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TECTONOPHYSICS

West margin of North America — a synthesis of recent seismic transects

Gary S. Fuis *

U.S. Geological Survey, 345 Middlefield Road, MS 977, Menlo Park, CA 94025, USA

Abstract

A comparison of the deep structure along nine recent transects of the west margin of North America shows many important similarities and differences. Common tectonic elements identified in the deep structure along these transects include actively subducting oceanic crust, accreted oceanic/arc (or oceanic-like) lithosphere of Mesozoic through Cenozoic ages, Cenozoic accretionary prisms, Mesozoic accretionary prisms, backstops to the Mesozoic prisms, and undivided lower crust. Not all of these elements are present along all transects. In this study, nine transects, including four crossing subduction zones and five crossing transform faults, are plotted at the same scale and vertical exaggeration (V.E. 1 : 1), using the above scheme for identifying tectonic elements. The four subduction-zone transects contain actively subducting oceanic crust, Cenozoic accretionary prisms, and bodies of basaltic rocks accreted in the Cenozoic, including remnants of a large, oceanic plateau in the Oregon and Vancouver Island transects. Rocks of age and composition (Eocene basalt) similar to the oceanic plateau are currently subducting in southern Alaska, where they are doubled up on top of Pacific oceanic crust and have apparently created a giant asperity, or impediment to subduction. Most of the subduction-zone transects also contain Mesozoic accretionary prisms, and two of them, Vancouver Island and Alaska, also contain thick, tectonically underplated bodies of late Mesozoic/early Cenozoic oceanic lithosphere, interpreted as fragments of the extinct Kula plate. In the upper crust, most of the five transform-fault transects (all in California) reflect: (1) tectonic wedging of a Mesozoic accretionary prism into a backstop, which includes Mesozoic/early Cenozoic forearc rocks and Mesozoic ophiolitic/arc basement rocks; and (2) shuffling of the subduction margin of California by strike-slip faulting. In the lower crust, they may reflect migration of the Mendocino triple junction northward (seen in rocks east of the San Andreas fault) and cessation of Farallon-plate subduction (seen in rocks west of the San Andreas fault). In northern California, lower-crustal rocks east of the San Andreas fault have oceanic-crustal velocity and thickness and contain patches of high reflectivity. They may represent basaltic rocks magmatically underplated in the wake of the migration of the Mendocino triple junction, or they may represent stalled, subducted fragments of the Farallon/Gorda plate. The latter alternative does not fit the accepted 'slabless window' model for the migration of the triple junction. This lower-crustal layer and the Moho are offset at the San Andreas and Maacama faults. In central California, a similar lower-crustal layer is observed west of the San Andreas fault. West of the continental slope, it is Pacific oceanic crust, but beneath the continent it may represent either Pacific oceanic crust, stalled, subducted fragments (microplates) of the Farallon plate, or basaltic rocks magmatically underplated during subduction of the Pacific/Farallon ridge or during breakup of the subducted Farallon plate. The transect in southern California is only partly representative of regional structure, as the structure here is 3-dimensional. In the upper crust, a Mesozoic prism has been thrust beneath crystalline basement rocks of the San Gabriel Mountains and Mojave Desert. In the mid-crust, a bright reflective zone is interpreted as a possible 'master' decollement that can be traced from

* Fax: +1 (650) 329-5163. E-mail: fuis@andreas.wr.usgs.gov

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the fold-and-thrust belt of the Los Angeles basin northward to at least the San Andreas fault. A Moho depression beneath the San Gabriel Mountains is consistent with downwelling of lithospheric mantle beneath the Transverse Ranges that appears to be driving the compression across the Transverse Ranges and Los Angeles basin.

Keywords: crustal structure; plate boundary structures and processes; continental structures; North America

1. Introduction

In the past fifteen years or so, a number of seismic transects have been collected across the west margin of North America. In this study we compile and examine nine of these transects from Alaska to southern California (Plate I, 1.1), including ones beginning in the Gulf of Alaska (Fuis et al., 1991; Brocher et al., 1994), offshore of southern Vancouver Island (Clowes et al., 1987, 1995, 1997; Hyndman et al., 1990; Fuis and Clowes, 1993), offshore of central Oregon (Trehu et al., 1994), offshore of northern California north of the Mendocino triple junction (Beaudoin et al., 1996) and south of the Mendocino triple junction (Beaudoin et al., 1996; Henstock et al., 1996; Godfrey et al., 1997), offshore of the San Francisco Bay region of central California at the Golden Gate (Holbrook et al., 1996) and at Santa Cruz (Fuis and Mooney, 1990; Page and Brocher, 1993), offshore of the San Luis Obispo region of central California (Miller et al., 1992; Howie et al., 1993), and offshore of the Los Angeles region of southern California (Fuis et al., 1996; Ryberg and Fuis, 1998). Interpretation of the southern California transect is preliminary; however, some tectonic elements are approximately known, and it is useful to include this transect for comparison with the other transects.

Researchers have, on occasion, compared individual transects with others, e.g., Fuis and Clowes (1993), Howie et al. (1993), and Trehu et al. (1994); however, no summary exists. Of course, an older summary of continent–ocean transects is available (Speed, 1991), but these transects were compiled largely before definitive seismic data were collected along them. The purpose of this paper is to summarize these nine transects using a common scale, vertical exaggeration (V.E. 1:1), and tectonic key.

Common tectonic elements that have been identified in these transects are as follows (along with the label used in Plate I): (A) actively subducting oceanic crust; (B1–B3) oceanic/arc (or oceanic-like) lithosphere accreted in the Mesozoic (B1), latest Mesozoic or early Cenozoic (B2), or Cenozoic (B3); (C) Cenozoic accretionary prism; (D) Mesozoic accretionary prism; (E) backstop to the Mesozoic prism; (F) undivided lower crust; and (G) other Cenozoic rocks (see Plate I, explanation 1.2). Element A has intermediate velocity (6.0–7.3 km/s), is tabular with a thickness of about 5–10 km, in most cases, and is associated with subduction-zone seismicity. Element B1, largely unexposed, dense magnetic rocks, has intermediate (6.0–7.3 km/s) to mantle (7.7–8.0 km/s) velocities. These rocks are interpreted as ophiolite and/or arc rocks. They are part of the backstop (E) to the Mesozoic accretionary prism, and are shown (Plate I, 1.2) as an overprint on E. Element B2, also largely unexposed, dense, magnetic rocks, has intermediate to mantle velocities and is interpreted as tectonically underplated oceanic lithosphere. Except in central Oregon, element B3, is largely unexposed on the continent but can in some places be traced seaward to Pacific oceanic crust. It has intermediate velocity and is tabular with a thickness of generally 5 to 10 km. It has been variously interpreted as stalled, subducted oceanic crust or as magmatically underplated basaltic rocks. (In central Oregon, the B3 unit is exposed and constitutes most, if not all of the crust; it is interpreted as a possible remnant of an oceanic plateau.) The Cenozoic and Mesozoic prisms (C and D) consist of sedimentary, volcanic, and metamorphic rocks. The Mesozoic prism (D) generally has a landward-dipping boundary on its landward edge. In some cases, a seaward-dipping lower boundary to this body is interpreted, making it a tectonic wedge (labeled D′). Most Mesozoic tectonic wedges include ophiolite in their upper part, interpreted to have been added to the wedge from the backstop (E/B1). Undivided lower crust (F) includes rocks with velocity higher than about 6.6 km/s, generally interpreted to be intermediate to mafic plutonic and metamorphic rocks. Table 1 summarizes the elements present in each transect. Not all tectonic elements are present along all transects.

Historical earthquakes are projected onto the transects in order to indicate how modern tectonics are related to the known structure. Most hypocenters are projected less than about 10 km, where the projection distance can be known from the historical record (e.g., Ellsworth, 1990). The great Alaskan earthquake is an exception: it was projected about 125 km (see below). Earthquake parameters were taken from the sources referenced in Plate I (explanation 1.2).

Interpretations presented here are largely consistent with original interpretations (see references above), with the exception that the transects are interpreted in terms of the tectonic elements defined in this study (Plate I, 1.2). An extensive discussion of the data and interpretation of each transect is beyond the scope of this paper, and the reader is referred to the original papers listed above. (The above references are not generally repeated below.)

2. Transects

2.1. Gulf of Alaska/southern Alaska (Plate I, 1.3)

Subducting crust in the Gulf of Alaska/southern Alaska (A) includes Pacific oceanic crust (middle and late Eocene in age) overlain by a pair of layers (6.9 and 6.1–6.4? km/s) interpreted as lower crust of the Yakutat terrane (early Eocene in age). The overriding North American plate includes a Cenozoic prism (C), a Mesozoic prism (D′), a backstop to the Mesozoic prism (E/B1), a tectonically underplated body of intermediate to mantle velocities (5.7–7.7 km/s; B2), and a lower-crustal root (F). The Cenozoic prism is the Prince William terrane; the Mesozoic prism includes the Chugach terrane and an ophiolite complex known as the Border Ranges ultramafic–mafic assemblage (BRUMA), interpreted to be a fragment of the basement of the Peninsular terrane; and the backstop to the Mesozoic prism includes sedimentary rocks of the Copper River basin, the Peninsular/Wrangellia terrane, and Mesozoic plutonic rocks. The Mesozoic prism and ophiolite complex are interpreted to have moved landward as an upper-crustal tectonic wedge into the backstop, the ophiolite complex having been transferred from the backstop to the wedge. The underplated body (B2), the tip of which is exposed in the Chugach Mountains as metabasalt, is interpreted as tectonically underplated fragments of the Kula plate (late Mesozoic/early Cenozoic in age); it underlies the seaward part of the Mesozoic prism but is truncated farther seaward by the Contact fault. A lower-crustal root is observed beneath the backstop and landward of the B2 body; maximum crustal thickness is 57 km.

Subduction of the lower crust of the Yakutat terrane is largely responsible for the current uplift of the Chugach Mountains and may constitute much of the giant asperity giving rise to great earthquakes in southern Alaska, such as the 1964 M_w 9.2 Alaskan earthquake (Page et al., 1994). The hypocenter of the Alaskan earthquake (Stauder and Bollinger, 1972) is projected about 125 km eastward onto the transect (Plate I, 1.3); therefore, its structural setting is not necessarily that shown, namely, occurrence at the base of the body of interpreted Kula-plate fragments. On the other hand, the projection was along a gravity ridge (Barnes, 1977) associated with the body of Kula-plate fragments, and the structural setting may not be too different from that shown. It is interesting to speculate on whether or not the interpreted lower crust of the Yakutat terrane will continue to subduct with the Pacific oceanic crust or become tectonically underplated like the older fragments of the Kula plate (B2).

2.2. Southern Vancouver Island (Plate I, 1.4)

The Juan de Fuca plate (A; late Cenozoic in age) is actively subducting beneath southern Vancouver Island. The overriding North American plate consists of a Cenozoic prism (C), a partly exposed and also a deeply subducted body of tectonically underplated oceanic rocks (B3), a Mesozoic prism (D), a backstop to the Mesozoic prism (E), and an underplated body of intermediate to high velocity (B2). The Cenozoic prism (exclusive of the bodies B3) includes the Olympic Core Rocks and Ozette and Hoh (melange) terranes. The upper body B3 is the Crescent terrane (early Eocene in age). It is defined in the subsurface chiefly by its magnetic properties (Dehler and Clowes, 1992). This terrane is correlative in age and composition with the lower crust of the Yakutat terrane in southern Alaska, but at southern Vancouver Island, it has been accreted to the North American plate. The Mesozoic prism is the Pacific Rim terrane and the backstop to this prism is the Wrangellia terrane. In contrast to southern Alaska, the Mesozoic prism has been juxtaposed against the backstop by thrusting and/or strike-slip faulting, not by tectonic wedging. The intermediate- to high-velocity body (B2) and the Mesozoic prism are truncated seaward at the Tofino fault, presenting a structural configuration somewhat similar to that in southern Alaska (Plate I, 1.3), where the Chugach terrane and interpreted Kula-plate fragments are truncated at the Contact fault. As in southern Alaska, the B2 body at southern Vancouver Island may be interpretable as fragments of the Kula plate.

Crustal thickness at Vancouver Island and in the western Coast Mountains is somewhat puzzling. Refraction/wide-angle reflection data indicate velocities of 7.9 km/s at about 37-km depth, but vertical-incidence reflection data in the western Coast Mountains show clear reflections extending well below this depth. In fact, these data suggest a smooth projection of the eastward-dipping 'C' and 'E' reflective zones at the top and bottom of the B2 body on Vancouver Island into the Coast Mountains. It appears from the reflection data that the B2 body passes through the 37-km 'Moho' depth without noticeable change in reflective character. Gravity data indicate non-mantle densities below 37-km depth (Clowes et al., 1997). It is possible that the high velocities indicated by the refraction/wide-angle reflection data are from a layer within the B2 body. Such layers are observed in the B2 body in Alaska.

2.3. Central Oregon (Plate I, 1.5)

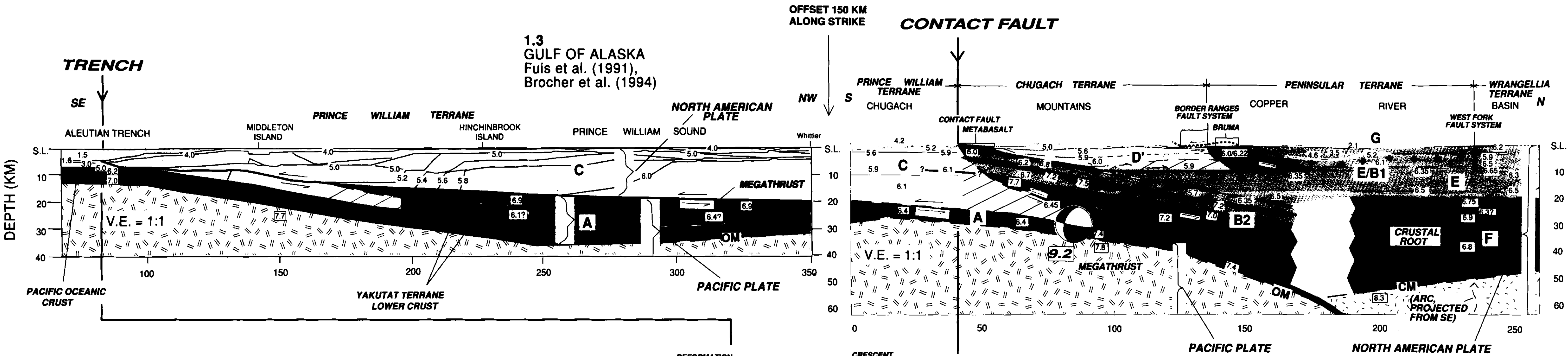
In central Oregon, as at southern Vancouver Island, the Juan de Fuca plate (A; late Cenozoic in age) is actively subducting. The components of the overriding North American plate include a Cenozoic prism (C), a body of intermediate- to high-velocity oceanic rocks (B3), and, east of the Cascade Range (beyond the transect), a Mesozoic backstop (E), revealed in spotty exposures. The Mesozoic prism (D) is buried beneath Cascade volcanic rocks (Stanley et al., 1990) or is missing (Parsons et al., 1996). The body B3 is the Siletz terrane (Paleocene and Eocene in age); it is correlative with and can be traced northward into the Crescent terrane at southern Vancouver Island but is four to six times thicker than the Crescent terrane at the latitude of central Oregon.

The Siletz terrane may be (a) an oceanic plateau resulting from the initiation of the Yellowstone hotspot in the early Cenozoic, or (b) the products of oblique rifting of the continental margin in the early Cenozoic (Wells et al., 1984).

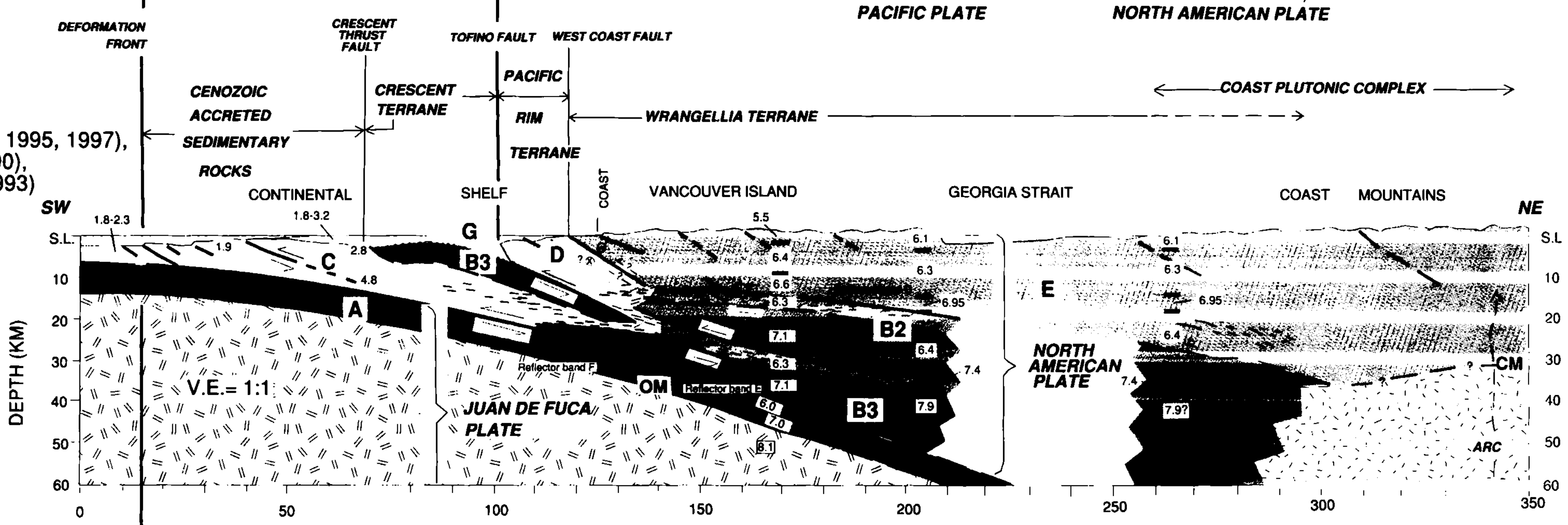
2.4. Northern California (Plate I, 1.6 and 1.7)

Transects north and south of the Mendocino triple junction reveal landward-dipping Mohos with 6-km-thick reflective zones immediately above the Mohos; reflectivity is especially strong along the southern transect. On the northern transect, the reflective zone correlates in part with subduction-zone earthquakes and is interpreted to be the actively subducting Gorda-plate crust (A; late Cenozoic). On the southern transect, this layer is either tectonically or magmatically underplated mafic rocks (B3). The crust above these mafic layers on both transects includes simply a Mesozoic/Cenozoic prism (labeled D and D') and a backstop to the Mesozoic prism (E). The Mesozoic/Cenozoic prism is the Franciscan assemblage, composed of three belts or terranes. On the northern transect, the backstop to this prism is the Klamath complex, an assemblage of island-arc and ophiolitic terranes. On the southern transect, the backstop is the Great Valley sequence and its ophiolite/island-arc basement, the Great Valley ophiolite (E/B1). On the northern transect, the prism underthrusts the backstop; whereas on the southern transect, the prism is interpreted to form a complex, two-tiered tectonic wedge that indents the backstop. The Great Valley ophiolite apparently includes a complete (but probably structurally disarrayed) section of oceanic lithosphere, including oceanic crust over mantle rocks. This section is interpreted to have been obducted onto the Sierra Foothills metamorphic complex in the Jurassic (Godfrey et al., 1997). The relationship of the Great Valley ophiolite to the Coast Range ophiolite, a component of the tectonic wedge

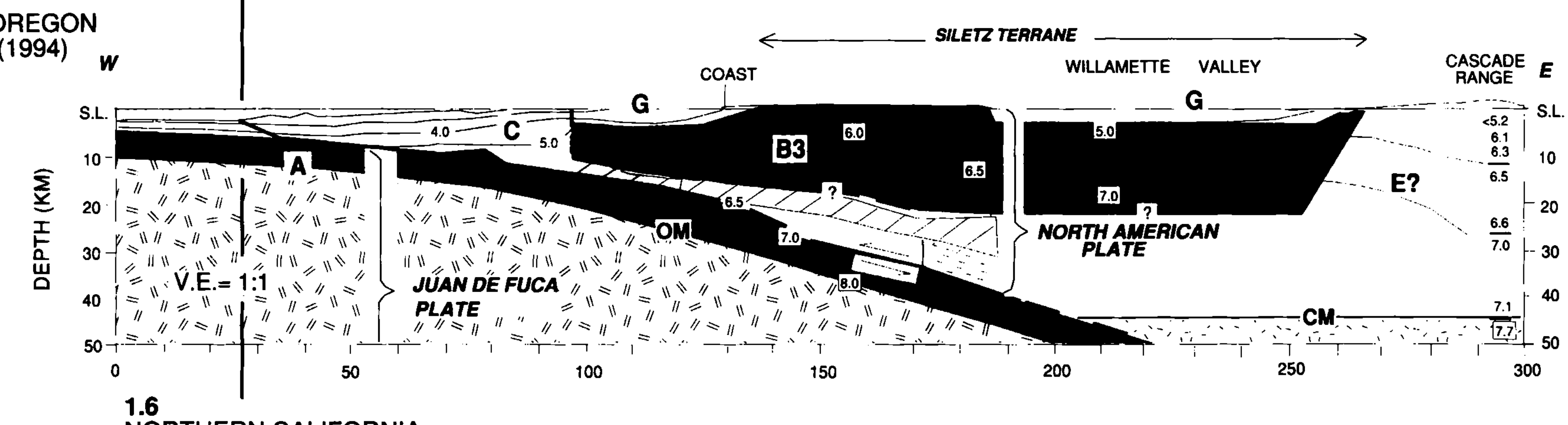
1.3
GULF OF ALASKA
Fuis et al. (1991),
Brocher et al. (1994)



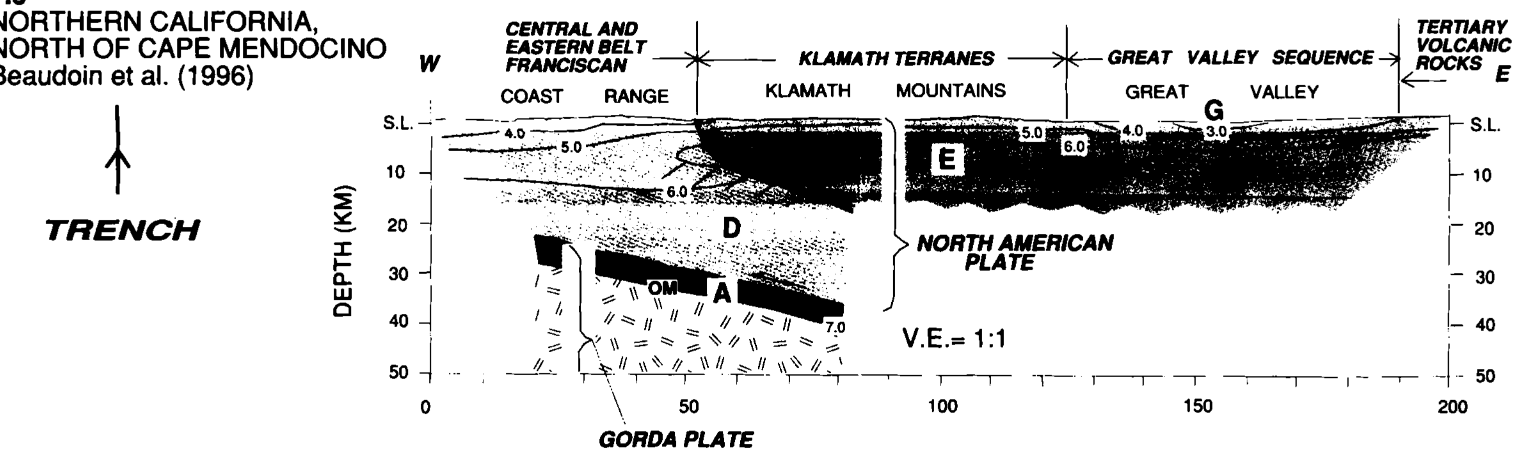
1.4
SOUTHERN VANCOUVER ISLAND, B.C.
Clowes et al. (1987, 1995, 1997),
Hyndman et al. (1990),
Fuis and Clowes (1993)



1.5
CENTRAL OREGON
Trehu et al. (1994)



1.6
NORTHERN CALIFORNIA,
NORTH OF CAPE MENDOCINO
Beaudoin et al. (1996)



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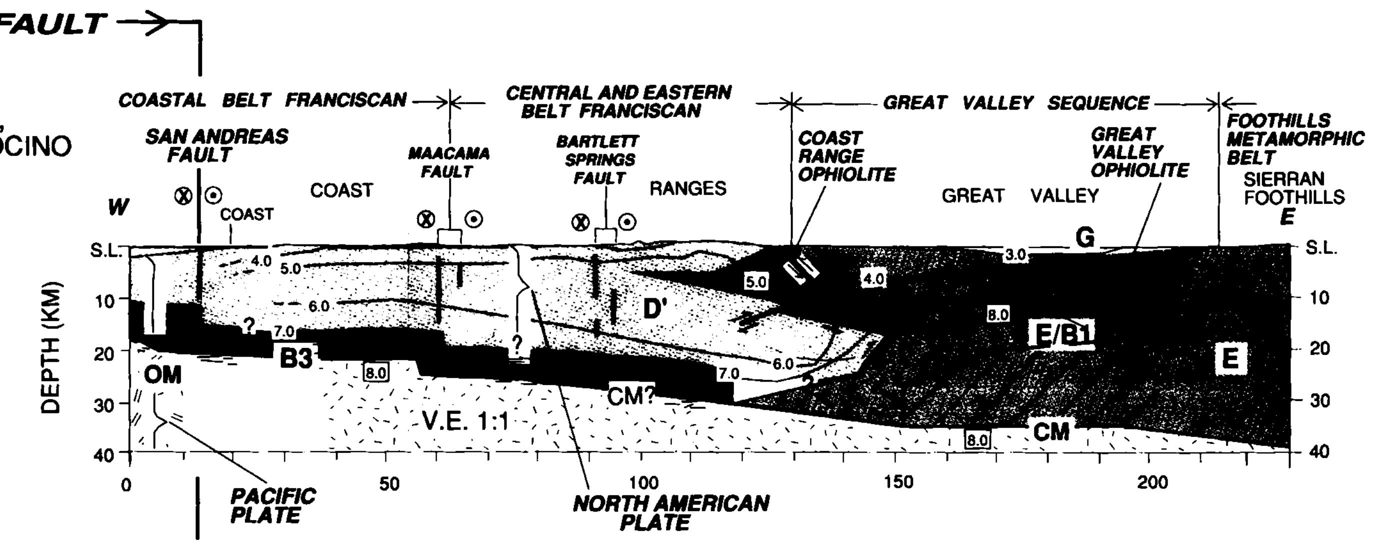
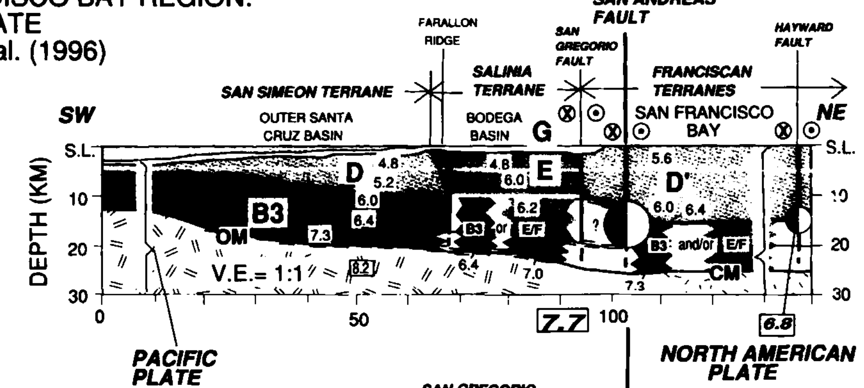
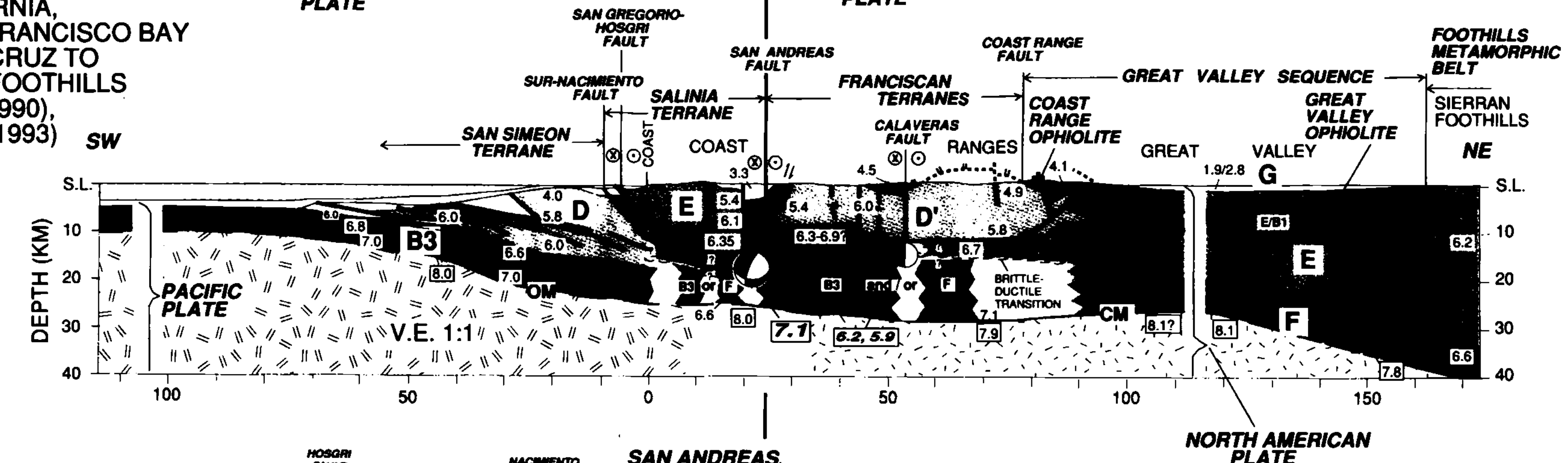
1.7
NORTHERN CALIFORNIA,
SOUTH OF CAPE MENDOCINO
Beaudoin et al. (1996),
Henstock et al. (1996),
Godfrey et al. (1997)



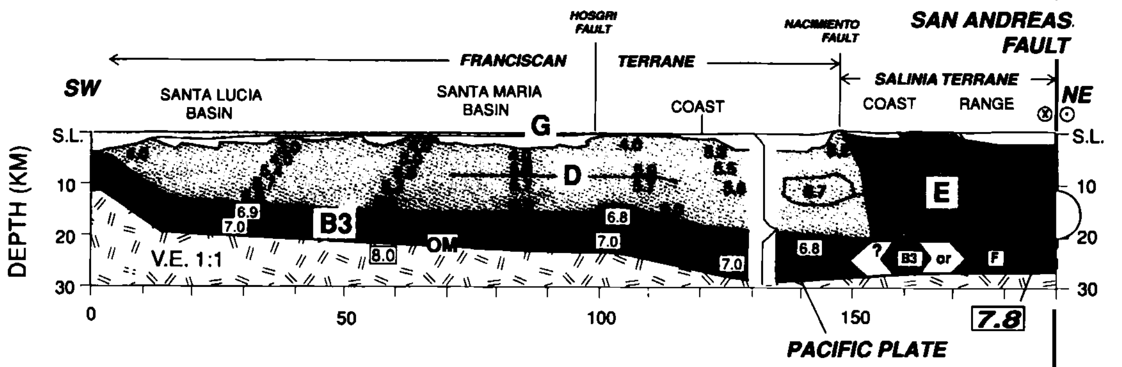
1.8
CENTRAL CALIFORNIA,
SAN FRANCISCO BAY REGION:
GOLDEN GATE
Holbrook et al. (1996)



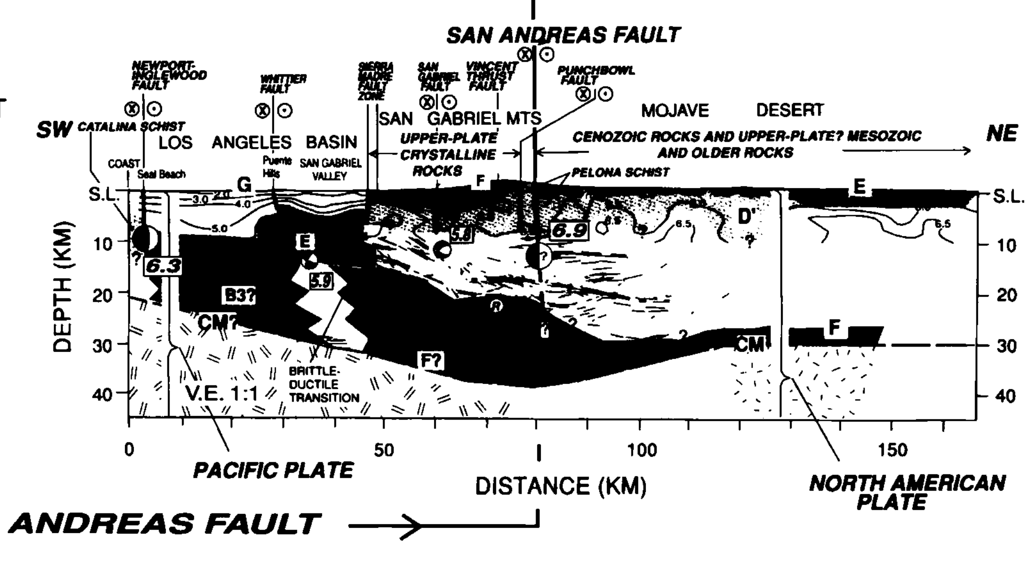
1.9
CENTRAL CALIFORNIA,
SOUTHERN SAN FRANCISCO BAY
REGION: SANTA CRUZ TO
SIERRA NEVADA FOOTHILLS
Fuis and Mooney (1990),
Page and Brocher (1993)



1.10
CENTRAL CALIFORNIA,
SAN LUIS OBISPO
Miller et al. (1992),
Howie et al. (1993)



1.11
SOUTHERN CALIFORNIA,
LOS ANGELES REGION:
SEAL BEACH TO MOJAVE DESERT
Fuis et al. (1996)
Ryberg and Fuis (1998)



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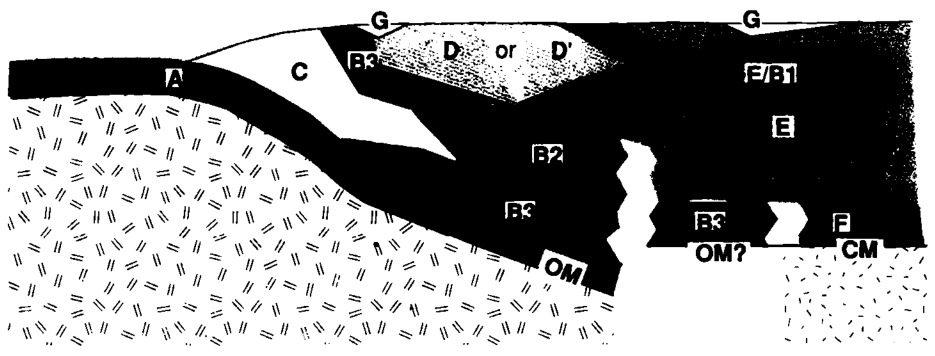
1.2 EXPLANATION

TECTONIC ELEMENT DIAGRAM

- A — Actively subducting oceanic crust; lighter color, relatively lower velocity within individual diagrams.
- Oceanic mantle. "OM", oceanic Moho.
- B1 — Accreted oceanic/arc (or oceanic-like) lithosphere.
  1) B1 with "+" overprint is magnetic rocks interpreted as ophiolite and/or arc rocks of Mesozoic age accreted in the Mesozoic. B1 with "/" overprint is interpreted as mantle rocks accreted in the Mesozoic. Modeled boundaries are approximately shown in some cases by dark gray lines.
- B2 — 2) B2 is interpreted as Mesozoic rocks accreted in late Mesozoic or early Cenozoic. Lighter color is relatively lower velocity within individual diagrams.
- B3 — 3) B3 is interpreted as Cenozoic rocks accreted in the Cenozoic. Lighter color is relatively lower velocity within individual diagrams.
- C — Cenozoic accretionary prism: sedimentary, volcanic, and metamorphic rocks.
- D or D' — Mesozoic accretionary prism: sedimentary, volcanic, and metamorphic rocks. D', tectonic wedge configuration; dark color with "+" overprint, ophiolite and/or arc rocks.
- E — Backstop to Mesozoic prism; see B1 for definition of overprinted "+" and "/".
- F — Lower crust undivided.
- Continental mantle. "CM", continental Moho.
- G — Other Cenozoic rocks.



SYMBOLS

- Contact; dashed where location uncertain by more than ~2 km.
- Fault; dashed where existence uncertain or location uncertain by more than ~2 km. Double barb on hanging wall of normal fault. Circled x and dot indicate motion away from and toward viewer, respectively, on strike-slip fault. Arrows indicate relative motion on thrust faults.
- 5.0 — Contour of seismic velocity (numbers in km/s).
- 5.8 / 6.7 — Velocities (km/s) above and below a velocity step; dashed at change of velocity gradient.
- 7.9 — Mantle velocity.
- /// — Region of velocity or density reversal with depth.
- Vertical-incidence reflections; wide-angle reflections in Pl. 1.8.
- Brittle-ductile transition (based on seismicity); shown in Pl. 1.9, 1.11.
- 5.8 — Historical earthquake projected onto cross section. Magnitude given in box. For great earthquakes, Mw is given; for others, intensity, local, or surface-wave magnitude. Beachball approximately proportional to magnitude. View is far hemisphere; compressional hemisphere darkened. Earthquake parameters taken from:

Alaska: Stauder and Bollinger (1972)
Golden Gate: Ellsworth (1990)
Santa Cruz: Reasenberg and Ellsworth (1982); Oppenheimer et al. (1988); and Oppenheimer (1990)
San Luis Obispo: Ellsworth (1990)
Los Angeles: Hauksson (1987); Hauksson et al. (1988); Ellsworth (1990); Hauksson (1994).

1.1 INDEX MAP FOR TRANSECTS

Transects labeled by plate numbers. Base map modified from Drummond (1981).

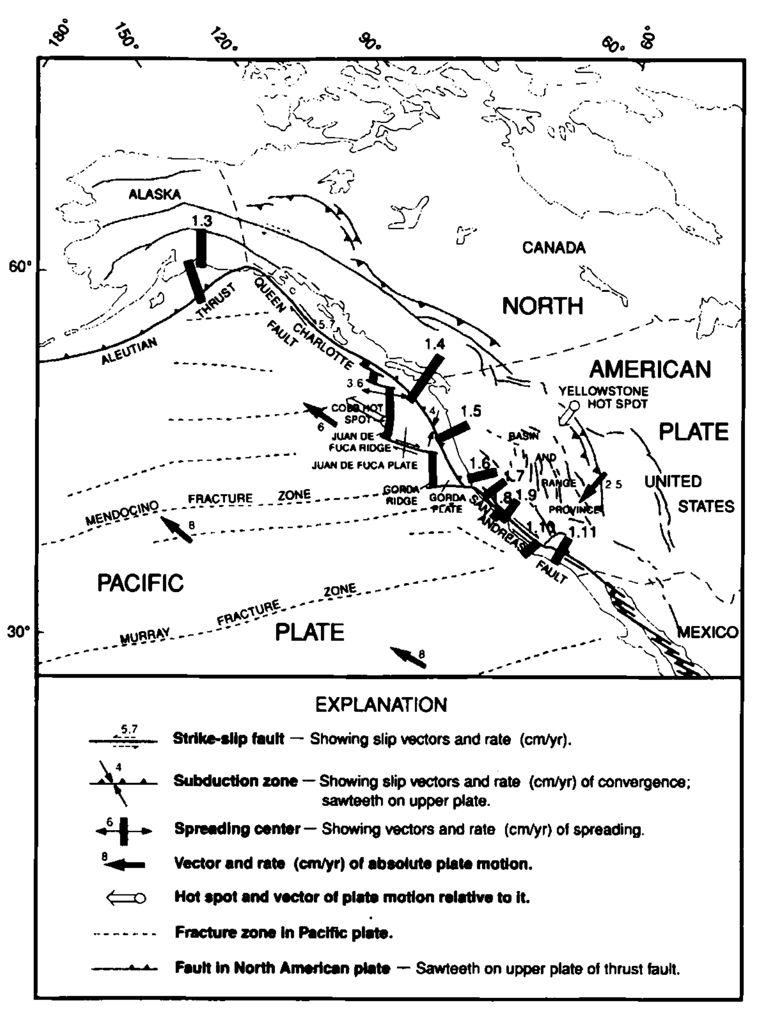


Plate 1. Transects of the west margin of North America.

(D'), is not entirely clear, although the two are likely to be parts of the same oceanic lithosphere brought together by wedging.

Possible interpretations of layer B3 on the southern transect include tectonically underthrust Pacific plate (mid-Cenozoic in age), magmatically underplated basaltic rock above a 'slabless' asthenospheric window (late Cenozoic to Holocene in age), or fragments of the receding Gorda plate (late Cenozoic in age). The first interpretation conforms to the model of Bohannon and Parsons (1995); the second, to the model of Furlong (1984) and Furlong et al. (1989); and the third, to no well-established model at all. Offsets in layer B3 below the San Andreas fault (Henstock et al., 1996) and the Maacama fault (Beaudoin et al., 1996; Henstock et al., 1996) suggest that the top of the layer is not a current plate boundary and argues against the model of Bohannon and Parsons (1995). If layer B3 is late Cenozoic to Holocene magmatically underplated rocks, it is also difficult (but not impossible) to understand offsets along the modern strike-slip faults, casting some doubt on the model of Furlong (1984) and Furlong et al. (1989). In summary, the interpretation of layer B3 remains controversial. (See also discussion in Hole and Beaudoin, 1996.) A final note on the offsets of layer B3: at both the San Andreas and Maacama faults, the offsets of the upper surface of the layer are east by 5–8 km from the offsets (or deflections) of the base of the layer, suggesting that these faults either acquire an abrupt westward dip or change into folds at the base of the crust.

2.5. *San Francisco Bay region of central California (Plate I, 1.8 and 1.9)*

In the upper crust west of the San Andreas fault, the Mesozoic/early Cenozoic subduction-zone rock belts of central California, consisting of accretionary-prism rocks, forearc rocks, and arc rocks, have been shuffled by strike-slip faulting. Accretionary prism rocks (D; San Simeon terrane, a Franciscan assemblage) are juxtaposed directly against arc rocks (E; Salinia terrane) along the Sur-Nacimiento fault (or its equivalent offshore of the Golden Gate); forearc rocks are essentially missing. In the lower crust, an oceanic-crust-like layer (B3; 6.0–7.3 km/s; 5–11 km thick) dips landward from the base of the continental slope to the San Andreas fault; however, the continuity of this layer beneath the Salinia terrane is uncertain in both the northern and southern parts of the Bay region. This lower-crustal layer corresponds to Pacific-plate crust where it is exposed west of the continental slope, but beneath the continental shelf, it may be interpreted as underthrust Pacific-plate crust (Page and Brocher, 1993), a stalled, subducted remnant of Farallon-plate crust, or, in part, magmatically underplated rock from a subducted Pacific/Farallon ridge (Bohannon and Parsons, 1995; note that a segment of the extinct Pacific/Farallon ridge projects beneath the Bay region, as shown in Atwater, 1989). In all of these cases, this lower-crustal layer is mid-Cenozoic in age (20–30 Ma).

In the upper crust east of the San Andreas fault, the Mesozoic prism (D') overlies lower crust (B3 and/or E/F) with a velocity of 6.4–7.3 km/s and a thickness of 10 km in the northern part of the Bay region to nearly 20 km in the southern part of the Bay region. In an interpretation by Wentworth et al. (1984), the Mesozoic prism is a tectonic wedge that indents a backstop (E/B1) consisting of the Great Valley sequence and the Great Valley ophiolite. The tip of the wedge follows chiefly the boundary between these units, peeling up the Great Valley sedimentary rocks and overriding the ophiolitic basement. This tectonic wedge is similar to that interpreted in southern Alaska by Fuis et al. (1991; Plate I, 1.3), and less complex than that interpreted in northern California by Godfrey et al. (1997; Plate I, 1.7). Fuis and Mooney (1990) and Jachens et al. (1995) have argued that mid-crustal rocks in the Coast Ranges east of the San Andreas fault are ophiolite/arc basement (E/B1) similar to that beneath the Great Valley that is being overridden by the tectonic wedge (D'). Furlong (1984) and Furlong et al. (1989) have argued that in the wake of the passage of the Mendocino triple junction (about 10 Ma in the San Francisco Bay region), magmatic underplating should occur in the mid- or lower crust above a postulated 'slabless' asthenospheric window east of the San Andreas fault; therefore, the lower-crustal layer may be also in part magmatically underplated basaltic rock (B3). In the Golden Gate transect (Plate I, 1.8), it is noteworthy that the deflection in the top of layer B3 at the San Andreas fault is

Table 1

Tectonic element:	Actively subducting oceanic crust	Accreted oceanic/arc (or oceanic-like) lithosphere			Cenozoic accretionary prism	Mesozoic accretionary prism	Backstop to Mesozoic prism	Lower crust undivided	Other Cenozoic rocks	References
		Accreted in Mesozoic	Accreted in late Mesozoic or early Cenozoic	Accreted in Cenozoic						
Label:	A	B1	B2	B3	C	D, D′ if wedge-like	E	F	G	
TRANSECT										
Gulf of Alaska/ southern Alaska	Pacific oceanic crust and lower crust of Yakutat terrane	Peninsular terrane (magnetic, inter-mediate-velocity rocks)	Interpreted fragments of Kula plate: metabasalt where exposed; velocities of 5.6–7.7 at depth	None	Prince William terrane	Chugach terrane and Border Ranges ultramafic–mafic complex (BRUMA; D′)	Peninsular and Wrangellia terranes, including Jurassic and Cretaceous plutons and Mesozoic sedimentary rocks of Copper River basin	Velocities 6.3?–6.9 km/s; maximum crustal thickness 57 km beneath Copper River basin	Cenozoic sedimentary rocks of Copper River basin	Fuis et al. (1991), Brocher et al. (1994)
Southern Vancouver Island, B.C.	Juan de Fuca plate crust	None (although Wrangellia terrane is similar to Peninsular terrane of Alaska)	Possible fragments of Kula plate, as in Alaska; velocity 6.3–7.1 km/s	Crescent terrane and unnamed, tectonically underplated basaltic (?) rocks; Crescent terrane similar to lower crust of Yakutat terrane, Alaska (A)	Olympic Core Rocks, Ozette and Hoh (melange) terranes	Pacific Rim terrane (D)	Wrangellia terrane, West coast plutonic complex, Coast plutonic complex, and Nanaimo sediments (in Georgia Strait)	None defined; in interpretation shown, lower crust near Georgia Strait is tectonically underplated oceanic crust (B2 and B3); crustal thickness here is uncertain: 37 km or greater	Cenozoic sedimentary rocks on the continental shelf and Pacific Ocean basin	Clowes et al. (1987, 1995, 1997), Hyndman et al. (1990), Fuis and Clowes (1993)
Central Oregon	Juan de Fuca plate crust	None	None	Siletz terrane; correlative with Crescent terrane, Vancouver Island	Unnamed Cenozoic sedimentary rocks west of Siletz terrane	None, or buried	Crust of the Cascade Range	None defined; lower crust may or may not be Siletz terrane	Sedimentary rocks on Siletz terrane, including those of continental shelf and Willamette Valley	Trehu et al. (1994)
Northern California, north of Cape Mendocino	Gorda plate crust	None	None	None	None in part of section shown, but present to west	Franciscan terranes (D)	Klamath terranes and Great Valley sequence	None defined	Cenozoic sedimentary rocks of Great Valley	Beaudoin et al. (1996)

Northern California, south of Cape Mendocino	None	Great Valley ophiolite (magnetic, dense, intermediate- to mantle-velocity rocks)	None	Layer at base of crust with intermediate to high velocity, oceanic crustal thickness, and patches of high reflectivity	None in part of section shown	Franciscan terranes, Coast Range ophiolite and deformed rocks of western Great Valley sequence (D′)	Sierra Foothills metamorphic belt, Great Valley ophiolite, and Great Valley sequence	None defined; crustal thickness is 33–35 km beneath Great Valley	Cenozoic sedimentary rocks of Great Valley	Beaudoin et al. (1996), Henstock et al. (1996), Godfrey et al. (1997)
Central California, San Francisco Bay region: Golden Gate	None	None in part of section shown; Great Valley ophiolite to east	None	Layer at base of crust with intermediate to high velocity and thickness of 7–11 km; can be traced seaward to Pacific oceanic crust	None	Franciscan terranes (D′)	West of San Andreas fault (SAF), Salinia terrane; east of SAF, similar to transect above; note: extent of E (and F) vs. B3 beneath Salinia and Franciscan terranes uncertain	Velocity ~7.0 km/s; see note under E	Cenozoic sedimentary rocks and continental shelf and slope	Holbrook et al. (1996)
Central California, southern San Francisco Bay region: Santa Cruz to Modesto	None	Great Valley ophiolite (magnetic, dense, intermediate- to high-velocity rocks)	None	Layer at base of crust with intermediate to high velocity and thickness of 5–18? km; can be traced seaward to Pacific oceanic crust	Small bodies of unnamed Cenozoic sedimentary rocks interfaulted with Franciscan assemblage	Franciscan terranes, Coast Range ophiolite, and deformed rocks of western Great Valley sequence (D′)	See above	Velocity ~7.0 km/s in most places; see note under E; crustal thickness is 26–35? km beneath Great Valley	Cenozoic sedimentary rocks of the continental slope, continental shelf, Salinia terrane and Great Valley	Fuis and Mooney (1990), Page and Brocher (1993)
Central California, San Luis Obispo	None	None in part of section shown; possibly present beneath Great Valley to east	None	Layer at base of crust with intermediate to high velocity and thickness of 6–9 km; can be traced seaward to Pacific oceanic crust	None	Franciscan terranes	See above	Velocity undetermined; see note under E	Cenozoic sedimentary rocks on continental shelf, including Santa Maria and Santa Lucia basins	Miller et al. (1992), Howie et al. (1993)
Southern California, Los Angeles region: Seal Beach to Mojave Desert	None	None	None	Possible existence beneath Los Angeles basin	None	Pelona Schist in San Gabriel Mountains and Mojave Desert; Catalina Schist in western Los Angeles basin and offshore	Mesozoic and older rocks of Peninsular Ranges and Mojave Desert	Mid- and lower-crustal rocks of the San Gabriel Mountains above the Vincent Thrust fault; rocks of unknown affinity beneath the San Gabriel bright reflective layer (feature R)	Cenozoic rocks of the Los Angeles basin and San Gabriel Valley	Fuis et al. (1996), Ryberg and Fuis (1998)

east of a corresponding deflection in the base of this layer, similar to the case in the transect to the north (Plate I, 1.7).

2.6. *San Luis Obispo region of central California (Plate I, 1.10)*

Structure west of the San Andreas fault is quite similar to that in the San Francisco Bay region: the Mesozoic prism (D; Franciscan terrane) is juxtaposed directly against the backstop (E; Salinia terrane) with no intervening forearc rocks. Beneath the Mesozoic prism, an oceanic-crust-like layer (B3; 6.8–7.0 km/s; 6–9 km thick) is observed in the lower crust. Where it is exposed on the sea floor west of the continental slope, it is Pacific oceanic crust; east of the continental slope, it is interpreted to be tectonically underplated oceanic crust of the Pacific and Monterey plates (the latter is a remnant of the Farallon plate; Atwater, 1989). The monocline at the continental slope is interpreted to have been created by folding (Miller et al., 1992) or strike-slip faulting (Howie et al., 1993) from 22 to 16 Ma, following the subduction of the Pacific/Arguello ridge. The region of thickened crust near the Hosgri fault is interpreted to be a region of convergence between the Monterey and Pacific plates, along a fracture zone. Sedimentation in offshore basins (Santa Maria and Santa Lucia basins) occurred during the same approximate time interval as folding/strike-slip faulting and imbrication in the oceanic-crustal layer. Thus, transtensional and transpressional regimes occurred in different parts of the crust at the same time or at closely successive times. If these regimes occurred at the same time, they were presumably separated by a crustal decollement (Miller et al., 1992).

2.7. *Los Angeles region of southern California (Plate I, 1.11)*

Tectonic elements in the Los Angeles region are somewhat differently configured from those in transects to the north. The Mesozoic prism (D′, Pelona Schist) is overlain by crystalline upper-plate rocks on both sides of the San Andreas fault. In the Mojave Desert, these are mid-crustal 'backstop' rocks (E); in the San Gabriel Mountains, they are mid- and lower-crustal rocks (F). It is not clear yet how extensive the Pelona Schist is beneath the Mojave Desert (Haxel and Dillon, 1978; Nourse, 1989), or how deeply it extends into the crust. Both upper- and lower-plate rocks of the San Gabriel Mountains may be juxtaposed against basement rocks of the Peninsular Ranges (E; plutonic and metamorphic arc rocks) along a steeply south-dipping(?) branch of the Sierra Madre fault system (Fuis et al., 1996). This relationship is somewhat surprising because most of the strands of the Sierra Madre fault system are moderately north-dipping reverse faults (Crook et al., 1987). In the mid-crust of the San Gabriel Mountains, a gently north-dipping, downward-stepping bright reflective zone ('R', Plate I, 1.11) is interpreted as a regional thrust fault, possibly a 'master' decollement (Ryberg and Fuis, 1998). One branch of this interpreted fault system projects to the hypocenter of the 1987 *M* 5.9 Whittier Narrows earthquake, which occurred on a blind thrust fault in the Los Angeles basin (Hauksson et al., 1988). In unmigrated data, this zone appears to be deflected and to change character at the San Andreas fault. Velocities for the rocks below this bright reflective zone have not yet been determined, but may be lower-crustal rocks similar to those of the Peninsular Ranges (F). The Moho is drawn at the base of reflectivity and is similar to that of Hafner and Clayton (1996; Mojave Desert and San Gabriel Mountains), ten Brink et al. (1996; offshore Continental Borderland), and Kohler and Davis (1997; San Gabriel Mountains and Los Angeles basin). In migrated data, maximum Moho depth is 37–38 km (vs. 40 km in Plate I, 1.11).

3. Discussion and conclusions

This study compares four subduction-zone and five transform-fault transects. The subduction-zone transects all contain actively subducting oceanic crust (A) and Cenozoic accretionary-prism rocks (C). (Note that in the northern California transect north of Cape Mendocino (Plate I, 1.6), such Cenozoic rocks do exist west of the part of the section shown; see Gulick et al., 1996). The Vancouver Island and Oregon transects (Plate I, 1.4 and 1.5) also contain an accreted basaltic terrane, the Crescent/Siletz terrane (B3), which may represent the remnants of a Paleocene/Eocene oceanic plateau (see discussion in Wells et al., 1984). The thickest remnant of this plateau was accreted in Oregon, and a thinner remnant was accreted at Vancouver Island. Rocks approximately correlative in age with this plateau, the lower crust of the Yakutat terrane, are currently subducting in southern Alaska (Plate I, 1.3), doubled up on top of Pacific oceanic crust. These rocks may eventually be accreted like the B3 bodies at Vancouver Island and Oregon.

Three of the subduction-zone transects contain prisms (D, D′) that record Mesozoic subduction. The Alaskan and Vancouver Island transects also contain a body of oceanic lithosphere that was tectonically underplated in the latest Mesozoic or early Cenozoic (B2). At least in Alaska, this body is interpretable as fragments of the Kula plate. Underplating of fragments of this plate likely occurred as a result of both its young age and its fast convergence rate with the North American plate (see discussion in Fuis and Plafker, 1991). The southeastern boundary of the Kula plate is poorly known from plate reconstructions, ranging in possible location from Vancouver Island to Mexico (see Atwater, 1989). Perhaps the occurrence of interpretable fragments of this body from Vancouver Island to Alaska suggests that Vancouver Island was the southeasternmost limit.

In southern Alaska, the Mesozoic prism (D′) is interpreted to have moved landward into the backstop (E) as a tectonic wedge, whereas at Vancouver Island and in northern California, the Mesozoic prism (D) is interpreted to be emplaced beneath the backstop by simple underthrusting and/or strike-slip faulting. Modeling of the subduction process indicates that wedge-type tectonics is expected in compressional regimes (e.g., Beaumont and Quinlan, 1994), suggesting that where wedge tectonics is not observed, a compressional regime may not have obtained during subduction. In such cases, strike-slip faulting may have dominated.

Exceptionally thick crust (F, 57 km) is observed in southern Alaska, just landward of the thick underplated body B2. Similarly, exceptionally thick crust (more than 60 km) is interpreted landward of body B2 on Vancouver Island in the western Coast Mountains.

In the upper crust, most of the five transform-fault transects reflect: (1) tectonic wedging of the Mesozoic accretionary prism (D′) into the backstop, which includes Mesozoic/early Cenozoic forearc rocks (E) and Mesozoic ophiolite/arc basement rocks (E/B1); and (2) shuffling of the subduction margin of California by strike-slip faulting. In the lower crust, these transects may reflect migration of the Mendocino triple junction northward (seen in rocks east of the San Andreas fault) and cessation of Farallon-plate subduction (seen in rocks west of the San Andreas fault).

In regions east of the San Andreas fault in northern and central California (e.g., Plate I, 1.7 and 1.9), the upper-crustal Mesozoic prism is interpreted as a tectonic wedge (D′) that moved eastward into the backstop, 'peeling up' the forearc sedimentary rocks (Wentworth et al., 1984; Fuis and Mooney, 1990). This interpreted tectonic wedge is similar to that in Alaska (Plate I, 1.3). From seismic and magnetic data on the Santa Cruz transect (Plate I, 1.9), the backstop/ophiolite rocks (E/B1) are interpreted to extend westward beneath the wedge at least as far as the Calaveras fault system and possibly as far as the San Andreas fault (Fuis and Mooney, 1990; Jachens et al., 1995). Beneath the San Francisco Bay area (Plate I, 1.8 and 1.9), the mid- and lower crust may be Cenozoic basaltic rocks (B3) and/or Mesozoic backstop/ophiolite rocks and lower crust (E/B1 and F).

As discussed above, Cenozoic basaltic rocks (B3) are expected to form by magmatic underplating above a 'slabless' window east of the San Andreas fault in the wake of northward movement of the Mendocino triple junction (Furlong, 1984; Furlong et al., 1989). Thus, the B3 rocks beneath the San Francisco Bay region (Plate I, 1.8 and 1.9) and beneath the Coast Ranges of northern California (Plate I, 1.7) may have originated by magmatic underplating. Alternatively, at least in Plate I, 1.7 and 1.8, they may be Farallon-plate rocks now attached to and moving with the Pacific plate (Bohannon and Parsons, 1995), although the fault offsets in these rocks argue against this model. Finally, they could be partly subducted, stalled Farallon/Gorda plate; however, none of this plate is supposed to be present in the wake of the migration of the Mendocino triple junction. As discussed by Hole and Beaudoin (1996), the interpretation of these rocks remains problematical.

In regions west of the San Andreas fault on transects through the Golden Gate (Plate I, 1.8), Santa

Cruz (Plate I, 1.9), and San Luis Obispo (Plate I, 1.10), the effects of strike-slip shuffling of terranes is seen in the upper crust. The effects of stalled subduction of the Farallon plate are possibly seen in the lower crust. In the upper crust, plutonic and metamorphic arc rocks (E; Salinia terrane) are juxtaposed directly against accretionary-prism rocks (D) along the Sur-Nacimiento fault and its equivalents, with essentially no intervening forearc rocks. In the lower crust, an oceanic-crust-like layer (B3) is seen, which may or may not extend beneath the Salinia terrane. This layer is clearly Pacific oceanic crust west of the abandoned trench (at the base of the slope), but beneath the continent may be either tectonically or magmatically underplated basaltic rocks: possibly underthrust Pacific crust (Page and Brocher, 1993), partly subducted, stalled Farallon plate, or basaltic rocks that were magmatically underplated during subduction of the Pacific/Farallon ridge or during breakup of the subducted Farallon plate (Bohannon and Parsons, 1995).

In southern California, crustal structure is 3-dimensional, and the transect shown (Plate I, 1.11) is only partly representative. The configuration of tectonic elements differs somewhat from transects to the north. The Mesozoic prism (D′; Pelona Schist) has been thrust beneath Mesozoic rocks in parts (perhaps all) of the Mojave Desert (E; Haxel and Dillon, 1978; Nourse, 1989) and beneath mid- and lower-crustal rocks in the San Gabriel Mountains (F; Ehlig, 1981), and may be configured as a tectonic wedge. At the south edge of the San Gabriel Mountains, the upper- and lower-plate rocks (D′ and F) may be faulted against rocks of the southern California batholith (E; Sorensen, 1984), although this relationship is covered by Cenozoic sedimentary rocks of the San Gabriel Valley (G; Fuis et al., 1996). Basaltic(?) rocks (B3; see Fuis et al., 1996) may or may not intervene between these batholithic rocks and the Mesozoic prism rocks of the California Continental Borderland (D; Catalina Schist; Sorensen, 1984; Crouch and Suppe, 1993). An interpreted mid-crustal decollement beneath the San Gabriel Mountains apparently connects the San Andreas fault with the fold-and-thrust belt south of the San Gabriel Mountains (Ryberg and Fuis, 1998). The affinity of rocks beneath the interpreted decollement is as yet unknown. A depression on the Moho beneath the San Gabriel Mountains is consistent with downwelling of lithospheric mantle beneath the Transverse Ranges as described, for example, by Humphreys and Clayton (1990). This downwelling is interpreted to drive the observed compression across the Transverse Ranges and Los Angeles basin (Humphreys and Hager, 1990).

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