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4. DEVELOPMENT OF A SEISMIC STRATIGRAPHY FOR THE PALEOGENE SEDIMENTARY SECTION, CENTRAL TROPICAL PACIFIC OCEAN[1]

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ABSTRACT

We identify four major seismostratigraphic units based on reflection packages in the Paleogene sediment column from the central tropical Pacific Ocean by utilizing the site survey for Ocean Drilling Program Leg 199. These units appear to be isochronous and regionally traceable and probably have paleoceanographic significance. We describe and name these seismic horizons and show characteristics that should help identify them. The full Paleogene stratigraphic sequence is almost never present at any given location. In fact, Site 1219 is the only drill site where we have identified all the seismic horizons. The older reflectors disappear to the east because of the younging of basement. To the north, younger seismic horizons cannot be found because of the increasing age of biogenic sediments immediately below the surficial red clay. North of ~15°N, the fossiliferous sediment sequence is early Oligocene or older. We also found it more difficult to identify the reflector sequence from drill sites sited on 56-Ma crust than those on 40-Ma crust because greater offsets along normal faults are present in the region of the older transect. We suspect the major plate reorganization at the time of magnetic reversal C22n (~49–50 Ma) may be responsible in part for the observed faulting at the older sites.

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[1] **Examples of how to reference the whole or part of this volume.**

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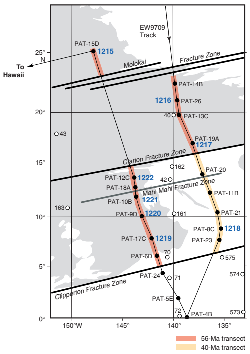
INTRODUCTION

Seismic profiles in the central equatorial Pacific have a remarkable acoustic stratigraphy, with seismic reflections traceable for >1000 km (Mayer et al., 1985; Bloomer et al., 1995). Mayer et al. (1985) identified reflectors in the sediment column associated with changes in carbonate content in equatorial sediments drilled during Deep Sea Drilling Project Leg 85 at Site 574 (4°13′N, 133°20′W). Furthermore, they hypothesized that major paleoceanographic events caused the impedance contrasts and specifically suggested that the seismic horizons are chronostratigraphic. At least two of these horizons were identified in the eastern equatorial Pacific in sediments recovered during Leg 138 at 110°W (Bloomer et al., 1995), which provides support for their chronostratigraphic nature and illustrates their widespread occurrence. The Leg 138 sites are >2500 km east of the "type" locality in the central Pacific.

Because very little sediment accumulates in the central Pacific Ocean outside of the equatorial region and the net drift of the Pacific plate is west-northwest, during Leg 199 only the lowest part of the Neogene section was drilled. The Neogene reflector set of Mayer et al. (1985) is only of marginal direct use as a guiding stratigraphy for sediments north of the Clipperton Fracture Zone. Nevertheless, because of the usefulness of the Neogene seismic stratigraphy of Mayer et al. (1985) for understanding regional Neogene sedimentation, we specifically designed the site survey for the Leg 199 cruise (*Maurice Ewing* 97-09) (Fig. **F1**) to collect data pertinent to constructing a Paleogene seismic stratigraphy for the east central tropical Pacific. Our study of the seismic reflection data collected on the site survey cruise has convinced us that such a seismic stratigraphy exists for the Paleogene (Moore et al., 2002). Here, we will identify a set of seismic reflections of probable paleoceanographic significance. Postcruise studies will test whether these seismic horizons are associated with the hypothesized specific sedimentary horizons.

F1. Cruise track of Leg 199 site survey cruise, p. 9.



Unlike the seismic stratigraphy of Vail et al. (1977), which is based on the effect of sea level change on continental margin sedimentary sequences, the stratigraphy described by Mayer et al. (1985) is based more on paleoceanographic events. Intervals of pronounced carbonate dissolution, rather than erosional episodes associated with sea level change, produce the seismic reflectors. To the extent that these paleoceanographic events represent synchronous and pervasive changes in deep-water chemistry and surface water production, the seismic stratigraphy of the deep sea is a chronostratigraphy. However, it does not rely solely on lapouts and truncations to define seismic sequence boundaries. Rather, the seismic stratigraphy of the deep sea relies more on the internal patterns of reflection packages to define groups of seismic reflections that can be traced over great distances and can be shown to have time, as well as facies, significance.

SETTING OF LEG 199

During Ocean Drilling Program (ODP) Leg 199, we drilled a transect (Fig. **F1**) across the position of the equator at 56 Ma to study the ocean dynamics of the Eocene equatorial Pacific. In addition, one site (Site 1218) was drilled on 42-Ma crust at the paleoequatorial position to document the middle–late Eocene and the Eocene–Oligocene transition in more detail. The Leg 199 transect extends from a paleolatitude of ~11°N to ~5°S and encompasses a relatively thick early Eocene sediment section, perhaps 8°N of the paleoequator (see **"Leg 199 Summary"** chapter).

The early Paleogene (~60–45 Ma) witnessed the warmest global climates recorded on Earth in the entire Cenozoic. Deepwater temperatures, as well as subtropical and temperate faunas at high latitudes, support the idea that polar regions were much warmer than modern conditions, whereas debate continues over the sea-surface temperatures that prevailed in the tropics (Bralower et al., 1995; Andreasson and Schmitz, 1998; Pearson et al., 2001).

There can be little doubt that latitudinal temperature gradients during the early Paleogene were substantially smaller than today (Crowley and Zachos, 2000). This observation raises an intriguing paleoclimate problem because if warmer high-latitude climates depend on enhanced wind-driven ocean currents or wind-carried heat and moisture to transport heat to the poles, it is difficult to explain how this transport was maintained under the weaker pole-to-equator thermal gradients. Instead, weaker latitudinal temperature gradients should give rise to weaker winds and diminished wind-driven transport. This apparent paradox is a persistent problem in numerical general circulation–model reconstructions of warm paleoclimates (Barron and Washington, 1984; Manabe and Bryan, 1985; Sloan and Huber, 2001)

Because the Pacific plate drifted northward through Cenozoic time, it has transported Paleogene biogenic sediments deposited under the high-productivity equatorial belt into a zone of extremely slow sediment (red clay) accumulation. Thus, the central tropical North Pacific Ocean is an ideal region in which to sample shallowly buried Paleogene sequences of equatorially deposited biogenic sediments. The thin Neogene cover of red clay in the area means that the sediments are typically unconsolidated and the entire Paleogene sediment section can be drilled by ODP advanced piston corer and extended core barrel methods. These drilling techniques allow for construction of the most detailed paleoceanographic reconstructions.

SEISMIC ACQUISITION AND PROCESSING

The seismic reflection data were acquired during cruise EW97-09 (*Maurice Ewing*), the site survey cruise for Leg 199. For all surveys except the first one (proposed Site PAT-14), we used a single 80-in^3 [**N1**] water gun for the seismic source and recorded on the Lamont-Doherty 4-channel streamer. Proposed Site PAT-14 was surveyed with dual 80-in^3 water guns to ensure penetration to basement. Shots were spaced at 10 s while the ship speed was maintained at 7–8 kt during the site surveys. The 4-channel data were recorded on a Geometrics engineering seismograph at 0.5-ms intervals for 2 s (after a trigger delay of 5 to 5.5 s) so that the seafloor at each site was within the recording window.

The data shown are stacked and migrated four-channel data, processed using Landmark's Promax software. We used the following parameters: (1) static shift to account for recording delay, (2) normal moveout correction using a constant velocity of 1500 ms, and (3) minimum-phase band-pass filter (40–200 Hz with a 1-octave ramp). The data were then stacked using a diversity-stack algorithm based on the power within a sliding gate of 100 ms. Data were then migrated in the following manner: spectral shaping (15 Hz = 0%, 30 Hz = 100%, 120 Hz

= 100%, and 240 Hz = 0%) followed by memory stolt F-K migration using 1500 m/s constant velocity and a stolt stretch factor of 1.

DESCRIPTIONS OF STRATIGRAPHICALLY IMPORTANT SEISMIC REFLECTIONS

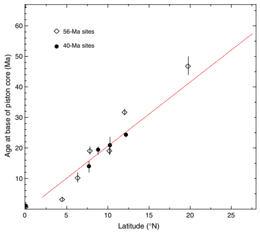
Because of age offsets along the major eastern Pacific fracture zones, the site survey cruise (Fig. F1) tracked over ocean crust of different age. We recombined segments of crust that are roughly the same age to make two major transects through the region: a 56-Ma transect (~53–60 Ma) and a 40-Ma transect (~38–43 Ma). Most drill sites for Leg 199 fall on the 56-Ma transect. A segment of Late Cretaceous crust was also surveyed, but we have not compiled this seismic information.

We have identified seismic reflections within the sediment column that appear regionally correlatable, and we have numbered them from P2 to P5, where P represents Paleogene. We have reserved P0 and P1 for further work in the Paleogene interval between 65 and 56 Ma (Table T1).

T1. Age control on central Pacific Neogene and Paleogene seismic horizons, p. 19.

We cored the upper sediments with a piston core on the site survey and found that the Leg 199 drill sites north of the Clipperton Fracture Zone are typically blanketed by 5–15 m of red clay above the first biogenic sediments. Biostratigraphic analysis of the core bases shows the age progression of near-surface sediment ages with latitude (Fig. F2) (Riedel, 1971). Because the uppermost biogenic sediments are older to the north, the younger horizons are not present at the northernmost sites.

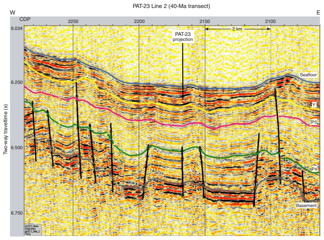
F2. Age of biogenic sediments immediately below surficial red clay, p. 10.



We hypothesize that the seismic horizons identified are chronostratigraphic (Moore et al., 2002), and we used age constraints from the site survey piston cores and initial correlations to Leg 199 drilling to place approximate ages on them. Postcruise analyses will better constrain the ties between the seismic horizons and drilled sediments. The ages for the seismic horizons are listed in Table T1, with updated ages for Mayer et al. (1985) Neogene seismic horizons. Mayer et al. (1985) used the Berggren et al. (1985) timescale. We have updated ages based upon newer age models (see the **"Explanatory Notes"** chapter). The hypothesis of chronostratigraphy for the Paleogene seismic horizons is being tested by Leg 199 drilling.

Seismic Horizon Yellow (~21 Ma)

F3. Seismic horizons at proposed Site PAT-23, p. 11.



T2. Summary of seismic character of seismic units, p. 20.

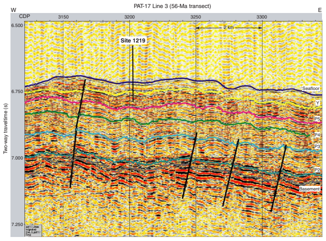
This is second lowest Neogene, or Y-reflector, from Mayer et al. (1985). Mayer et al. (1985) noted that this horizon is in part diagenetic in character, since it is present in the transition from ooze to chalk at Site 574. Nevertheless, it is marked by significant change in carbonate content as well, so it should be a reflector in unconsolidated sediments of similar age drilled during Leg 199. We can identify this reflector in the uppermost sediments of the southern drill sites (Sites 1218 and 1219, Fig. F3: proposed Site PAT-23 reflectors, Table T1), but biogenic sediments of this age are not preserved to the north. It is a prominent seismic reflection that marks the top of a series of relatively high-amplitude, high-frequency reflections in the region north of the Clipperton Fracture Zone (Table T2). South of the Clipperton Fracture Zone, these reflections are much lower amplitude, perhaps because diagenesis of the sediments has cemented them. The age of the y-horizon is poorly defined but lies within the range of 19–23 Ma based on biostratigraphy (Mayer et al., 1985) and revised age assignments used for Leg 199 biostratigraphy (see the "Explanatory Notes" chapter). The seismic layer may mark a drop in carbonates in the early Miocene that can be found throughout the Pacific basin (see Lyle, 1998).

Initial correlations from drilling at Site 1218 and Site 1219 associate the Y-seismic horizon with a major change in $CaCO_3$ in the lower Miocene at 61.5 meters composite depth (mcd) at Site 1218 and at 31 mcd at Site 1219, both in the middle of magnetic Chron C6n (~19.5 Ma).

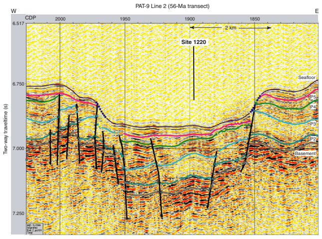
Seismic Horizon P5 (~26 Ma)

Seismic horizon P5 lies at the base of a series of high-frequency reflections in the unconsolidated sediments of proposed Site PAT-23 (Fig. F3). It can also be found at all site surveys on 40-Ma crust (e.g., Site 1218 and proposed Site PAT-21) but only is conformable with the underlying sediments at Site 1219 on the 56-Ma line (Fig. F4). We believe we can identify a P5 horizon at Site 1220, but it drapes over faulted earlier sediments (Fig. F5). Sites farther north (Sites 1215, 1216, 1217, 1221, and 1222) do not have this horizon.

F4. Seismic horizons at Site 1219, p. 12.



F5. Seismic horizons at Site 1220, p. 13.



We can also identify P5 at Site 574, which provides one way to attach an age to this seismic horizon. P5 is not very strongly developed at Site 574, perhaps because of the diagenesis that has occurred in this interval (Mayer et al., 1985). Nevertheless, it appears at ~450 ms two-way travel time (TWTT) below the seafloor (~370 meters below seafloor [mbsf]). Biostratigraphically, the reflector lies in late Oligocene sediments in the foraminifer Zone P22, CP19 nannofossil zone, and the *Dorcadospyris ateuchus* (RP21) radiolarian zone. The age for the reflector based on this correlation is ~25–27 Ma.

Initial correlations from drilling at Sites 1218 and 1219 associate this seismic horizon with the base of the large carbonate cycles in the upper Oligocene (~130 mcd at Site 1218 and ~80 mbsf at Site 1219). This places the P5 seismic horizons at the top of magnetic Chron C8r (26.6 Ma; Site 1218) to the top of C9n (27 Ma; Site 1219).

Seismic Horizon P4 (~29–30 Ma)

Seismic horizon P4 is situated at the top of the first packet of high-amplitude low-frequency reflectors in the sediment column. It is the lowest of the identified seismic horizons in surveys above the 40-Ma basement but is within the upper sediment column in the southern sites along 56-Ma crust. At Site 1219 on 56-Ma crust (Fig. F4), the seismic unit is identifiable but not prominent, whereas at Site 1218, it forms the top of the low-frequency sequence near basement.

We identify this horizon near the base of the Site 574 seismic reflection profile, at 550 ms TWTT, where high-amplitude, low-frequency reflectors appear. Using the Mayer et al. (1985) time-depth conversion, this is equivalent to ~460–470 mbsf in the sediment column. The seismic horizon falls within nannofossil Subzone CP16C, foraminifer Zone P19, and the *Theocyrtis tuberosa* (RP20) radiolarian zone (~32 Ma). Initial correlations to the drilled section at Sites 1218 and 1219 identify this horizon with large lower Oligocene carbonate cycles beginning at ~180 mcd at Site 1218 and ~120 mcd at Site 1219 (Table T1). If the correlations are correct, the seismic horizon marks the top of C11n.1n at Site 1218 (29.4 Ma). P4 lies within the only interval of poor magnetic signal at Site 1219. However, it lies in the lower part of the nannofossil Zone CP18, which has an age of 29–30 Ma.

P4 is best developed at the sites on 40-Ma crust, where it marks the upper surface of the high-amplitude, low-frequency basal sediment package. It is present at the southern sites (Site 1219 and Site 1220) on 56-Ma crust, but sites north of Site 1220 (10°N) do not preserve sufficient biogenic sediments of this age. The P4 horizon has been faulted at Site 1220, suggesting that faulting associated with abyssal hill formation continued throughout the Eocene at this site. This is significantly longer than our estimate of cessation of faulting at Site 1221, now at 12°N (see below).

Seismic Horizon P3 (~34 Ma)

Seismic horizon P3 is readily identifiable only at drill sites along the 56-Ma transect. Along the 40-Ma transect, we have not specifically picked this horizon. It is difficult to identify it based on preliminary data because it is associated with other, older seismic horizons not enumerated here. These older seismic horizons are associated with rapid middle Eocene changes in calcite compensation depth (CCD), which affect sediments above a depth of ~3500 meters below sea level. On the deeper crust of the 56-Ma transect that remains below the late Eocene CCD, only one seismic horizon exists. P3 marks the abrupt changes in $CaCO_3$ associated with the Eocene–Oligocene transition. It is most prominent in sites between 10°N and ~20°N (Sites 1217, 1220, 1221, and 1222 and proposed Site PAT-13) (Fig. F7; proposed Site PAT-10 profile) but can also be found at Site 1219.

The age on P3 is assigned based on its association with the prominent drop in carbonate downcore in the southern sites at the Eocene/Oligocene (E/O) boundary. At the sites north of the Clarion Fracture Zone (Sites 1217 and proposed Site PAT-13) (Fig. F6), the horizon represents a hiatus between Eocene radiolarian oozes and younger clays overlying them rather than the E/O boundary. P3 is not always conformable to the older sediments. At Site 1221 for example (Fig. F7), the sediment packet above the P3 horizon drapes over faulted older sediments and begins to fill in older topography.

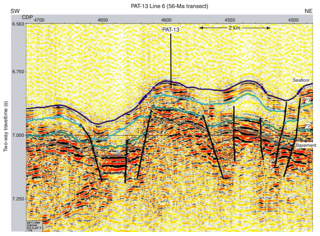
Seismic Horizon P2 (~45 Ma)

Seismic horizon P2 identifies the top of a lower packet of high-amplitude, low-frequency reflections typical of the basal sediments along the 56-Ma line. Based on drilling during Leg 199, we correlate this horizon to the depth of the first consistently chertified zone in the Eocene. The age of the first chert varies from site to site (Table T1) but seems to define a horizon at ~45 Ma.

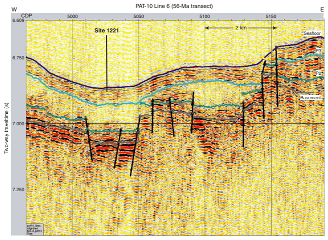
ENHANCED FAULTING ALONG THE 56-MA LINE

One major feature that stands out from the site survey is the difference in seismic "character" between the sites on 40-Ma crust and those surveyed on 56-Ma crust. Horizons are more continuous in the sediments along the 40-Ma line in both the east-west direction (roughly perpendicular to the abyssal hill strike) (Fig. F3) and in the north-south direction (almost parallel to the strike of the hills) (Fig. F8) than along the 56-Ma transect in either the east-west (Figs. F5, F6) or north-south

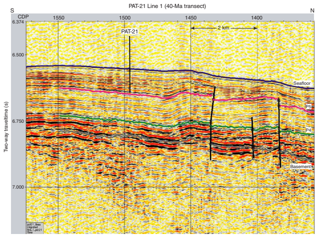
F6. Seismic horizons at proposed Site PAT-13, p. 14.



F7. Seismic horizons at Site 1221, p. 15.



F8. Seismic horizons at proposed Site PAT-21, p. 16.

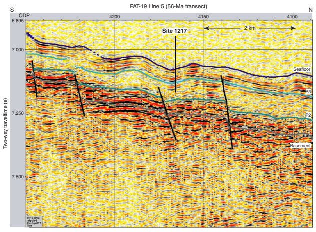


(Fig. F9; Site 1217) direction. It takes only a brief examination to determine that sediments along the 56-Ma line are much more extensively faulted than those along the 40-Ma line.

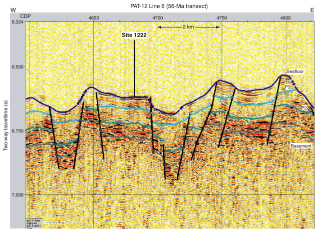
The faulting along the 56-Ma line cuts through not only the older sediments but sometimes offsets the P3 horizon (Figs. F9, F10), suggesting that faults stayed active through the Eocene and developed offsets of 75–100 m. At Site 1220 and Site 1219, the P4 horizon (~30 Ma) may be offset by the faulting as well. In contrast, faulting is much less extensive on 40-Ma crust. On this younger crust offsets occasionally extend to P4 and P5, but they are usually on the order of 10 m and sediments appear to drape over the faults in low abyssal hills.

The difference in tectonism between the two transects is significant and deserves explanation. We hypothesize that the more highly faulted early Eocene crust may result from the significant reorganization of plate motion, ridge axes, and transform faults in this time period or shortly afterward (Rea and Dixon, 1983), when the early Eocene crust was relatively young (Menard, 1978; Rea and Dixon, 1983; Rosa and Molnar, 1988; Atwater, 1989). Better age control from drilling should help to better constrain this problem, and further surveys after drilling will better define the extent of anomalous faulting.

F9. Seismic horizons at Site 1217, p. 17.



F10. Seismic horizons at Site 1222, p. 18.



CONCLUSIONS

We have identified four Paleogene seismic horizons in the central tropical Pacific. Their distribution is bounded by younger basement to the east and by preservation of biogenic sediments to the north. These seismic horizons apparently mark important paleoceanographic events, and postcruise studies of Leg 199 physical properties will be important to better define the paleoceanographic links. Development of this seismic stratigraphy has been critical to defining differences in tectonics at sites along the 56-Ma transect vs. the 40-Ma transect. The 56-Ma transect is much more highly faulted than the younger crust, perhaps because of an Eocene plate reorganization.

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Figure F1. Cruise track of Leg 199 site survey cruise EW9709, showing transects on 56-Ma crust and 40-Ma crust. Shading marks water depths greater than 5000 m. Leg 199 drill sites are identified by both their drill site number (blue) and their survey identification. Deep Sea Drilling Program drill sites are shown by open circles. The Mahi Mahi Fracture Zone was discovered during the site survey cruise.

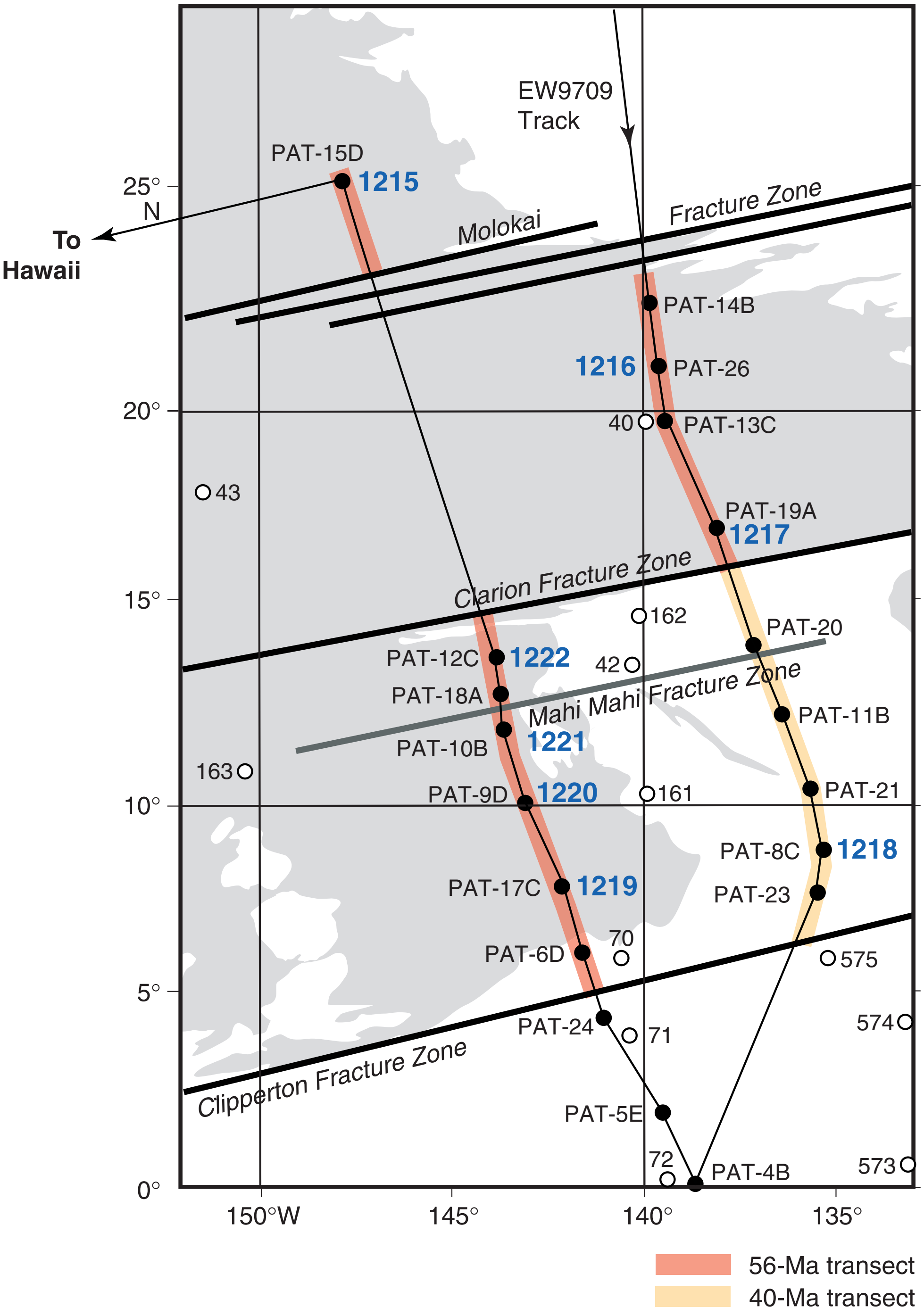

Figure F2. Age of biogenic sediments immediately below surficial red clay showing aging of the sediment pile to the north.

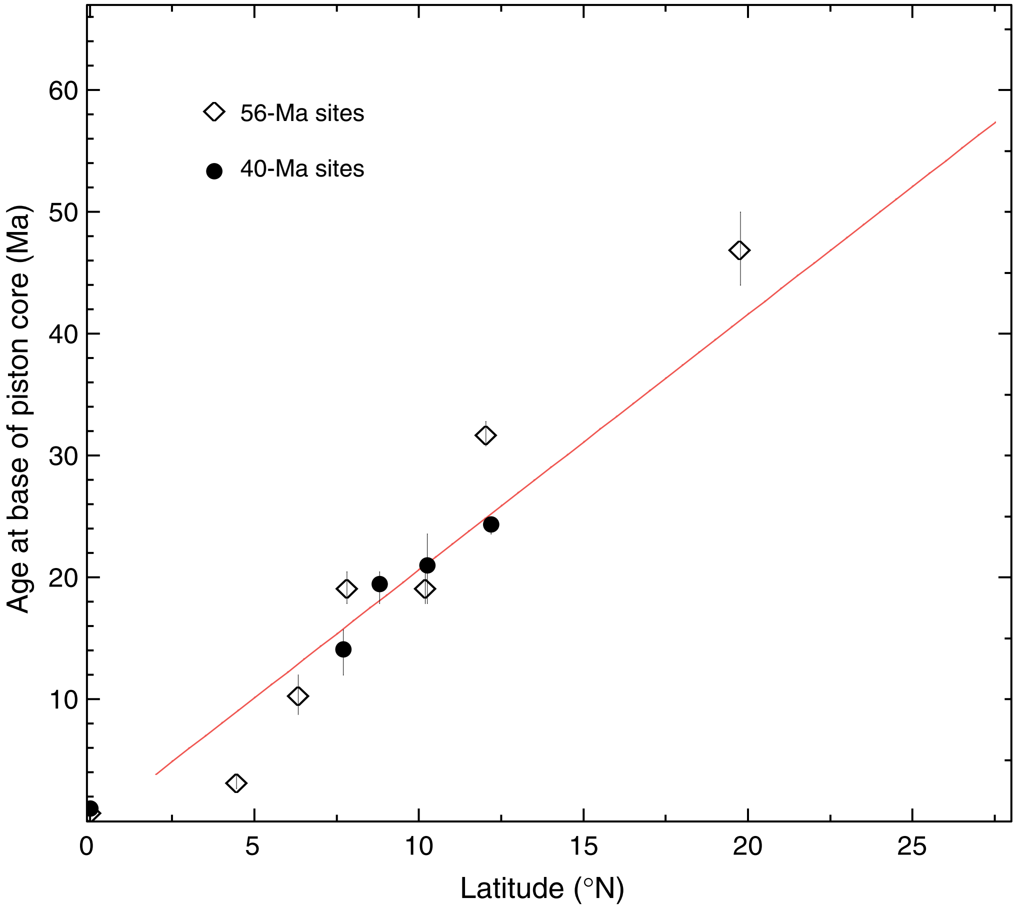

Figure F3. Seismic horizons at proposed Site PAT-23 (7°42′N, 135°33′W) on the 40-Ma transect. Proposed Site PAT-23 is actually ~300 m south of Line 2, shown here, and is projected onto the line. Yellow horizon marks the early Miocene yellow reflector of Mayer et al. (1985).

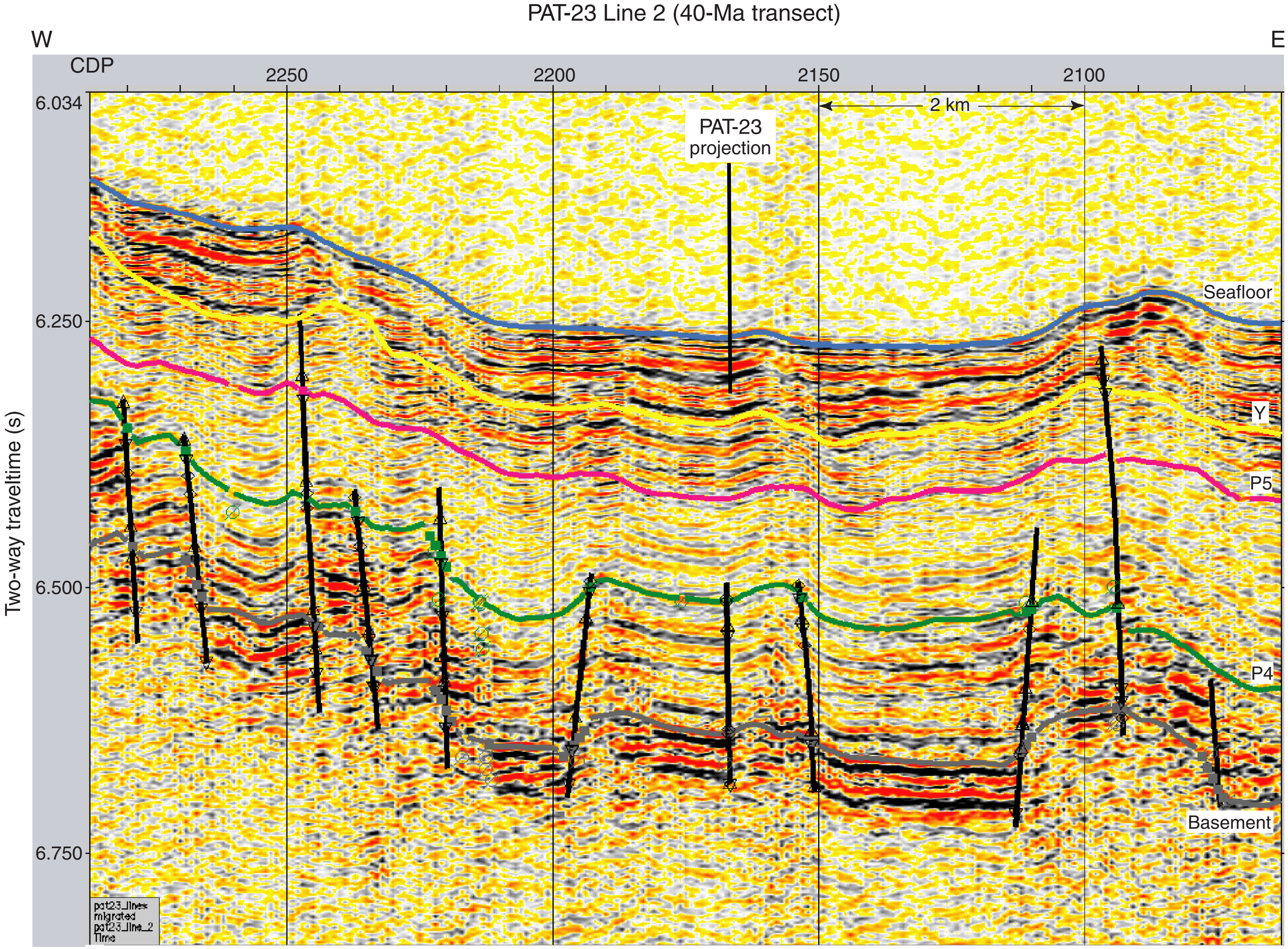

Figure F4. Seismic horizons identified at Site 1219 (7°48′N, 142°01′W) on the 56-Ma transect, the southernmost site drilled during Leg 199. Site 1219 is the only Leg 199 drill site with all of the Paleogene reflectors we identify. Yellow horizon marks the early Miocene yellow reflector of Mayer et al. (1985).

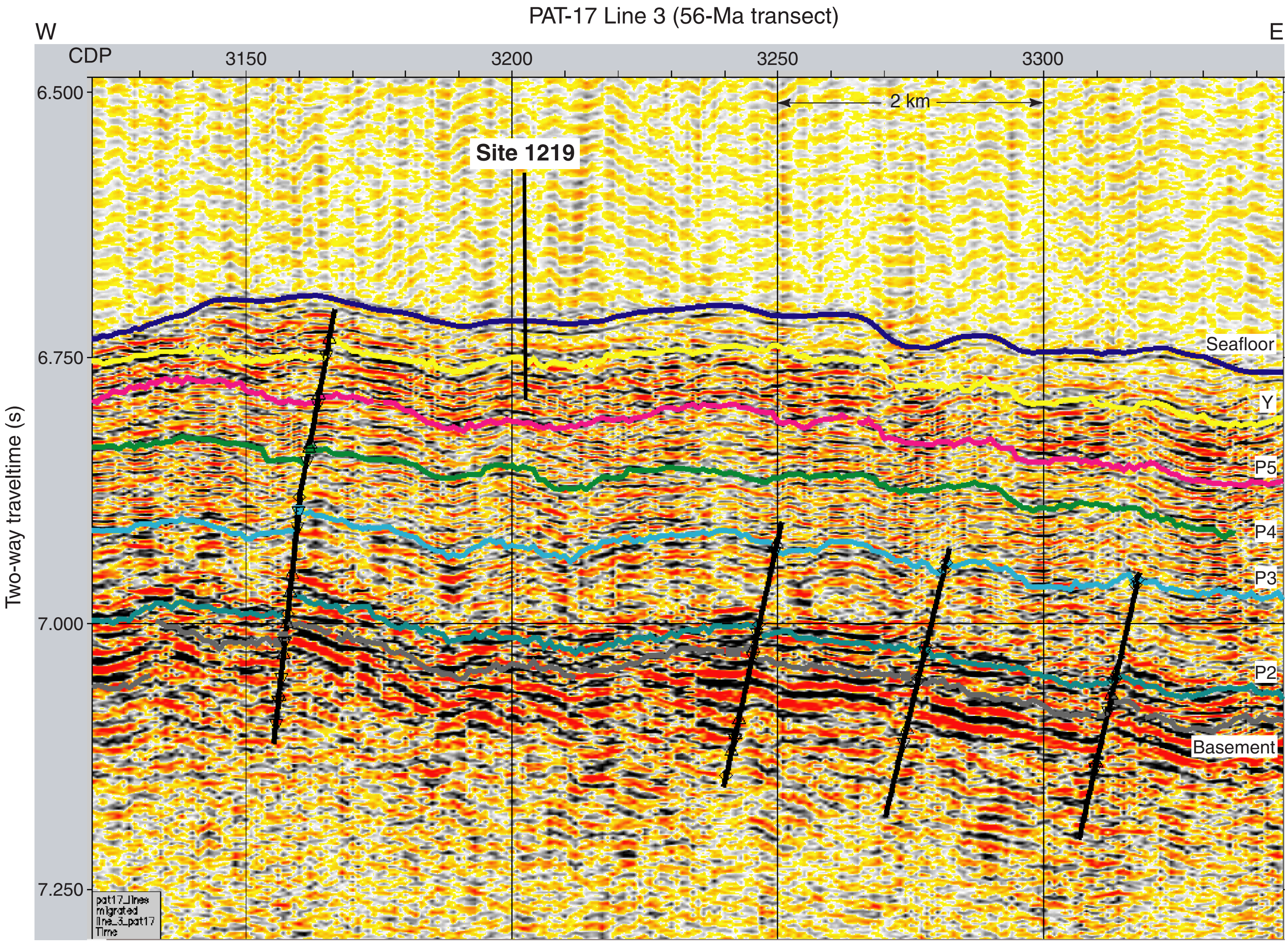

Figure F5. Seismic horizons at Site 1220 (10°11′N, 142°46′W) showing the unconformable contact between P5 and lower seismic horizons and the high level of faulting of 56-Ma crust.

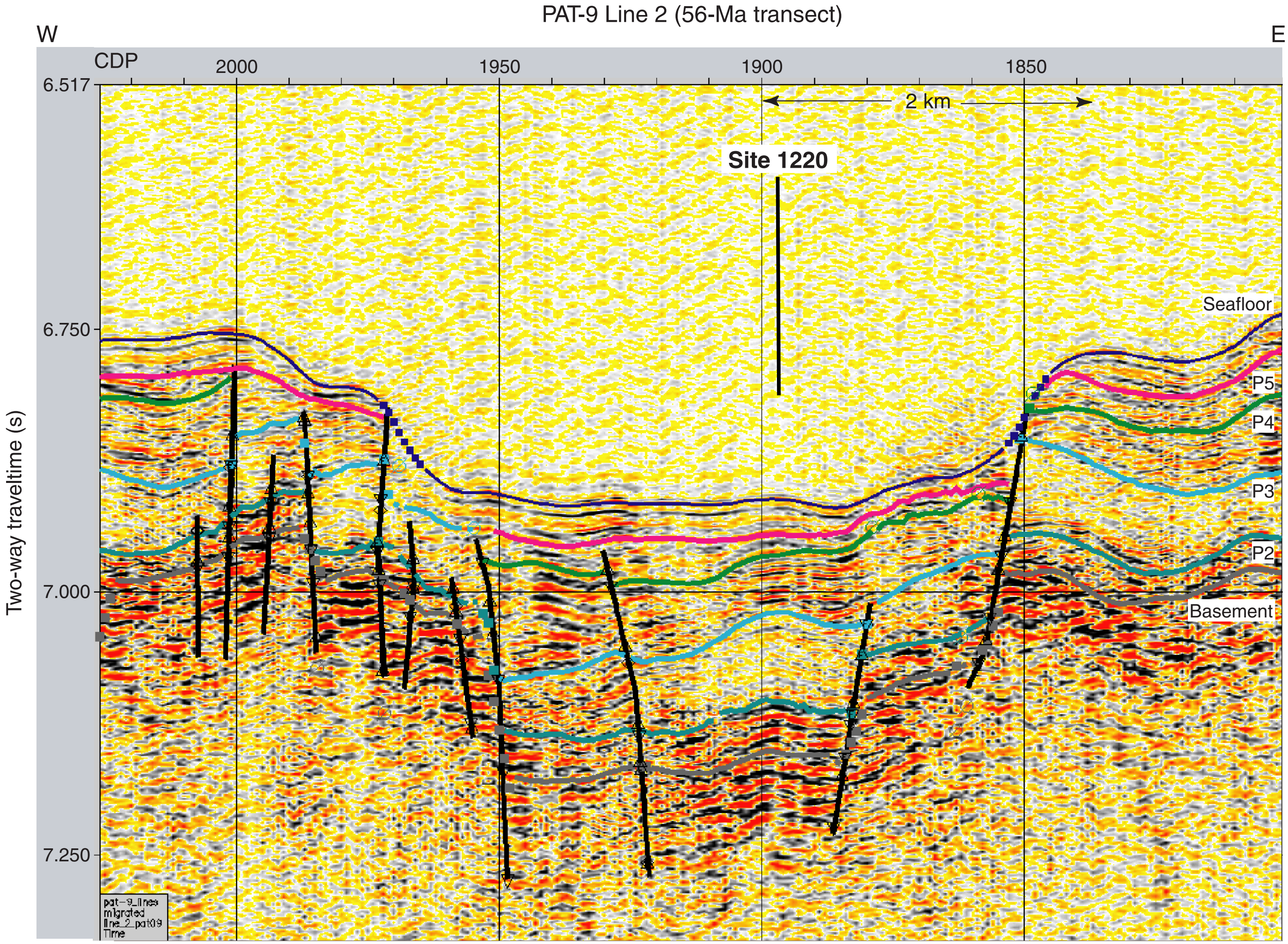

Figure F6. Seismic horizons at proposed Site PAT-13 (19°46′N, 138°55′W). Recovery of middle Eocene radiolarian ooze by piston coring at proposed Site PAT-13 during the EW9709 site survey shows that the P3 horizon can represent a hiatus between Eocene and younger sediments north of Clarion Fracture Zone.

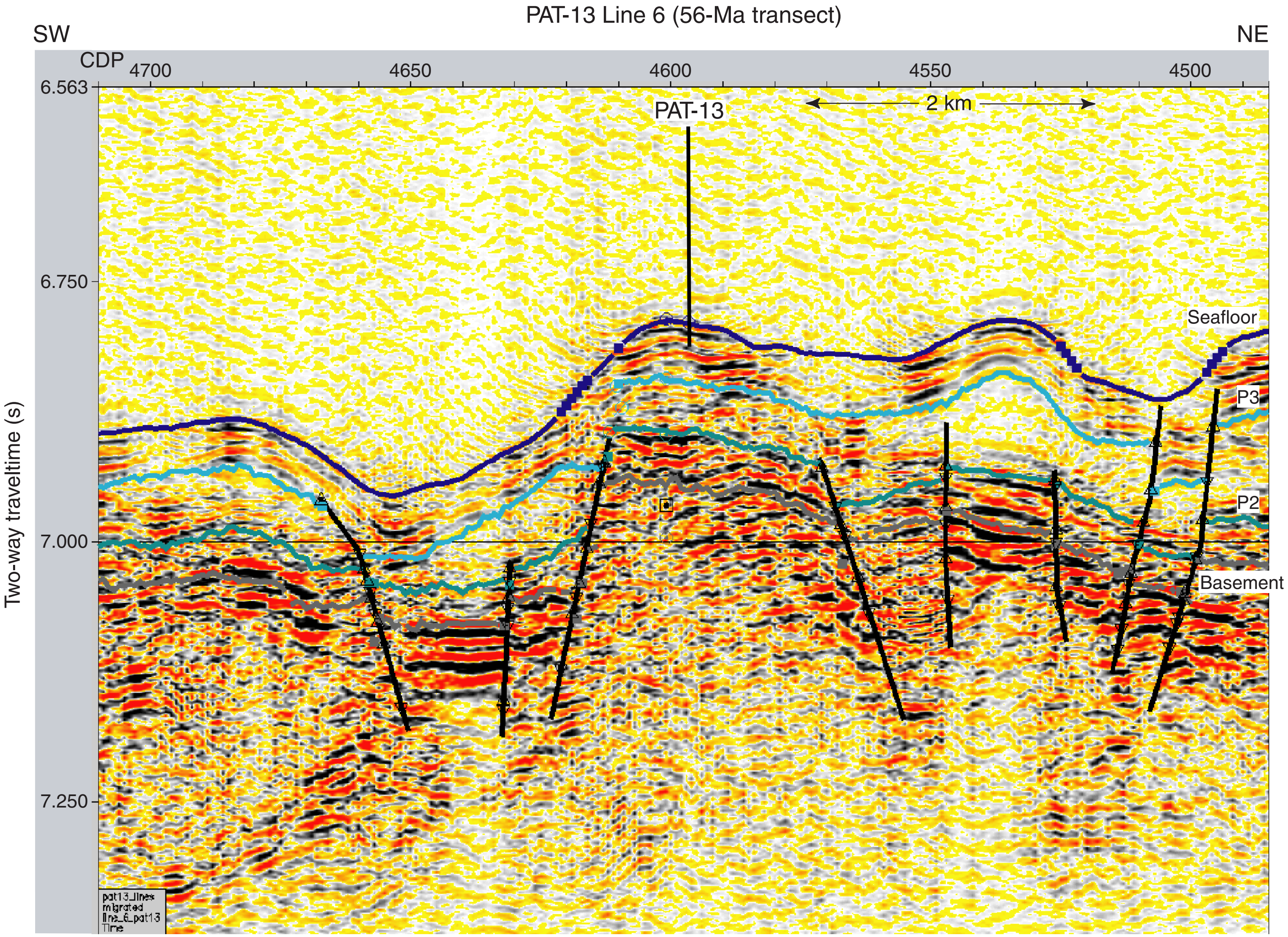

Figure F7. Seismic horizons at Site 1221 (12°02′N, 143°42′W) on the 56-Ma line. Note that the sediments above P3 drape over earlier faulted sediments.

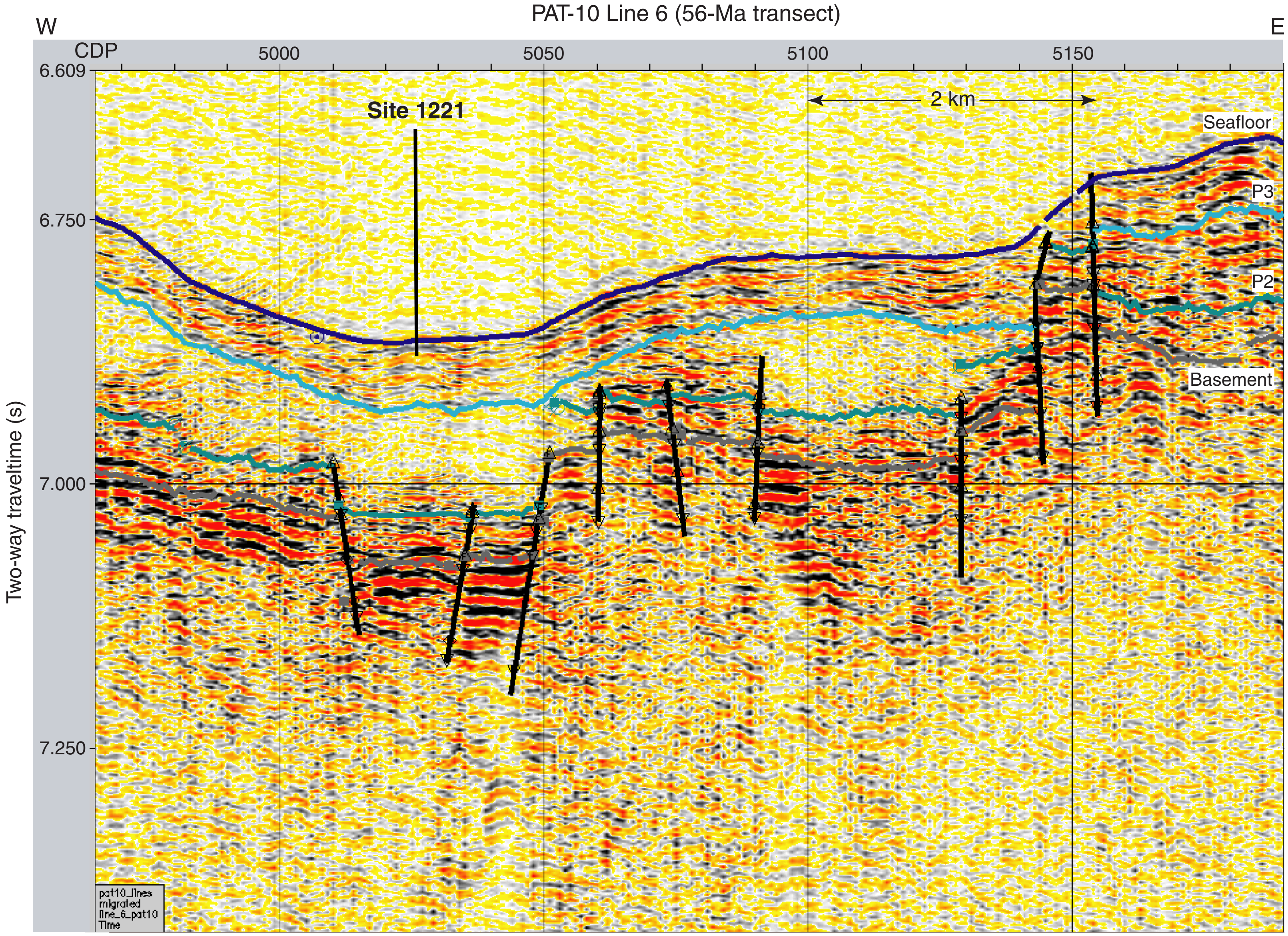

Figure F8. Seismic horizons at proposed Site PAT-21 (10°12′N, 135°32′W) along the 40-Ma transect. This seismic line shows typical faulting in the north-south direction along 40-Ma crust.

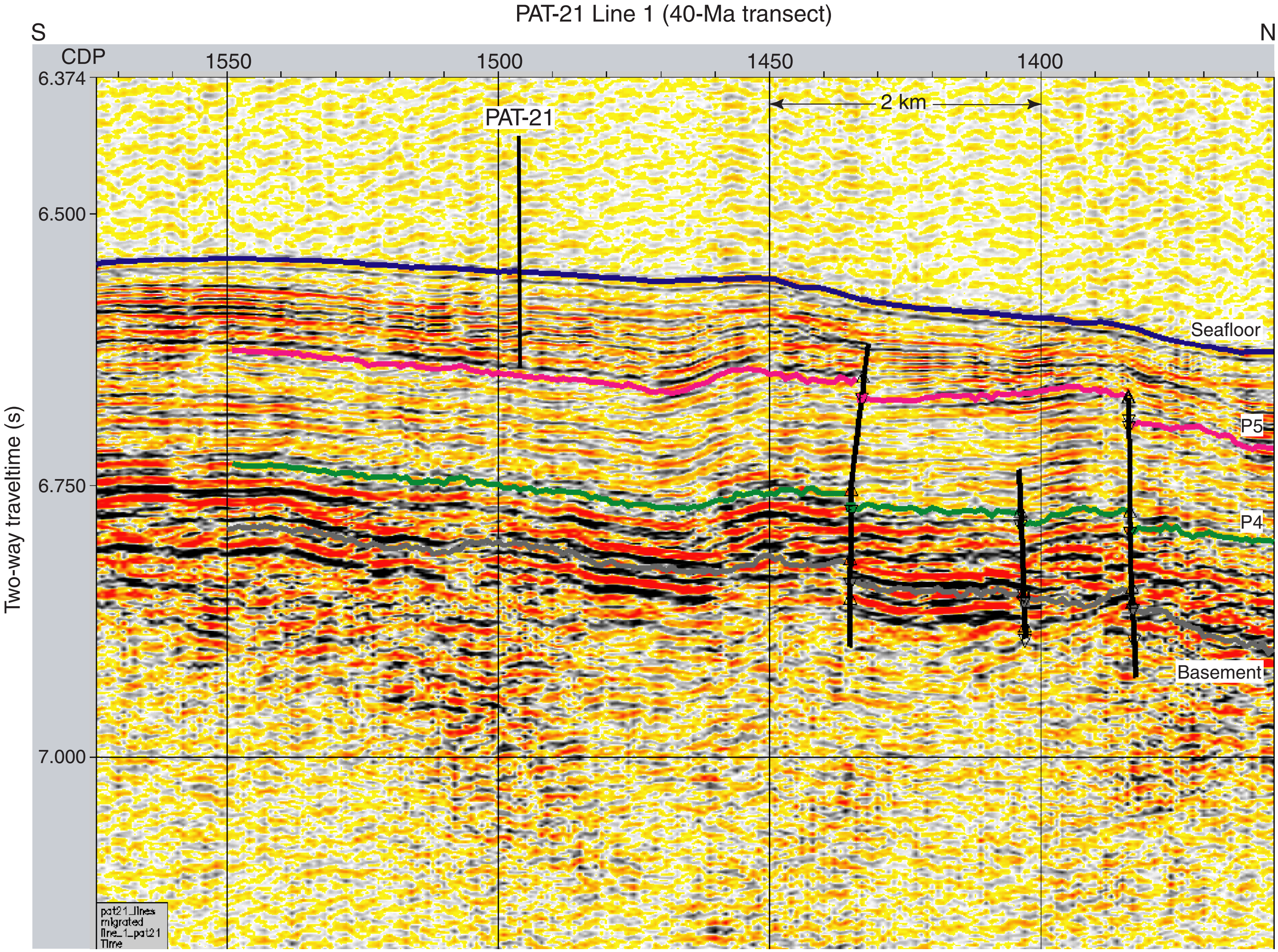

Figure F9. Seismic horizons at Site 1217 (16°52′N, 138°06′W) showing faulting in the north-south direction on 56-Ma crust.

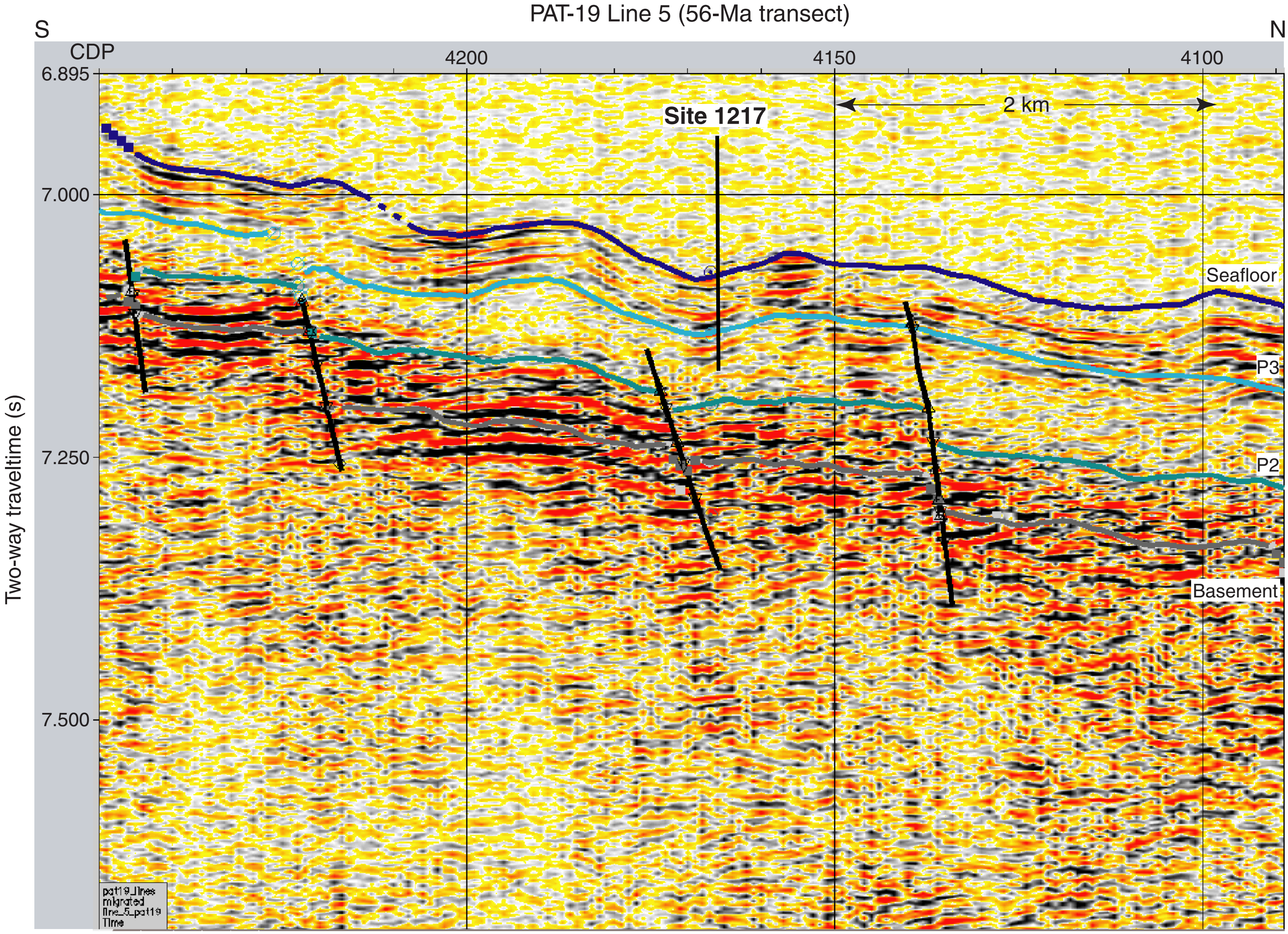

Figure F10. Seismic horizons at Site 1222 (13°49.0′N, 143°53.3′W) showing extensive faulting at this 56-Ma transect site.

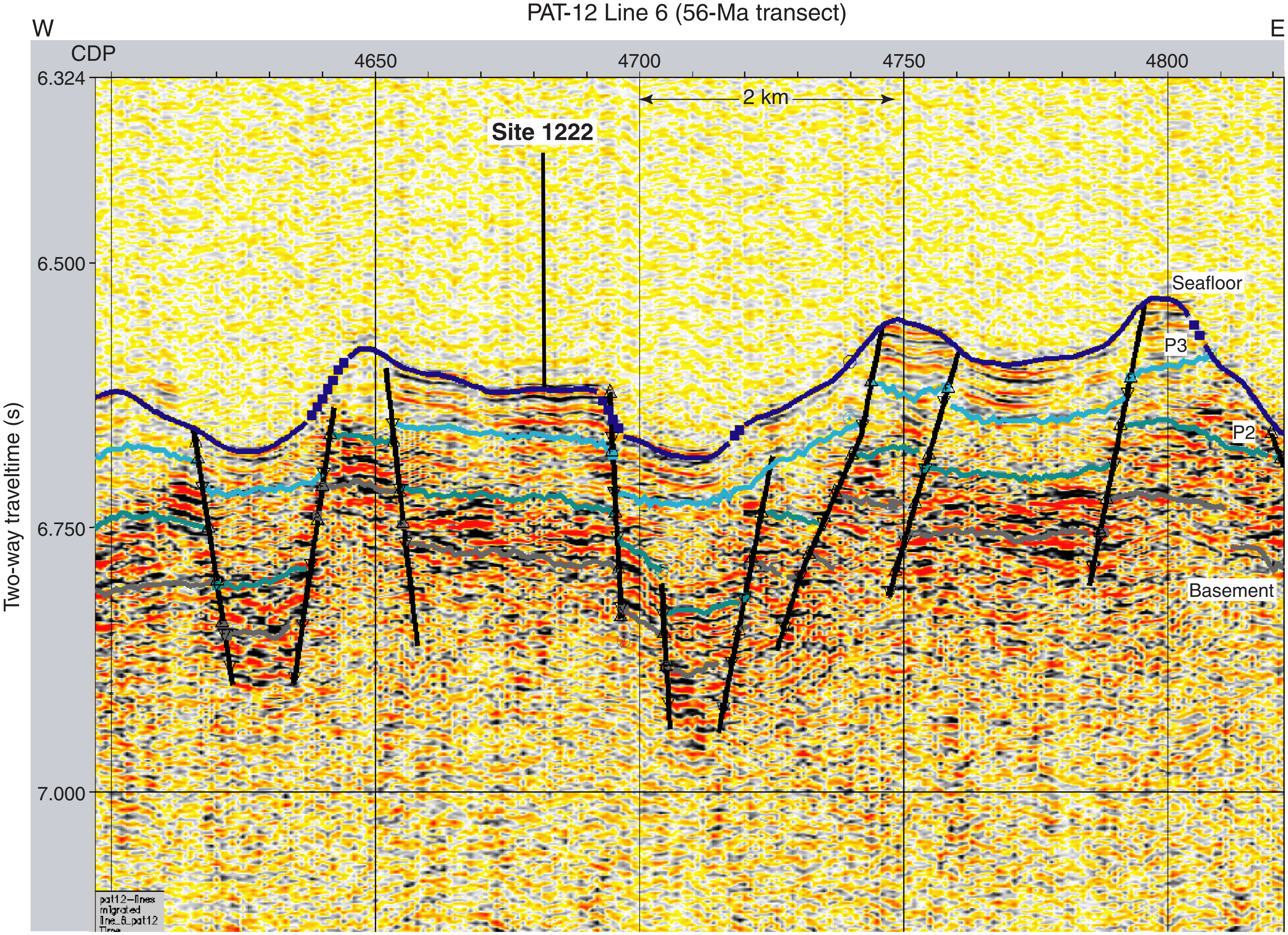

Table T1. Age and stratigraphic position of Paleogene and Neogene seismic horizons in the central equatorial Pacific.

Seismic horizon identification	Site	Planktonic foraminiferal zone	Nannofossil zone/subzone	Radiolarian zone	Magnetochron	Age (Ma)
Neogene (Mayer et al., 1985):						
Green	574	N19	CN11			3.8–4.6
Brown	574	N17	CN8	RN9/RN8		8.3–8.8
Purple	574	?(N16-14)	CN7	RN7		9.6–10.5
Red	574	N10	CN4	RN6		13.5–15.0
Lavender	574	?(N8-N6)	CN3	RN5		15.7–17.0
Yellow	574	N4	CN1	RN3/RN2		19–23
Orange	574	N4	CN1	RN2/RN1		21.5–24.6
Paleogene (this volume):						
P5	574	P22	CP19	RP21		25–27
	1218				Top C8r	26.6
	1219				Top C9n	27
P4	574	P19	CP16c	RP20		~32
	1218				Top C11n.1n	29.4
	1219		Lower CP18			29–30
P3	1218		NP21			32.8–33.8
	1219				Top C13r	33.7
P2	1217			RP14	C20n?	~43
	1219			RP12	C20r?	45–46
	1220			RP11		47.4–48.4

Table T2. Summary of seismic character.

Seismic reflection packets	Amplitude	Frequency	Continuity
O–P5	High	High	Good
P5–P4	Moderate–low	Moderate	Moderate
P4–P3	Moderate–high	Moderate–low	Moderate–low
P3–P2	Low–moderate	Low	Low
P2–base	High	Low	Moderate–high

CHAPTER NOTE*

N1. 5 December 2002—After this chapter was published, it was found that the capacity of the water gun was incorrect. The correct water gun volume (80 in^3) appears in this version.

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*Dates reflect file corrections or revisions.