Deep Duplex Thrust in the Sangzhi-Shimen Tectonic Belt, in the West Hunan and Hubei Areas

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ABSTRACT: Recent studies indicate that there is a large buried body developing in the Sangzhi-Shimen tectonic belt, which is between the Xuefeng intracontinental deformation system and the Xiangxi tectonic belt. In order to explore the tectonic evolution and main deformation-controlling factors of the buried body, we carried out a series of studies and built two new models based on the latest seismic data and fault-related fold theory. These new models show that the deformation of the buried body in the north segment of the study area is different from that in the middle-south segment. After further study, we found the main factors leading to these differences were: (1) the magnitude of the principal stress, (2) the range of tectonic movements, and (3) the morphology and depth of the basement detachment. Subsequently, with the physical simulation experiments, a 3D evolution model of the study area was built.

KEY WORDS: Sangzhi-Shimen tectonic belt, concealed structures, deformation-controlling factors, basement detachment, evolution model, faulting.

0 INTRODUCTION

The Sangzhi-Shimen tectonic belt is located in the Middle–Upper Yangtze Block, and belongs to the transition zone between the Xiangxi tectonic belt and the Xuefeng intracontinental deformation system. Because of the lack of high-resolution seismic data on the Sangzhi-Shimen tectonic belt, understanding of the study area has been focused on shallower tectonic level, and researchers have focused more on the Xuefeng intracontinental deformation system, than on the Sangzhi-Shimen tectonic belt (Chu et al., 2015; Wang et al., 2013, 2005; Cui et al., 2009; Ding et al., 2007; Li and Li, 2007; Ma, 2004; Song et al., 2003; Yan et al., 2003; Qiu, 1999; Qiu et al., 1996). All these studies have contributed greatly to understanding the overall evolution of the study area.

However, previous understanding of shallow structure is not completely applicable to deep structure. Because of the existence of regional detachment, there is decoupling between the shallow structure and the deep structure in the study area, which leads to their different deformations. Besides, the shallow structure is formed on the basis of the development of deep structure. At a time when the shallow structures are clearly understood, how the deep structures deformed remains unknown. Therefore, we need to further deepen the study of deep structures in the study area.

In recent years, with the depletion of surface resources, exploration of deep oil and gas reservoirs has become more important. Coincidentally, the latest seismic and magnetotelluric data have shown that there is a large buried body, composed of the strata below the Silurian, developing at the western margin of Xuefeng Mountain and in the Sangzhi-Shimen area (Dong et al., 2015). Questions associated with this body include: (1) What is the nature of this buried body? (2) How has it evolved, and what have been the main factors controlling its deformation?

In order to answer these questions, this study involves depiction of the structural characteristics of the Sangzhi-Shimen tectonic belt, and of the Xuefeng thrust belt. Tectonic evolution models of the study area were then built, based on the latest 2D seismic data, surface geological data and previous research results, according to the principle of fault-related folds (Medwedeff and Suppe, 1997; Suppe, 1983). After review of these models, we were able to deduce the main factors affecting the structural evolution, and the role of each factor in the deformation process. Later, with physical simulation experiments, we summarized the results of the research mentioned above and built a 3D evolution model of the study area. The purpose of this study is to distinguish the nature of the deep buried body, which provides a basis for the evaluation of the hydrocarbon potential in the Sangzhi-Shimen tectonic belt, and the surrounding areas.

1 REGIONAL GEOLOGICAL BACKGROUND

The study area includes the Sangzhi-Shimen tectonic belt and the Xuefeng thrust belt (i.e., the NW margin of the Xuefeng intracontinental deformation system) which are located in the middle and upper parts of the Yangtze Block, in the South China Block. It borders the Eastern Sichuan tectonic belt in the west, the Jianghan Basin, where massive Quaternary strata are exposed at the surface, in the east, and the Qinling-
Dabie Mountains and Xuefeng Mountain in the north and southeast, respectively. Surface geological information shows that the Sangzhi-Shimen tectonic belt is characterized by a series of right-step echelon folds, behaving as an arc, protruding to the northwest. Besides, the cores of the synclines in the tectonic belt are well preserved, with Triassic strata filling inside. As shown in Fig. 1, the strike of the folds transitions from NE-SW through ENE-WSW, before exhibiting a near E-W deflection, from south to north (Liu et al., 2010; Mei et al., 2010).

The occurrence of this geological phenomenon is not only the result of the combined action of multi-stage tectonic movements since the Indosinian epoch, but also the result of the tectonic evolution of Qinling-Dabie Mountains in the north, which has restricted the development of the Sangzhi-Shimen tectonic belt. As for the interior of the fold belt, there are fewer faults exposed to the earth’s surface. Most of them are reverse faults with NE-SW strike, and the rest are strike-slip faults. The Xuefeng thrust belt, located on the SE side of the tectonic belt, is mainly characterized by a large nappe, formed by thrusting of extensive old strata, whose major strata exposed to the surface are mainly composed of Sinian to Proterozoic strata (Liu et al., 2010). The faults exposed to the surface in the thrust belt are mainly SE-dipping reverse faults, between which there are a small number of strike slip faults, presumed to be converted faults with adjusted displacement (Fig. 1c). The tectonic unit located on the western side of the Sangzhi-Shimen tectonic belt is the Xiangexi tectonic belt, which is a typical trough-like fold belt. Inside it, the components in the anticlinal core are mainly Cambrian–Silurian strata, while the components in the core of elongated banded synclines between the anticlines are Permian–Triassic strata. Relative to the Sangzhi-Shimen tectonic belt, more reverse faults have developed in the Xiangexi tectonic belt, which indicates that Sangzhi-Shimen tectonic belt deformation has been obstructed by the Xiangexi tectonic belt, and the corresponding reverse structures were formed accordingly.
Consistency between the fold axis of the Sangzhi-Shimen tectonic belt (and even the Xiangxi tectonic belt) and the fold axis of the Xuefeng thrust belt can be seen in the geological information shown in Fig. 1. This indicates that formation of the Sangzhi-Shimen tectonic belt has been deeply influenced by deformation of the Xuefeng thrust belt, that is to say, these two tectonic units can be regarded as a whole, whose deformation has been controlled by compression trending NW-SE. At the same time, development of the internal reverse structure has been caused by the fact that the compressive stress has been constantly blocked by the geologic body during its forward transmission, from multiple directions (Yan et al., 2003, 2000).

As for the developmental state of the study area strata, the formation mainly includes Proterozoic to Quaternary strata, most of which are well preserved (Fig. 2). The composition of the Proterozoic strata mainly includes marine terrigenous clastic rocks, volcaniclastic rocks and carbonate rocks. The Paleozoic–Middle Triassic strata consist of marine carbonate rocks and clastic rocks, while the Upper Triassic series and the strata above them are continental clastic deposits. There are also multiple unconformities developed between different strata, with most of them being parallel unconformities. The absent strata corresponding to the main unconformities are Lower Devonian, Upper Jurassic, and Neogene, which means that at least three tectonic movements, namely the Indosinian, Yanshan, and Himalayan movements, have had a profound impact on the study area (Yan et al., 2000).

In addition, there are many strata with detachment characteristics in the study area. These include the Lower Triassic Jialingjiang Formation (T1j), the Lower Silurian Longmaxi Formation (S1lm), and a basement detachment. All of the detachments, with their different characteristics, have played an important role in the tectonic evolution of the study area (Wang et al., 2012; Yan et al., 2008; Massoli et al., 2006).

From the perspective of petrophysical properties, the detachment usually consists of gypsum rock strata, coal strata, phyllite, and shale rocks, and metamorphic rocks such as gneiss, which are soft, porous, and water-rich. The main strata mentioned above are mostly shale, with large amounts of dolomite or limestone distributed above and below. Shale, widely distributed in the region, is relatively soft in nature, compared with its surrounding rock, so it is very suitable for structural morphology as a regional detachment (Fig. 2). While the lithology of the basement strata is relatively simple, there are also a number of relatively weak strata that can be regarded as detachments, as can be seen from the seismic data.

These detachments, with their different depths and characteristics, limit the development of faults, making the deformation of each tectonic level relatively independent, while having important influence on the tectonic evolution of the study area (Yan et al., 2008).

From the point of view of regional stratigraphic plane distribution, the strata in the study area and its surrounds have clear zoning characteristics. For example, the outcropping strata in the Xuefeng thrust belt is mainly Sinian–Proterozoic strata, while that between the Cili-Baoqing and Fangdoushan faults consists of Early Paleozoic strata, with Late Paleozoic strata occasionally observed in the core of the anticline. As for the strata between the Fangdoushan and Huayingshan faults, it is mainly made up of Jurassic strata, with Triassic strata distributed in long, narrow belts in the anticline core. In conclusion, in the whole area, old strata tend to appear in the SE, with strata ages becoming younger to the NW.

2 STRUCTURAL ANALYSIS

2.1 Structural Style

Based on the existing seismic data (more than 5 seismic profiles), the study area can be segmented by identifying the continuity and morphology of deep faults. Each segment has its own master fault. On this basis, the study area can be divided into three segments—the southern, middle, and northern segments. In order to identify the structure of each segment, 5 inlines and 1 crossline were selected for structural analysis, based on surface data obtained from the 1:000,000 geological map and the digital elevation model data (Fig. 1).

Figures S1 and S2 show the original morphology of the 5 inlines, in which seismic lines $AA'$ and $BB'$ are located in the northern segment of the study area, while lines $CC'$ and $DD'$ are located in the middle of the study area, and seismic line $EE'$ is located in the south of the study area. In the original seismic profile, some strong reflection wave groups were identified, which could be used as the basis for seismic horizon identification. According to surface geological data, and to layer tracing of the whole area, the characteristics of the lower boundary of the Cambrian strata are similar to those of the Silurian Longmaxi Formation. They are all a set of strong amplitude wave groups, which are filled with blank reflections of $>1$ s two-way travel time. As well, in some areas, a clear medium-strong reflection wave group, which refers to the lower boundary of the Middle Cambrian, can be distinguished inside the blank reflection. These two sets of seismic waves, corresponding to the lower boundary of the Cambrian strata and Silurian Longmaxi Formation, are visible in all seismic profiles. Furthermore, they are similar in morphology, and can be classified into the same set of tectonic levels, that is, the middle tectonic level.

Due to the existence of the Silurian shale, the upper and middle tectonic levels were separated and deformed independently. Relatively independent deformation refers to the fact that the deformation is similar in general, but not in all details, which can be seen from many seismic profiles. The reason of deformation seen in the study area being similar is that the vertical deformation originated from the deep basement fault, while the shallow structure was inherited from development of the deep structure.

Not far below the lower boundary of the Cambrian strata, there is a regional angular unconformity. This set of unconformities is difficult to identify, because the wave group below the lower boundary of the Cambrian is weaker and more cluttered, but in some areas, blank reflection beneath the lower boundary of the Cambrian strata has intersected wave groups in the basement, at an angle of about 15°–30°, which can still be observed. The strata under the unconformity are named as the lower tectonic level, and consist of Sinian and basement strata. Its deformation is different from the tectonic levels mentioned above, which often develop large, high angle thrust faults and recoil faults originated from the basement detachment. These
Figure 2. Stratigraphic comprehensive histogram of Sangzhi-Shimen tectonic belt.

<table>
<thead>
<tr>
<th>Era</th>
<th>Period</th>
<th>Epoch</th>
<th>Start (Ma)</th>
<th>Duration (Ma)</th>
<th>Lithologic system</th>
<th>Lithuania description</th>
<th>Thickness (m)</th>
<th>Detachment layer</th>
</tr>
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<tbody>
<tr>
<td>Cenozoic</td>
<td>Neogene</td>
<td>N</td>
<td>2.58</td>
<td></td>
<td>Conglomerate</td>
<td></td>
<td>0 - 205</td>
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<tr>
<td>Paleogene</td>
<td>Jurassic</td>
<td>K</td>
<td>145.0</td>
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<td></td>
<td></td>
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<td>174.1</td>
<td>157.0–190.1</td>
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<td></td>
<td></td>
<td>201.3</td>
<td>190.1–251.5</td>
<td>lower part-conglomerate</td>
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<td></td>
<td></td>
<td></td>
<td>237.0</td>
<td>251.5–299.5</td>
<td>Sandstone interbedded with mudstone</td>
<td></td>
<td>&gt; 638</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>247.2</td>
<td>299.5–307.5</td>
<td>Sandstone interbedded with shale</td>
<td></td>
<td>&gt; 281</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>252.2</td>
<td>307.5–316.2</td>
<td>Upper part-starsandite, middle part-sandstone, lower part-conglomerate</td>
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<td></td>
<td></td>
<td>298.9</td>
<td>344.1–362.9</td>
<td>lower part-pelagic dolomite</td>
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<td></td>
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<td>382.7</td>
<td>390.6–394.3</td>
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<td>393.3</td>
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<td>397.4–399.5</td>
<td>Limestone and sandstone</td>
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<td>399.5–408.1</td>
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<td>0–520</td>
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<td>408.1–419.2</td>
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<td></td>
<td></td>
<td>446.4</td>
<td>419.2–425.2</td>
<td>Upper part-carbonaceous shale</td>
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<td></td>
<td></td>
<td>470.0</td>
<td>425.2–429.8</td>
<td>Lower part-carbonaceous shale</td>
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<tr>
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<td></td>
<td></td>
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<td>429.8–436.5</td>
<td>Limestone interbedded with shale</td>
<td></td>
<td>91–160</td>
<td></td>
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<td>516.4–541.0</td>
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<tr>
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<td></td>
<td></td>
<td>563.0</td>
<td>541.0–563.0</td>
<td>lower part-dolomite</td>
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<tr>
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<td>574.9</td>
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<tr>
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<td></td>
<td>603.0</td>
<td>574.9–603.0</td>
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<td></td>
<td>102–1185</td>
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<td></td>
<td></td>
<td>630.0</td>
<td>603.0–630.0</td>
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<tr>
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<td></td>
<td></td>
<td>650.0</td>
<td>630.0–650.0</td>
<td>lower part-black shale</td>
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</table>

**Tectonic event**

- **Overall uplift and denudation:**
  - In the early stage, the cratonic depression basin was formed.
  - Then, the Pacific Plate subducted beneath the Eurasian Plate. Subsequently, under the strong compression action, the Xuefeng intra-continental orogenic belt was formed.

- **During the Devonian–Permain period, the Xuefeng area entered the depression stage once again. This stage was a relatively stable period in this area. At this time, Xuefeng area has been transformed into a unified continental crust block.**
  - After the early Indosinian movement, the area was subjected to the influence of extrusion again.

- **In the Neoproterozoic, the Rodinia Continent cracked. Because of the instability of the crustal structure, the Xuefeng area gradually formed rift basins. Later, in the Late Ordovician–Silurian period, the Rodinia continental cracking was suppressed, making the Xuefeng rift basin squeezed and contracted.**
basement faults, which develop in a SE-NW extrusion setting, promote the whole, passive uplifting deformation of the overlying strata. At the same time, because of the existence of multiple sets of detachments, the upper and middle tectonic levels developed small structures independently, making the entire structural form more complicated.

As shown in Fig. S1, the SE segment of the seismic line in the northern part of the study area is similar to that in the middle part of the study area, and both developed large recoil faults in the basement layer (Fig. S1c), indicating that the transmission of extrusion stress has been hindered here, for the first time. To the NW, in seismic lines BB' and CC', we can see that the seismic wave group above the lower tectonic level has uplifted, turning into an arc. Meanwhile, the wave group in the lower tectonic level is uplifted to the NW, and intersects with the overlying wave group at high angles. This indicates that there have been several thrust faults, with top-to-the NW thrusting, developing below the wave group, which leads to the dip and uplift of the basement layer, and to the passive uplift of the strata above it. Furthermore, the wave groups above the lower tectonic level, which are in seismic line AA', are also bent, turning into the shape of the overturned anticline (Fig. S1a). This indicates that this anticline is different from the corresponding anticlines in seismic lines BB' and CC', and should be the result of the complex uplifting deformation of the basement thrust fault and the shallow recoil fault.

Further NW, a fault wave can be found at the bottom of seismic line AA', and its morphology is similar to that of folds in the overlying strata, indicating that the formation of the overlying fold was directly controlled by the fault. Signs of this recoil fault can also be found in seismic line BB', which can be identified from the dislocation of the seismic wave group (Fig. S1b), indicating that a reverse structure existed in the bottom of the NW limb of the Sangzhi-Shimen tectonic belt. This also meant that the transmission of extrusion stress was blocked for the second time, near the Xiangexi tectonic belt, rather than inside the Sangzhi-Shimen tectonic belt.

As for the southern segment of the study area, two large recoil faults, and folds sandwiched between them, can also be seen (Fig. S2). As shown in the figure, the forms of the trailing edges in seismic lines DD' and EE' are very similar, being large-scale folds filled with a large set of Ordovician–Proterozoic strata, which have been limited by large recoil faults, and affected by a plurality of reverse faults. Although the overall structure is similar, detailed review reveals differences. The uplift amplitude and width of the deep buried body (large-scale folds), whose existence has been confirmed in published studies (Dong et al., 2015), are significantly different. The uplift amplitude of the deep buried body in seismic line EE' is higher and its width is narrower, while the morphology of the deep buried body in seismic line DD' is basically flat.

Figures S3 and S4 show the final interpretation results for the 5 main inlines in the whole district, in which the important faults and layers are thickened by lines to highlight their variation tendency from the overall structural style. As can be seen, from south to north, the overall pattern of the study area is basically consistent, with gradual change. In the interpretation scheme of the five seismic lines, the common point is that recoil faults developed along the leading and trailing edges of the deformation. What’s more, the recoil fault at the trailing edge constitutes the left boundary of the deep buried body beneath the Xuefeng thrust belt. Along with the similarities, there are four main differences between them: (1) the morphologies of the deep burial bodies beneath the Xuefeng thrust belt, (2) patterns and genesis of the folds between the two large recoil faults, (3) the size, number and deformation pattern of the recoil faults at the deformation leading edge, and (4) the depth of the basement detachment, which gradually decreases from SE to NW.

To sum up, large structures in the study area are formed based on growth of the basement faults developed beneath them. Thus, the kind of structural style developed in each study area segment has depended on the number, morphology, and development position of the basement faults. Whether these basement faults developed, where they developed, and how they grew, was closely related to the morphology of the basement detachment (the place where the morphology of the basement detachment changes is easier to develop faults). Therefore, the fact that the tectonic style changes from the south to the north is the result of gradual deformation of the basement detachment, under the action of compressive stress at different stages (He Z L et al., 2011; Li et al., 2011; Liu et al., 2010; Yan et al., 2003). It is not difficult to see, from the existing seismic interpretation scheme, that the basement detachment has experienced two uplifts, from SE to NW. As well, the depth of the basement detachment in the south is generally greater than that in the north (Figs. S3, S4), which corresponds well with the known major tectonic movements.

Similarly, Fig. S5 shows an interpretation scheme for a NE-SW seismic line. Unlike Fig. S3 and Fig. S4, the deformation illustrated in Fig. S5 is relatively weak, rendering the geological structure more stable, as the shallow strata are relatively flat, with only a sizable anticline. The deformation of the deep part is stronger than the shallow part, and is mainly concentrated on the NE side—with many large recoil faults developing in this area. The formation of these recoil faults should be related to the development of the Qinling-Dabie Mountains, which are located on the north side. At the same time, it is worth mentioning that, as shown in Fig. S5, the depth of the basement detachment gradually deepens from the SW to the NE, which is the reverse of the main tectonic movement direction. This occurrence of the phenomenon could also be attributed to the hindrance provided by the Qinling-Dabie Mountains.

2.2 Tectonic Evolution

Deformation is complicated in the study area, as, since the Paleozoic, it has undergone reformations by the Caledonian, Indosinian, Yanshan, and Himalayan movements (Zhang et al., 2013; Shu, 2012, 2006; Chen et al., 2011; He D F et al., 2011; Li et al., 2011; Wang et al., 2010; Yan et al., 2000), with the Yanshan movement being one of the most influential (Li et al., 2014; He Z L et al., 2011; Liu et al., 2010). By collecting thermal chronology data for the various predecessors, and combining this with apatite fission track data, we can confirm that there have been five key structural changes over time in the study area, at 251, 201, 163, 103 and 51 Ma (Zou et al., 2018; Mei et al., 2010; Yuan et al., 2010; Li et al., 2008). On this basis, under the
premises that the thickness of the strata was constant. (The study of He D F et al. (2011) showed that the tectonic belt had experienced many times of extension and convergence before the main deformation period, namely Yanshanian. Thus it’s obvious that the tectonic belt does have several sets of stable stratigraphic deposits. At the same time, the tectonic movement before Yanshanian had little influence on the evolution of this tectonic belt, which also stressed there would be no large-scale stratigraphic loss), that the stress intensity in the northern segment was less than that of the middle-south segment (the tectonic stress is mainly from the southeastern side of the tectonic belt, resulting in the deformation of the northern segment of the study area is significantly weaker than that of the middle and south segments), and that the impact of the small structure on the whole structure was ignored (the impact of small structures will be discussed in the section “deformation-controlling factors”), tectonic evolution models for the south-middle segment (Fig. S6B1–Fig. S6B7), and north segment (Fig. S6C1–Fig. S6C4) were obtained, and the tectonic evolution of the study area could be divided into six stages (Fig. S6).

1) The original sedimentary stage (Fig. S6A) was before the Early Triassic (~251 Ma). Previous studies have shown that in the Late Ordovician–Silurian, under the influence of compressive stress, the nature of the original rift basin gradually changed, and that the rudiment of the Xuefeng orogenic belt gradually formed (He D F et al., 2011). Then, during the period of 416–251 Ma (D–T), the area underwent another extensional rifting. This tectonism offset most of the influence brought about by early compressive stress, resulting in a southeast dipping normal fault, with a dip angle of 20º, developed in the southeast side of the buried body. Later, a large nappe developed along this normal fault. The pre-existing normal fault cannot be directly observed, but evidence of its existence is apparent, as in the seismic line, the basement strata in the nappe is thinner than that of the corresponding strata in the leading edge of the deformation. As the compressive stress was gradually transmitted from the SE to the NW, however, the strata involved in deformation in the nappe are considered to have been equal to, or greater than, those in the leading edge. One reasonable explanation for this phenomenon is that, under the effect of compressive stress in the early stage, the Proterozoic strata in the nappe had experienced an uplift and denudation, and then they dropped, and were preserved under the subsequent extension, resulting in unequal thickness of the strata, between the two sides. In addition, if there was no extension which turned the reverse fault into a normal fault, it would be impossible for the thickness of the strata involved in the nappe deformation to either remain stable, or be less than that of the leading edge.

After 251 Ma, structural inversion occurred in the study area again. Under the action of compressive stress, the strata on the upper wall of the normal fault began to thrust upward, forming a large nappe in the trailing edge. Therefore, the main deformation time for the study area is considered to be 251 Ma or later, and the time before this stage has been regarded as approximately the original sedimentary stage.

2) The formation stage of the large thrust nappe and deep buried body beneath it occurred from the Early to Late Triassic (251–201 Ma) (Fig. S6B1, Fig. S6B2, Fig. S6B3, Fig. S6C1, Fig. S6C2 and Fig. S6C3). As mentioned above, the hanging wall of the pre-existing normal fault gradually uplifted, connecting the strata above the Silurian strata with the corresponding strata of the footwall (Fig. S6B1 and Fig. S6C1). Later, they experienced the deformation stage together, gradually forming the large-scale nappe. Under the sustained action of compressive stress after the formation of the large thrust nappe, two SE-dipping thrust faults developed, in the bottom of the basement, in front of the thrust fault formed by structural inversion of the normal faults (Fig. S6B2, Fig. S6B3, Fig. S6C2 and Fig. S6C3). The last developed basement fault in this period connected two sets of basement detachments, at 22 and 15 km, and led to the uplift deformation of the overlying strata, which laid the foundation for development of later deep buried bodies (Fig. S6B4 and Fig. S6C4). In this stage, the evolution process and deformation results of the middle-south segment and north segment had few differences, and the strata shortening rate was similar.

3) The formation stage of large recoil structures (Fig. S6B4 and Fig. S6C4) occurred from the late Late Triassic to the late Middle Jurassic (201–163 Ma). In the process of advancing NW, a recoil fault formed at the leading edge of deformation, resulting in a large suite of strata reverse thrusting on the buried bodies (and nappe). The scale of this recoil fault was not inferior to that of the pre-existing nappe fault. In addition, the lithology of the hanging wall was different to that of the contiguous footwall, which meant that conditions were in place for forming a lithologic hydrocarbon reservoir. Therefore, the fault played a role in blocking rather than intensifying oil and gas dissipation.

The boundary faults, with their deep burial and good sealing properties, and the shape of the giant bulge, indicated that the buried body was suitable for oil and gas storage. In this stage, the evolutionary processes of the middle-south segment (Fig. S6B4), and the northern segment (Fig. S6C4) were different, mainly reflected in whether or not the hanging wall strata overlay the nappe. Because the compressive stress of the northern segment was relatively small, the displacement of the reverse structure formed after the obstruction was smaller than that of the middle-south segment under the same conditions, meaning that the strata on the hanging wall were not active enough to move on the nappe. This differential evolution was also reflected in the shortening rate of the strata: the shortening rate of the northern segment was 18.7%, while the shortening rate of the middle-south segment was higher, at 27.3%.

4) The second development stage of the nappe fault (Fig. S6B3) took place from latest Middle Jurassic to latest Early Cretaceous (163–103 Ma). During this period, the intensity of the tectonic compressional movement weakened, so the deformation pattern of the study area was not greatly changed, simply becoming more complicated in local areas. In the middle-south segment of the study area, the nappe continued to move forward under the action of compressive stress. Because the hanging wall of the recoil fault overlay the nappe, however, they were in direct contact, without any buffer zone between them. This meant that the movement of the nappe would be blocked, and that the nappe fault would develop again, cutting through the recoil fault ahead, to change it into two, small-scale
recoil faults. In contrast, in the northern part of the study area, because the reverse structure and the hanging wall of the nappe were unconnected, there was a buffer space between the two structures, deforming the strata slightly.

(5) The basement thrust fault, located on the southeast side of the large recoil fault, developed again during the latest Early Cretaceous to Early Paleogene (103–51 Ma). Similarly, under the influence of compressive stress, in order to break through the recoil fault ahead, the thrust fault, like the nappe fault, cut through the large recoil fault, and acted as a bridge connecting the two sets of detachments, at 15 and 11 km. At the same time, it also caused the passive deformation and uplift of the overlying strata, complicating the structural style. In this period, the tectonic evolution processes of the middle-south and north segment were virtually the same. The shortening rates of the strata were very small for them both, at less than 1%.

(6) Since the Early Paleogene (51 Ma), we have mainly seen the vertical uplift stage (Fig. S6B7 and Fig. S6C6). After 51 Ma, the overall structural style has been basically stable, and the structural deformation has been mainly reflected in vertical uplift. After this vertical uplift, the earth’s surface has been extensively eroded, as a result, most of the strata on the thrust fault hanging wall, and the strata above the Sinian strata on the nappe, disappear, destroying the original tectonic form, which made the tectonic restoration process much harder.

3 DISCUSSION
3.1 Deformation-Controlling Factors

As mentioned above, the overall deformation of the study area has been controlled by morphological changes to the basement detachment. After integrating 5 seismic interpretation schemes, the change rules for the basement detachment depend on the depth. From SE to NW, the basement detachment has uplifted twice, while in the NE-SW direction, it behaves like an anticline (Fig. 3).

Figure 3 is a sketch map showing how the basement detachment evolved into today’s form. In the Indosinian Period, compression folded the basement detachment quickly, while subsequently, the basement detachment was hindered by the Qinling-Dabie Mountains, making its central part uplift to be a type of anticline. By the Yanshan Period, the study area was affected by more powerful, NW-SE extrusion stress, at which time the basement detachment deformed again, based on the original deformation, controlling the deformation of the overlying strata and finally turning it into the present pattern.

The question remains as to whether there were any other factors that controlled deformation of the study area apart from the morphological change of the basement detachment. Previous studies have shown that, in the study area and in the Xiangxi area, the ENE-WSW trending structure was mainly formed in the Indosinian Period, while the NE-SW and NNE-SSW trending structures were products of the Yanshan I and Yanshan II movements, respectively (Yan et al., 2003, 2000). Influenced by different tectonic movements, the different strike structures gradually grew to the west, along the front of the Xuefeng thrust belt. By identifying the fold axis, it was not difficult to see that structural development of the ENE-WSW strike stopped in the Hefeng-Longshan area, structural development of
Figure 4: Sketch map of controlling factors influencing the evolution of Sangzhi-Shimen tectonic belt. F0, F1 and F2 refer to extrusion stresses of different sizes. Among them, F2>F1>F0. While X, X1 and X2 respectively refer to the displacement of the deformation body advancing forward under extrusion stresses of F0, F1 and F2. Finally, Y1 and Y2 refer to the distance between termination lines of various tectonic movements.

Model A: Without considering the magnitude of principal stress, only the range of tectonic movement in each period is taken into account.

Model B: Without considering the range of tectonic movement in each period, only the magnitude of principal stress is taken into account.

Model C: Both factors are taken into account.
the NE-SW strike stopped in the Enshi-Zigui area, and structural development of the NNE-SSW strike only existed to the east of the Qiuyueshan fault. The termination position of the structure was roughly consistent with the termination position of the influence range of each tectonic movement, which indicates that the tectonic deformation was related to the ranges of the tectonic movements.

In addition to the morphology and depth of the basement detachment, and the ranges of tectonic movements for each period, there has been another factor that has affected the deformation of the study area—the magnitude of principal stress. In studying the structural evolution of different segments of the study area (Fig. S6), we neglected the deformation at the leading edge of the deformation, and focused on the effect of the magnitude of the principal stress on the morphology at the nappe trailing edge. Therefore, in this section, we will address these neglected factors and focus on the effect of the two main factors controlling deformation at the leading edge (Fig. 4).

As shown in Fig. 4, model A was based on the assumption that only the range of tectonic movements in each period was taken into account, without considering the magnitude of the principal stress. This model shows that the lesser the distance between the cut-off line of the tectonic movement and the deformable body, the more intense the degree of deformation at the leading edge of the deformation would be, with the basement detachment gradually uplifting, resulting in the formation of folds in the overlying strata, and finally forming a reverse structure with a fault propagation fold as the main body. Model B was based on the assumption that only the magnitude of the principal stress was taken into account, without considering the range of tectonic movements for each period. Similarly, deformation of the strata near the leading edge of deformation gradually deformed under the action of compressive stress, forming a reverse structure, with the fault turning fold as the main body. However, unlike model A, the effect brought about by the difference in the magnitude of principal stress was mainly concentrated on the trailing edge of deformation, and its influence on the leading edge of deformation should be less than the influence brought about by the difference in the ranges of tectonic movement for each period. Therefore, the detachment at the leading edge of deformation in model B has not uplifted, while the shape of the deep buried body at the trailing edge changed differently, in that the stronger the compressive stress, the more closed the deep buried body was.

Model C was developed after considering the two factors mentioned above. This model has strong similarity to the final results of the structural analyses shown in Fig. S3 and Fig. S4.

In summary, both factors controlled the deformation at the leading edge, but the effect of compressive stress was more concentrated in the deep buried body.

3.2 3D Geological Evolution Model

After completing the above research, in order to verify the feasibility of the model, we carried out a physical simulation experiment for the whole Xiangxi region. The basic data needed for the experiment are from our own shortening rate and apatite fission track data. In this physical simulation experiment, quartz sand is used to refer to brittle strata, and silica gel refers to detachments. Among them, the red quartz sand is the marker layer, while the other quartz sand with different colors represents different tectonic levels (Fig. 5a). The results of the experiment are shown in Fig. 5b. When \( d = 10.2 \) cm (\( d \) is the amount of compression), a large basement thrust fault developed on the trailing edge, which refers to the super-large thrust fault developed at the southeastern side of the deep buried body. When \( d = 23.8 \) cm, the basement detachment had uplifted, and a smaller thrust fault was developed near the uplift. Apparently, it is consistent with B2, B3, C2 and C3 stages in the evolution model. At the same time, a recoil fault developed on the leading edge. Unlike the recoil fault in the evolution model, the recoil faults in the physical simulation experiment do not develop from the basement. This indicates that the physical simulation experiment needs further improvement. If one more set or even more sets of detachments are set in the basement strata, the result may be more consistent with the evolution model. This recoil fault continues to develop and eventually terminates at the thrust fault, forming the buried body (Fig. 5b).

After verifying the feasibility of the evolution model, it became possible to develop the 3D geological evolution model for each segment of the study area. Figure 6 shows the specific evolution process.

(1) In the Indosinian Period, under the action of S-N trending compressive stress, the basement detachment gradually developed and uplifted. Subsequently, because of the hindrance brought about by the Huangling anticline in the north, the morphology of the basement detachment changed from being ladder-like to that of uplift.

(2) After the Indosinian Period, under the action of regional SE-NW trending compressive stress along the pre-existing normal fault, a large set of strata thrust upward, forming a broad and gentle anticline structure. Because the extrusion stress in the northern segment of the study area was smaller than that in the middle-south segment, under similar conditions, the displacement of the north segment was be smaller, resulting in the formation of a smaller scale of anticline. During the whole deformation, the basement detachment was gradually raised from SE to NW, which complicated its morphology.

(3) In the process of progressively moving towards the NW, large recoil faults formed at the leading edge, and large sets of strata on the hanging wall thrust upwards. During this period, the influence brought about by the difference in stress magnitudes was still much stronger than that brought about by the differences in the range of tectonic movements in different periods. The evidence for this is that, though the termination line of the tectonic movement in the middle-south segment was further away from that in the north segment, the strata on the hanging wall of the recoil fault were still overlying the nappe.

(4) After formation of the overall structure, the influence brought about by the difference in the ranges of the tectonic movements in each phase gradually deepened. Reverse structures developed at the leading edge of the deformation, and the morphology changed sharply under the influence of complex factors. To sum up, it can be concluded that the influence brought about
by the difference in magnitude of the principal stresses was mainly concentrated on the trailing edge and middle-early stages of the deformation phase. This led to the forms of the thrust nappe structure and the deep buried body changing differently. The influence brought about by the difference of tectonic movement range in each period was concentrated on the leading edge and late stage of the deformation phase, as mainly reflected in the form of small reverse structures. The entire deformation was mainly controlled by the change of morphology and depth of the basement detachment.

4 CONCLUSIONS

(1) The structural style of the study area is similar, from the south to the north: a large nappe developed at the trailing edge of the study area, while at the same time, a large, deep-buried developed buried beneath the nappe. In addition to the similarities, however, there are still differences. One of the most impressive is as follows: in the middle-south segment, the nappe fault overlying the deep-buried body cut through the thrust fault in front of it, while in the northern segment the opposite occurred.

(2) There are three factors leading to the differences in the tectonic evolution: (a) the magnitude of principal stress, (b) the range of tectonic movements, and (c) the depth and morphology of the basement detachment. The depth and morphology of the basement detachment controlled the overall deformation, while the influence brought about by the difference in magnitude of the principal stress was mainly concentrated on the

Figure 5. Physical simulation experiment and its results in Xiangxi region. (a) The basic model; (b) the experimental results. \(d\) refers to the amount of compression, and the red line refers to the fault.
trailing edge, and the middle-early stages of the deformation phase. This led to the shape of the thrust nappe structure and the deep-buried body being changed, as the influence brought about by the difference of the tectonic movement’s range was concentrated on the leading edge, and on the late stages of the deformation phase, as reflected mainly in the shapes of the small reverse structures.

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