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Rapid forearc basin uplift and megasplay fault development from 3D seismic images of Nankai Margin off Kii Peninsula, Japan

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ABSTRACT

Offshore Kii Peninsula, Japan, a large thrust within the overriding forearc, the megasplay fault, appears to move coseismically during great earthquakes. 3D seismic images of the Kumano forearc basin that overlies the megasplay, correlated with IODP drilling data, are a potential record of the history of large-scale motion along this structure. In the early Quaternary, uplift occurred in the southwest portion of the basin that may be a preliminary phase of motion along the megasplay. More extensive landward tilting of the outer basin sediments across the seismic volume occurred over ~300 kyr in the middle to late Quaternary (1.3–1 Ma); this tilting event may represent the major period of motion along the megasplay that formed the modern fault geometry. Extensive normal faulting that cuts the forearc basin sediments clearly formed subsequent to the late Quaternary tilting and in many cases offset the modern seafloor; these faults may form either due to gravitational response to the uplift or as a by-product of sediment underthusting. These results suggest that the megasplay is a recently formed and transient structure and support the idea that out-of-sequence thrusts serving as the dominant structure for convergence-driven shortening in a subduction zone may be short-lived geologically but dominate a margin during these intervals.

1. Introduction

An important structural feature of the eastern Nankai margin offshore Kii Pennisula (Fig. 1) is a high-amplitude seismic reflection interpreted as a regionally continuous megasplay fault system. The megasplay is an out-of-sequence thrust and may be a pathway for updip seismic rupture propagation (Park et al., 2002) enhanced by a large volume of likely fluid-rich sediments that lies below the megasplay in the region beneath the Kumano forearc basin (Bangs et al., 2009). These observations within the Nankai Trough are significant globally as they may represent an important type of subduction zone geohazard; a coseismic rupture pathway up a large-scale, upper plate thrust such as the megasplay may result in the efficient delivery of slip close to the seafloor and thus contribute to tsunamigenesis (Moore et al., 2007).

The discovery of the megasplay fault off Kumano has resulted in discussions as to whether megasplay thrusts exist on other margins, potentially providing coseismic rupture pathways and contributing to tsunamigenesis (e.g., Collot et al., 2008; Moore et al., 2007). So far seismic imaging suggests the Kumano region has the most apparent large-scale, out-of-sequence thrust system that clearly soles into the megathrust and exhibits continuity and seismic amplitudes that are normally observed along a décollement (e.g., Bangs et al., 2009; Moore et al., 2007). In contrast, for instance, the large thrust slice zone off the Muroto Peninsula in the central Nankai margin (Fig. 1) also acts as an out-of-sequence thrust system (Moore et al., 2001) but consists of numerous smaller thrusts that do not have the lateral continuity or bright seismic returns that we observe along the megasplay fault in the Kumano region (Bangs et al., 2006, 2009). The recognition of megasplay-type thrusts on other subduction margins could be important in assessing hazards and examining the role of this class of out-of-sequence thrusts on margin development.

The Kumano forearc basin overlies the inner portion of the megasplay fault. Forearc basins, where present, can be used to unravel the geohistory of a subduction margin (e.g., Beaudry and Moore, 1985; Berglar et al., 2008, 2010; Contardo et al, 2008; Gulick and Meltzer, 2002; Gulick et al., 2002; Matson and Moore, 1992; Melnick and Echtler, 2006; Susilohadi et al., 2005). Forearc basin formation is still debated, with ideas ranging from the change in subducting plate

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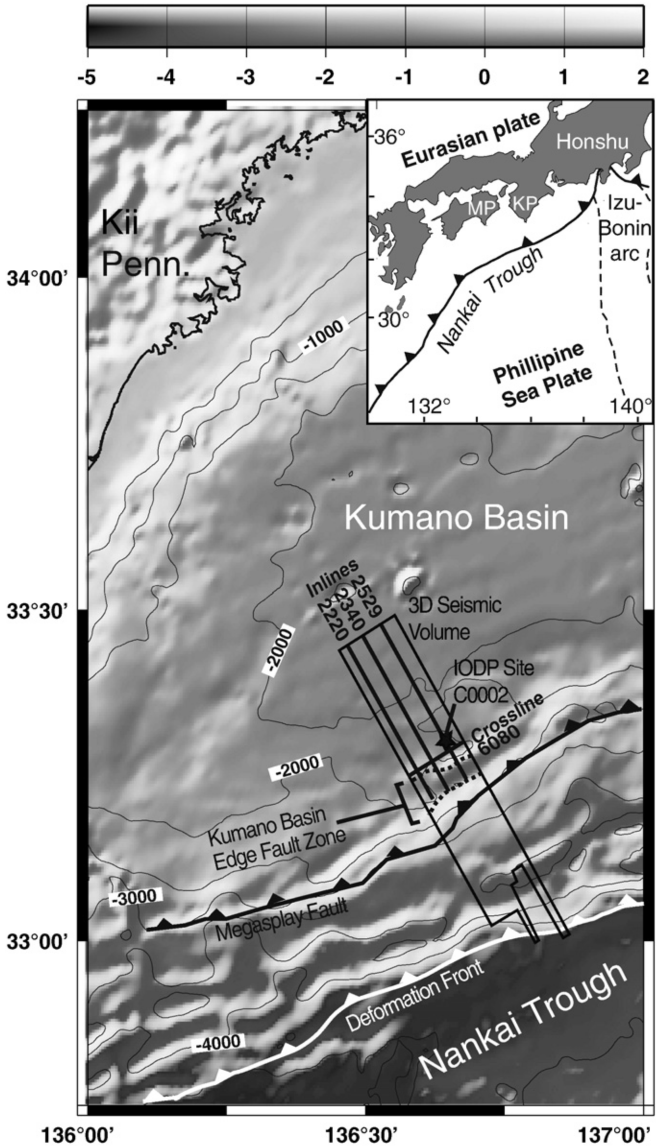

Fig. 1. Kumano 3D seismic volume is displayed within the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) study area. Seismic volume images a seaward portion of the Kumano forearc Basin which lies in the hanging wall of the megasplay fault. Three inlines displayed in Fig. 2, Crossline presented in Fig. 5, IODP Site C0002 location, and traces of the megasplay fault, deformation front, and Kumano Basin Edge Fault Zone are shown for reference. The inset shows tectonic setting where MP is Muroto Peninsula and KP is Kii Peninsula.

dip (e.g., Fuller et al., 2006) to the strength of inner accretionary wedges providing dynamic stability (e.g., Wang and Hu, 2006). Forearc basins exhibit a wide range of subsidence and uplift histories, suggesting a variety of potential factors can influence basin history in these settings (Clift and MacLeod, 1999; Xie and Heller, 2009) but that structural deformation within the upper plate can be a dominant factor (Berglar et al., 2010; Contardo et al., 2008; Gulick and Meltzer, 2002). A proposed correlation of forearc basins and seismogenic rupture suggests these basins are important not just as recorders of margin history but potentially as indicative of locations landward of the updip limit of seismogenesis (Song and Simons, 2003; Wells et al., 2003); however, not all forearc basins fit this model as some lie landward of coseismic rupture (Dean et al., 2010).

As megasplay formation may also be related to strength contrasts within the accretionary wedge (Wang and Hu, 2006), the correlation between the location of the Kumano forearc basin, the potentially coseismic megasplay fault (Park et al., 2002) and the coseismic rupture area for 1944 Tonankai earthquake is intriguing (Baba et al., 2006). In this paper we seek to demonstrate that forearc basins, where they overlie out-of-sequence thrusts or megasplay type faults, may aid in determining the history of motion along these potentially coseismic faults and therefore yield clues as to how long-lived these structures are or what the timing of significant shortening might be. Using the Kumano 3D seismic volume (Moore et al., 2009) and age control from IODP Expedition 315 (Kinoshita et al., 2009), we define and map both the seismic stratigraphy and faulting in the seaward part of the Kumano Basin and suggest that the basin records both a local interval and pronounced period of uplift likely related to motion on the megasplay fault.

2. Data, resolution, and methods

In 2006, a 3D seismic survey was acquired by Petroleum GeoServices (PGS) and processed through prestack time migration by Compagnie Générale de Géophysique (CGG), resulting in unparalleled images of the outer Kumano Basin (Figs. 1 and 2) (Moore et al., 2009). The bin size is 12.5 m by 18.75 m and the vertical resolution decreases from ~5 m to 7 m for the near surface through ~10—20 m for the lowermost sediments in the basin. Dips reported are based on depth sections (e.g., Bangs et al., 2009; Martin et al., 2010; Moore et al., 2007), which are not shown here due to imaging in the pre-stack time sections being clearer within the forearc basin.

The excellent shallow resolution allows mapping of the faults present within the basin; the decrease in resolution with depth results in mapped faults with throw lower than ~10 m appearing to die out with depth, while in reality these faults may continue deeper but they are below the limit of seismic resolution. Higher throw faults are easily mapped as cutting through all the forearc basin sediments and into the underlying accretionary prism. We present cross-sectional and time-slice views of these faults (Figs. 2 and 3d).

We map sequence boundaries throughout the imaged portion of the forearc basin and present three representative inlines from the 3D volume (Fig. 2). We define the sequence boundaries based on toplap, downlap, onlap, or angular relations and map these unconformable surfaces along with their correlative conformities as seismic stratigraphic sequence boundaries. To assess development of the basin through time, we generate an isopach map for each of these sequences in travel-time thickness and flatten each of the boundaries to look for key time intervals where depositional patterns shifted (Figs. 3a–c and 4).

Logging-while-drilling data were acquired at the Integrated Ocean Drilling Program (IODP) Hole C0002A, which penetrated the entire forearc basin during Expedition 314 (Expedition 314 Scientists, 2009). Basin sediment ages from nannofossil analyses and lithology data were sampled in IODP Holes C0002B and C0002D drilled during Expedition 315 (Expedition 315 Scientists, 2009).

3. Observations, interpretations, and analysis

The Kumano Basin divides into lower sequences that unconformably overlie the accretionary prism section (Expedition 315 Scientists, 2009) and twelve clearly imaged upper Kumano Basin stratigraphic sequences that young (based on superposition) in a landward (northwest) direction (Fig. 2). This paper focuses on the upper sequences, each separated by sequence boundaries and their correlative conformities and integrates seismic stratigraphy and fault mapping with IODP drilling results.

To the northwest, the strata within the twelve upper Kumano Basin sequences onlap the unconformity that separates the lower sequences from the upper sequences (Fig. 2). To the southeast, the strata are perturbed to varying degrees by the Kumano Basin Edge Fault Zone (KBEFZ), a transtensional fault possibly caused by strain-partitioning; this fault zone is presently close to the outer arc high along the margin and within our 3D volume is observed to truncate the Kumano Basin

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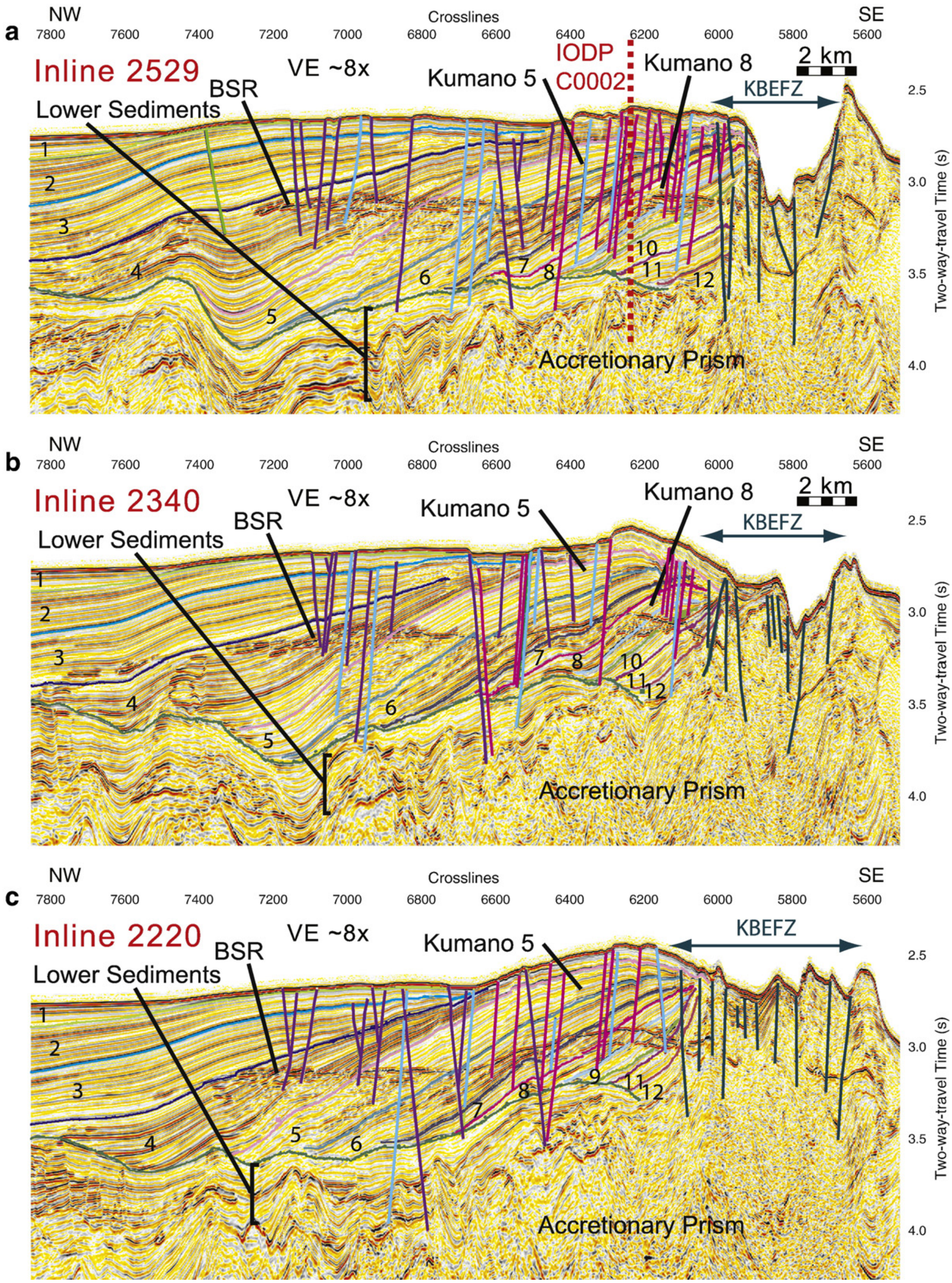

Fig. 2. Seismic inlines are shown from the Kumano 3D volume. a–c. Inlines 2220, 2340, and 2459 show the boundary between the Lower Kumano Basin and the seismic sequences Kumano 4 through Kumano 12 within the Upper Kumano Basin. Also shown are numerous normal faults that cut the basin sediments organized into 5 groups (see Fig. 3d for a map view of these faults).

strata in the east and dissect the edge of basin to the southwest due to the fault zone widening (Fig. 1, Martin et al., 2010).

The oldest upper Kumano Basin sequences, Kumano 12 and 11, lie only beneath the trenchward end of the basin (Fig. 2a–c). These sequences appear tilted landward in increasing amounts from the east—southeast (e.g., INLINE 2529, Fig. 2a) to the west—southwest (e.g., inlines 2340 and 2220, Fig. 2b–c.). An isopach map of Kumano 12 shows it is thickest in the east—southeast, where it reaches a

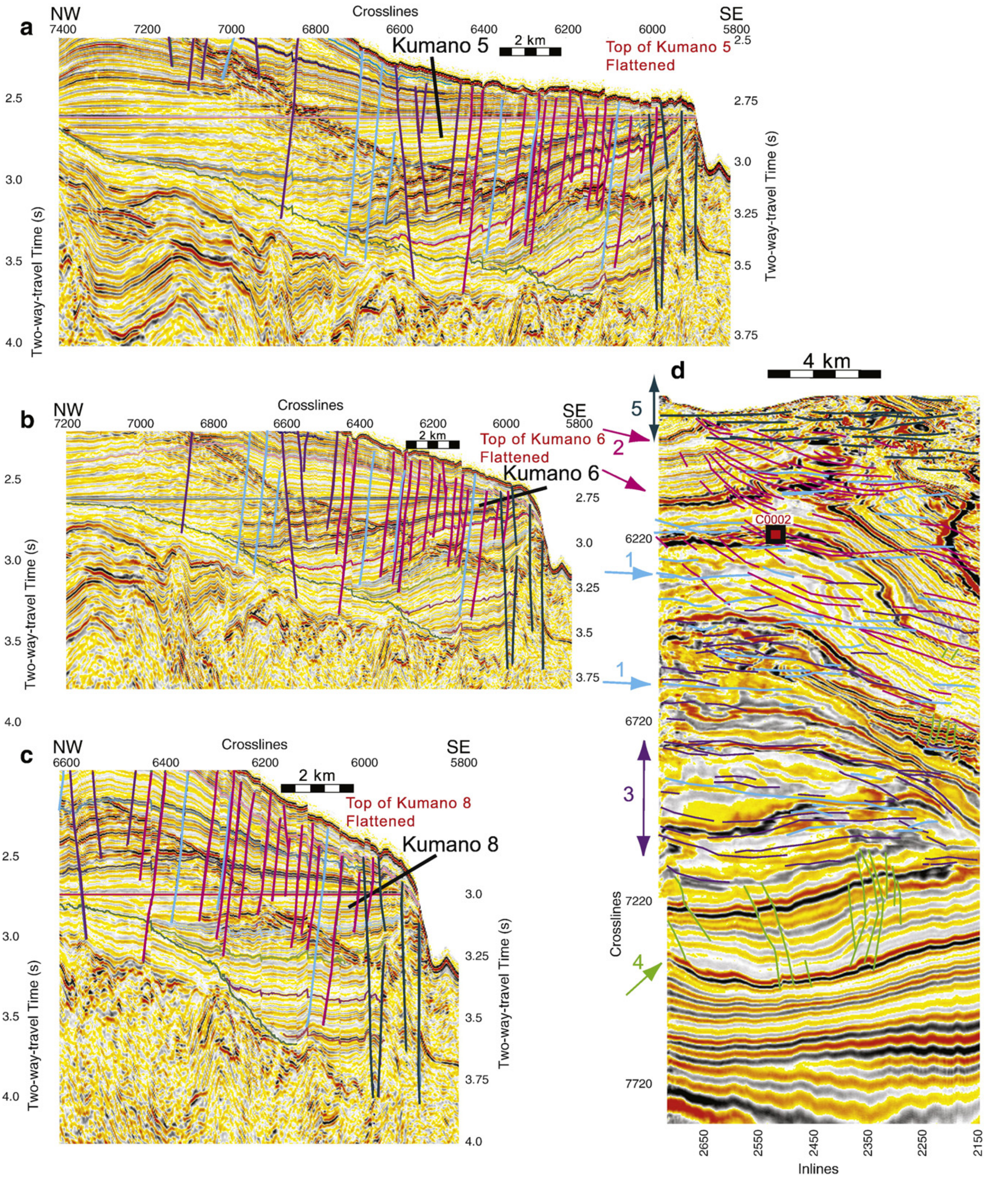

Fig. 3. Seismic inlines from Fig. 2 are shown flattened alongside a timeslice through the 3d volume. a–c. Results of flattening analysis on Inline 2529 show that Kumano 8 and earlier sequences where deposited in a shelf-edge low, Kumano 6 through Kumano 8 exhibit a landward shift in depocenter, and Kumano 5 and younger draped the most titled region (seaward) and infilled landward. d. Timeslice through 3D volume at 2888 ms shows the numerous faults cutting through the basin and allows for identification of cross-cutting relationships. Five populations of faults exist, which are labeled and draw with uniform color within each group and match the colors in Fig. 2; the oldest group strikes northeast–southwest, and three younger sets include a group of east–northeast trending arcuate faults, a series of graben-forming faults, and some minor translational faults associated with the grabens. Group 5 faults are within the Kumano Basin Edge Fault Zone. With the exception of these last two sets of faults, all are extensional based on offsets seen in Fig. 2, and all are recent.

maximum thickness of ~340 m based on pre-stack depth migration velocities from Moore et al. (2009). This greater thickness is due to the presence of an isolated package that is not subdivided from Kumano 12 and present only in the southeast corner of the basin; the upper parts of Kumano 12 and Kumano 11 are largely uniform in thickness across the volume (Fig. 5).

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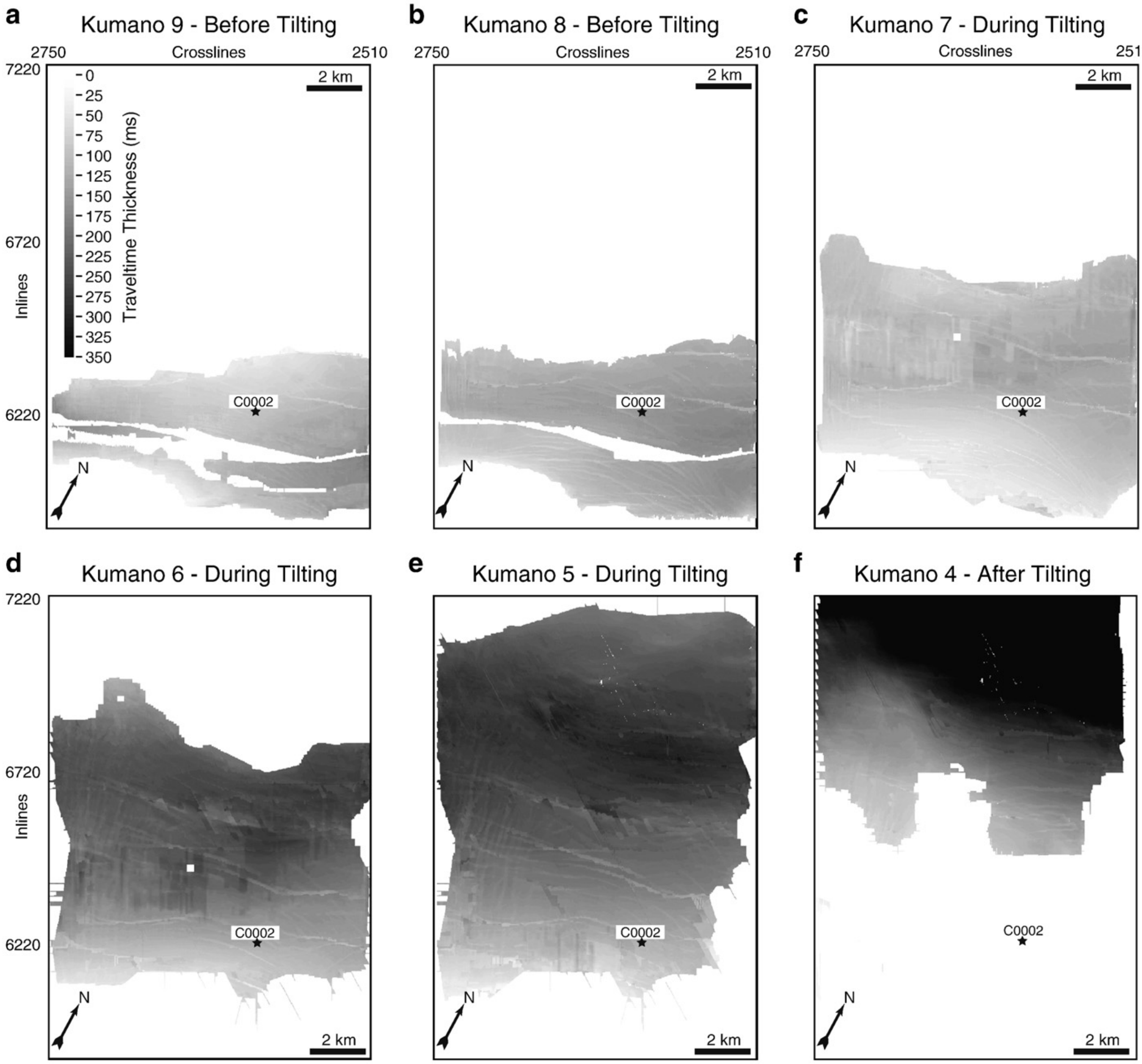

Fig. 4. Representive isopach maps in two-way-travel time thickness are shown. a and b. Kumano 9 and 8 show the same pattern of shelf-edge deposition that occurred prior to the tilting. c–e. Landward shifting depocenters of Kumano 7 through Kumano 5 show these sequences were deposited during the tilting of Kumano 4 and younger sequences were deposited after the primary tilting ceased and largely infill in a landward direction.

The reason for the difference in tilt laterally within the basin for these two sequences can be seen on Crossline 6080 (Fig. 5), where sequences Kumano 12 and 11 are shown to be deformed in the southwest part of the volume with an apparent dip towards the eastern part of the volume. As these sequences do not appreciably thin across the top of this high, unlike the subsequent sequences, they were likely deposited prior to the onset of shortening or uplift in this area.

Similar to Kumano 12 and 11, Kumano 10, 9, and 8 all are present only on the seaward edge of the modern forearc basin; however, each younger sequence covers an increased area at the edge of the basin as shown in inlines and isopachs (Figs. 2a–c and 4a and b). The sequences range in maximum thickness from ~180 m to 308 m. Isopach maps of Kumano 8 and earlier sequences show a distinctly similar pattern of thickest deposition at the basin edge (Fig. 4a and b are representative). Crossline 6080 shows that Kumano 10 through Kumano 8 thin or are absent across the top of the southwestern uplift and thicken away from the structure. Sequences Kumano 10–Kumano 8 were therefore deposited syntectonically. No evidence of deformation is present away from this uplifted region within the basin during this interval.

Kumano 7, 6, and 5 sequences are all tilted landward and on average decrease in dip from 5.9° to 4.7° to 3.8°, respectively, while increasing in maximum thickness from 135 to 233 to 280 m (Fig. 2a–c). Isopach maps of these three sequences show a pronounced landward shift in the depocenter progressively as the sequences young (Fig. 4c and d are representative). Crossline 6080 does not show as pronounced thinning across the top of the southwest anticline in sequences Kumano 7–Kumano 5. This observation suggests the local deformation in the southwestern

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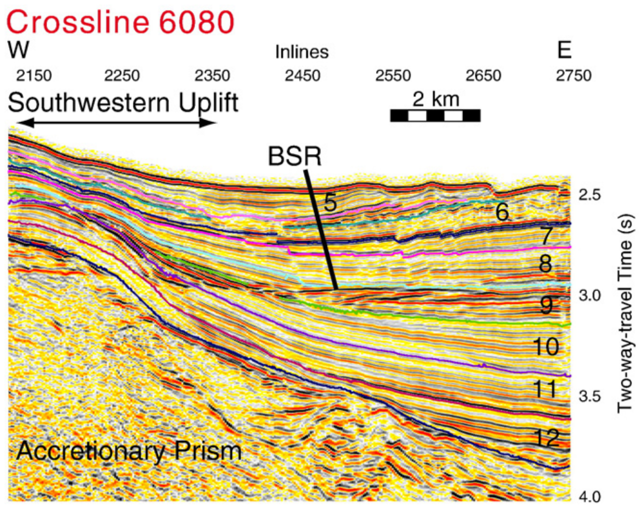

Fig. 5. Crossline 6080 (see location in Fig. 1), which shows local uplift structure in southwest. Kumano 12 and 11 are observed not to thin over this structure while Kumano 10 through Kumano 8 do; less evidence of thinning is present subsequent to Kumano 8.

edge of basin may have been waning during this interval or even ceased. However the landward shifting depocenters suggests the onset of a significant, basin-wide tilting event.

Kumano 4, 3, 2, and 1 overlie the earlier sequences and progressively infill the outer basin. These sequences each onlap the previous sequence in the seaward direction and exhibit waning dips (Fig. 2a–c). An isopach map of Kumano 4 (Fig. 4f) is representative of these younger sequences and exhibits thinner (~50 m thick) deposition over the tilted older sequences on the seaward edge of the basin and thicker and fairly uniform (>300 m thick) deposition towards the basin center. These waning dips suggest the tilting even may have ceased by deposition of the final four sequences.

To determine the exact timing of the tilting to confirm our interpretations of the seismic data and isopach maps, we performed a flattening analysis on several inlines. Fig. 3 (a–c) shows this analysis for Inline 2529, which is representative of the majority of the volume. Flattening is a technique optimal for examining which sequences were deposited on a relatively flat-lying surface and which sequences where deposited on a strongly tilted surface. For the majority of the volume, prior to deposition of Kumano 7, flattening suggests that all the sequences were deposited on flat lying to gently tilted strata except for where affected by the local uplift in the southwest. However significant tilting across the whole outer edge of the basin occurred from Kumano 7 deposition through Kumano 5 when the flattening technique shows pronounced landward shifts and asymmetric deposition.

Based on these analyses we conclude that local shortening or uplift event occurred in the southwest, seaward corner of the basin after deposition of Kumano 11 and waned by deposition of Kumano 7. A more significant phase of uplift, which caused the tilting of the upper Kumano Basin strata across the width of our volume, occurred from the time of deposition of Kumano 7 through Kumano 5.

Normal faulting is pervasive in the outer Kumano Basin. We map 169 faults, all exhibiting extension as shown both in cross section (Fig. 2a–c) and on a timeslice, where they are grouped into three populations (Fig. 3d); two additional populations of faults are dominantly strike–slip.

Based on cross-cutting relationships, the oldest of the three populations of normal faults (~14% of the total faults, population 1 on Fig. 3d), trend in a northeast–southwest direction, dip landward from 56–68° (62° avg.) and exhibit up to 30-m throw (average ~13 m). The second population (~35%, population 2 on Fig. 3d) are accurate in geometry, strike east–northeast–west–southwest, dip landward from 53° to 68° (average 61°), and exhibit up to 38 m throw (~14 m avg.). In map view (Fig. 3d), these population 2 faults lie on the flank of the high in the southwestern part of the basin.

The third group of faults forms grabens with paired landward and trenchward dipping faults (~51%, population 3 on Fig. 3d) and are roughly oriented northeast southwest except for near the buried anticline. These faults dip 48°–70° (average 62.5°) and exhibit up to 23 m throw (9.4 m avg.). In map view, the grabens are the narrowest on the southwest side of the basin where they lie along the base of slope of the residual high from the buried anticline and widen to the northeast away from this region (Fig. 3d). These graben-forming faults cross cut population 1 faults or in a few cases reactivate them and are younger. A fourth population of faults show lateral offset of reflections in timeslices, very minor extension in cross-section and are orthogonal to the grabens. The fifth population of faults is associated with the transtensional Kumano Basin Edge Fault Zone and lie at the seaward edge of the basin (Figs. 1 and 3d). These were examined in detail in Martin et al. (2010).

4. Discussion

Stratigraphically, the upper sequences in the Kumano Basin record local uplift in the southwest during sequences Kumano 10 through Kumano 8, followed by a period of significant deformation that tilted the sequences on the seaward edge of the basin throughout our volume by up to ~12° or over 500 m of net uplift. Based on isopach and flattening analysis the timing of this tilting can be constrained to be during deposition of sequences Kumano 5, 6, and 7.

Our analysis shows that this tilting of the edge of the forearc basin started after the deposition of Kumano 8 and ceased prior to the deposition of Kumano 4. The unconformity at the top of Kumano 8 lies at ~420 mbsf, which is within Logging Unit II, as defined on Expedition 314 (Expedition 314 Scientists, 2009). Unfortunately on Expedition 315 no coring operations took place between 204 and 475 mbsf (Expedition 315 Scientists, 2009). The youngest analyzed sediments, located at ~478 mbsf, in Hole C0002B were older than 1.24 Ma based on the absence of *Gephyrocapsa* spp (Expedition 315 Scientists, 2009). However, these sediments, which lie within the unit Kumano 8, must be younger than 1.34 Ma due to the last occurrence of *Helicosphaera sellii* between ~490 and ~495 mbsf (Expedition 315 Scientists, 2009). Thus the tilting episode started no earlier than the middle Quaternary (between 1.24 and 1.34 Ma). The unconformity at the top of Kumano 5 lies at ~125 mbsf, which is close to the Logging Unit I/II boundary, where there is a distinct increase in the gamma ray and resistivity logs (Expedition 314 Scientists, 2009). Two nannofossil ages exist within sediments close to the top of Kumano 5; the sediments at ~125 mbsf must be older than 0.9 Ma at ~115 mbsf and younger than 1.04 Ma at ~129 mbsf. Therefore, this tilting event ceased by ~1 Ma.

Structurally, a series of normal faults developed in association with this tilting. Despite a clear age progression of population 1 faults (east–west trending) being older than population 2 or 3 faults, there are no growth strata within the basin associated with any of the three fault populations and individual faults within all three populations are observed to offset the seafloor (Fig. 2). The lack of growth strata suggests all three populations are quite young and likely formed after the period of uplift. Given the cross-cutting relationships of the population 2 and 3 faults relative to the population 1 faults, we suggest the population 1 faults that offset the seafloor today are reactivated as part of the graben-forming process associated with population 3. Population 4 faults appear to be translational or transtensional (based on offsets observed in timeslices) and are orthogonal to the grabens; we suggest these minor tear faults are accommodating differential motion generated by the westward opening graben-formed syncline. Based on the age models from Expedition 315 (Expedition 315 Scientists, 2009) and the lack of

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growth strata, the Kumano Basin normal faults are Late Quaternary to modern in age forming only after the tilting period ceased at ~1 Ma. The KBEFZ is responsible for the fifth population of faults, which truncate or dissect the seawardmost Kumano Basin strata and have a clear seafloor expression showing motion along these faults continues to Recent (Martin et al., 2010).

The arcuate population 2 faults are clearly coincident with the flanks of the southwest uplift (Figs. 3 and 5), yet significant uplift in this region occurred between deposition of Kumano 10 and Kumano 8 or within the early Quaternary and was largely replaced by the tilting of the along the whole basin edge subsequent to deposition of Kumano 8. Several explanations exist for the formation of the population 2 faults: 1) that some shortening occurred in the southwest uplift region subsequent to the 1.3–1 Ma tilting event, 2) that differential motion along the splay fault displaced one part of the basin relative to the other perturbing stress orientations, and 3) that the motion along the KBEFZ in concert with the position of the southwest high torqued the outer part of the basin causing a clockwise rotation in stress orientation.

In Bangs et al. (2009), an analysis of the megasplay fault reflection where it lies beneath the Kumano Basin suggests a large volume of sediment has been underthrust beneath the fault. Bangs et al. (2009) show that the thickness of the underthrust sediments are greater beneath the southwest side of the megasplay and thinner beneath the northeast side; additionally they point out the apparent causal relationship where the thicker underthrust section has a steeper megasplay above it and this coincidence with the overlying uplifted region. Based on stratigraphic thinning (Fig. 5), initial uplift in the southwest pre-dates the regional tilting but may have had some later stage reactivation. Additionally, Bangs et al. (2009) show that while the largest amount of underthrust sediments are in the southwest significant thicknesses exist across the whole volume.

Our results and correlation with the Expedition 315 drilling results show that local uplift in the southwest part of the basin in the early Quaternary was followed by a more significant period of uplift tilting of the entire basin edge within our volume which started by the middle Quaternary (~1.3 Ma). This significant tilting period lasted until the late Quaternary for a maximum of 300 kyr. Given the southwest anticline is associated with a shallow part of the megasplay (Bangs et al., 2009) and that its timing preceded this larger event, this 300 kyr of major uplift likely did not amount to the entire history of megasplay fault slip. Rather, we suggest that this period of uplift reflects a time of maximum shortening along the megasplay that later waned. Recently, Strasser et al (2009) has examined the timing of the seawardmost branch of the megasplay fault system to determine relative timing of shortening; they concluded that that region underwent shortening by out-of-sequence thrusting as early as 1.95 Ma and had a renewed phase of thrusting ~1.55 Ma. Additionally, the analysis of Moore et al. (2007) suggested that activity in the shallow branches of the megasplay fault system may have shifted successively landward.

Putting these results together with the assumption that these shortening or uplift episodes are all reflective of megasplay history results in the following possible chronology: 1) early Quaternary saw shortening on different parts of the megasplay system resulting in uplift in the southwestern part of the Kumano Basin (Fig. 5) and thrusting seaward of the outerarc high (Strasser et al., 2009), 2) middle to late Quaternary was the period of most intense shortening on the megasplay resulting in tilting of the outer part of the Kumano Basin (Fig. 2), and 3) late Quaternary to Holocene included a waning of megasplay motion with a switch to an extensional stress state within the Kumano Basin and continued evolution of the megasplay system seaward of the outer arc high (Moore et al., 2007). Exact timing of the formation of the transtensional KBEFZ (Martin et al., 2010) is not clear, however it is clearly active currently due to maintaining a seafloor expression and it may have perturbed the orientation of the normal faults within the Kumano Basin in the late Quaternary.

The middle to late Quaternary tilting period is a candidate for when the megasplay thrust system developed into a dominant crustal scale fault that moves coseismically with significant shorting. Subsequent to 1.0 Ma, the megasplay may have slipped during coseismic rupture, but the transition to extension within the overlying forearc basin suggests the majority of the slip likely shifted after 1 Ma to along the décollement or elsewhere in the prism. Sediment underthrusting may have started prior to this period of significant motion (1.3–1 Ma) given the correlation with the southwest uplift in the basin, but clearly continued through it to result in the entire uplifted edge of the Kumano Basin overlying the thick zone of underthrust sediments (Bangs et al., 2009). The extensional deformation within the Kumano Basin that followed this period of uplift could be caused by a gravitational response to the uplift or a change in strength as the base of the wedge due to sediment underthrusting (Byrne et al., 2009), or a combination of both effets.

Megasplay faults with significant coseismic component are likely transient events of limited duration (Strasser et al., 2009). Based on the Kumano Basin results, they may form geologically rapidly with greatest shortening and uplift occurring during a short time interval. However, once formed they represent a significant potential geohazard due to providing a pathway for rupture to reach the seafloor along a more directly and closer to land (e.g., Moore et al., 2007).

The large thrust slice zone off Muroto Peninsula in the Nankai Trough is a good counter example where an out-of-sequence thrust system exists, but it is unlikely to be coseismic. This fault system consists of numerous smaller thrusts that do not have the lateral continuity or bright seismic returns that we observe along the megasplay fault in the Kumano region (Bangs et al., 2006, 2009), and does not have a well-developed forearc basin. Therefore, in examining other convergent margins for the presence of megasplay faults, results here suggest it worthwhile to examine forearc basins as a recorder of upper plate geometric changes that can be interpreted in a critical wedge framework. If a significant portion of the convergence rate is expressed as discrete strain on a megasplay type fault, then the accompanying shortening may result in significant uplift that should be exhibited in the wedge geometry and sediment cover provided there is sufficient sediment accumulation during thrusting to record the thrust activity.

5. Conclusions

After some local shortening (beneath the southwest part of the Kumano Basin and seaward of the outer arc high) in the early Quaternary, regional tilting of the Kumano forearc Basin occurred in the middle to late Quaternary, resulting in landward shifting depocenters during uplift and then basin infilling subsequent to uplift. Uplift appears to track the timing of significant shortening on the megasplay that also contributed to a large volume of sediment being underthrust beneath it.

Normal faulting within the Basin developed in response to this uplift in two stages. Initial uplift generated NE trending normal faults throughout the seaward portion of the Basin. Pertubation of the stress field in the southwest region by renewed local uplift in the southwest or effect of the Kumano Basin Edge Fault Zone generated a later phase of ENE trending normal faults, while gravitational extension formed graben-bounding and related faults (some of which we reactivated NE trending faults). This second phase of faulting is ongoing. Both phases and therefore the transition to an extension-dominated basin must have occurred no earlier than ~1 Ma given the lack of growth strata. This extension could be a gravitational response to uplift and/or the effect of changing strength at the base of the accretionary prism due to sediment underthrusting.

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Our results suggest megasplay type faults, of which the Kumano megasplay is the type-example, are transient features that undergo episodic periods of significant shortening; once formed, megasplay faults dominate the structural and stratigraphic evolution of a margin. Forearc basins may contain the best record of megasplay shortening history occurring within a given subduction margin; unraveling these histories and their transient nature is worthwhile due to the potential geohazard represented by coseismic upper plate faults.

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