetan Plateau to its present high was approximately coincident (Harrison *et al.,* 1992). The first and second phases (42 to 15 Myr) produce an increase in horizontal stress transmitted between the Indian and Eurasian plates, because of the nappe stacking and the Indian indentation. Because the horizontal stress is parallel to the former (Eocene-Oligocene) orientation of the eastern margin of Eurasia (see reconstructions of Hall, 1997; Jolivet *et al.,* 1989, amongst others), and according to our model presented before, widespread formation of island arc and marginal basin occurs during the period 42-15 Myr (see table 1) at the western Pacific (Fig. 4.1). At the last phase, convergence is transfered basically to easward movement of Tibet, and then the NNE-SSW horizontal stress between India and Eurasia is greatly reduced, and also marginal basin formation: only the Mariana and the Okinawa basins formed during this last phase of India-Eurasia collision (Fig. 4.2).

Considering the Cordilleran thrust and folded belt, several authors (Coney and Harms, 1984; Malavieille, 1987; Wernicke *et al.,* 1987) have proposed that early Tertiary extensional deformation, characterized by low-angle shear zones in the core complexes, is the result of postorogenic collapse of the Cordilleran crust, thickened in these domains during the Mesozoic to Paleogene compressional tectonic events. Although the crust was significantly thickened in all the Cordilleran domain, several studies (Coney and Harms, 1984; Malavieille, 1987) suggest that the thickening was maximum in a north-south-striking belt localized under the metamorphic core complexes. This assumption seems realistic if we consider the fact that the metamorphic core complexes are situated in the hinterland of the Cordilleran fold and thrust belt exactly where major thrusts are rooted. Our

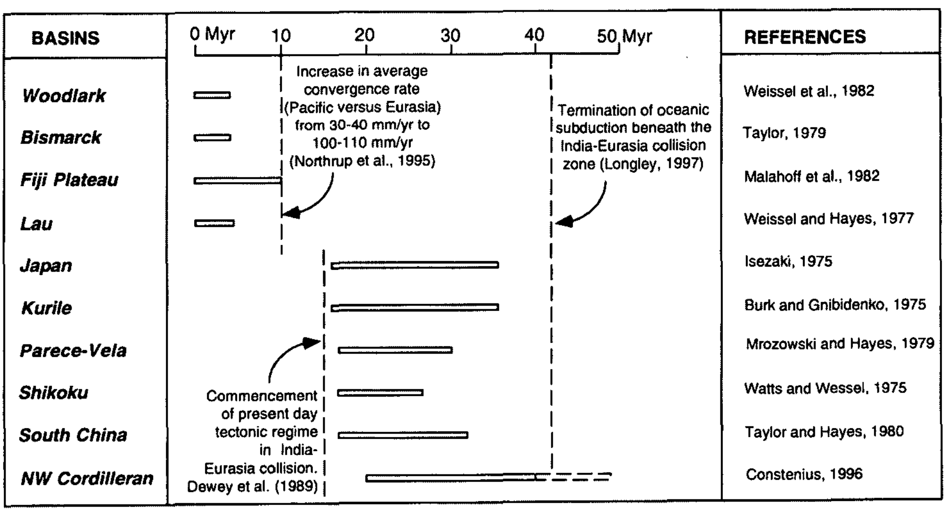

Table 1. Ages of extension at the basins cited in the text.
Taula 1. Edats de l'extensió a les conques citades al text.

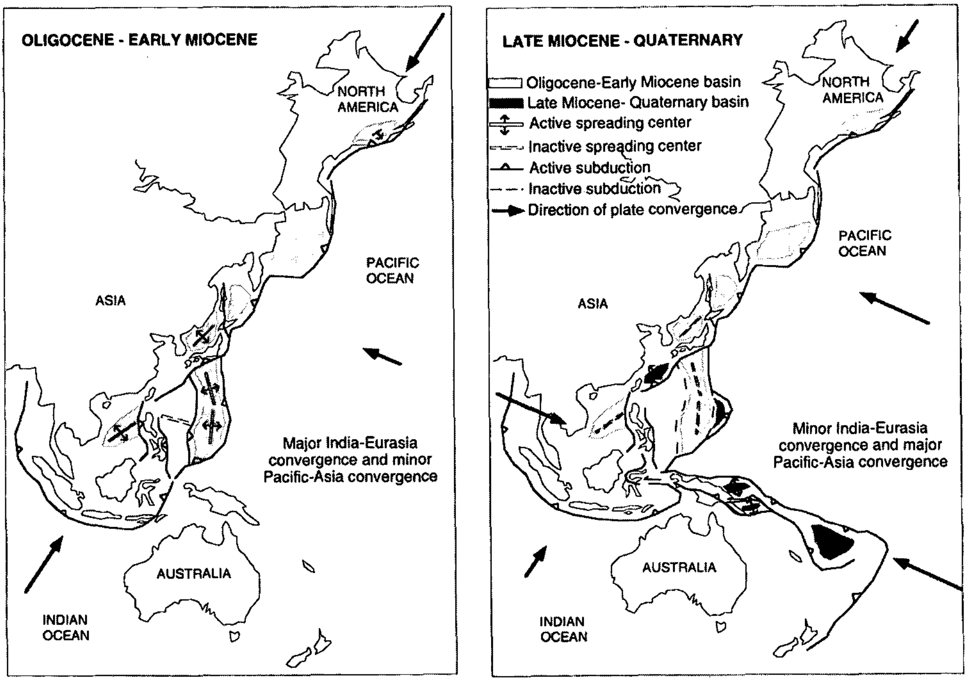

Fig. 4. Tectonic evolution of SE Asia and SW Pacific since Early Tertiary time. Explanation in the text.
Fig. 4. Evolució tectònica del SE d'Asia i del SW del Pacífic, des de l'Eocè. Explicació al text.

hypothesis of ellipsoidal-basin formation explain three important facts: 1) the ellipsoidal shape of the overall paleogene extension at the North-America Cordillera (McQuarrie and Chase, 2000; Suppe, 1985; amongst others) 2) the presence of core complexes in the former position of maximum thickening, due to the presence of steeper thrust faults (susceptible of being bowed-out) at the hinterlands 3) and the fact that not in all positions of maximum thickness, extensional basins develop. As a conclusion, and considering the timing of extension, the overall ellipsoidal shape of the area of extension, and the facts that the Cordillera is aligned with others marginal basins (formed simultaneously) of the western Pacific and that the extension develops at the hinterland of a previous orogen, we suggest that the paleogene extensional phase of the North American Cordillera is a far-field effect of the India-Eurasia collision.

Constenius (1996) and Northrup *et al.* (1995) relates these Oligocene-Early Miocene episode of extension at the Cordillera and eastern margin of Eurasia, respectively, with drops in the rate of plate convergence between the Pacific and Eurasian plates (for the eastern Asia) and Pacific and North-America (for the Cordillera). These hypothesis dont account for the arcuate shape of the island arcs or mountain belts and neither for the ellipsoidal shape of the extensional basins. Furthermore, extension was not restricted to basins along the east-trending strike-slip faults that bound the possibily ejected crustal blocks described by Tapponier *et al.* (1982). It occurred all along the east Eurasian and western North-American , including areas directly in front of the possibly extruded blocks.The strenght of our model, despite the fact of being a two-dimensional model, is that explains the arcuate geometry of the orogens and the ellipsoidal shape of the extensional basins and also the fact that some locations affected by extension along the margin were more than 4000 km distant from the India-Eurasia collision zone (Northrup et al., 1995).

Australasia: Pacific *versus* Australia

The boundary between north Australia and Pacific plates has a general WNW-SSE orientation, which is parallel to the convergence direction between Pacific and Eurasia-Australian plates (Fig. 2). At the diffuse zone boundary between North-Australian and Pacific plate, several marginal, ellipsoidal-shaped basins exists, aligned in a WNW-ESE direction and formed since Late Miocene time: Lau (Weissel and Hayes, 1977), North Fiji basin (Malahoff *et al.,* 1982), Woodlark basin (Weissel *et al.,* 1982) and Bismarck Sea (Taylor, 1979).

An analysis of the motion of the Pacific plate relative to Eurasia reveals a low rate of convergence during early and middle Tertiary time, with a minimum in Eocene time of 30-40 mm/yr; After this period of low convergence, the average convergence rate increased to 100-110 mm/yr from late Miocene time to the present (Northrup *et al.,* 1995). An increased rate of convergence may have been related to a net increase in horizontal compressional stress trasnmitted between the Pacific and Eurasian-Australian plates, which resulted in widespread island arc and marginal basin formation adjacent to the northern continental margin of Australia (Fig. 4.2).

The special case represented in Fig. 1 agress very closely with the map structure of the Bismarck, Solomon, Woodlark islands and the Papua-New Guinea area (Figs. 2 and 4), a complex structural area in which very close opposite subductions (of Pacific and Australian plates) co-exists with the nearby spreading ridges of the Bismarck and Woodlark basins.

Conclusions

We present here a simple model that allows to explain the creation of oceanic (extensional in general) areas in a regional tectonic setting of relative plate convergence. We relate the termination of oceanic crust subduction at the India-Eurasia collision or an increase in the average convergence rate between the Pacific and Eurasian plates with a net increase in horizontal compressional stress, which triggered island arc and marginal basin formation at, respectively eastern Eurasia and northern Australia, because plate convergence was parallel, in both cases, to the previous continental margin.

References

Armijo, R., Tapponnier, P., Mercier, J. L. and Han, T.L. 1986. Quaternary extension in southern Tibet: Field observations and tectonic implications. *Journal of Geophysical Research,* 91: 13,802-13,872.

Burchfiel, B.C., and Royden, L.H. 1985. North-south extension within the the convergent Himalayan region. *Geology,* 13: 43-58.

Burk, C.A., and Gnibidinenko, H.S. 1977. The structure and age of acoustic basement in the Okhotsk Sea; in Island Arcs, Deep Sea Trenches and Back-Arc basins, Maurice Ewing Series, Vol. 1, p. 451-461.

Coney, P.J., and Harms, T. 1984. Cordillerna metamorphic core complexes; Cenozoic extensional relics of Mesozoic compression. *Geology,* 12: 550-554.

Constenius, K.N. 1996. Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt. *GSA Bulletin,* 108(1): 20-39.

Crespi, J., Chan, Y., and Swaim, M. 1996. Synorogenic extension and exhumation of the Taiwan hinterland. *Geology,* 24(3): 247-250.

Dewey, J.F., Cande, S. and Pitman, W.C. III. 1989. Tectonic evolution on the India/Eurasia collision Zone: *Eclogae Geologicae Helvetiae,* 82: 717-734.

Doglioni, C. 1993. Some remarks on the origin of the foredeeps. *Tectonophysics,* 228: 1-20.

Hall, R. 1997. Cenozoic tectonics of SE Asia and Australasia. *In: Petroleum systems of SE Asia and Australasia:* IPA Jakarta, p. 1-13.

Hamilton, W. 1979. Tectonics of the Indonesian region: U.S. Geological Survey Prof. Pap. 1078, 345 pp.

Harrison, T.M. Copeland, P., Kidd, W.S.F. and An Yin 1992. Raising Tibet. *Science,* 255: 1663-1670.

Isezaki, N. 1975. Possible spreading centers in the Sea of Japan. *Marine Geophysical Research,* 2: 265-277.

Jolivet, L., Huchon, P. and Rangin, C. 1989. Tectonic setting of Western Pacific marginal basins. *Tectonophysics,* 160: 23-47.

Longley, I.M. 1997. The tectonostratigraphic evolution of the SE Asia. *In:* Fraser, A.J., Matthews, S.J. and Murphy, R.W. (eds.). *Petroleum Geology of Southeast Asia.* Geological Society Special Publication, 126, p. 311-339.

Malahoff, A., Feden, R. and Fleming, H. 1982. Magnetic anomalies and tectonic fabric of marginal basins north of New Zealand. *Journal of Geophysical Research,* 87: 4109-4125.

Malavieille, J. 1987. Extensional shearing deformation and kilometer-scale "a"-type folds in a Cordilleran metamorphic core complex (Raft River Mountains, Northwestern Utah). *Tectonics,* 6: 423-448.

McQuarrie, N and Chase, C.G. 2000. Raising the Colorado Plateau. *Geology,* 28(1): 91-94.

Mrozowski, C.L. and Hayes, D.E. 1979. The evolution of the Parece Vela basin, eastern Philippine Sea. Earth Planetary Science Letters, 46, p. 49-67.

Müller, R., Royer, J. and Lawver, L. 1993. Revised plate motions to the hotspots from combined Atlantic and Indian Ocean hotspot tracks. *Geology,* 21: 275-278.

Northrup, C.J., Royden, L.H. and Burchfiel, B.C. 1995. Motion of the Pacific plate relative to Eurasia and its potential relation to Cenozoic extension along the eastern margin of Eurasia: Geology, 23(8): 719-722.

Packham, G. 1996. Cenozoic SE Asia: reconstructing its aggregation and reorganization. In: Hall, R. and Blundell, D. (eds.), Tectonic *Evolution of Southeast Asia.* Geological Society Special Publication, 106, pp. 123-152.

Patriat, P. and Achahe, J. 1984. India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. *Nature,* 321: 615-621.

Royden, L.H. 1993 Evolution of retreating subduction boundaries formed during continental collision. *Tectonics,* 12: 629-638.

Suárez, G., Molnar, P. and Burchfiel, B.C. 1983. Seismicity, fault plate solutions, depth of faulting, and active tectonics of the Andes of Peru, Ecuador, and southern Colombia. *Journal of Geophysical Research,* 88: 10,403-10,428.

Suppe, J. 1985. *Principles of structural geology. In:* Prentice Hall, Inc., Englewood Cliffs, New Jersey. 537 pages.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R. and Cobbold, P. 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. *Geology,* 10: 611-616.

Taylor, B. 1979. Bismarck Sea: Evolution of a back-arc basin. *Geology,* 7: 171-174.

Taylor, B. and Hayes, D.E. 1980. The tectonic evolution of the South China Sea. In: *The tectonic and geologic evolution of Southeast Asian Seas and Islands.* Geophysical Monogr. Ser., 23: 89-104.

Watts, A.B., and Weissel, J.K. 1975. Tectonic history of the Shikoku marginal basin. *Earth Planetary Science Letters,* 25: 239-250.

Weissel, J.K., and Hayes, D.E. 1977. Evolution of the Tasman Sea reappraised. *Earth Planetary Science Letters,* 36: 77-84.

Weissel, J.K., Taylor, B. and Karner, G.D. 1982. The opening of the Woodlark basin, subduction of the Woodlark spreading system, and the evolution of northern Melanesia since mid-Pliocene time. *Tectonophysics,* 87: 243-251.

Wernicke, B. 1992. Cenozoic extensional tectonics of the U.S. Cordillera, *In:* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., (eds.) The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 553-582.