Expanding the Wilson Cycle Based on Worldwide Comparison of Continental Structures Revealed by Lithospheric Geophysical Investigations

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Abstract: Worldwide comparison of lithospheric investigation results achieved from projects of COCORP, BIRPS, DEKORP, LITHOPROBE, ICDP, ECORS and SINOPROBE enables us to expand the classical Wilson cycle, which mainly describes evolution of ocean plates, into a complete and detailed cycle that describes generation, development and evolution of both ocean and continent plates. The expanded Wilson cycle presented in this paper introduces the evolution sequences of continental lithospheric processes by adding into the classical Wilson cycle with ocean-continent transition, continental collision and accretion, as well as continental rifting and splitting in details. These mentioned continental lithospheric processes have been presented by the author in a series of recent review papers in detail, and their summary and further deduction is presented in this paper.

Key words: plate tectonics, Wilson cycle, worldwide comparison, lithospheric investigation, tectonic process, ocean-continent transition, continental accretion

The Wilson cycle of classical plate tectonics mainly describes the generation, development and closing of ocean plates (Wilson, 1973; Cox and Hart, 1986; Molnar, 1988; Gubbins, 1989; Moores and Twiss, 1995; Rogers, 2004; Fowler, 2005). In 1982, Professor Wilson said to me that the Wilson cycle was incomplete as it had not described the behavior regulations of the continent plates yet, and that you gays must investigate continents with geophysical techniques, find out continental dynamic laws to perfect the Wilson cycle. In 1985, Professor Morgan said to me, the key to find continental dynamic laws via geophysical investigations must be comparison of lithospheric structures, which includes worldwide collecting lithospheric structures correlated to typical types of tectonic processes; the sequentially ordering them according to the evolution stages of the tectonic processes; and finally finding out the dynamic laws of these continental lithospheric processes (Yang, 2014a). Since 1975, successively implemented COCORP, BIRPS, DEKORP, LITHOPROBE, ICDP, ECORS, CCSD and SINOPROBE projects have revealed many detailed continental structures worldwide through joint efforts of countless geoscientists (James, 1989; Pakiser and Mooney, 1989; Klemperer, 1998; Klemperer and Mooney; 1998; Clowes et al., 1999; Cloetingh and Negendank, 2009; Wencai Yang, 2003). Supported and helped by a lot of geoscientists (see Acknowledgements), I have accumulated a lot of data on lithospheric continental structures and as well practiced geophysical investigations myself in China (Yang et al., 1997, 1999, 2002, 2003, 2005, 2006, 2009, 2014b), trying to perfect the Wilson cycle after the instructions given by Professors Wilson and Morgan. Five review papers (Yang et al., 2014c-g) on the ocean-continent transition, continental accretion and rifting processes have been published in Chinese with English abstracts. Orderly inserting these continental tectonic processes into the original Wilson cycle enables me to supplementing continental tectonic processes in details and to expand the original cycle for both oceanic and continental plate processes. This work will be the brief summary of what I have done in this subject. The tectonic vocabulary will follow plate tectonics and comply with encyclopedia (James, 1989); for example, "continent" And "ocean" means "the continent lithosphere" and "ocean lithosphere", respectively.

The classical Wilson cycle shows the development course (Davices, 1999; Jolivet and Hataf, 2001; Turcotte and Schubert, 2001) from a mature continental rift to an ocean basin, and finally ocean closing via collision of continents. After adding main continental dynamic

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processes (Yang et al., 2014c-f), its framework can be expanded as shown in Table 1.

The expanded Wilson cycle shown in Table 1 starts from the classical Wilson cycle that has been fully explained by the plate tectonics. Following sea floor expanding, the ocean-continent transition (OCT) process, as an important intermediate stage (James, 1989; Pakiser and Mooney, 1989; Jolivet, 2001; Yang and Song, 2014), comes to build up a thicker crust and to differentiate the crust into three layers (see Fig. 1). The first stage in OCT turns out the ocean lithosphere into an OCT lithosphere, i.e., doubling thickness of the crust and uppermost mantle, and gradually differentiating the crust to form the upper, middle and lower crust. The thicknesses increase of the crust, and as well as the lithosphere, is the results of some processes, such as sedimentation, mantle magma underplating, and subduction of ocean plate (Yang and Song, 2014). Some additional remarks about the OCT stage will be followed later.

Just shown by the lithospheric structures of Papua New Guinea, the processes of combining an OCT zone into continents include rather complicated mechanism that should further increase lithosphere thickness (Yang and Yu, 1014). The continent collision between India and Asia makes crustal thickness of Qinghai-Tibet Plateau rising to more than 70km, but the crustal density and thickness of the uppermost mantle are decreased, so, rigidity of the lithosphere of continent collision belts also decreased. The continent accretion process (Taylor and Mclennan, 1995) includes continental collision, terrain amalgamation and cratonization that doubles thickness of the uppermost mantle and plate impel rigidity (Yang and Yu, 1014). The thickness of the uppermost mantle can grow in both ways of upward and downward; in other words, the growth reduces the crustal thickness and creates continental root at the same time.

The classical Wilson cycle has already indicated the importance of development of continental rifts, but has not explained the details of rifting processes that reform the continental lithosphere. The expanded Wilson cycle shows a sequence of four processes that belong to continent rifting and splitting, including the crustal fracturing, crustal detachment and stretching, Lithospheric faulting

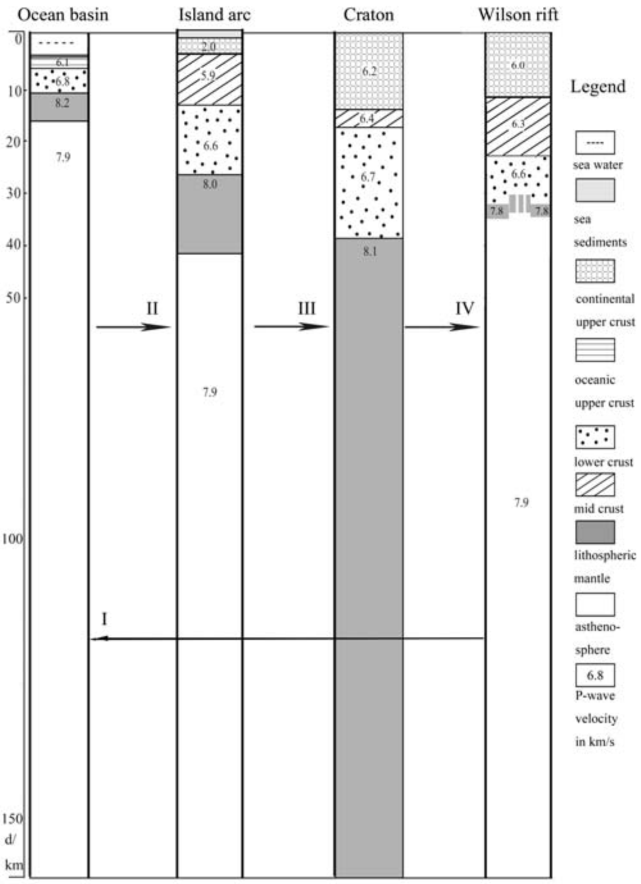

Fig. 1. A carton showing the typical transition of oceanic lithosphere to continental lithosphere, numbers in columns indicate P-wave velocity with unit km/s.

plus basaltic intrusion, and finally development of a Wilson rift (Yang, 2014g). The Wilson rift refers to the continental rift that continually opens and finally becomes the spreading center of a new ocean. Most of continental rift valleys would not reach the over-mature stage and could not become a Wilson rift. The continent splitting and rifting processes usually correlate to upwelling of the asthenosphere, which results in rheological creeping of lower crustal rocks, magma intrusion, or delamination of part of the continental lithosphere.

The solid earth evolution has made the inhomogeneous crust and mantle and many different lithospheric structures. Because of ergodicity of the tectonic

Table 1 Framework of the expanded Wilson cycle

No.	Tectonic process	Features of process	Products of process	Example of typical area
I	Sea floor spreading and forming a ocean	ridge expanding and thickening oceanic lithosphere	Forming the ocean basins	The Atlantic Ocean
II	Ocean-continent transition	Creating a new ditch and then arc-like crust that is thickening and dividing to 3 layers	Subduction zones and arc-like lithosphere	West Pacific region, the Mediterranean
III	Continental collision and accretion	crustal compacting and thickening, then lithospheric mantle thickening and firming	cratonic rigid lithosphere, continental accretion	Qinghai-Tibet Plateau, Mongolia-Okhotsk belt
IV	Continental rifting and splitting	The crust stretching, the lithosphere thinning and the asthenosphere invading upward	Lithosphere faults and rift-type lithosphere	Basin-range province, East African Rift Valley
Return to serial number I				

movements, products of the lithospheric processes with different space-time scales are different place by place. In addition, most of the products have been eroded or buried deeply, unable us to obtain rock samples for direct research. Therefore, one must recover the processes via worldwide comparison of the lithosphere structures along some representative regions where the products have preserved by good fortune, and via searching the evolution fingerprints hidden in the lithospheric inhomogeneity and arranging them into an order according to development stages of the processing. That is our way of finding out the expanded Wilson cycle under the guidance of general physical laws (Yang, 2014a). In the worldwide comparison, recovery of the stages of regional evolution processes requires carful distinguishing differences of the crust and mantle structures and correct dating of geological events occurred in the region. No matter for OCT, continent accretion or lifting processes, any process starts from the initial stage, then steps to early stage, youth stage, mature stage, and finally enters later stage. According to the plate tectonics, each of the developing stages is distinguished by changes of the lithospheric structures. Following this procedure, I will explain the stages of the lithospheric processes included in the above-mentioned expanded Wilson cycle. For example, the ordered stages of typical ocean evolution is explained by the Wilson Cycle can be explained in Table 2.

The stages of OCT process come from comparing lithospheric structures in following regions (Yang and Song, 2014c): margin of New Jersey, southeast coast of U.S.A., Andean subduction belt, northwest Pacific island arcs, Australia - Papua New Guinea, and Mediterranean, see Table 3. The OCT process starts from the ocean spreading stage，going through trench opening, oceanic plate subduction accelerating, expanding the OCT zones, and subduction zones convergence; when the crustal thickness is gradually increasing. As the crust finally tends to like continents, it rises upward by the effect of gravitational equilibrium; the island arcs finally become high mountain ranges after island-continent collision while marginal seas become lakes, causing the ocean fully closing.

The stages of continental convergence and accretion processes (Yang and Yu, 1014d-f) are constructed from comparing lithospheric structures in following regions: Kalimantan-Palau and West Mediterranean, Himalaya-Alps orogenic belt, Mongolia- Okhotsk belt, High Himalaya mountain range, Dabie-Sulu orogenic belt, Songpan-Ganzi flysch basin, Baltic and Sichuan, as well as Canadian shield. This stage starts from the continental collision, going through Crust thickening and shortening, continent-continent subduction or high-pressure metamorphic massif exhumation, forming collisional accretion wedge, heavy magma intrusion, land lithosphere cooling and continental root growing. The structures of continental collision belts are very complicated and have several different types. As a collision belt can reach as long as ten thousand kilometers, the lithospheric structures are different along its different segments. The protruding parts of the involved continents may collide strongly, but the concave holes may miss the collision. As a result, the continental convergence process contains mainly four different types: strong collision of Himalaya-Alps type, strong collision of Dabie-Sulu type，weak collision and terrain amalgamation type, and without collision flysch-basin type, see Table 4. In order to complete continental accretion, the lithosphere of a collision belt must be further solidified via magma intrusion, growing the

Table 2 Processing stages of typical ocean evolution

No.	Stage name	Features of process	Typical regions	Explanatory notes
I-1	Initial stage	Forming a Wilson rift	East African Rift Valley	Over-mature Continent rifting and splitting
I-2	Early stage	Opening a ocean ridge	Red Sea	The ridge reaching oceans
I-3	Youth stage	Expanding to oceanic basins	The Atlantic Ocean	Mantle -origin magma overflowing
I-4	Mature stage	Forming a mature ocean	The South Pacific Ocean	Ocean plate subduction developed
I-5	Over-mature stage	Ridge subduction and ocean shriveling	Northwest Pacific Ocean	After ridge subduction
Turning to stage II-1 in Table 3				

Table 3 Processing stages of typical ocean-continent transition

No.	Stage name	Features of process	Typical regions	Explanatory notes on process
II-1	Initial stage	Thick sedimentation and magma underplating in passive margins	North America New Jersey coast sea	Crust is thickening and under differentiation
II-2	Early stage	The trench opening and forming an over hydropressure head gun	Southeast coast of U.S.A.	Ocean wedges set beneath the continental crust
II-3	Youth stage	Ocean plate subduction accelerating	Andean subduction zones	Ocean plate subduction goes to the asthenosphere
II-4	Mature stage	Expanding the OCT zones with back-arc basins or marginal seas	Northwest Pacific trench-arc-basin system	Subduction goes through whole upper mantle, stop ocean expansion
II-5	Over mature stage	Subduction zones convergence and crust rising	Australia - Papua New Guinea, East Mediterranean	Ocean ridge subducted under OCT zones
Turning to stage III-1 in Table 4				

Table 4 Processing stages of typical continental convergence and accretion

No.	Stage name	Features of process	Typical regions	Explanatory notes on process
III-1	Early stage In convergence	Crust thickening and shortening	Kalimantan-Palau, West Mediterranean	Ocean shrinks, islands colliding with other islands or a continent
III-2	Youth stage in convergence/ Initial stage in accretion	Strong collision and continent-continent subduction afterwards	Himalaya orogenic belt during 65-35Ma	Continental convergence and collision while ocean seals
		Weak continent collision together with terrain amalgamation	Mongolia- Okhotsk belt in Jurassic	Island-island or island-continent collision while ocean shrinks and seals
III-3	Mature stage in convergence/ Early stage in accretion	continent-continent subduction, forming collisional accretion wedge	High Himalaya mountain range	OCT materials create the collisional accretion wedge
		continent-continent subduction, ultra-high pressure metamorphic massif exhumation	Dabie-Sulu (East China) orogenic belt during 230-210 Ma	Collision and rebound causing the exhumation if OCT zones undeveloped
		No collision takes place but development of flysch formations	Songpan- Ganzi flysch basin (China) during 220-190 Ma	No collision occur in concave part of the continents but compression and rise of OCT materials
		The large area magma intrusion making land lithosphere	Mongolia-Okhotsk belt in Cretaceous	Terrain amalgamation with magma intrusions
III-4	Youth stage in accretion	Continental collision belts metamorphism, magma underplating, finally cratonization	Baltic, Albert, Sichuan	Forming strong crystallization basement, thickening lithospheric mantle
III-5	mature stage in accretion	The lithosphere cooling and continental root growing	Canadian shield	Form rigid continental roots and cores gradually
		Convergence into a super continent	Eurasia continent	Convergence of multiple continental plates
Turning to stage IV-1 in Table 5				

Table 5 Processing stages of typical continental splitting and rifting

No.	Stage name	Features of process	Typical regions	Explanatory notes on process
IV-1	Initial stage	Lithosphere rupturing	Baikal lake	Lithosphere cracks occur in week continental crust
IV-2	Early stage	Continental root delamination or lower crustal extension	Basin-range province	break of continental root, lithosphere thinning with horizontal stretching
IV-3	Youth stage	Crustal stretching developing grabens	Shuangliao Basin (EN China)	mantle-origin magma underplating, expanding basins
IV-4	Mature stage	The lithosphere detachment and faulting with mantle-origin magma intrusion	Rhine Basin, Rio Grande rift valley (USA)	the lithospheric mantle breaking apart together with magma intrusion
IV-5	Over mature stage	Rift valley expansion and linking to oceans	East African Rift Red sea	Asthenosphere upwelling through the rift valley
Turning to stage I-1 in Table 2				

uppermost mantle and finally cooling (Yang and Yu, 2014f). Some continents might move closer and closer to form a supercontinent, which in turn accumulates heat energy beneath its lithosphere, possibly causing development of a continental rift valley.

The stages of continental splitting and rifting processes are constructed from comparing lithospheric structures in following regions: Baikal lake, Basin-range province, Shuangliao Basin, Rhine Basin and Rio Grande rift valley, East African Rift Valley (Yang, 2014g), see Table 5. These processes start from lithosphere rupturing, going through possible continental root delamination, lower crustal extension and stretching, developing grabens and expanding basins, lithospheric detachment together with rift valley expansion, and lithospheric mantle breaking to create a Wilson rift. Formation of continental rifts is mainly caused by asthenosphere upwelling, mantle delamination, mantle-origin magma intrusion, and gravitation equilibrium. Finally, the Wilson rift would develop into a spreading center of a new ocean.

In summary, thanks to the achievements obtained by COCORP, BIRPS, DEKORP, LITHOPROBE, ICDP, ECORS and SINOPROBE projects, I am able to follow the instructions of Wilson and Morgan, to expand the classical Wilson cycle in plate tectonics to a complete cycle for lithospheric evolution of both oceanic and continental plates since the Proterozoic Era. The details of additional continental tectonic processes supplemented in the expanded Wilson cycle can be found in the references (Yang et al., 2014c-g) from the website: "www.geojournals.cn/georev".

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