Active continental subduction and crustal exhumation: the Taiwan orogeny

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ABSTRACT

A tectonic model of active continental subduction followed by crustal exhumation is proposed to explain the orogeny in Taiwan. The subducted crust is represented by a low-velocity zone dipping eastwards beneath the major part of Taiwan, while the exhumed crust is marked by a high-velocity bulge, high heat flow and absence of seismicity beneath the eastern Central Range. The boundary between the subducted and exhumed crust has been identified from surface geology and analyses of thermal history across the Central Range. The dynamic force that has been driving the exhumed crust is identified by results from focal mechanisms, structural geology and geodetic survey in the eastern Central Range. Such a tectonic model may provide a good explanation for the evolution of the Taiwan Orogeny, as well as an active case for studying other long-extinct systems of continental subduction and exhumation.

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Introduction

It is generally accepted that continental subduction and crustal exhumation play an important role in the evolution of many orogenic belts. A variety of geological evidence suggests that continental crust is occasionally subducted to depths of tens to perhaps 150 km (e.g. Chopin, 1984; Dewey et al., 1993; Matte et al., 1997). Recently, a series of simulations (Chemenda, 1993; Chemenda et al., 1995, 1996; 2001) has further suggested not only that continental crust can be subducted to depths of tens to 200 km, but also that the buoyancy of subducted continental crust eventually will lead to failure seaward of the subduction front and the subsequent return of the previously subducted crust to the surface. However, evidence of active crustal exhumation has heretofore been missing as most of the postulated examples of crustal exhumation are from long-extinct systems such as the Urals and Oman (Chemenda et al., 1996). In addition, the significance of continental subduction is often dismissed because a number of simple observations argue for the persistence of continental crust at the Earth’s surface. These include the longevity of the continents, and the shortening (rather than disappearance) of continental crust during collision.

Because the Taiwan orogeny is very active, dynamic processes are largely represented by significant crustal deformation and strong seismic activity. A lot of useful data can be directly extracted from surface geology as well as from deep crustal structures. Although Taiwan is frequently characterized as an archetypal steady-state accretionary wedge (e.g. Suppe, 1981; Platt, 1987; Dahlen and Barr, 1989), recent studies of seismic tomography (Lin et al., 1998) and thermal modeling constrained by heat flow and seismicity (Lin, 2000) suggest that continental subduction and crustal exhumation have occurred not only in the past, but also in the present in eastern Taiwan. Thus, detailed examination of the Taiwan orogeny might provide many valuable data for improving understanding of the dynamic processes of continental subduction and active crustal exhumation.

Firstly, in this paper, general tectonics and geology are briefly reviewed. Then, data including seismic tomography, earthquake locations and focal mechanisms, GPS geodesy, leveling, isotope, fission track, and illite crystallinity, will be discussed in the light of prevailing models for orogenic processes in Taiwan. Finally, these data will be used to argue that the best explanation of the geophysical and geological data from this area is the active exhumation of previously subducted continental crust.

General background

The island of Taiwan is located at a complex intersection between the Philippine Sea and Eurasian plates (Fig. 1). East of Taiwan, the Philippine Sea plate subducts northward beneath the Ryukyu arc, while south of the island Eurasian plate oceanic lithosphere beneath the south China Sea subducts to the east beneath the Philippine Sea plate (Tsai et al., 1977). The major part of the island results from the strong convergence between the two plates and the convergent boundary is along the Longitudinal Valley, i.e. the suture (Ho, 1988). The main structures are parallel to the strike of the suture in a NNE–SSW direction. East of the suture, the Coastal Range is a manifestation in Taiwan of the Luzon volcanic arc of the Philippine Sea plate. West of the suture, the principal geological units are the eastern Central Range (Tana- niao schist), the western Central Range (Slate belt), the Western Foothills and the Coastal Plains. Among them, the eastern Central Range exposed on the surface comprises greenschist facies rocks.

Recent observations

In the past few years, a number of geophysical, geological and geochemical observations have been amassed...
Fig. 1 (a) Generalized tectonics in and around the Taiwan area. Lines with triangles mark major convergent boundaries between the Philippine Sea and Eurasian plates. Triangles along one side of the boundary indicate the direction of subduction. The large arrow shows the direction of motions of the Philippine Sea plate with respect to the Eurasian plate. (b) Earthquakes with magnitude of greater than three located by the Central Weather Bureau Seismograph Network (CWBSN) in the Taiwan area between 1992 and 1995, and 30 focal mechanisms obtained in the Eastern Central Range. Three grey areas mark two velocity cross-sections and one hypocentre cross-section shown in (c)-(e). (c) P-wave velocity structures (after Rau and Wu, 1995) along cross-section I in (b). Grey scales with ‘L’ mark a major low-velocity region. The dashed arrow indicates the motion of the subducted crust. (d) P-wave velocity structures (after Lin et al., 1998) along cross-section II in (b). Grey scale with ‘H’ marks a major high-velocity region. The dashed arrow represents the motion of the exhumed crust. (e) Hypocentre projections along cross-section III in Fig. 1(b).

to explore how the eastern Central Range evolved in Taiwan Orogeny. They include crustal structures, seismicity and focal mechanisms, crustal deformation, thermal boundary, uplift rate and heat flow.

Crustal structures. Two interesting images have been obtained from recent investigations of seismic velocity structures in Taiwan. One is a low-velocity zone (L at Fig. 1c) that thickens eastwards beneath the major part of Taiwan (Roecker et al., 1987; Rau and Wu, 1995). The depth of this low-velocity region is greater than that expected from isostatic crustal thickening and was interpreted as continental crust carried down with the subducting Eurasian lithosphere (Roecker et al., 1987). A similar pattern of crustal thickness increasing eastwards has been obtained from the wide-angle seismic refraction and reflection (Lin et al., 1997; Shih et al., 1998). Although there is a high-velocity zone (H), that is roughly demarcated in Fig. 1(c), a detailed image (H in Fig. 1d) can be found from a high-resolution tomographic study of the eastern Taiwan region (Lin et al., 1998). This higher velocity region does not extend as far east as the Coastal Range, but is confined to the eastern Central Range by another region of low velocities beneath the Longitudinal Valley (L0 in Fig. 1d). This result suggests that the eastern Central Range is not simply the result of crustal thickening or underplating, and nor does it appear to be a simple accumulation of crust above a shallow decollement (Lin et al., 1998).

Seismicity and focal mechanism. It is worth noting that seismicity and focal mechanisms in the eastern Central Range are different from the surrounding area. Surprisingly, the eastern Central Range (Fig. 1b and 1e), despite its location at the eastern front of deformation, is nearly aseismic. Moreover, in contrast to the rest of the island (Yeh et al., 1991), many of the earthquakes (Fig. 1b) that do occur in this region have normal faulting mechanisms (Cheng, 1995; Lin et al., 1998), which suggests a predominance of vertically, rather than horizontally, orientated maximum principal stress.

Crustal deformation. The extension in the eastern Central Range is also supported by recent geological studies of rock deformation and GPS surveys. Lee (1995) interpreted drag folds and quartz veins as evidence of normal faulting. Crespi et al. (1996), in a study of late-stage brittle normal faults and semibrittle-to-ductile normal-sense shear zones, suggested that normal faulting in the eastern Central Range extends at least to the depths of the brittle-ductile transition. Results from GPS surveys of Taiwan (Yu et al., 1997) show that while Taiwan is in general under horizontal contraction, most of the eastern Central Range is extending.

Uplift rates. Uplift rates in Taiwan are much higher than average. A study of zircon fission track ages of rocks in the eastern Central Range by Tsao (1996) suggested that the rate of uplift increased from 7 to 16 mm yr⁻¹ over the past 1.5 Myr. Furthermore, levelling measurements (Liu, 1995) showed rates of uplift of 36–42 mm yr⁻¹ in the eastern Central Range over the past decade. Thus, it seems that uplift of much of the eastern Central Range is recent and has accelerated over the past several million years.

Thermal boundary. A tectonic boundary between the western Central Range (the Slate belt) and the eastern Central Range (the Tananao Schists) is clearly revealed by the thermal history of the metamorphic terrain (Tsao et al., 1992; Tsao, 1996). The line dividing rock units with different metamorphic grade is the boundary of different textural zones (Fig. 2). For example, the illite crystallinity of the metasedimentary rocks is less than 0.25 in the Tananao Schist, but it increases westwards from 0.25 to 0.5 in the Slate belt. The fission-track and K–Ar isotope dating consistently give ages usually less than 5 Ma in the Tananao Schists, but these gradually increase westwards from 10 Ma to about 80 Ma in the Slate belt because some rocks might not be totally reset during the last thermal event. These phenomena indicate that metasedimentary rocks in the Slate belt and Tananao Schists were buried at different structural levels before exhumation and were adjointed by tectonic movements.

Heat flow. Lateral variation of the heat flow pattern in Taiwan is strong, ranging from about 30–254 mW m⁻² (Lee and Cheng, 1986). The heat flow pattern roughly correlates to geology units and/or topographic relief. In general, contours of the heat flow increase to the east and parallel the general NNE trend of the principal geological units, with the highest values obtained in the Eastern Central Range. Further east, in the Coastal Range, the heat flow returns to the low values found in the western Coastal Plains.

Discussion

The recently acquired evidence suggests that the wedge models (e.g. Suppe, 1981; Platt, 1987; Bar and Dahlen, 1989; Dahlen and Barr, 1989; Bar et al., 1991; Hwang and Wang, 1993) may be inadequate. For example,
both high heat flow and sharp lateral variation of seismicity beneath the Central Range are hardly explained simultaneously by any of thermal regimes constructed from such wedge models. Nor do such existing models allow for normal faulting observed both in the earthquake mechanisms and in rock deformation, particularly at depths of tens of kilometres. It is also difficult to model observed gravity anomalies with only a simple wedge model (Ellwood et al., 1996 and Yen et al., 1998). Finally, it is difficult to explain the tomographic images of the subsurface, particularly those of Lin et al. (1998), which suggest a connection between the eastern Central Range with structures at depths of several tens of kilometres, in the context of any model that restricted its attention to the region above a shallow decollement.

Alternatively, a tectonic model of active continental subduction followed by crustal exhumation provides a better explanation (Fig. 3). In the context of the proposed model of crustal subduction and exhumation, the evolution of the Central Range of Taiwan is as follows (e.g. Ernst, 1983; Pelletier and Stephan, 1986). The current arc-continent collision began following the subduction of the Oligocene–Miocene South China Sea along the Manila Trench, initiating at the northern part of Taiwan and propagating south. In accordance with the simulations conducted by Chemenda et al. (1995, 1996, 2001), as subduction progressed, the continental shelf of the Eurasian plate was dragged down into the mantle, carrying with it some thickness of continental crust. As more crust was consumed in this fashion, the resistive buoyancy of the lighter material eventually increased to the point where decoupling occurred near the base of the crust, forming a crustal slice which, through the combined effects of buoyancy and erosion, made its way back up to the surface, while the lithospheric mantle continued to subduct. The overlying oceanic crust beneath the forearc basin was either deformed or subducted (Tang and Chemenda, 2000; Chemenda et al. 2001; Malavieille et al., 2001). The exhumed crustal slice is now exposed at the surface in the eastern Central Range.

To first order, general features of both the subducted crust and the exhumed crust in this newly proposed model can be imaged from 3D seismic velocity structures and thermal history across the Central Range. An E-dipping low-velocity zone, similar to the Hindu Kush (Roecker, 1982) and New Zealand (Eberhart-Phillips and Reyners, 1997), probably reveals active subduction of continental crust of the Eurasian plate beneath the major part of Taiwan. On the other hand, a bulged high-velocity zone beneath the eastern Central Range is interpreted as exhumed crust. The boundary between the subducted crust and the exhumed crust can be
marked by the significantly different thermal and chronological history between the eastern and western Central Ranges.

The existence of the exhumed crust is consistent with a variety of observations. First, the existence of the exhumed crust can explain the observed high temperatures and the absence of seismicity in the Central Range. The exhumed crust can be imagined simply as crustal material ascending to a shallower depth because thermal and rheological characteristics distinctively different from surrounding rocks at the same depth. Secondly, the prevalence of normal faulting and extension observed resulting from the stress pattern of the maximum principle axis can be explained by the exhumation of a slice of crust. Thirdly, the ongoing exhumation can explain the acceleration of the uplifting observed during the last million years. As the development of a crustal slice occurs only after an extended period of continental subduction, the evolution of the range was not a steady-state process, and was characterized by an acceleration of uplift after decoupling. In other words, the acceleration of the uplift observed in the Central Range over the past million years resulted from a non-isostatic equilibrium in Taiwan. Finally, the extended width of the greenschist facies rocks can be explained as a wide slice of exhumed crust in the eastern Central Range.

Conclusion

A tectonic model of active crustal subduction and exhumation is proposed to explain a variety of geophysical and geological evidences recently observed in Taiwan. A low-velocity zone thickens eastward beneath the whole island of Taiwan is resulting from the continental subduction, and a high-velocity zone beneath the eastern Central Range is the locus of active crustal exhumation. The general boundary of active crustal exhumation can be evidently depicted from topography, surface geology and analyses of thermal history. The active exhumation process with a vertically orientated maximum principal stress beneath the eastern Central Range is consistent with a variety of data of crustal deformation such as normal faulting, focal mechanisms, extension from GPS, accelerated uplifting from isotope and fission track. The phenomena collected in this paper evidently indicates that the Taiwan

Fig. 3 (a) A 3D tectonic model in the Taiwan area. East of Taiwan the Philippine Sea plate subducts northward beneath the Ryukyu arc, while south of the island Eurasian plate oceanic lithosphere beneath the south China Sea subducts to the east beneath the Philippine Sea plate (Tsai et al., 1977). General geological regions in Taiwan (after Ho, 1988) include: CP, Coastal Plain; WF, Western Foothills; WCR, western Central Range; ECR, eastern Central Range; LV, Longitudinal Valley; and COR, Coastal Range. The bathymetry is shown by contour on a grey scale. (b) Schematic diagrams summarizing the evolution model of active continental subduction and crustal exhumation. The model is also presented in Profiles 1–4 from south to north. Profile 1 that cuts through the Manila Trench is a typical subduction of the oceanic crust. Profile 2 just cutting through the southern area of the Hengchung Peninsula shows the subduction of the continental margin and failure in the front of the subducting crust. Also the overlying oceanic crust beneath the forearc basin is initially deformed. Profile 3 cutting through southern Taiwan shows exhumation in the Eastern Central Range originally resulting from buoyancy, and the strong deformation of both the exhuming and overlying crusts. Profile 4 cutting through central Taiwan shows the acceleration of exhumation in the Eastern Central Range owing to the combination of both rapid erosion and buoyancy.
Orogeny largely results from active crustal subduction and exhumation, and further investigation might provide the best opportunity to improve the understanding of dynamic process and tectonic evolution for other long-extinct systems of continental subduction and exhumation.

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