by Yang Wencai

Analysis of deep intracontinental subduction

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Intracontinental subduction has been recognized as a tectonic process that occurred after continent-to-continent collision. However, it is not clear how deep the light continent can be subducted, how much of the continental materials may have been recycled in the mantle, and what kind of effects the process may induce, especially in regard to mountain building. Based on integrated investigations, a typical intracontinental subduction belt, named the Dabie-Sulu orogenic belt in East-Central China is examined, revealing the lithospheric structures and the geometry of the subducting Yangtze craton. The volume of the continental crust of the Yangtze that sank into the upper mantle, the total buoyancy force caused by the sinking continental crust, and the total mass of crustal silicon entered into the upper mantle are estimated. The results suggest that formation of an old orogenic belt may contain several processes and corresponding causal stages with the intracontinental subduction stage followed by uplifting and extension; all these contribute to mountain building.

Introduction

Intracontinental subduction has been recognized as a tectonic process that occurred during or after continent-to-continent collisions (Oxburgh, 1972). Today we identify two types of subduction involved in the mountain building processes: the A-type for continent-to-continent subduction and the B-type for oceanic subduction which has been well studied in plate tectonics. However, the A-type or intracontinental subduction has received much less attention from geoscientists, as many basic questions related to it remain unanswered. These questions include how deep the subduction can reach? How much of the crustal materials are recycled into the mantle during the subduction? What are the consequences of subduction to mountain building? How significant is the process in respect to the formation and evolution of the continents? In order to understand this process we need detailed investigations of typical intracontinental orogenic belts in which the A-type subduction process has been completed.

As far as we know, intracontinental subduction belongs to a post-collision orogenic process and contributes to uplifting of mountain ranges. Geological observation and analogue modelling suggest that collision does not immediately produce high topography. Buoyancy forces may become dominant after enough continental crust has been subducted, causing uplifting and exhumation of high-pressure metamorphic rocks; thus high mountains seem to result from intracontinental deformation rather than a collision (Burg & Ford, 1997). Notably, the Himalayas overlie an intracontinental thrust, called the Main Central Thrust, rather than the India-Asia suture as marked by the ophiolites and Tibet is nearly 40 Ma younger than the collision (Brown et al., 1996). As the Himalayas are uplifting today,

indicating that the intracontinental subduction process might not be completed, it is better to find other orogenic belts to study the A-type subduction processes. The Dabie-Sulu orogenic belt, located in the East-central China, is a favorable area for these studies (Coleman et al., 1995; Liou et al., 1994, 1996, 1997, Jahn, 1998; Rumble, 1998; Xu et al., 1998). Supported by the Chinese Continental Scientific Drilling Project, recent geophysical and geological investigations along the orogenic belt have provided abundant and reliable data to reveal the crustal and uppermost mantle structures (Xu et al., 1998, Yang, et al. 1997, 1998, 1999). Taking the Dabie-Sulu orogenic belt as a typical example, the present paper discusses the above-mentioned questions about intracontinental subduction, dissects the subduction structures based on newly obtained data, estimates the subduction parameters, and analyzes its consequences and significance in relation to mountain building and other geological processes.

The Dabie-Sulu Orogenic Belt

The Dabie-Sulu orogenic belt is located in the eastern part of the Qinling-Dabie-Sulu orogenic belt between the Sino-Korean and Yangtze cratons where the largest ultrahigh-pressure (UHP) metamorphic zone in the world is exposed (Figure 1). Paleozoic strata are missing along the Dabie-Sulu belt and it is different from the Sino-Korean and Yangtze cratons. The ultrahigh-pressure metamorphic zone, indicated by the occurrence of coesite and diamond, is located in the northern Sulu and central Dabie areas, whereas the high-pressure/temperature metamorphic zone, indicated by kyanite-topaz combination, is located south to the UHP zone. Still to the south

Figure 1 A simplified tectonic map of Dabie-Sulu areas. The Dabie and the Sulu were linked before the Mesozoic but offset by a long strike-slip fault named Tan-Lu fault following the collision between the Sino-Korean and the Yangtze cratons.

there is a blueschist zone indicating high-pressure/low-temperature metamorphism (Okay, 1993; Coleman, et al., 1995; Liou et al., 1994, 1996, 1997, Jahn, 1998; Rumble, 1998; Xu et al., 1998; Yang, et al. 1998, 1999). This pattern of decreasing metamorphic pressure-temperature implies that the subduction of the Yangtze craton was directing from south to north. According to geological dating (Liou et al., 1997; Harrison et al., Li et al., 1993, 1994; Liu, 1999), the metamorphic ages of UHP eclogites and their associated gneisses in the Sulu area are around 232–216 Ma, meaning that the collision between the Sino-Korean and Yangtze cratons and formation of Sulu UHP rocks occurred at 240–216 Ma. Before the collision event, the Dabie-Sulu terranes were northern margins of the Yangtze continent. However, they were segmented later into two by the Tanlu fault and the Sulu terrane was displaced northward. The Sulu terrane

is bounded by the Yuntai-Wuliang Fault (YWF) to the northwest and the Xiangshui-Jiashan fault (XJF) to the south. The terrane consists of fault-bounded UHP and HP zones, and was unconformably overlain by Jurassic clastic rocks and Cretaceous volcanic-clastic cover. Many Jurassic volcanics and Cretaceous granite intrusions are distributed all along the Dabie-Sulu belt (not shown in Figure 1).

The crustal structures of the Sulu area have been investigated by integrated geophysical surveys and their line-locations are shown in Figure 1. The resulting seismic reflection profile across the Sulu terrane (Line III) is shown in Figure 2. After integrated interpretation of all available geophysical and petrotextonic data, the correlated crustal structure profile is shown in Figure 3. In the northern part of the section, the Yuntai-Wuliang Fault (YWF) appears as a normal fault, representing the collision suture between the Sino-Korean cra-

Figure 2 Seismic reflection profile across the Sulu terrane obtained by linking Lines I and III whose locations are shown in Figure 1. Distinct reflectors are marked by A-A and B-B, and the current Moho by M-M.

Figure 3 Structures across the Sulu orogenic belt based on recent geophysical investigations along the orogenic belt. The vertical coordinate denotes two-way times in seconds like common seismic reflection profiles. S-K: Sino-Korean craton, M: Moho, UHPM: ultrahigh pressure metamorphic zone; HPM: high pressure metamorphic zone; Gn: gneiss, Ec+ : eclogite and ultramafic rocks, Ky+Tp : kyanite and topaz, Ph: glauconite, E-Q: Eocene-Quaternary deposits, Z: Sinian deposits, RC: rift complex, +: granitic batholite, and V: underplating basalts.

ton and the Sulu terrane. In the south, the Xionshui-Jiangshan Fault (XJF) contains several normal faults, representing an intracontinental rift that developed later in the Cretaceous. A very distinct reflector, marked by A-A in Figures 2 and 3, occurs at the crust and uppermost mantle, indicating a regional thrust fault that will be called the Main Sulu Thrust (MST). Because geological data suggest that the Yangtze craton was subducting from south to north, and this thrust is spatially located in the north of the Yangtze craton and north-dipping, therefore it may represent the top of the subducting Yangtze crust. In addition, magnetotelluric data also support this interpretation. Figure 4 shows the resistivity profile of Line III. The Sulu crust is characterized by high resistivity because it consists of crystallized rocks, while beneath the Main Sulu Thrust (A-A), the rocks are characterized by lower resistivity which may represent the Yangtze crust because it contains Paleozoic sediments (Yang Wencai et al., 1999). Another distinct reflector occurs under the current Moho, marked as B-B in Figures 2–4. It is approximately parallel to the reflector A-A and may represent the bottom of the subducting Yangtze crust, i.e., the old Moho discontinuity following the Yangtze subduction. There is a set of thrusts named Donghai thrusts (DHT), that developed in the upper crust above the Main Sulu Thrust and beneath the UHP zone; they could be the front thrusts related to the subduction of the Yangtze craton. The history of the Yangtze subduction may be divided into three sub-stages as follows. The first sub-stage (240–216 Ma) was the subduction of the Northern margins (the Dabie and Sulu terranes). This sub-stage will be called the Sulu subduction hereafter. The second (216–200 Ma) was a short-period lithospheric extension along the northern boundaries of the Dabie-Sulu terranes; this event enabled the exhumation of UHP rocks and occurred only in Sulu and Dabie. The third, or the main sub-stage (200–160 Ma) was the subduction of the Yangtze continent, resulting in the MST and DHT as shown in Figures 2–4. The subduction of the Yangtze continent should be a typical intracontinental subduction, and the thrust MST acted in a similar way to the Main Central Thrust in Tibet which operates today (Harrison, et al., 1992).

Another tectonic event was large-scale eruption of volcanics (J_3), followed by granitic intrusion (K_1) along the Dabie-Sulu belt and rifting along the Tanlu and the Xionshui-Jiangshan faults in the Cretaceous. The intrusion event resulted in a magmatic complex in Dabie (Figure 1) and in northern Sulu. The reflectors at about 10s in Figure 2 show the present-day Moho which might have been formed by the uplifting of heat flow and underplating after the subduction of the Yangtze. The heat-flow value at Donghai County is 76 mW/m^2 , very high comparing with other orogenic belts (Wang Jiyang et al., 1998). The high heat flow implies that this area has undergone a severe geothermal process since the Late Mesozoic. These extensional processes indicate that the convergent stage of the Sulu lithosphere had terminated before the Cretaceous.

Estimation of the subduction parameters

The average dipping angle of the main thrust A-A from the seismic profile is at about 20° , and the thickness of the subducting Yangtze crust is about 35 km today. In order to delineate the geometry of the subducting Yangtze we need velocity images, in which the subducting Yangtze slab should have relatively lower velocity compared with the exhumed Sulu UHP rocks. Recent tomographic studies show that the depth of the intracontinental subduction slab reaches about 130–170 km (Xu Paifeng, 1998). Setting the depth at 150 km and considering all available geophysical data, the schematic geometry of the subducting Yangtze slab is shown in Figure 5. The dipping angle of the Main Sulu Thrust is extrapolated into a depth of 120 km, while the thickness of the lithosphere around the Sulu area is about 80 km based on geothermal and magnetotelluric data (Xu Zhiqin et al., 1998; Yang et al., 1997, 1998, 1999). From this geometry we can see that about 250 km of Yangtze crust has been subducted into the uppermost mantle beneath the Sulu terrane and the Sino-Korean craton. In other words, the crustal shortening caused by the Yangtze subduction is about 250 km.

Based on this estimated geometry some parameters might be significant for understanding the scale and consequences of the intracontinental subduction. First of all, the volume of the continental crust which sank into the uppermost mantle during the Yangtze subduction was calculated by multiplication of the lengths of the Dabie-Sulu belt (800 km), the shortening distance (250 km) and the thickness of the Yangtze crust (35 km). Thus the volume is about $7 \times 10^{15} \text{ m}^3$. Assuming the average density of the Yangtze crust to be 2880 kg/m^3 , then the mass of the sinking crust of the Yangtze would be approximately $2.016 \times 10^{16} \text{ tons}$. Considering the average density of the uppermost mantle be $3,380 \text{ kg/m}^3$, density difference between the sinking crust of the Yangtze and the uppermost mantle would be 500 kg/m^3 . According to Archimedes' principle, the static buoyancy force caused by the sinking crust could be calculated by multiplication of the density difference, the volume, and the gravitational force per unit mass, which can be approximately taken as 9.8 N/kg . Thus the total buoyancy force induced by the subduction of the Yangtze continent could reach a magnitude of $3.43 \times 10^{19} \text{ N}$. This buoyancy force must have played an important role in tectonic processes in the Dabie-Sulu areas after the completion of the Yangtze subduction. As the buoyancy force accumulated and reached the same level as the load, the compressional processes would be terminated and the lithosphere around Sulu would transfer to an extensional state. The Cretaceous extension and rifting around the Sulu area might be a consequences of the accumulation of the buoyancy force.

Based on the geometry shown in Figure 5, one can calculate how much fertile crustal elements sank into the uppermost mantle

Figure 4 Resistivity profile of Line III obtained by 2-D inversion of magnetotelluric data.

Figure 5 Schematic geometry of the subducting Yangtze craton recovered from geophysical data. The black arrows denote that the crustal shortening was about 250 km.

after the Yangtze subduction. For example, the average silicon content is 26.8 wt. % in the crust (Taylor & McLennan, 1995), the total mass of silicon that sank into the uppermost mantle caused by the Yangtze subduction would be approximately $0.268 \times 2.016 \times 10^{16} = 0.54 \times 10^{16}$ tons. So much silicon, together with a great amount of quartz recycling into the mantle, would induce instability around the crust-mantle boundary and cause geochemical reactions. Considering the existence of the buoyancy force, these fertile crustal elements might enter the crust, inducing granitic intrusions and volcanic eruptions in the Dabie-Sulu regions during the later Mesozoic. The recycling of crustal materials into the mantle and the reentering back to the crust in the orogenic belt can explain the complexity of mountain buildings.

Summary and discussions

Many tectonic and geological processes can be involved in mountain building, which seems to take a longer time-period than we had previously thought. Some very young mountain ranges, such as the Andes, have been built mainly by processes related to the subduction of oceanic lithosphere, however, this does not mean that the event has been completed. After oceanic subduction, collisions between two continents might occur, causing crustal deformation and readjustment of thermal-rheological states in the crust and upper mantle, but the convergent forces that caused the collision may still exist and continue to act. Consequently, a regional thrust may be developed in the subducting slab near the suture line owing to continuing convergence, as occurs in the Himalayas today. Further development of these regional thrusts may cause deep intracontinental subduction as exemplified by geophysical investigations in the Dabie-Sulu orogenic belt. Comparing it to the Himalayas, the development of the Main Central Thrust has taken about 40 million years to reach the peak of topographic uplifting (Xiao Xuchang, 1997). Assuming that it took 40 million years for the development of the Main Sulu Thrust from the surface to the depth of 150 km, the average vertical movement rate of the subduction of the Yangtze continent would be about -3.75 mm/year. As the subduction might cause folding and front thrusting (DHT), intracontinental subduction can also contribute to mountain buildings.

Subduction of the continental lithosphere into the upper mantle results in both crust-mantle interaction and physical disturbance of the upper mantle. The cold subducted plate sticks into the hotter asthenosphere and should change thermal circulation modes, causing dynamic instability in the upper mantle. Furthermore, accumulation of so much light crustal rocks in the upper mantle increases buoyancy, inducing the upwelling of mantle materials and crustal extensions. All these factors imply that deep intracontinental subduction may be followed by another stage of orogeny which may be characterized by doming and extension processes.

Geochemically deep intracontinental subduction reaching about 150 km in Sulu, as mentioned before, carries both the crustal and the uppermost mantle into deeper mantle. The thickness of the crust today is about 35 km (10s reflectors in Figure 2-3), the thickness of the lithosphere is about 80 km, and the temperature at the bottom of the lithosphere is about 1307°C (Wang Jiyang et al., 2000). Comparing it with the subduction geometry as shown in Figure 5, we know that the root of the Sulu orogenic belt has been wiped away by some geological processes after the intracontinental subduction. Huge amounts of crustal materials enter the mantle making it fertile with Si, Al, Ca, Na, K; re-balance and recycling of the crustal materials may cause volcanic eruption (J_3) and granitic intrusion (K_1) around the Dabie-

Sulu belt and the southern boundary of the Sino-Korean craton. Compatible heavy elements, such as Au, Ag and U, may move upward from the upper mantle to the crust during the intrusion event, forming corresponding ore deposits. Some giant Au, Ag and U ore deposits have been found around the southern boundary of the Sino-Korean craton (Song Shuhuo, 1992).

Based on the above-mentioned analysis, the author suggests that the mountain building process may involve several tectonic processes and it may contain four main stages. The first stage is the subduction of oceanic plate and the collision of two continents; these processes are well known from plate tectonics. Three post-collision stages include subduction of the continental margin, the subduction of the continent and the reentering of crustal materials into the crust respectively. The deep intracontinental subduction is the consequence of continuing convergence at the plate boundaries, whereas the reentering of crustal materials is characterized by extension and mantle upwelling, caused by accumulation of subducted crustal materials and the resulting buoyancy force. In some orogenic belts the second or fourth stages might be missing due to shallow intracontinental subduction, whereas in some particular cases more stages could be involved such as in the Dabie-Sulu UHP terranes. In these areas, the first stage occurred at about 260–240 Ma; the Sulu subduction occurred at 240 and 116 Ma. The subduction of the Yangtze continent might occur at about 200–160 Ma, and the recycling stage at about 140–110 Ma. Intermittency might exist between the third and the fourth stages because heat transportation, as well as melting of the colder subducted plate in the asthenosphere, might take a considerable time.

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Hutchison 'Young Scientist' Fund

William Watt Hutchison, "Hutch" to his many friends around the world, was a Scots-born Canadian geologist who served Canada and the IUGS in myriad dynamic and creative ways. Most notably, he served as the IUGS Secretary General (1976-1980) at a pivotal time in its history, and as IUGS President (1984-1987). The same boundless energy, enthusiasm, skill in communications, and ability to foster teamwork that characterized his work with the IUGS also carried him to preeminent scientific administrative positions in the Canadian Government, where he served as Director General of the Geological Survey of Canada and as Assistant Deputy Minister of Earth Sciences. His distinguished career was terminated in 1987 by his untimely death at the age of 52, following a painful struggle with cancer.

One of Hutch's last wishes was to establish under IUGS auspices a memorial foundation intended to promote the professional growth of deserving, meritorious young scientists from around the world by supporting their participation in important IUGS-sponsored conferences. The first 3 beneficiaries of the Hutchinson "Young Scientist Foundation" attended the 28th International Geological Congress (IGC) in Washington, D.C., in 1989.

Currently, income earned as interest on the Hutchison fund is insufficient to sustain comparable grants every four years without seriously eroding the principal. For that reason, the IUGS made no grants from the fund for the 30th IGC, preferring instead to strengthen the fund by allowing it to earn interest for a longer period of time and by appealing for donations from the international geologic community. It is expected that grants from the fund will again support deserving young scientists to attend the 31st IGC in the year 2000. The Hutchison "Young Scientist Foundation" is a worthy cause that honors a fine, caring man and a distinguished, public-spirited scientist and administrator. The foundation also celebrates and promotes those things that gave Hutch the most professional satisfaction: geology, international scientific collaboration, and stimulating young minds.

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