行政院國家科學委員會補助專題研究計畫成果報告

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行政院國家科學委員會專題研究計劃成果報告

斜向碰撞板塊前緣之下部岩圈動力流場側向變化
Lateral variation of convective instability within the continent lithosphere during oblique plate convergence

計畫編號：NSC 90-2611-M-002-002
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一、中文摘要

台灣造山運動的研究一向主要依賴地表淺部地質以及反射震測。「薄層刮積模型」則是據以解釋觀測資料以及嘗試瞭解造山之理論架構。近年來，根據若干較能反應深部構造之地球物理觀測則顯示深達岩圈範圍之機制似乎亦積極參與。但是發展已趨完整的「薄層刮積模型」至少可以提供半定量的描述與預測，而岩圈模型則尚處於揣度，屹未建立物理模型。其中尤以岩圈下段之地幔中可能啟動之動力流場之角色不易評估。事實上，板塊碰撞前緣之可能地幔動力過程已成為甚受國際地體動力學界矚目之研究課題。對於許多著名之板塊碰撞區，已有重要的研究工作嘗試建構簡化之二維理論模型以據以解釋不易以傳統地質模型概括之若干地物觀測。這些模型在基本觀念上則主要考慮可能發生在地幔岩圈(mantle lithosphere)中簡化之雷力_泰勒不穩定(Rayleigh-Taylor instability)，或比較完整考慮溫度結構之對流不穩定(convective instability)。根據這些模型，發生於碰撞板塊前緣之下部岩圈不穩定將導致明顯的地球物理信號，包括剪波的非均向性以及岩圈深處之波速異常構造。對於台灣造山而言，類似的觀察已有文獻報導。因此對於本構造區岩圈深度角色之理論架構有必要探索。我們發展三維非牛頓對流系統數值模型來探討歐亞岩圈深處由對流不穩定所帶動的可能變形，並討論據以解釋地球物理觀測的可能。我們發現，本構造區內從北而南，在數百公里波長尺度範圍內板塊碰撞強度以致於地幔岩圈內之對流不穩定強度有明顯的變化，理論上，在相對而言甚短的空間及時間尺度內這種顯著側向變化極可能是銜接南北不同極性之隱沒在上地幔之轉圜。本研究的主要最終目的是希望對於台灣造山運動研究，以及其他類似斜向架構之造山活動提供新的視野。

關鍵詞：對流擾動、板塊聚合、台灣造山運動。

二、英文摘要：

Taiwan orogeny has been interpreted in terms of the “thin-skinned tectonics” model based on observations of surface geology and shallow seismic reflection profiles. It has been challenged that deep process in the lithospheric depth might be actively involved based on deep geophysical observations. The potential involvement of dynamic flow of the mantle lithosphere further complicates the construction of a feasible theoretical model. In fact, dynamic processes during plate collision have been a research topic of great interest in recent years. Conceptual models constructed to account for a suit of geophysical observations that are otherwise un-comprehensible based on geological models in several noted collision zones have been devised. The physics behind these models concern mainly the Rayleigh-Taylor instability, or the more general convective instability, if the thermal effect is incorporated into the analysis of the instability, occurring within the mantle lithosphere. It has been shown that these types of lithospheric instability result in various geophysical manifestations, including seismogenic structure, S-wave anisotropy and seismic velocity anomaly in the deep lithosphere. For the Taiwan orogeny, there have already been documented signatures of this type that demands the exploration of how such lithosphere-wise process might be adopted in the Taiwan tectonic region. We build the three-dimensional, thermal-mechanical, numerical modeling tool to explore the theoretical aspects of the potential convective instability within the deep Eurasia lithosphere, and the capability of consistently interpreting geophysical observations. It is found that due to the significant lateral variation of the rigors of the plate collision within a wavelength of only a few hundred kilometers form north to south, convective instability within the relatively short wavelength and timescale is not only very likely to occur but also may serve as the critical transition in between the two subduction systems to the north and south that has flipping polarity. Our ultimate goal in this study is to shed insights on the theoretical framework of the Taiwan Orogeny and other orogeny with similar oblique configurations.

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Keywords：convective instability, oblique plate convergence, Taiwan orogeny.

三、研究計畫之背景及目的

The young and ongoing Taiwan orogeny, being the key of unwrapping the complicated geological configuration of the region as well as providing critical insights on orogeny in general, has attracted significant amount of domestic and international research interests. Based upon geological observations and shallow seismic reflection profiles, the widely adopted "thin-skinned tectonics" model has been formulated (Suppe, 1981; Davis et al, 1983) to interpret the deformation of Tertiary sediments in a thin wedge deformed by the advancing Philippine Sea plate. Implicitly, the Eurasian plate is assumed to subduct the Philippine Sea plate with the Taiwan orogenic belt on top as an accretionary wedge. Although it has gained significant popularity among geologists when invoked to interpret the geology of Taiwan and other tectonic characteristics, it is noted that the basic assumption of having a decollement at the base of the thin wedge, implying that the main body of Taiwan sits on top of an east-subducting Eurasian plate has only been vaguely justified by observational constrains (Sara et al, 2002). Furthermore, to account for the lateral variations in tectonic characteristics along the axis of the Taiwan island by assuming a progressive younging of the collision seems to largely downplay the potential interplay of the Taiwan orogeny and the southern Ryukyu subduction system. To account for the extensional regime within the northern Taiwan, a scenario of "extensional collapse of the northern Taiwan mountain belt" due to the flipping of subduction from the Luzon arc system to the Ryukyu arc system (Teng, 1996), possibly engineered by the slab breakoff (Teng, 2000), has also been proposed. Although the timescale of the Taiwan orogen is relatively short and the transition from the Ryukyu subduction system to the north and the Luzon system to the south is accomplished within only a few hundredth of kilometers, it is doubtful that this transition can be portrayed as a simple lithospherical-wise tear fault (Lallemend et al., 2001). A conceptual model depicting the geometry, the kinematics and even the dynamics of lithospherical structures within this transition zone has critical importance in comprehending the regional tectonics in this area. We believe that the fundamental dynamic process that deserves to be carefully studied is the Rayleigh-Taylor instability of the lower portion of the continental lithosphere provoked by lithospheric collision within the transition zone.

The proposed "lithospheric collision" hypothesis (Wu et al, 1997) as an alternative to the "thin skin tectonics" hypothesis is encouraged by the recent observation on the shear wave anisotropy beneath the Taiwan orogen (Rau et. al., 2000). It is reported in their work that the orientations of anisotropy for the Taiwan stations are generally parallel to the strike of the mountain belt, with a clockwise rotation following the trend of regional geologic fabric in north Taiwan. The delay times, vary greatly from 0.5 to 2.1 seconds is attributed to main sources of anisotropic region between 25 and 230 km depths. In other words, the observed splitting parameters are consistent with upper mantle anisotropy resulting from the collisional tectonics that built the Taiwan orogen.

While the observation on the shear wave anisotropy that might be manifested from deep process is relatively new, and might be counter intuitive in the context of the "thin skin tectonics", in the Taiwan region. 0.6 to 2.2 seconds delay times have been reported for the New Zealand collision zone (Klosko et. al., 1999), where the tectonic configuration of the major collision sandwiched between two subduction zones with flipping polarity has been compared to similar tectonic framework of Taiwan (Wu, 1999). In addition to the shear wave anisotropy, it is also reported that a high velocity zone exists directly under the South Island, New Zealand at the depth of 100-250 km (Stern et. al., 1999). Similar structure is also observed beneath the Transverse Ranges of California, where the oblique convergence of Pacific and North America plates is actively taking place across the San Andres Fault, where an anomalous ridge of seismically fast upper mantle material extending at least 200 km into the mantle. Although similar oblique convergence between Philippine Sea and Eurasian plates across the Longitudinal Valley fault is closely related to the Taiwan orogeny, there has not been observations of similar deep reaching fast anomaly within existing tomographic models (Rau and Wu, 1995; Ma et. al., 1995). However, since none of existing models incorporated teleseismic wave delays, they are not capable of resolving such structures even if there are indeed such anomalies. This might in fact be one of the crucial issues that need to be addressed in the next generation tomographic studies.

Both the seismic anisotropy and P-wave delays in New Zealand has been interpreted as implying widespread deformation in the underlying mantle, rather than slip on a narrow fault zone, across the plate boundary where oblique convergence is taking place (Molnar et. al., 1999). The possibility of having ductile shear and continuous distributed horizontal shortening within continental lithosphere as opposed to narrow fault zones penetrating both crust and upper mantle, the usual consensus built from plate tectonics, has in fact been an important research topics in the international community of geodynamics (e.g., Houseman et. al., 1981; Houseman and Molnar, 1997; Conrad and Molnar, 1999; Conrad, 2000). Existing modeling efforts have concentrated on lithospheric instability during 2D simplified convergence. Either the Rayleigh-Taylor instability, if only gravitational instability induced by lithospheric shortening is considered, or the convective instability if the effect of thermal diffusion is also taken into account. Different choice of system parameters leads to either exponential or super-exponential growth rate of the lithospheric instability. In short, it is argued that mantle lithosphere (the mantle part of the lithosphere), being colder and therefore denser than the underlying mantle, is prone to convective instability that can be induced by horizontal shortening. Simplified 2D numerical experiments dealing with the normal compression component of plate convergence (ignoring the strike-slip component) has been undertaken to examine the relative importance of mechanical thickening, thermal diffusion and gravitational instability in deforming the layer. For example, Houseman et. al. (2000) focuses on constructing plausible interpretation for the observed high-velocity anomaly extending to 200 km depth beneath the Transverse Ranges of California. Houseman and Molnar (1997), on the other hand, was motivated by the fact that several active mountain belts demonstrated that where convergence by thrust faulting has already created thick crust and a high terrain, normal faulting and crustal extension characterize current deformation within the interiors of the belts (e.g., Tibet, Basin and Range province). They propose that it is related to the convective removal of the mantle lithosphere and induces lithospheric extension after significant convergence induced thickening (Fig.4). Conrad (2000) emphasizes the importance of thermal diffusion, and suggests that the removal of a large downwelling ‘finger’ of cold lithosphere generated by shortening might be responsible for the rapid uplift of the Tibetan interior at ~8 Ma, after a shortening of 50% for ~30 Myr.

Although it is noted from these previous studies that the theory of lithospheric instability is far from established, the rich context of dynamics involved and their potential implications on offering consistent interpretation for various critical observations needs to be further explored. For the Taiwan orogen, it is believed that the oblique convergence between Philippine Sea and Eurasian plates and the resulted progressive younging of the recent arc-continent collision comprises significant lateral variations within a relative short distance in the north-south direction. Studies of the convective instability of the mantle lithosphere in this configuration are needed to clarify several basic issues concerning Taiwan orogeny. Among which, whether does the different strain regime of the northern Taiwan induced by variation of rigors of plate convergence? Whether or not does the downwelling finger take place within such short period of time? And why wasn’t it observed in terms of deep reaching fast anomaly along with the shear-wave anisotropy? These will be the issues that we intend to address with numerical modeling in the current and future study.

四、結果與討論

A series of systematic experiments is undertaken to appraise the theoretical plausibility of development of Rayleigh instability underneath the Coastal Range where the PSP is believed to encounter with the EUP. The boundary conditions are symmetry except that in the surface. Surface velocity is defined as equation (3) in Houseman et al. (2000), in which velocity is tapered to be zero by a function of sine. Models include three different materials (crust, lithospheric mantle, asthenosphere). The viscosity of crust is equal to that of lithospheric mantle (8×10^{19} Pa s), but ten times larger than that of asthenosphere. The densities are 2800 kg/(m^3), 3300 kg/(m^3), 3330 kg/(m^3). The convergent zone is 90 x 2 km. In the numerical calculation, the compositional buoyancy has been included in the equation of motion and the material propagation is traced by the advection equation for composition. The material advection is calculated by the 3rd order upwind method combined with central difference for advection in space, and the 4th order Runge-Kutta method for the time integration.

As indicated in Figure 1, significant downwelling convection within the mantle litosphere is driven by the compositional buoyancy when we apply the compression provoked by plate convergence for 1.5 Ma. Significant crustal thickening within the convergence width occurs first due to the compression which then triggers the Rayleigh instability. To simulate the southward younging of the Taiwan orogen, we purposely deactivate the compression after the first 0.5 Ma. The result reveals a fast rebound and followed by continuously downward development of the instability. That is, as log as the plate convergence is applied for a short period of time, even if the compression is then removed, it does not annihilate the eventual growth of the downwelling instability, which would then results in convective dellamination and potentially modify the local stress regime.

五、計劃成果評估

Based on comparisons with other collision zones where well-developed Rayleigh instability have occurred within the mantle lithosphere and result in observations providing significant upper mantle imprints, we conclude that there are not particular characteristics that differentiate the Taiwan orogen from other collision zones with documented Rayleigh_Taylor instability developed underneath the collision front. Numerical experiments further verify our speculation that there should be surporting upper-mantle observations based on the geometric, kinematic and dynamic setup of the Taiwan orogen.

Although observations comprised by the shear wave anisotropy indirectly support this, the reason that there are not more direct evidences, e.g., high angle sheet of fast P anomaly aligned with the orientation of the collision front, is simply because we have not looked hard enough. We think that there might be two approaches that will result in fundamental contributions toward improving our understanding of the tectonics of the Taiwan region. One approach is certainly to sharpen our capability and efforts toward all sorts of upper-mantle observations. This might include the deployment of Ocean Bottom Seismometer (OBS) to critically improve the sampling of the structures beneath the offshore area to the northeast. Another important research approach such as the present one is to point out what kind of large-scale upper mantle structures that we should be looking for. This should be improved by having more elaborate efforts of numerical modeling of the 3D configuration and evolution of the Taiwan orogeny, focus especially on both the geometric configuration of the collision front in the upper-mantle and the spatial transition of the flipping of the subduction polarity from north to south. The possibility of having Rayleigh instability developed underneath the northern segment of the collision front serving as the transition from the northern Ryukyu subduction to the southern east-verging subduction of the lithosphere of the South China Sea should be examined more closely from the perspectives of both the numerical modeling and the upper-mantle sampling that might be offered from the teleseismic observations.

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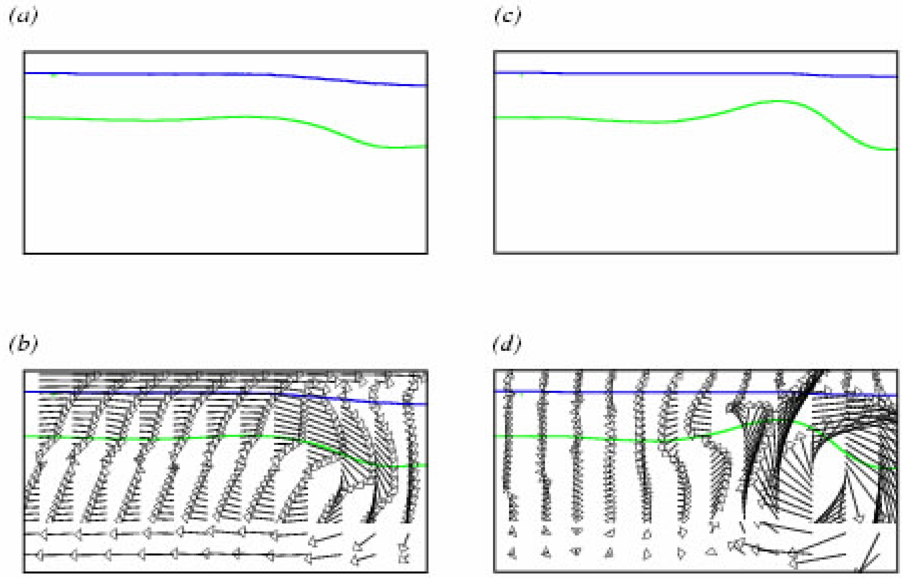

Figure 1. Continuous convergence that lasts 1.5 Ma results in significant downwelling instability of the mantle lithosphere shown in (a) the compositional layering and (b) the flow field. (c), (d) are for the case that convergence stops after the initial 0.5 Ma.