行政院國家科學委員會專題研究計劃成果報告

近脊溫度異常在擴張方向之脊外傳輸機制：三維動力模型
On the mechanism of off-axis conveying of near-ridge thermal anomalies in the spreading direction: A 3-D dynamic modeling

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一、中文摘要

海洋岩圈自中洋脊成形而逐漸向脊外擴張，冷卻並且具體表現於海床沉降．此一地球物理過程不但是海洋地球物理研究中發展最為成熟的理論之一，並且構成近代對於瞭解海洋岩圈之溫度及力學構造之基本理論基礎．古典傳導冷卻模型所預測的：海床深度-年齡 $^{1/2}$，熱流值-年齡 $^{-1/2}$ 以及大地水準面-年齡等理論關係均已在歷來之全球海洋地球物理觀測中獲得證實．近年來，更精準之觀測則顯示：沿著中洋脊之走向，洋脊深度(岩圈之初生深度)以及各該區之海床沉降率有顯著相關的變化趨勢．主流的研究一般均試圖將造成此一現象的原因訴諸沿洋脊方向的上地幔溫度變化．而為了涵蓋觀測沉降率變化與觀測初生深度變化呈現明顯相關之重要現象，一般均沿用標準冷卻模型所發展之共識，即柱狀上地幔物質會在海床擴張作用中統合的同步向脊外傳輸．我們先前的研究已經顯示任意調整沿脊軸之溫度變化有可能啟動顯著的動力流場而破壞隱藏於大部分海洋岩圈冷卻模型中，假設柱狀上地幔物質同時向脊外傳輸而導致之一維簡化．其他過去未受到應有重視的物理機制必須重新檢視，以解決此一海洋地球物理基礎理論之可能漏洞．我們利用數值模型探討近脊溫度異常之三維動力海床擴張系統．研究之重點著重於檢視擴張被動流場與在擴張方向暨沿軸方向之動力流場之間的互動效應，以及深入軟流圈之大陸根基在張裂過程中對於軟流圈流場之影響．結果顯示：除非軟流圈黏滯度高於一般的接受值，否則冷異常將無以藉擴張向脊外傳送；而張裂陸根雖有助於強化擴張流場，幫助冷異常之脊外傳輸，但其效果只能延續於擴張早期的數十百萬年。

關鍵詞：擴張被動流場，動力流場，冷卻模型，大陸深根，沿脊地幔溫度變化。

二、英文摘要：

Being one of the most well developed geophysical processes, the thermal contraction of the oceanic lithosphere away from the mid-ocean ridge that manifests into seafloor subsidence has constituted our most fundamental understanding of the thermal and mechanical structure of the oceanic lithosphere. The classical conductive cooling model has been confirmed over the years by various geophysical observations, including the general trend of the global depth-age$^{1/2}$, heat flow-age$^{-1/2}$, and the geoid-age relationships. However, the observed along-ridge variations of the zero-age depth and the subsidence rate have demanded an additional degree of freedom of the cooling model. Main stream efforts have been attributing the cause to upper mantle temperature variations across seafloor corridors. To take into account of the observation that subsidence rate variations are correlated with zero-age depth variations, it has been implicitly assumed that vertical columns of upper mantle materials are conveyed coherently in the spreading direction. Our recent study indicates that allowing along-ridge temperature variations within the asthenosphere will potentially invalidate the 1-D simplification of off-axis transportation of mantle column due to thermally driven buoyant flow. Important mechanisms that have been neglected in our established comprehension of the fundamental process of dynamic spreading are needed to resolve this paradox. We study the 3-D dynamics of the seafloor spreading with the presence of significant near-ridge thermal anomalies by numerical modeling. The focus is concentrated especially on the effects of interactions between spreading induced passive flow and the dynamic buoyant flow in both the spreading and the along-axis directions, and the possible impacts on the asthenospheric flow of the continent root during rifting. Preliminary results indicate that unless the asthenospheric viscosity is much higher than the generally accepted value, cold anomaly underneath the mid-ocean ridge will not be able to manifest in the off-axis area. Furthermore, continent roots does enforce the spreading flow field and thus aids in conveying cold anomaly, however, the influence is effective only for a few tens of mys in the early stage of the spreading.

Keywords：passive spreading flow field, dynamic bouyant flow field, cooling model, along-axis variation of uppermantle temperature.

三、研究計畫之背景及目的

One of the most well established geophysical observations is the dependence of the seafloor depth on the age of the oceanic lithosphere. Classical study of Parsons & Sclater [1977] reveals the well known linear relationship between seafloor depth and the square root of age, with the constant slope as the subsidence rate for lithosphere younger than about 70 Ma. However, accumulated studies have shown that there are pronounced along-ridge subsidence rates variations. For example, in Western Atlantic, the subsidence rate varies from about 500 to 300 m/m.y.$^{1/2}$ within 30-degree latitude [Calcagno and Cazenave, 1994]. Why does the subsidence rate vary along the ridge? Main stream models tend to explain the seafloor depth vs. age variation in terms of spatial variation of the mantle temperature [e.g., Parsons and Sclater, 1977; Eberle and Forsyth, 1995]. In short, the smaller the subsidence rate, the lower the mantle temperature is expected. An example of such a possible prominent along-ridge temperature variation is around the Antarctic-Australian Discordance (AAD), beneath which mantle is expected to be colder. The subsidence rate of AAD is indeed observed to be smaller than that on both sides. To explain the presence of the "cold spot" beneath AAD, Gurnis [1998] proposed that an ancient slab subducted about 130 my ago is presently being drawn up beneath the Southeast Indian Ridge, and consequently, cools the ridge and forms the deep topography around AAD. However, in his model, low-viscosity asthenosphere is not taken into consideration. When a model that incorporates a low asthenospheric viscosity with temperature dependency, a very different scenario of interaction between the passive flow and the dynamic flow is shown in the 2-D numerical experiment [Chiao and Wang, 1999]. When the asthenospheric viscosity is lower than 10^{20} Pa-s, cold material beneath ridge would produce significant negative thermal buoyancy, which prevents the cold material from ascending to the surface and manifesting in the off-axis area. The spreading of plates actually draws material outside the cold region and as a result imposes no signature of the thermal anomaly on the subsidence of the seafloor. The main purpose of the present study is to further examine the 3-D nature of the dynamics, especially on how does low temperature material beneath the ridge might be conveyed off-axis.

Our calculations consider 3-D thermal convection of Boussinesq fluid with infinite Prandtl number. Governing equations, including conservation of mass, momentum and energy are solved by the multi-grid, finite-volume method [Blankenbach et al., 1989; Christensen et al., 1995; Moresi and Solomatov, 1995; Patankar, 1982]. Careful benchmarks of our code have been undertaken and compared with published results. The model setting has a 3-D spatial domain of 9000 km (across ridge) by 3000 km (along ridge) by 200 km (depth). We start with a uniform mantle temperature model but assign zero-temperature on the surface as the initial condition. Surface plate kinematics is imposed as boundary condition to model the plate spreading. The resulting flow consists of two components, i.e., the passive flow due to plate spreading, and the dynamic flow due to thermal buoyancy. Beneath the ridge, a thin sheet of $200^o K$ negative anomaly is fixed at the bottom.

四、結果與討論

We examine the flow field and the thermal structure in cross sections in the spreading direction representing corridors with and faraway from the cold anomaly beneath the ridge. It is found that because the presence of the cold anomaly, the upwelling beneath the ridge is suppressed or even reversed for the corridor with the cold anomaly, as compared with normal flow pattern faraway from the anomaly. The cold material cannot be drawn close to the surface by plate-driven flow, and therefore cannot spread off-axis. It is consistent with the previous 2-D result of Chiao and Wang [1999] although the important effects from the along-axis flow was not considered in their model. Similar to their result, the predicted subsidence rate from our 3-D model is the same as the one prescribed according to the simple depth vs. age relationship for normal mantle temperature.

It has been inferred from seismological studies that the depth of continental roots may range from 150-km to 400-km. The impact of the deep root in the asthenosphere during spreading on the flow field is potentially capable of reshape the scenario of how ridge material being transported. In the next experiment, we introduce a high viscosity region from surface to 175-km depth to model the continental lithosphere. The initial separation of continents is 375 km. After the spreading proceeds 30 my, it is found that with the aid of the two departing continents, upwelling beneath the ridge is enhanced. Consequently, the cold anomaly reaches up beneath the ridge and is conveyed off ridge. The subsidence rate in the corresponding corridor is now much smaller than that in the normal corridor faraway from the anomaly. That is, the lower temperature material beneath ridge behind the spreading continents indeed creates lower subsidence.

However, as spreading continues to 80 my, the effect of continental lithosphere dies out and low temperature plume that once drawn up to the surface collapsed again. The subsidence rate in this case is thus time-dependent, with three different trends. At the early stage of spreading, there is a shallower subsidence rate reflecting the effect of continents. Then, when the cold material collapses, a steeper subsidence rate is obtained. And finally, the mantle temperature as well as the subsidence rate return to the normal state.

五、計劃成果評估

In summary, our 3-D experiments confirm the previous 2-D result. Cold anomaly cannot be maintained dynamically beneath a ridge, for the generally accepted asthenospheric viscosity on the order of 10^{19} Pa-s. As a result, to explain subsidence rate variation, factors in addition to dynamics of thermal origin are required. From our experiments, we find that the continental spreading helps to sustain anomalously cold ridge, but only for a short period of time. The exact time duration depends on the spreading rate and the initial continent seperation. However, it is robustly concluded that continental separation may generate transient subsidence rate, which may have some implications for seafloor topographic variations in some regions.

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