Widely distributed thrust and strike-slip faults within subducting oceanic crust in the Nankai Trough off the Kii Peninsula, Japan

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We identified widely distributed thrust and strike-slip faults within subducting oceanic crust in the Nankai Trough, southeast of the Kii Peninsula, Japan, on the basis of 2D and 3D seismic reflection data. The seafloor seaward of the trough axis is deformed by displacement on these intraoceanic reverse faults, producing topographic highs (part of Kashinosaki Knoll). Because the thrust faults extend to the Moho and offset the Moho reflection, they may be related to serpentinization of the mantle due to seawater invasion. These faults are seismically active, given that their geometries are consistent with the focal mechanisms of intraplate earthquakes and microearthquakes. The thrust faults appear to extend landward to a high-density dome within the accretionary prism off the Kii Peninsula. Because the dome and the associated thick accretionary prism are expected to generate high friction at the plate interface due to their large vertical load, the intraslab thrusts are likely to have grown with ongoing subduction. Furthermore, because the geometry of the fault system we identified off the Kii Peninsula has characteristics similar to faults at Zenisu Ridge east of our study area, the thrusts observed in the study area may be considered to be the westward continuation of those at Zenisu Ridge. Since the Euler rotation pole of relative motion between the Philippine Sea plate and Zenisu Ridge is consistent with the high-density dome off the Kii Peninsula, we interpret the high-density dome as well as Kashinosaki Knoll as a westward termination of the Zenisu compression zone.

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1. Introduction

The Nankai Trough is a convergent margin where the Philippine Sea plate is subducting beneath southwest Japan. Because this subduction zone has repeatedly generated great earthquakes with Mw > 8 (Ando, 1975), seismic studies have been carried out over the entire Nankai Trough region (Fig. 1) (e.g., Moore et al., 1990; Park et al., 2002), as well as numerous drilling operations aimed at characterizing the accretionary prism and seismogenic mega-splay faults (e.g., Taira et al., 1991; Tobin et al., 2009). However, the role of subducting oceanic crust at this convergent margin remains poorly understood. On the eastern part of the Nankai Trough, the intraoceanic thrust and its relationship with the collision of Japan and the Izu–Bonin arc have been extensively studied (e.g. Lallemant et al., 1989; Le Pichon et al., 1987; Mazzotti et al., 1999, 2002). Active thrusting in the area off the Kii Peninsula has also been reported (Aoki et al., 1982; Lallemant et al., 1989; Le Pichon et al., 1987). However, because of the low resolution of seismic reflection data, the intraoceanic faulting system in the deep oceanic crust has not been fully revealed. This low resolution arises because signal attenuation and a broad Fresnel zone result in a dominantly low-frequency seismic signal within the deep oceanic crust (Yilmaz and Doherty, 2001).

Recent analyses of 3D seismic reflection data have revealed the presence of intraoceanic thrusts developed as imbricate structures within the subducting Philippine Sea plate off the Kii Peninsula (Tsuji et al., 2009; Fig. 2). Three-dimensional prestack depth-migrated seismic data have relatively high signal-to-noise ratio even in the deep oceanic crust, mainly because 3D geometrical effects can be taken into account during data processing (French, 1974). These intraoceanic thrusts are located around the hypocenters of the 2004 intraplate earthquakes off the Kii Peninsula (Mw > 7), and their geometry could explain the complex rupture pattern of the earthquakes (Tsuji et al., 2009). Therefore, the intraoceanic thrusts identified from 3D seismic data appear to be active.

In this study, we extracted the geometry of faults in the oceanic crust from dense multi-channel seismic reflection data. Intraoceanic thrusts identified previously from 3D seismic data (Tsuji et al., 2009) are limited to the area of the 3D seismic survey, whereas we determined the distribution of intraoceanic thrusts using 2D seismic data from more than 40 survey lines widely distributed in the Nankai Trough off the Kii Peninsula (Fig. 1). A comparison of the 2D and 3D seismic data (Fig. 3) enabled us to characterize and map intraoceanic thrusts from 2D seismic data. In this paper we discuss seismic activity on the intraoceanic thrusts and their origin.
2. Seismic data

We used multi-channel seismic reflection data acquired by 3D seismic surveys as well as several 2D seismic surveys. Many seismic data have been acquired in the Nankai Trough off the Kii Peninsula, mainly by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), to map seismogenic faults of interplate earthquakes (i.e., plate boundary décollement and mega-splay faults) (Fig. 1). In this study, however, we focus on delineating intraplate structures using these seismic data.

Two 3D seismic reflection surveys have been performed in the Nankai Trough southeast of the Kii Peninsula. The first of these was on the landward side of the trough axis. The data were acquired by M/V Nordic Explorer in 2006 (Moore et al., 2009) and interpreted by Tsuji et al. (2009) as showing intraoceanic thrusts. The 12 × 56 km survey area includes a plate boundary décollement as well as a mega-splay fault within the thick accretionary prism. In this area, we can identify the fault system within the oceanic crust even beneath the accretionary prism. The second survey was by R/V Kairei in 2006 (Park et al., 2008) on the seaward side of the trough axis. The survey area of 3.5 × 52 km partially overlaps the area of the first 3D survey (Fig. 1), allowing us to integrate them both in a long (~100 km) seismic profile along the direction of plate subduction (Fig. 2). We applied 3D prestack depth migration to the 3D seismic data using a tomography-based approach (Fig. 2; Moore et al., 2009; Park et al., 2008). Strong seafloor multiples were attenuated before migration processing. For seismic velocities within the deep oceanic crust for prestack depth migration, we used P-wave velocity structures estimated by the wide-angle ocean-bottom seismograph study of Nakanishi et al. (2008).

To characterize intraoceanic thrusts of the wide area off the Kii Peninsula, we relied mainly on 2D seismic reflection data acquired around the area of the 3D seismic surveys (Figs. 4 and 5). We used the data from five multi-channel seismic reflection surveys conducted by R/V Kairei: KR9806, KR0108, KR0114, KR0211, and KR0512 (Fig. 1). These surveys employed an airgun array of ~200 L (12,000 in.³) volume fired at 50 m intervals and a streamer ~5 km long with 204 receivers. We also used multi-channel reflection data acquired during cruise ODKM03 by R/V Polar Princess in 2003, which employed a tuned airgun array with a total volume of ~70 L (4240 in.³) fired at 50 m intervals and a streamer 6 km long with 480 channels. Data processing for the 2D seismic reflection data involved filtering, velocity analysis, stacking, deconvolution, and post-stack migration (Yilmaz and Doherty, 2001). To extract fault planes from intersecting seismic reflection lines (using fence diagrams; Fig. 6), we did not apply depth conversion to the time-domain seismic profiles, because the seismic velocity was not accurately determined in the deep oceanic crust due to small movoent in the velocity analysis.

3. Results

3.1. Intraoceanic thrusts on seismic profiles

Seismic reflection data reveal that intraoceanic thrusts are widely distributed in the Nankai Trough southeast of the Kii Peninsula (Figs. 2–5).
Fig. 2. Intraoceanic thrusts identified on the 3D prestack depth-migrated profile at the location shown in Fig. 1. This profile was extracted from two 3D seismic data (M/V Nordic Explorer and R/V Kairei). Yellow, red, green, and blue lines on the bottom profile indicate the surface of the oceanic crust, intraoceanic thrusts, oceanic Moho, and faults within the sedimentary sequence, respectively. It was difficult to identify intraoceanic thrusts landward (left) of the outer ridge because of signal attenuation.
The significant faults within the oceanic crust can be identified both on 2D and 3D seismic data (Fig. 3), although the resolution (and signal-to-noise ratio) of 2D seismic reflection data is lower than that of 3D data. Because we clearly observed these intraoceanic thrusts as continuous reflections in 3D seismic volumes (Tsuji et al., 2009), as well as on intersecting 2D seismic profiles (fence diagrams; Fig. 6), these reflections are not sideswipe noise derived from formation geometry. Furthermore, we confirmed from the travel-time information that the interpreted intraoceanic thrusts are not related to seafloor reflection multiples.

We observed landward-dipping (north-dipping) thrust faults and related backthrusts within the oceanic crust on seismic profiles parallel to the plate subduction direction (NW–SE; Figs. 2 and 4). On profiles normal to the subduction direction, we detected east-dipping intraoceanic thrusts and west-dipping backthrusts (Fig. 5). These thrusts and backthrusts are clearly related in the fence diagrams (Fig. 6). Displacements on these intraoceanic thrusts southeast of the Kii Peninsula amount to more than 1 km of cumulative offset at the surface of the oceanic crust (Fig. 2). A topographic high on the surface of the crust, formed in response to displacement on the thrusts, appears to influence the structure of the sedimentary accretionary prism, because the frontal thrust seems to be splayed from the décollement above the basement high (Fig. 2). As topographic highs further influence the development of a low-velocity zone located at the transition from the landward mega-splay fault to the seaward décollement (Kamei et al., 2012; Tsuji et al., 2007), the role of intraoceanic thrust displacements in creating topographic highs appears to be important for understanding the fault system within the accretionary prism as well as interplate earthquake mechanisms.

The western part of Kashinosaki Knoll, ~40 km seaward of the trough axis (e.g., Ike et al., 2008), is also uplifted by movement on intraoceanic thrusts, forming lineaments on the seafloor (Fig. 4e and f). Fig. 7b shows that the seafloor topography seaward of the trough axis is controlled in part by displacement on intraoceanic thrusts. Some parts of the Nankai Trough axial channel northwest of Kashinosaki Knoll are also influenced by seafloor deformation derived from intraoceanic thrust displacements (white dashed line in Fig. 7b), although most of the channel is controlled by slumping from the frontal thrust area. The thrust displacement observed on the seafloor (Figs. 4f and 5b) indicates that these intraoceanic faults have ruptured recently. Conversely, NE–SW lineaments southeast of Kashinosaki Knoll (Fig. 7a and b) differ from the intraoceanic thrusts identified on the seismic profiles, because we cannot identify the fault as clear reflections beneath the lineaments. Since these faults resemble normal faults, there is a possibility that they were generated at the spreading ridge or are reactivated normal faults (abyssal hill faults). However, because the strike of the lineaments southeast of Kashinosaki Knoll is not consistent with the ancient plate spreading ridge in this region (Kido and Fujiwara, 2004), these are likely to correspond to inherited transforms (Ike et al., 2008).

The intraoceanic thrusts cut through the entire oceanic crust as discontinuous fault planes (Figs. 2 and 4). We observed an offset of the Moho reflection at ~6.8 km below the surface of the oceanic crust (~2.2 s in two-way travel time) due to displacement on these thrusts. A strong reflection signal was identified at the intersection
of the thrusts and the oceanic Moho (Figs. 2 and 4). However, we could not identify any clear signals related to the faults beneath the Moho.

3.2. 3D geometry of intraoceanic thrusts

To evaluate fault geometry (i.e., strike and dip of the fault system), we extracted 3D fault planes of the intraoceanic thrusts (Fig. 7) by using fence diagrams consisting of several 2D seismic profiles (Fig. 6). These show that most of the faults strike approximately parallel to the axis of the trough, dipping to the north about 30°. These fault planes extend upward from the western margin of an underlying fault plane near the oceanic crust interface (Fig. 5). The faults have steeper dips at their NW-striking landward ends (western margin of the fault) than at their southeast ends. These observations demonstrate that the large-scale faults in the oceanic crust have imbricate structures, as observed in the area of the M/V Nordic Explorer 3D seismic survey (Fig. 7c; Tsuji et al., 2009).

Because these intraoceanic thrusts move almost parallel to the subduction direction according to the focal mechanism of the 2004 intraplate earthquake (Ito et al., 2005; Tsuji et al., 2009), the NW-striking landward portions of the faults function as oblique strike-slip faults. Although it is difficult to extract continuous fault planes from discontinuous 2D reflection profiles on the landward side of the trough axis (red dashed lines in Fig. 7a), the interpreted dominant strike-slip fault (the western margin of the underlying thrust) appears to extend from Kashinosaki Knoll to Cape Shionomisaki.

4. Discussion

4.1. Activity of intraoceanic thrusts

The 3D seismic data obtained by R/V Nordic Explorer demonstrated that the intraoceanic thrusts are related to the 2004 intraplate earthquake, because the inferred fault geometry can account for the temporal change of focal mechanism in the 2004 earthquake (Hara, 2005; Tsuji et al., 2009). The seismic activity of the intraoceanic thrust system (thrusts and strike-slip faults) off the Kii Peninsula is corroborated by micro-earthquake studies (Kodaira et al., 2006; Obana et al., 2003, 2005) showing that the orientation of the P-axes of the composite focal mechanisms is consistent with the interpretation of the NW–SE oriented structures as thrusts (Fig. 7). It is also consistent with the maximum horizontal stress direction derived from borehole breakouts (Saito et al., 2010) and fault diagrams (Henry et al., 2012a) at Integrated Ocean Drilling Program (IODP) Site C0011 (blue bar in Fig. 7b). Although the stress state estimated at Site C0011 represents the state within the sedimentary sequence, Henry et al. (2012b) argued that the stress state of the sedimentary sequence at Site C0011 is influenced by intraplate compressive deformation within the underlying Philippine Sea plate.

The deformation of the seafloor due to thrust displacement was almost the same as it is at deeper geologic boundaries (e.g., the boundary between middle and upper Shikoku Basin facies) near Kashinosaki Knoll (Fig. 4e and f), thus the thrust faults within oceanic crust were ruptured near the trough axis. On the other hand, the turbidite sequence rapidly
Fig. 5. Seismic profiles and structural interpretations showing intraoceanic thrusts in trough-parallel time-domain seismic profiles: (a, b) KR0211-S1 and (c, d) KR0512-NT0502. Locations of survey lines are shown in Fig. 1. Red, yellow, and green lines represent intraoceanic thrusts, the sediment–igneous crust interface, and the Moho, respectively. Black arrowheads indicate the intersections with seismic profiles in Fig. 4.

Fig. 6. Example of an intraoceanic thrust identified on two intersecting profiles (fence diagram). (a) Location of the seismic profiles (yellow lines). Arrows indicate the view direction in panels (b)–(d). (b) Fence diagram of seismic line ODKM03-17 and one line of 3D seismic data acquired by R/V Nordic Explorer. Seismic profile of ODKM03-17 is enhanced by seismic attributes (instantaneous phase; Taner et al., 1979; Tsuji et al., 2005). (c) Fence diagram of seismic line KR0512-501 and one line of 3D seismic data acquired by R/V Kairei. (d) Fence diagram of seismic lines ODKM03-A and KR0512-501. Red dashed lines indicate faults within the oceanic crust interpreted on both seismic profiles.
sedimented in the trough axis laps onto the hemipelagic sequence deformed by intraoceanic thrust displacements, therefore the faults have not been extensively displaced during the time the turbidite sediments were deposited at the trough axis. Therefore, the intraoceanic thrusts should display gradually increasing displacement from the seaward side of the trough axis.

Because the intraoceanic thrusts have recently deformed the seafloor (Fig. 7b), related displacement on these faults is likely to cause a tsunami. Indeed, a tsunami was generated by the 2004 intraplate earthquake. The probable tsunamiogenic faults of that earthquake (Satake et al., 2005) are distributed around the intraoceanic thrusts (i.e., Kashinosaki Knoll), although the distribution of tsunamiogenic faults estimated from tsunami inversion is too complicated to compare with the imbricate thrusts identified in this study. Therefore, it is possible that these intraoceanic thrusts are capable of generating tsunamis and strong ground motions that would affect the Japanese Islands.

4.2. Origin of intraoceanic thrusts and strike-slip faults

We observed mainly reverse and strike-slip faults within the oceanic crust in the Nankai Trough southeast of the Kii Peninsula. The focal mechanisms estimated for the 2004 intraplate earthquake off the Kii Peninsula (Mazzotti et al., 1999). The yellow ellipse on the western edge of the high density dome is the Euler pole of rotation between Philippine Sea plate and the Zenisu–West Izu block (33.25° N and 135.50° E; Mazzotti et al., 1999). The white dashed line is the segmentation boundary between the 1944 Tonankai and 1946 Nankai earthquakes, as estimated from tsunami records (Baba and Cummins, 2005). (b) Detail of the seafloor topography around Kashinosaki Knoll, showing traces of intraoceanic thrusts. Earthquake focal diagrams are shown for microearthquakes (Obana et al., 2005). The direction of maximum horizontal stress at Site C0011 is shown as a blue bar (Saito et al., 2010). (c) Detail of the upper surface of the oceanic crust within the 3D seismic survey area (Tsuji et al., 2009) showing traces of intraoceanic thrusts at the crust surface.
Peninsula also indicated thrust movement in the relatively shallow oceanic crust (e.g., Ito et al., 2005). Therefore, horizontal compressive stress may accumulate strain within the subducting oceanic crust southeast of the Kii Peninsula. Compressive stress within the subducting crust is often explained by strong coupling (or high friction) at the plate interface (Christensen and Ruff, 1988; Park and Mori, 2005). One of the candidates for the strong coupling source in our study area is the high-density (high-velocity; \( V_p = \sim 6.2 \text{ km/s} \)) dome identified off Cape Shionomisaki in a seismic refraction analysis of wide-angle ocean bottom seismograph data (Figs. 6a, 7, 8) (Kodaira et al., 2006). The high-density dome can be clearly identified on our reflection profile, because of its low reflectivity (Fig. 8a, b). The dome may be an igneous intrusion (Miyake and Hisatomi, 1985) that is isolated from the subducting crust (Kodaira et al., 2006), because igneous rock of the Shionomisaki igneous complex is exposed onshore to the north of the dome (Miyake, 1988). The dome would generate a vertical stress at the plate interface. Furthermore, the presence of the dome has resulted in the formation of a thick accretionary prism southeast of the Kii Peninsula (Figs. 8, 9, 10), as reverse faults are developed southeast of the dome due to its interaction with accreted sediment. Seafloor topography indicates that strike-slip faults with normal components are developed at the boundary of the thick accretionary prism and the thin accretionary prism east of the dome (black lines in Fig. 9). The sediment thickness above the plate interface is further increased because of the steep angle of subduction east of the Kii Peninsula (e.g., Shiomi et al., 2008). Because the thick accretionary prism in combination with the high-density dome generates a large vertical load on the plate interface and may cause strong coupling at the plate interface (Fuller et al., 2006) compared to the west side of Cape Shionomisaki, thrusts within the oceanic crust are likely to grow with the ongoing subduction of oceanic crust southeast of the Kii Peninsula (Fig. 10). Indeed, the crustal stress orientation estimated from seismic anisotropy (Saiga et al., 2011) is changed at the high-density dome, suggesting strong coupling along the plate interface around the high-density dome at the Cape Shionomisaki. The plate coupling ratio estimated by using a GPS network (Miyazaki and Heki, 2001) further supports this interpretation.

Another possible explanation for the origin of the intraoceanic thrusts is their relation to the intraoceanic thrust system in the Zenisu

Fig. 8. (a) Seismic profile showing a high-density dome (igneous rock). Location is shown in Fig. 1. (b) Interpretation of panel (a). The dashed white lines indicate the surface of an accretionary prism and the high-density dome beneath cover sediment, the surface of the oceanic crust, and a possible strike-slip fault within the accretionary prism. The high-velocity dome is apparent as an anomaly with low reflection strength because of its homogeneous nature. (c) Seismic profile showing a thick accretionary prism southeast of the high-density dome. (d) Interpretation of panel (c).
Ridge system, northeast of our study area. Seismic surveys performed as part of the KAIKO project have revealed intraoceanic thrusts beneath Zenisu Ridge (e.g., Le Pichon et al., 1987). Reverse and strike-slip faults at Zenisu Ridge are related to collision between the Izu–Bonin arc and the Japanese Islands (Lallemant et al., 1989; Mazzotti et al., 2002) (Fig. 1). The geometry of the fault system in our study area (red lines in Fig. 7a) is similar to that at Zenisu Ridge (orange lines in Fig. 7a; e.g., Mazzotti et al., 1999). Furthermore, the continuous distribution of aftershocks of the 2004 earthquake from Zenisu Ridge to southeast of the Kii Peninsula (Fig. 1; Ito et al., 2005) indicates that the stress state within the subducting crust at the Zenisu Ridge is connected to our study area (Henry et al., 2012b). Therefore it is possible that the intraplate fault system observed off the Kii Peninsula is the westward continuation of faults at Zenisu Ridge. Furthermore, the estimated Euler rotation pole of relative motion between the Philippine Sea plate and Zenisu Ridge is at 33.25°N, 135.5°E (Fig. 7a; Mazzotti et al., 1999), which coincides with the location of the high-density dome at Cape Shionomisaki (the coupling zone). Therefore, we interpret the high-density dome and Kashinosaki Knoll as a westward termination of the Zenisu compressive zone (Fig. 10; Fig. 4 of Mazzotti et al., 1999).

If the western edge of the Zenisu block is Kashinosaki Knoll off the Kii Peninsula, the compression within the subducting plate due to intraoceanic reverse faulting at the Zenisu block (Mazzotti et al., 1999) occurs only on the east side of Kashinosaki Knoll (Fig. 10). Therefore, shear stress within the subducting Philippine Sea plate should be generated on the east side of the Kii Peninsula (Fig. 10). Due to the shear stress, the western margin of the intraoceanic thrusts off the Kii Peninsula could be strike-slip faults. They would be nearly parallel to the ancient ridge structures there, which strike NNW–SSE (Kido and Fujiwara, 2004; Okino et al., 1999). Furthermore, Mochizuki et al. (2010) demonstrated from the hypocenters and focal mechanisms of earthquakes off the Kii Peninsula that the intraplate earthquakes off Cape Shionomisaki are strike-slip events. Therefore, it is possible that the activity of the intraoceanic thrusts in our study area arises from reactivation of normal faults formed during the backarc opening of the Shikoku Basin. Ide et al. (2010) have proposed that the subducted plate beneath the Kii Peninsula was split along an extinct ridge due to an abrupt change of subduction direction, followed by elastic deformation of the plate and an accumulation of stress near the ridge. Therefore, the faults within the oceanic crust can also be interpreted as the seaward extension of a deep tear fault beneath the Kii Peninsula.

Seismic refraction data revealed a low-velocity zone in the oceanic mantle beneath the high-density dome, possibly indicating mantle serpentinization (Kodaira et al., 2006). The seaward extension of the western margin of the intraoceanic thrusts (the strike-slip portion) is roughly consistent with the location of this low-velocity zone (Fig. 10). Because the faults extend to the mantle and act as conduits for the movement of seawater (e.g., Faccenda et al., 2009), the fault system may have contributed to hydration of the crust as well as mantle serpentinization (Ranero et al., 2003). Strong reflection signals from the intersection between the intraoceanic thrusts and the Moho (Figs. 2 and 4) can be explained by fluid invasion into the mantle, because hydration of the mantle during serpentinization is accompanied by a decrease in density and seismic velocity. Although reverse faults usually do not have wide fracture zones, the strike-slip faults parallel to the subduction direction may transmit water to the crust and mantle. The serpentinization of oceanic lithosphere results in a marked decrease in its strength, possibly accelerating the localized crustal deformation (fault generation and splitting of the subducting plate) off the Kii Peninsula.

5. Summary

The main results of this study are the following:

(1) We identified widely distributed intraoceanic thrusts within the subducting Philippine Sea plate in the Nankai Trough southeast of the Kii Peninsula from 2D and 3D seismic reflection data.

(2) Because the faults within the oceanic crust deform the crustal surface and generate topographic highs, they influence the fault...
system within the accretionary prism (e.g., the position of fault branching).

(3) Because the faults cut the oceanic Moho and act as conduits for movement of water to the crust and upper mantle, they may contribute to serpentinization of the mantle. The strong reflection signal at the intersection between the thrusts and the Moho may indicate fluid interaction with the mantle.

(4) The thrusts within oceanic crust are seismogenically active, in that their locations and geometries are consistent with observed intraplate earthquakes and microearthquakes.

(5) Given that a thick, consolidated accretionary prism in combination with a high-density dome generates a large vertical load on the plate interface and causes high friction at the interface, the intraoceanic thrusts are likely to grow with the ongoing subduction of oceanic crust southeast of the Kii Peninsula.

(6) The fault geometry of Zenisu Ridge is similar to that off the Kii Peninsula. Furthermore, since seismicity is continuous from Zenisu Ridge to Kashinosaki Knoll, the intraplate fault system observed off the Kii Peninsula may be considered the westward continuation of those at Zenisu Ridge (compressive zone).

(7) Mantle serpentinization and the influence of ancient ridge structures may accelerate the crustal deformation off the Kii Peninsula.

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