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Tectonics and cycle system of the Cretaceous Songliao Basin: An inverted active continental margin basin

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ABSTRACT

Recent ICDP drilling and deep basin volcanic exploration of 3000 m below the surface in the Songliao Basin (SB) have highlighted the 3-D delineation of the basin. The integrated new data led us to reevaluate the basin tectonics, for which the basin type, basin evolution and a number of geodynamic aspects have been controversial topics. We outline the position of a main lithospheric scale detachment fault beneath the SB, based on apparent crustal scale displacements, Moho breaks, the thinning of the Moho transition zone beneath the SB and the changing mantle thickness. This fault interpretation is consistent with simple shear as the rift mechanism.

Based on a comprehensive analysis of the tectonic setting, underlying crust, structural style, sequence stratigraphy, subsidence history and volcanism, we propose an active continental margin model for the SB which shows some similarities to aulacogens but also notable differences. Situated between two Late Mesozoic active continental margins, the northern/northwestern Mongol–Okhotsk and the eastern Sikhote-Alin orogenic belts, the Cretaceous basin evolved on a pre-Triassic structurally weak basement mosaic. Its development began with regional mega-rifting from 150 to 105 Ma, followed by significant sagging between 105 and 79.1 Ma and ended with regional uplift and basin inversion from 79.1 to 64 Ma.

Three regional angular unconformities separate the basin fill into three respective tectono-stratigraphic sequences. (1) The syn-rift stage is characterized by widespread fault-bounded grabens and volcanogenic successions, corresponding upward to the Huoshiling, Shahezi and Yingcheng Formations. (2) The post-rift stage includes the Denglouku, Quantou, Qignshankou, Yaojia and Nenjiang Formations. It is a special feature that the subsidence rate is abnormally high (mean of 103 m/Ma), and that flood basalt erupted along an axial wrench fault zone, associated with several marine intervals from the mid-Turonian to early Campanian (K_2qn to K_2n), possibly (not certainly) indicating incipient sea floor spreading characterized by Moho breaks along the basin axis in the SB around 88 Ma. Stretching stopped abruptly at approximately 79.1 Ma and was followed by uplift and rapid erosion (−145 m/Ma). (3) Recorded by the Sifangtai and Mingshui Formations the structural inversion stage included a continuous depocenter migration to the northwest. The basin was shrinking to demise as a result of changing subduction parameters of the Pacific subduction zone.

In addition to the three tectonic basin cycles, a cyclic basin fill pattern exists with three volcanic basin fill intervals of Huoshiling, Yingcheng, and upper Qingshankou Formations that alternate with sedimentary basin fill intervals of Shahezi, Dengloukou-Quantou, and Yaojia-Nenjiang Formations.

When determining the subsidence rates, we observed not only anomalously fast subsidence but also found an intricate link between the subsidence rate and type of basin fill. After each volcanic interval, the subsidence rates increased in a cyclic fashion during the sedimentary intervals. Thus, there is a system of three different types of important, basin-wide geological cycles that controlled the evolution of the SB.

The subsidence rate was especially high (up to 199 m/Ma) after the last volcanic episode at 88 Ma. In addition to thermal subsidence and loading by the basin fill as causative processes, we also consider magmatic processes related to asthenospheric upwelling beneath the SB. They involve the roof collapse of shallow, depleted magma chambers, the igneous accretion of initially hot, dense, basic rocks, and lithospheric delamination beneath the SB. The difference in the subsidence rates during the volcanic and sedimentary intervals may in part also have been due to heating-related uplift during the volcanic intervals. The particularly high subsidence during the Late Cretaceous sedimentary cycles was partly increased by transtension.

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We put forward a general model for active continental margin basins. They are generally similar to aulacogens but display the following differences. In active continental margin basins, rifting depends on the subduction parameters that may cause strong to mild extension in the giant marginal region. The geochemical composition of the volcanic rocks is more calc-alkaline in nature because they are suprasubduction-related. These basins will eventually enter a post-rift sag stage that involves thermal subsidence. However, the basin will still be near an active continental margin, and, thus, some dip- and/or strike-slip faulting may occur coevally, depending on the subduction parameters. Sag cycles in active continental margin basins will likely include volcanism. Basin inversion will after all affect active continental margin basins. Such basins strike parallel to the respective continental margin. Thus, basin inversion by subduction/collision may be more intense than in the case of aulacogens, which do not tend to strike parallel to the continental margin. Basin inversion may also precede a collision due to changing subduction parameters. Subsidence behavior may also differ because many aspects of subsidence may be at work. Subsidence curves in active continental margin basins may be fairly individual. The application of our model only requires settings with the presence of one Pacific margin type.

Contents

1. Introduction

The Songliao Basin (SB), situated on the Mongol-North China Plate, reputedly contains China's largest oil field, the Daqing Field, which is one of the very few super giant fields in the world that produces lacustrine oil (e.g., Yang, 1985; Li et al., 1995). During the Late Jurassic and Early Cretaceous, hundreds of rift basins developed in Northeast Asia (Ren et al., 2002), covering an area of more than 4 million km^2 from Lake Baikal to the Sikhote-Alin Region in E-W direction and from the Mongol–Okhotsk Fold Belt to the Xilamulun River-Yanji Suture Zone in N-S direction, as shown in Figs. 1 and 2. The SB is a unique case among them as it evolved into the largest rift basin and because it is the only one with a sizable Upper Cretaceous basin fill. These Upper Cretaceous deposits may reach a thickness of up to 6000 m (Figs. 3 and 4) and represent the most important oil and gas generating sequence in China (Feng et al., 2010).

These features have attracted considerable attention, especially since the early 1980′s with the beginning of the Chinese policy termed “open door”. The attention is mainly paid to the basin's resources, its intriguing evolution and geodynamics. Several basin models have been proposed, including the back-arc (Ma et al., 1989), intra-cratonic “polyphase” (Cheng, 1982) and rift basin models (Feng et al., 2010; He et al., 2014), as well as an Andean-type basin and range system (Wang et al., 2007a). Although meritorious, most of these models do not match some of the recent observations related to the SB and its geological development. This indicates that the basin type is not well understood.

The plate tectonic setting of the SB is the northeastern corner of the Mongol-North China Plate, which suggests a marginal rather than a cratonic setting. The Jurassic to Early Cretaceous Mongol–Okhotsk Collisional Belt are in the north and northwest, where the Siberian Plate was sutured to the Mongol-North China Plate (Bazhenov et al., 1999; Cogné et al., 2005). In addition, there is the Pacific subduction zone beneath the Mongol-North China Plate in the east, which formed the Sikhote-Alin Orogenic Belt during the Late Mesozoic and Neogene (Soloviev et al., 2006; Kemkin, 2008).

Oceanward-aging oceanic crust of the Pacific Plate progresses from the Cenozoic to the Jurassic (Fig. 1), implying that the continental boundary was not a typical Andean-type margin (Ramos, 2010). New results regarding the basin architecture show that the structural style of the SB has a polyphase evolution, and rifting is an important process (P.J. Wang et al., 2015).