Cenozoic rifting and volcanism in eastern China: a mantle dynamic link to the Indo–Asian collision?

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Abstract

The Indo–Asian continental collision is known to have had a great impact on crustal deformation in south-central Asia, but its effects on the sublithospheric mantle remain uncertain. Studies of seismic anisotropy and volcanism have suggested that the collision may have driven significant lateral mantle flow under the Asian continent, similar to the observed lateral extrusion of Asian crustal blocks. Here we present supporting evidence from P-wave travel time seismic tomography and numerical modeling. The tomography shows continuous low-velocity asthenospheric mantle structures extending from the Tibetan plateau to eastern China, consistent with the notion of a collision-driven lateral mantle extrusion. Numerical simulations suggest that, at the presence of a low-viscosity asthenosphere, continued mass injection under the Indo–Asian collision zone over the past ~50 My could have driven significant lateral extrusion of the asthenospheric mantle, leading to diffuse asthenospheric upwelling, rifting, and widespread Cenozoic volcanism in eastern China.

1. Introduction

Following the initial Indo–Asia collision ~50–70 My ago, tectonic evolution in western China has been dominated by crustal compression (Yin and Harrison, 2000). The continued post-collisional plate convergence has telescoped >2000 km of crust, leading to the present Himalayan–Tibetan plateau, rejuvenating the Tien Shan orogen, and affecting regions as far north as the Baikal rift (Molnar and Tapponnier, 1975; 1977; Tapponnier and Molnar, 1979; Tapponnier et al., 1982) (Fig. 1). Consequently, western China has been characterized by crustal shortening and mountain building throughout the Cenozoic (Allegre et al., 1984; Dewey and Burke, 1973; Harrison et al., 1992; Hu et al., 2000; Molnar and Tapponnier, 1977; Owens and Zandt, 1997; Yin and Harrison, 2000).
In contrast, eastern China has been dominated by widespread rifting and basaltic volcanism through the Cenozoic (Deng et al., 1997; Liu et al., 1983; Tian et al., 1992; Ye et al., 1987; Zhou et al., 1988). The North China Plain rift system was reactivated in Eocene along a series of major Mesozoic-originated NNE and/or NE faults, and widespread subsidence developed over the area since early Miocene (Gilder et al., 1991; Tian et al., 1992; Ye et al., 1987). Some of the rifts developed after the Indo–Asia collision and are active today, such as the Yinchuan–Hetao rift and the Shanxi rift system (Xu and Ma, 1992; Zhang et al., 1998) (Fig. 1). Prevalent Cenozoic basalts have occurred along many rift–graben systems (Fig. 1). Paleogene olivine tholeiites and tholeiites occurred mainly in the North China Plain rift zones and the Subei basins. Neogene alkali olivine and phonolitic basanites occurs mainly along major fault system in eastern China, and Quaternary alkaline basalts had a wide, dispersive distribution in northeast and southern China (Liu et al., 1983, 2001; Tian et al., 1992; Zhou et al., 1988). The present eastern China is characterized by abnormally thin crust (~30–35 km) and lithosphere (as thin as 70 km), low elevation (<500 m), elevated heat flow (~60–80 mW m⁻²), and high seismicity (Hu et al., 2000; Ma, 1989; Ma and Wu, 1987).

The contrasting Cenozoic tectonics between western and eastern China may be genetically linked. Part of the ~2000 km plate convergence (Molnar and Tapponnier, 1975) following the initial Indo–Asian collision has been accommodated by large-scale eastward–southeastward lateral “escape” of Asian continent...
along numerous strike-slip faults (Avouac and Tapponnier, 1993), which may have transmitted the collisi-
onal stresses to eastern China and contributed to the rift-
ing (Tapponnier et al., 1982; Tapponnier and Molnar, 1977). Previous studies of the far-field effects of the
Indo–Asia collision have focused on stress trans-
mission through the lithosphere (Kong et al., 1997;
Tapponnier et al., 1982), but the dynamic effects of the
Indo–Asian collision may have extended much deeper.
Seismic anisotropy under the Tibetan plateau shows a
strained mantle extending to >200 km depth (Lave et
al., 1996; McNamara et al., 1994). The orientation of
the polarized fast S-wave is consistent with the strain
field in the Tibetan crust, suggesting coherent defor-
mation in the mantle (Holt, 2000). Owens and Zandt
(1997) interpreted the seismic anisotropy under the
northern Tibetan plateau, where the mantle is hot and
weak, as indicative of an E–W directed lateral mantle
flow. The lateral extend of such mantle flow is not clear.
Based on the geochemistry of the dispersive Cenozoic
volcanic rocks in eastern China and southeastern Asia,
a large-scale, collision-driven lateral mantle extrusion
under the Asian continent has been speculated (Basu et
al., 1991; Flower et al., 1998).

The collision-driven, large-scale lateral mantle flow
under the Asian continent, similar to the observed
escaping lithospheric blocks, may help to explain the
broad and dispersive mantle upwelling under eastern
China indicated by seismic tomography (Liu and Jin,
1993; Zhang, 1998) and the Cenozoic volcanism
(Basu et al., 1991; Liu et al., 1994; Zhou et al.,
1988). Here we test this hypothesis by firstly inves-
tigating the mantle structure under Asia using P-wave
seismic tomography. The results show continuous low-
velocity asthenospheric mantle structure extending
from the Tibetan plateau to eastern China, consistent
with collision-driven lateral mantle extrusion. We then
explore the feasibility and conditions for such lateral
mantle extrusion using numerical modeling.

2. Seismic tomography of mantle structure

We derived the three-dimensional mantle structure
under China and surrounding regions using P-wave
travel time tomography. The inversion used P-wave
arrival times from 745 Chinese seismic stations and the
global data set from the International Seismological
Center (Fig. 2). The rays were selected from 3712 local
events and 4623 teleseismic events from year 1978 to
1995. A total of 217,569 rays was used in the study, a
significant improvement over the <100,000 rays used
in the study by Liu and Jin (1993). As a result, the
spatial resolution is much improved. Under eastern
China where stations are dense, the spatial resolution is
better than 50 km. Table 1 shows the reference velocity
model used in this study, based on an averaged
velocity structure of the Chinese continent and
adjacent regions (Liu and Jin, 1993). The average
crustal thickness is taken to be 45 km. The depth 45 °
and 45 ° in Table 1 represent the interface immediately
above and below the reference Moho depth. The
analytical procedures and the algorithm used for
inversion of the velocity perturbations were described
in previous papers (Liu and Jin, 1993; Liu et al., 1990).

Fig. 2 shows velocity perturbations at 110 and 220
km depths, within the typical depth ranges of litho-
sphere and asthenosphere, respectively. As usual for
seismic tomography, velocity structures near the
margins of the model domain are not well constrained
by the data. At the 110 km depth (Fig. 2a), a major
velocity low is found in the North China Plain,
consistent with thin lithosphere and high heat flow
there (Hu et al., 2000; Ma, 1989). Other significant
velocity lows includes those under the northern rim of
the Tibetan plateau and the eastern end of the
Songpang–Ganzi fold-thrust belt near the northeastern
margin of the Tibetan plateau. Major velocity highs are

Table 1
Reference velocity model

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Velocity (km s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.80</td>
</tr>
<tr>
<td>45 °</td>
<td>6.70</td>
</tr>
<tr>
<td>45 °</td>
<td>8.00</td>
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<tr>
<td>110</td>
<td>8.15</td>
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<tr>
<td>220</td>
<td>8.47</td>
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<tr>
<td>400</td>
<td>9.15</td>
</tr>
<tr>
<td>600</td>
<td>10.10</td>
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<tr>
<td>800</td>
<td>10.35</td>
</tr>
</tbody>
</table>
Fig. 2. P-wave travel time seismic tomography of China and the surrounding regions. (a) P-wave velocity perturbation at 110 km depth. The dashed line indicates the approximate direction and dimension of the model domain in Figs. 3–7, and the solid white lines show the directions and dimensions of the two vertical sections in (c) and (d). (b) P-wave velocity perturbation at 220 km depth. (c) A vertical section of the P-wave velocity structure across northern China (line 1 in (a)). (d) A vertical section of the P-wave velocity structure across southern China (line 2 in (a)).
Himalayas and south Tibet, the Tarim basin and Tian Shan mountain ranges, the Sichuan basin and the Qingling–Dabie orogenic belt. Recent study by Xu et al. (2002) using regional events recorded in China and Kyrgyzstan seismic networks reveals more detailed structures in northwestern China, but the broad patterns are similar.

Some of the high-velocity structures extend to the asthenosphere, notably those under the Himalayas, the Tarim basin, and the Siberian shield surrounding western China and northern Mongolia. These results are similar to those from previous studies (Cipar et al., 1993; Liu and Jin, 1993; Lyon-Caen, 1986). The main feature in Fig. 2b, however, is the diffuse velocity lows in eastern China and northern Tibet, connected by two broad low velocity channels, one runs through northern China and southern Mongolia and another through southern China. The relatively high velocity regions
under central China may reflect lithospheric roots of the Mesozoic Qinling–Dabie orogenic belt (Fig. 1).

Fig. 2c and d show vertical sections of the mantle structure crossing northern and southern China, respectively. In both sections the asthenospheric layer, indicated by the low velocity zone in the depth range of ~150–350 km, is well defined. Obviously, these results depend on the reference velocity model. The reference model used here (Table 1) is based on the average velocity structure of the Chinese continents and the neighboring regions, which may be biased by the abnormally low velocities under eastern China and the back-arc basins. If we choose the velocity structure of the stable Chinese continent as the reference, the velocity values would be higher than the reference model in Table 1. Consequently, the velocity highs in Fig. 2 would be weakened, but the low-velocity asthenospheric channel would be enhanced. Although some of the velocity perturbations may result from compositional variations, we believe that the results in Fig. 2 reflect primarily temperature perturbations, because similar structures were derived from surface-wave tomography (Zhang, 1998; Zhang and Tanimoto, 1993), which are more sensitive to temperature perturbations than P-waves.

3. Numerical modeling

The continuous low-velocity asthenospheric mantle extending from the Tibetan plateau to eastern China cannot prove lateral mantle flow under Asia, but it is consistent with the notion of collision-driven lateral mantle extrusion. Furthermore, we show below that the low-velocity asthenosphere channels in Fig. 2 make large-scale lateral mantle extrusion mechanically feasible.

The >2000 km post-collisional convergence between the India and Eurasian plates implies that large volumes of mantle lithospheric material was injected under Tibet in the past 50–70 My. Did all the convergent mantle lithospheric material sink into the deep mantle, or could some of the mass injection have been accommodated by lateral mantle flow, presumably in the asthenosphere? Here we test the feasibility of collision-driven large-scale lateral asthenospheric flow in a two-dimensional (2-D) finite element model (Fig. 3). The model domain encompasses the crust, mantle lithosphere, asthenosphere and underlying mantle regions with different viscosity for each layer (Table 2). The initial Tibetan lithosphere is assumed to

![Fig. 3. Model geometry, initial thermal structure and boundary conditions of the numerical model. The thick thermal boundary layer represents an initially thickened Tibetan lithosphere. The imposed velocity boundary conditions are used in the cases in Figs. 5 and 6.](image-url)
be thicker and weaker than the lowland Asian continent (Fig. 3). With the Boussinesq approximation, the mantle flow and thermal evolution were described by the coupled mass, heat, and momentum equations:

$$\nabla \cdot \mathbf{u} = 0$$

(1)

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T - k \nabla^2 T = 0$$

(2)

$$\rho \left( \rho \mathbf{u} \cdot \nabla \mathbf{u} - \mu \nabla^2 \mathbf{u} + \nabla P + \alpha \rho (T - T_0) \mathbf{g} \right) = 0$$

(3)

where $\mathbf{u}$ is velocity vector, $T$ is temperature, $T_0$ is reference temperature at bottom of the lithosphere, $t$ is time, $k$ is thermal diffusivity, $\rho$ is density, $P$ is fluid pressure, $\mu$ is viscosity, $\alpha$ is thermal expansivity, and $\mathbf{g}$ is gravity. The values of model parameters used in this study are given in Table 2.

The crust and mantle were approximated as viscous, incompressible Newtonian fluids. The model domain approximates a roughly SW–NE vertical section across China (see Fig. 2a). Although continental deformation and mantle structures in south-central Asia are three-dimensional in nature, the 2-D model as first order approximation is justifiable because of the tectonic boundary conditions around the Tibetan plateau. As shown in Fig. 2 and suggested by other seismic studies (Cipar et al., 1993; Lyon-Caen, 1986; Zhang, 1998), the Tibetan plateau is surrounded by deep (>250 km), cold mantle structures on all sides except the east. The major outlet for mass injected into the collision zone is downward and to the east and southeast, where a relatively free boundary may be assumed because of the observed continental extrusion and the presence of back-arc spreading centers along the eastern Asian continental margins throughout the Cenozoic (Northrup et al., 1995; Tapponnier and Molnar, 1977).

The initial thermal gradient was conductive within the lithosphere, and adiabatic within the sub-lithospheric mantle (Fig. 3). The temperature is fixed at the top and bottom boundaries; the left and right edges of the model domain are insulated from horizontal heat flux. To focus on collision-induced mantle flow, possible internal heat was excluded from the model. For the velocity field, the bottom of the model is permeable, allowing vertical flow. Various velocity boundary conditions were applied to simulate the effects of plate collision and crustal rift on the mantle flow (see blow). The governing equations were solved using the finite element method based on the DIFFPACK library codes (Langtangen, 1996). The numerical grid for most simulations is 20 by 60, corresponding to vertical and horizontal spatial resolution of 35 km. Results using a finer 40×120 mesh differ by <8%.

To better understand the effects of mass injection associated with the Indo–Asian collision, we present first a reference model where no external velocity is imposed on the boundaries of the model domain. Fig. 4 shows the sequential snapshots of the predicted thermal and velocity fields. During the first 30 My or so the major feature was downwelling mantle flow beneath the initially thickened Tibetan lithosphere (Fig. 3), similar to results of previous studies (England, 1993; Houseman et al., 1981). The downwelling flow and the induced small-scale upwelling flows work together to thin the Tibetan lithosphere. This process has been proposed as a major cause of volcanism and accelerated uplift in central and north Tibet (Molnar et al., 1993). By ~50 My most of the Tibetan lithosphere has been significantly thinned, and some small convection cells within the asthenosphere started under eastern China. However, the convection was weak, the thermal structure of the lithosphere in eastern China was hardly perturbed.

The results are significantly different when mass injection associated with the Indo–Asian collision was considered (Fig. 5). The mass injection was simulated with a linear velocity profile imposed on the left side of the model domain (Fig. 3). Considering possible mantle flow not contained in the model plane, we used only a fraction (up to 2 cm year$^{-1}$) of the total
Fig. 4. Sequential snapshots of the simulated thermal and velocity fields for the reference case at 12 My (a), 28 My (b), and 52 My (c). The mantle flow results from gravitational instability of the thickened lithosphere. Zero velocity is imposed on the surface and the two vertical edges, and the bottom is permeable to vertical flow. The scale of velocity is shown on the top left corner of each panel.
Fig. 5. Sequential snapshots of the simulated thermal and velocity fields resulting from gravitational instability of the thickened lithosphere and continued mass injection into the collision zone. The imposed velocity boundary conditions are shown in Fig. 3. (a), (b), and (c) show the temperature and velocity fields at 12, 28, and 52 My, respectively. See text for discussion.
convergence rate (~5 cm year\(^{-1}\)). The velocity boundary condition on the right side of the model is used to be consistent with the back-arc spreading along eastern China continental margins throughout the Cenozoic (Fig. 1). In this case we also imposed a horizontal velocity field on the top left boundary to simulate the distributed crustal contraction in western China (England and Molnar, 1997), and a velocity field on the top right boundary to simulate the effects of crustal rifting in eastern China (see Fig. 3). Although the predominantly NW–SE extension in eastern China (Fig. 1) cannot be fully represented in the NE–SW model section, the model nonetheless helps to illustrate the physical effects of crustal rifting on mantle dynamics.

Fig. 5 shows a downwelling mantle flow developing from the gravitational instability of the thickened Tibetan lithosphere during the first few million years, similar to that in Fig. 4. However, because of the continued mass injection under Tibet, the downwelling flow spread out eastward within the asthenosphere, driving asthenospheric upwelling and causing lithospheric thinning under eastern China. The combined free convection resulting from gravitational instability of the thickened Tibetan lithosphere and forced flow from mass injection into the collision zone produced a complicated mantle flow pattern over time. Part of the Tibetan lithosphere is thinned by small-scale upwelling flow, while a large-scale lateral mantle flow extended to eastern China (Fig. 5b). By ~50 My small-scale asthenosphere plumes formed under eastern China, producing diffuse mantle thermal perturbations and significant lithospheric thinning (Fig. 5c). The results are comparable to the observed mantle structure under eastern China (Fig. 2).

### 4. Discussion and conclusions

It is well known that lithospheric deformation may induce significant mantle flow. However, such flow is often predominantly vertical, resulting from thermally induced buoyancy forces (England, 1993; Houseman et al., 1981; Liu and Zandt, 1996). The evidence for large-scale lateral mantle flow has been inferred mainly from seismic anisotropy (Owens and Zandt, 1997; Russo and Silver, 1994), but interpretation of seismic anisotropy is not unique (Holt, 2000; Savage, 1999). Our seismic tomography shows that the mantle structure beneath China and the neighboring regions is consistent with the notion of collision-driven lateral mantle extrusion, and our numerical results suggest that, at the presence of well-developed low-viscosity asthenospheric channels, it is feasible for the Indo–Asian collision to have driven large lateral mantle extrusion. This process could have led to broad asthenospheric upwelling under eastern China, contributing to the Cenozoic rifting and basaltic volcanism in eastern China and southeast Asia.

The numerical results are dependent on model parameters; some of them, especially the viscosities, are poorly constrained. We have explored the effects of major model parameters and boundary conditions with numerical experiments; our results indicate that the most critical condition for the predicted lateral mantle extrusion is a well-developed low-viscosity asthenospheric layer. Without this layer the lithospheric material injected into the collision zone would flow predominantly downward because of its relatively low temperature, and the Tibetan lithosphere may be thickened further by the mass injection (Fig. 6). The upwelling flow in the right half of the model domain in Fig. 6 results from the imposed mass conservation in the rectangular model domain. In the real Earth, the descending mantle flow under Tibet would not require an equal amount of upwelling mantle flow under eastern China.

Our seismic tomography (Fig. 2) indicates that well-developed asthenosphere channels exist beneath the Asian continent at present, and we may assume that a hot and weak asthenosphere existed throughout much of the Cenozoic time when volcanism and continental deformation were active in east and southeast Asia. With such a low-viscosity asthenosphere, the Indo–Asian collision could have driven large-scale lateral mantle flow under Asian continent. The predicted rates and scale of the lateral mantle flow correlate positively with the rate of mass injection and are affected by the viscosity of the model asthenosphere and its contrast with that of the rest part of the upper mantle. Viscosity values used in this study are typical for the mantle (Cathles, 1975). The viscosity of \(5 \times 10^{19}\) Pa s for the model asthenosphere is probably a conservative estimate. It has been
suggested that the effective asthenospheric viscosity could be as low as \(10^{18}\) Pa s beneath young oceanic and active continental regions (Buck and Parmentier, 1986). We tested a broad range of mantle viscosity values and found that, within typical ranges of viscosity for the asthenosphere (\(10^{18}–10^{20}\) Pa s) and the upper mantle (\(10^{21}–10^{23}\) Pa s), significant lateral mantle flow beneath Asia is predictable.

The causative relationship between crustal rifting and mantle upwelling under eastern China has been controversial. Some workers suggested that the broad mantle upwelling beneath eastern China resulted directly from crustal rifting (Ma and Wu, 1987; Xu and Ma, 1992), others suggested active role of mantle upwelling in inducing crustal rifting (Liu, 1987; Ye et al., 1987; Yin, 2000). We imposed a surface velocity gradient in eastern China to simulate the effects of crustal rifting (Fig. 5) and find the effects minimal—we obtained essentially identical results as those in Fig. 5 without imposing the surface velocity gradient. The broad and dispersive velocity lows in the upper mantle under eastern China (Fig. 2) would be explained better by active mantle upwelling. Such mantle upwelling more likely originated from the asthenospheric mantle, rather than deep-rooted mantle plumes as some workers have suggested (Deng et al., 1998), because our tomography (Fig. 2) as well as those from other studies (Zhang, 1998) all indicate that the low-velocity structures under eastern China are limited to the upper mantle, above the transition zone.

Many studies have linked Cenozoic rifting and volcanism in eastern China to the rollback of the subducting Pacific plate away from the Eurasian continent (Allen et al., 1998; Northrup et al., 1995; Ye et al., 1987). The supporting evidence includes (1) that the early Tertiary reactivation of eastern China rift system predates the Indo–Asia collision at \(~50\) Ma (Ye et al., 1987) and (2) the timing of extension correlates to the change of converging rate between the Eurasia and Pacific plates (Northrup et al., 1995). The low-velocity mantle structures to the east of the Chinese coast (Fig. 2) would be best explained by subduction-induced mantle upwelling in the back-arc setting. However, the diffuse mantle upwelling under much of eastern China (Fig. 2a,b) and many of the rifts in eastern China, located thousands of kilometers from the Eurasian–Pacific...
plate boundary, cannot be readily linked to the subduction of the Pacific plate.

We suggest that both the Indo–Asian collision and subduction of the Pacific plate played important roles in the Cenozoic rifting and volcanism in eastern China. Our results indicate that, in addition to the observed crustal “escaping”, the Indo–Asian collision may have also driven significant lateral extrusion of the mantle asthenosphere. Such lateral mantle flow would help to explain many features of Cenozoic tectonics in eastern China, including (1) the reactivation of the pre-existing NNE trending and basin-bounding faults and the resurgence of basaltic volcanism along these faults during Neogene and Quaternary (Tian et al., 1992), (2) the rifting migration along the Pliocene Shanxi rift and the extensive Quaternary eruption of basalts (Tapponnier and Molnar, 1977), (3) the high heat flow and high historical seismicity in the North China Plain basin (Hu et al., 2000; Ma, 1989), and (4) the presently elevated asthenosphere and thinned crust and lithosphere in northern and northeastern China (Fig. 2). The collision-driven mantle extrusion may also help to account for the DUPAL-like composition of most Cenozoic basalts in eastern China (Flower et al., 1998). Such a mantle flow was speculated to have triggered the opening of Japan Sea (Okamura et al., 1998), and, in conjunction with intraplate stress associated with the Indo–Asia collision, contributed to the Cenozoic rifting and magmatism in the Baikal rift zone (Logatchev and Zorin, 1992; Molnar and Tapponnier, 1975).

Fig. 7 summarizes our preferred model of mantle dynamics for Cenozoic rifting and volcanism in eastern Asia. Continued injection of voluminous lithospheric material under Tibet associated with >2000 km Indo–Asian convergence, facilitated by the low-viscosity asthenospheric channels under Asian continent and the convective instability of the thickened lithosphere in western China, have driven a lateral mantle extrusion. Because of the deep cratonic roots west and north of the Tibetan plateau, mantle extrusion has been predominately eastward, similar to the observed lateral crustal extrusion in Asia. Such mantle extrusion, together with extensional stresses induced by rolling back of the Pacific plate (Northrup et al., 1995), may have driven a broad asthenospheric upwelling under eastern China, reactivated preexisting rifting systems and produced widespread volcanism. Both the seismic tomography and numerical results presented here are meant to illustrate this conceptual model and to test its physical feasibility. Further investigation of the impacts of the Indo–Asian collision on mantle dynamics would lead to a better understanding of many key observations in east and southeast Asia, including significant lithospheric thinning during the Cenozoic (Liu, 1987), opening of the South China sea (Taponnier et al., 1982), broad regions of low-velocity upper mantle, isotopically anomalous asthenosphere, and dispersed Cenozoic

Fig. 7. A sketch of the suggested relationship between Indo–Asia collision and Cenozoic extension and volcanism in eastern China. See text for discussion.
basalts derived from upwelling asthenosphere (Basu et al., 1991; Flower et al., 1998).

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