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ANALYSIS OF CENOZOIC SUBSIDENCE AT THREE SITES IN VICINITY OF THE SEATTLE BASIN, WASHINGTON

by

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INTRODUCTION

The Puget Lowland region of Washington has experienced a complex history of Cenozoic tectonism (for example, Johnson, 1984, 1985; Johnson and Yount, 1992). This history is at present poorly understood, largely because most important geologic features and units are either submerged beneath Puget Sound or are covered by a thick mantle of Quaternary deposits and(or) vegetation. Reconstructions of the Cenozoic history of this region are critical to understanding regional seismic hazards and the distribution of energy resources. As part of an effort to develop these reconstructions, data from outcrops, a petroleum industry borehole, and seismic reflection profiles are here combined to reconstruct Cenozoic subsidence at three locations in the vicinity of the Seattle basin: (1) the Mobil Kingston #1 borehole; (2) the western part of the Seattle basin; and (3) the Tiger Mountain-Newport Hills area (fig. 1). The constraints and uncertainties for each of the three subsidence reconstructions are also described, however significant discussion and interpretation awaits future publication.

SUBSIDENCE ANALYSIS

The purpose of subsidence reconstructions (geohistory diagrams of Van Hinte, 1978) is to graphically represent the vertical movement of the basement or lowest known stratigraphic unit through time. Model input consists of the age, thickness, lithology, and paleobathymetry of designated stratigraphic units. Model output consists of plots that show (1) total subsidence corrected for compaction, and (2) subsidence corrected for the load induced by the weight of sediment through time, also known as "tectonic subsidence."

As with all models, the quality and utility of the output is dependent on the accuracy of the input parameters. The input parameters used in this study for the three locations are summarized in Table 1, and the rationale and uncertainties for each parameter are discussed in the following text. Stratigraphic units are designated and their thicknesses and lithologies determined based on information from outcrops, petroleum boreholes, and seismic reflection profiles. The ages of units used in the analyses are based on stratigraphic position, paleontologic studies of foraminifera conducted by Weldon Rau (written commun., 1992, 1993) and to a lesser extent by isotopic dates. W. Rau is presently preparing a USGS stratigraphic chart that document the paleontology of strata penetrated in about 24 petroleum boreholes from western Washington and northwestern Oregon, and data from the Mobil Kingston #1 borehole cited in this report are part of that effort. Ages were assigned to foraminiferal stages following Armentrout and others (1983a), Prothero and Armentrout (1985), Almgren and others (1988), and Niem and Niem (1992).

Probably the greatest uncertainties in the subsidence reconstructions are introduced by estimates of paleobathymetry in units deposited in deep-marine environments. In this study, these estimates were based on the inferred paleoecology of benthic foraminifera, determined Weldon Rau (written commun., 1992, 1993) and to a lesser extent by me, mainly through comparison to biofacies lists generated by Ingle (1980). These lists designate biofacies by depth: inner shelf - 0 to 50 m; outer shelf - 50 to 150 m; upper bathyal - 150 to 500 m; upper middle bathyal - 500 to 1,500 m; lower middle bathyal - 1,500 to 2,500 m; lower bathyal - > 2,000 m. Most foraminiferal assemblages contain species characteristic of more than one biofacies. Where this occurs, the deepest biofacies or a range of biofacies was assigned to the assemblage based on the premise that benthic foraminiferal tests can more readily be transported downslope into deeper water than upslope into shallower water. Because of the significant range in paleobathymetric estimates (Table 1), separate plots were made for each location using maximum and minimum paleobathymetric estimates.

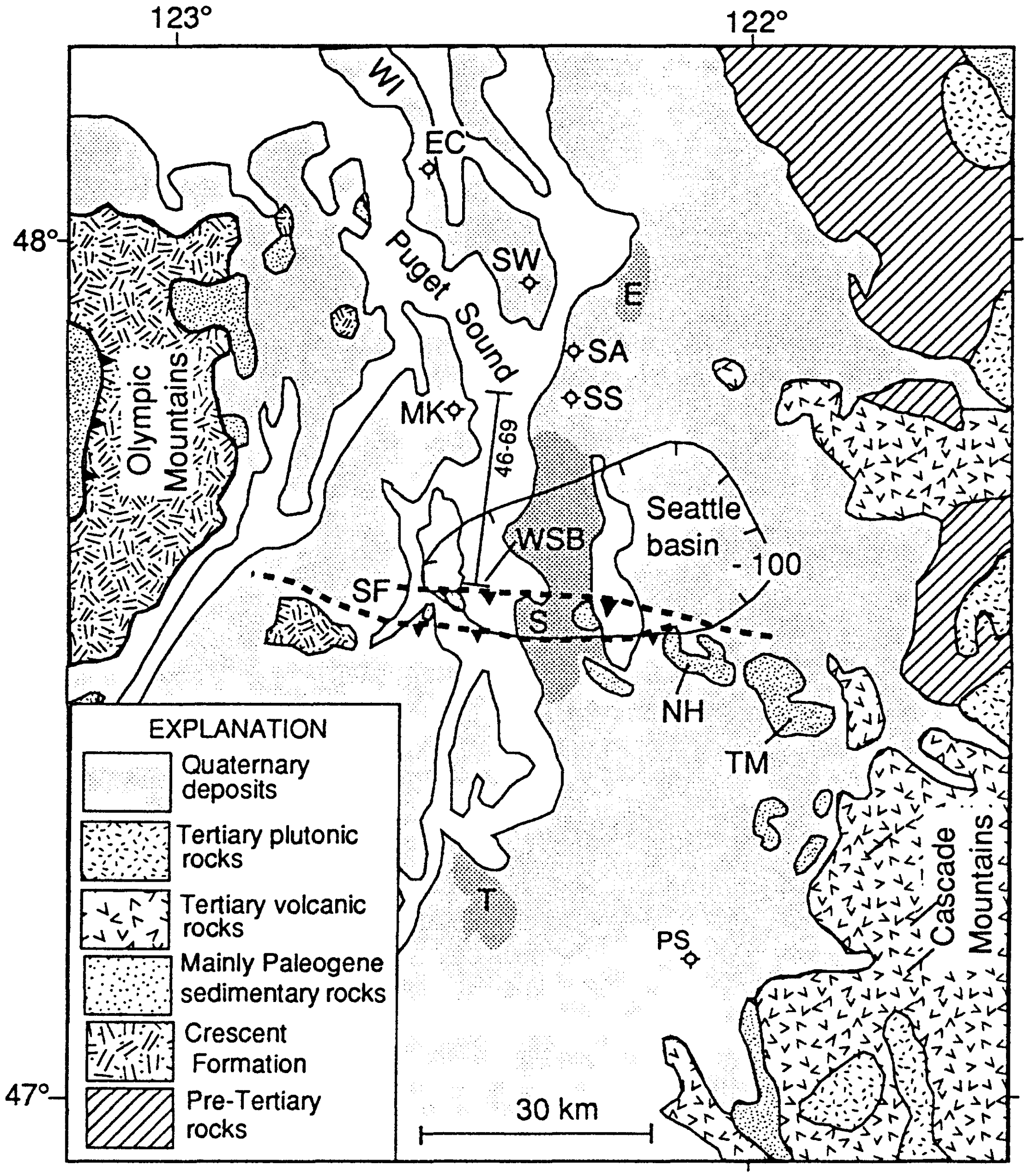

Figure 1. Map showing the central Puget Lowland and Puget Sound. Seattle basin is area enclosed by -100 milligal gravity contour. Line of seismic profile interpreted in Figure 4 is labelled 46-69. Subsidence reconstructions are for strata in the Tiger Mountain (TM)-Newport Hills (NH) area, the Mobil Kingston #1 borehole (MK), and the western part of the Seattle basin (WSB). Other abbreviations as follows: E = Everett; EC = Engstrom Community #1 borehole; MK = Mobil Kingston #1 borehole; PS = Phillips State #1 borehole; S = Seattle; SA = Standard Alderwood #1 borehole; SF = Seattle fault; SS - Socal-Schroeder #1 borehole; SW = Socal-Whidbey #1 borehole; T = Tacoma; WI = Whidbey Island.

SUBSIDENCE RECONSTRUCTIONS

Tiger Mountain -Newport Hills area

The Tiger Mountain-Newport Hills area (fig. 1) occupies a position on the southeast flank of the Seattle basin, south of the inferred eastern extent of the Seattle fault. The information from this area comes largely from outcrop studies, and is based on a composite section of Cenozoic sedimentary rocks pieced together from stratigraphic sections and geologic cross sections of Vine (1969) and Yount and Gower (1991). The oldest rocks in the section are best exposed to the east on Tiger Mountain, whereas younger rocks are best exposed to the west in the Newport Hills. In compiling the composite section, I assumed that the older rocks described at Tiger Mountain continue westward and underlie the Newport Hills. The stratigraphic information described below is summarized in Table 1, and the subsidence models are shown in Figure 2.

The Raging River Formation (Vine, 1962, 1969; Johnson, 1992) is the lowest stratigraphic unit exposed at Tiger Mountain. The lower part of the Raging River Formation (units 1 and 2 of Johnson, 1992) has an outcrop thickness of about 515 m, however cross sections (Vine, 1969) indicate this part of the unit has a minimum thickness of 700 m, the value used in subsidence models. Basement to the Raging River Formation is not exposed, nor has it been penetrated by borehole. The lower part of the Raging River Formation consists mainly of sandstone and siltstone and was deposited in nonmarine to shallow marine environments (Johnson, 1992). The upper part of the Raging River Formation (unit 3 of Johnson, 1992), 300 m thick, is more fine-grained. On the basis of sedimentologic and paleontologic data, Johnson (1992) concluded the upper Raging River Formation was deposited in a bathyal slope setting. Based on foraminifera, the upper Raging River Formation has an early Narizian age. The base of the Narizian is now placed at approximately 48.7 Ma (Almgren and others, 1988). For the subsidence models, the upper Raging River was assigned an age of 49 to 47 Ma in order to allow sufficient time for the overlying Tiger Mountain Formation to accumulate prior to deposition of the isotopically dated Tukwila Formation. Assigning an age to the lower (early Narizian or older) part of the Raging River Formation is more arbitrary. Assuming relatively constant sediment accumulation rates through the Eocene, the lower Raging River Formation represents about 2 million years of deposition. Accordingly, an age of 51 to 49 Ma was assigned to this unit.

The Tiger Mountain, Tukwila, and Renton Formations overlie the Raging River Formation and comprise the Puget Group. These three units interfinger considerably and thus have variable thicknesses across the Tiger Mountain-Newport Hills area. The thickness values used in the subsidence analysis were based on the stratigraphic and geologic cross sections of Vine (1969) for the Tiger Mountain area.

Vine (1962, 1969) and Johnson (1992) have described the fluvial-deltaic depositional environment of the Tiger Mountain Formation. This unit has a thickness of about 860 m and consists mainly of clastic sedimentary rocks but includes significant volcanic rocks in its upper part (Vine, 1969). For the subsidence analysis, the Tiger Mountain Formation was assigned an age of 47 to 44 Ma, based on its position between early Narizian beds of the upper Raging River Formation and the overlying, relatively well-dated Tukwila Formation.

The Tukwila Formation consists mainly of andesitic volcanic and volcaniclastic rocks deposited in a nonmarine environment. This section is approximately 1,890 m thick. I assigned an age of 44 to 40.5 Ma to the Tukwila Formation based on isotopic dates reported in Turner and others (1983). The Renton Formation is 686 m thick in the Tiger Mountain area (Vine, 1969) and consists of nonmarine sandstone, siltstone, shale, and coal. Based on stratigraphic position between the Tukwila Formation and overlying well-dated marine rocks (see below), I assigned the Renton Formation an age of 40.5 to 38 Ma.

The Renton Formation is overlain by undifferentiated marine and minor nonmarine volcanic siltstone and sandstone (Yount and Gower, 1991). This unit has a thickness of

Table 1. Input parameters for subsidence models.

Tiger Mountain - Newport Hills area

Stratigraphic unit	Age (Ma)	Thickness (m)	Paleobathymetry (m)	Lithology[1] (%)
Miocene strata	15 to 6	700	0	50 l,50 sl
Late Eocene-Oligocene strata	38 to 27	2,350	0 to 50	70 sl, 30 l
Renton Formation	40.5 to 38	686	0	60 ss, 20 sl, 15 sh, 5 c
Tukwila Formation	44 to 40.5	1,890	0	80 v, 20 l
Tiger Mountain Formation	47 to 44	861	0 to 20	40 ss, 25 v, 25 sl, 10 l
Upper Raging River Formation	49 to 47	300	500 to 2,000	80 sl, 20 l
Lower Raging River Formation	51 to 49	700	0 to 50	50 l, 50 sl

Mobil Kingston #1 borehole

Stratigraphic unit	Age (Ma)	Thickness (m)	Paleobathymetry (m)	Lithology[1] (%)
Quaternary deposits	2 to 0	524	0	80 sh, 20 ss
Upper Refugian strata	37.5 to 36.5	363	150 to 500	90 sl, 10 l
Lower Refugian strata	38 to 37.5	180	500 to 2,000	90 sl, 10 l
Narizian strata	48.7 to 38	396	500 to 2,000	45 ss, 45 sl, 10 sh
Ulatisian strata	51 to 48.7	171	150 to 1,500	40 sh, 40 sl, 20 ss
Penutian strata	52 to 51	561	500 to 2,000	70 sl, 30 ss
Crescent Formation	53 to 52	441	500 to 2,000	80 v, 20 sl
Crescent basement	>53			

Seattle basin

Stratigraphic unit	Age (Ma)	Thickness (m)	Paleobathymetry (m)	Lithology[1] (%)
Quaternary deposits	2 to 0	600	0	70 sh, 30 ss
Miocene strata	20 to 4	3010	0	80 l, 20 sl
Refugian to Zemorrian strata	38 to 24.5	3,540 to 3,990*	1,500 to 2,000	45 l, 45 sl,10 sh
Narizian strata	48.7 to 38	1,080 to 1,360*	500 to 2,000	45 ss, 45 sl, 10 sh
Ulatisian strata	51 to 48.7	270 to 340*	150 to 1,500	40 sh, 40 sl, 20 ss
Penutian strata	52.5 to 51	500 to 700*	500 to 2,000	70 sl, 30 ss
Crescent Formation	> 52.5			

*Range in thickness estimate is based on the two assigned assumed maximum depths (9,000 and 10,000 m) for the western Seattle basin.

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[1] Lithologic abbreviations: Sandstone = ss; Litharenite = l; Siltstone = sl; Shale = sh; Coal = c; Volcanic rock = v.

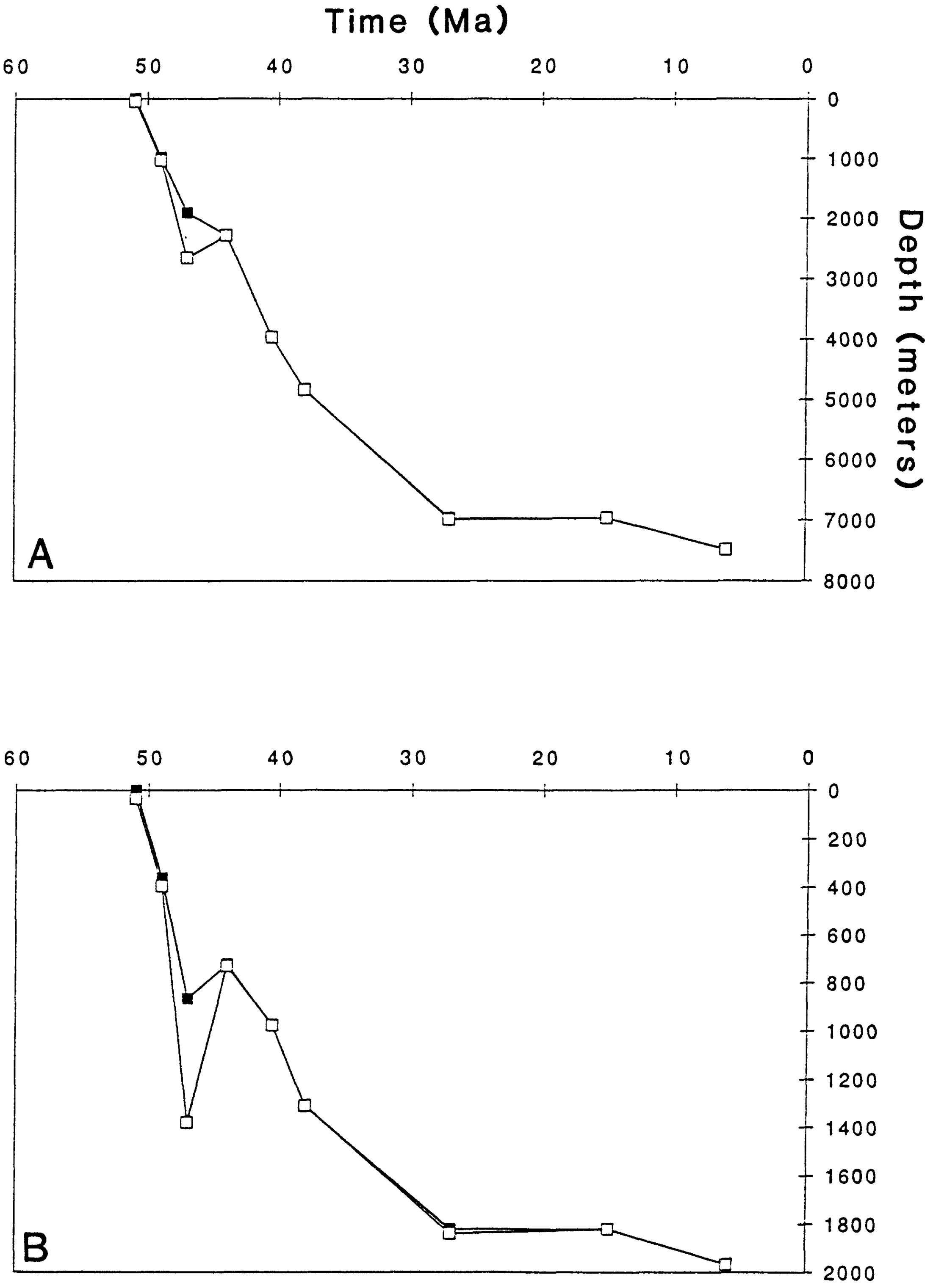

Figure 2. Graphs showing (A) total subsidence and (B) tectonic subsidence of the Tiger Mountain-Newport Hills area. Dark squares show data points using minimum paleobathymetric estimates; open squares show data points using maximum paleobathymetric estimates. See text for discussion.

about 2,350 m based on cross sections in Yount and Gower (1991). This section lies within and(or) adjacent to the Seattle fault zone (Yount and Gower, 1991), so the thickness estimates may not be reliable because of structural complications. Correlative strata on strike to the west probably have even greater thickness (see below). The lower part of the unit contains Refugian foraminifera and the upper part contains a Zemorrian fauna (Yount and Gower, 1991). An age of 38 Ma (corresponds to base of Refugian; Prothero and Armentrout, 1985) to 27 Ma (corresponds to late Zemorrian) was assigned to these undifferentiated strata.

An unconformity separates the undifferentiated Refugian-Zemorrian rocks from unnamed, nonmarine, tuffaceous sandstone and siltstone of Miocene age. This unit has a likely minimum thickness of 700 m based on map data presented by Yount and Gower (1991). An age of 15 to 6 Ma was here assigned to the unit based on isotopic dates reported in Yount and Gower (1991) and following Armentrout and others (1983b).

Mobil Kingston #1 borehole

W. Rau (written commun., 1992, 1993) recognized six stratigraphic units in the Mobil Kingston #1 borehole, which was drilled near Kingston on the Kitsap Peninsula (fig. 1). Stratigraphic information described below is summarized in Table 1 and the subsidence models are shown in Figure 3. Volcanic and interbedded sedimentary rocks of the early Eocene (Penutian foraminiferal stage) upper part of the Crescent Formation occur between depths of 2,195 and 2,637 m. These rocks contain a sparse foraminiferal fauna suggesting middle bathyal water depths (W. Rau, written commun., 1992, 1993). Spencer (1984) similarly noted bathyal foraminifera in the Crescent on the eastern Olympic Peninsula. An age of 53 to 52 Ma is assigned to this upper part of the Crescent Formation, corresponding to the lower half of the Penutian stage (Almgren and others, 1988).

This upper part of the Crescent Formation is overlain by 561 m of early Eocene (Penutian) siltstone and sandstone (W. Rau, written commun., 1992, 1993). An age of 52 to 51 Ma is assigned to these sedimentary rocks, extending from the middle to the end of the Penutian. Foraminiferal assemblages suggest the Penutian rocks were deposited at middle bathyal water depths.

Strata of late early and early middle Eocene age (Ulatisian foraminiferal stage) overlie the Penutian sediments (W. Rau, written commun., 1992, 1993). Ulatisian strata are 171 m thick and consist of shale, siltstone, and sandstone. The rocks are assigned an age of 51 to 48.7 Ma, coinciding with the duration of the Ulatisian stage (Almgren and others, 1988). Foraminiferal assemblages suggest deposition at upper to upper middle bathyal water depths.

Ulatisian strata are overlain by approximately 400 m of middle to early late Eocene (Narizian foraminiferal stage) sandstone, siltstone, and shale (W. Rau, written commun., 1992, 1993). These strata were deposited at middle bathyal water depths based on foraminiferal assemblages. The rocks are assigned an age of 48.7 to 38 Ma, coinciding with the duration of the Narizian stage (Almgren and others, 1988; Prothero and Armentrout, 1985).

Narizian strata are conformably overlain by approximately 540 m of late Eocene to early Oligocene age (Refugian foraminiferal stage) siltstone and minor sandstone. The lower 180 m of this interval contains foraminifera which suggest deposition at middle bathyal water depths; foraminifera in the upper 363 m suggest upper bathyal deposition (W. Rau, written commun., 1992, 1993). Refugian strata are unconformably overlain by 524 m of Quaternary clay and sand. Because Refugian strata are overlain by this unconformity, it is not certain how much of Refugian time they represent. Refugian strata are 1,323 m thick in the nearby Standard Alderwood #1 borehole and partial Refugian sections in three other nearby wells (Engstrom Community #1, Socal-Schroeder #1, Socal-Whidbey #1; fig. 1) are 525 to 800 m thick (W. Rau, written commun., 1992, 1993). Assuming locally uniform sediment accumulation rates, the Refugian strata in the Mobil Kingston #1 borehole may represent only about half of Refugian time. Accordingly, the

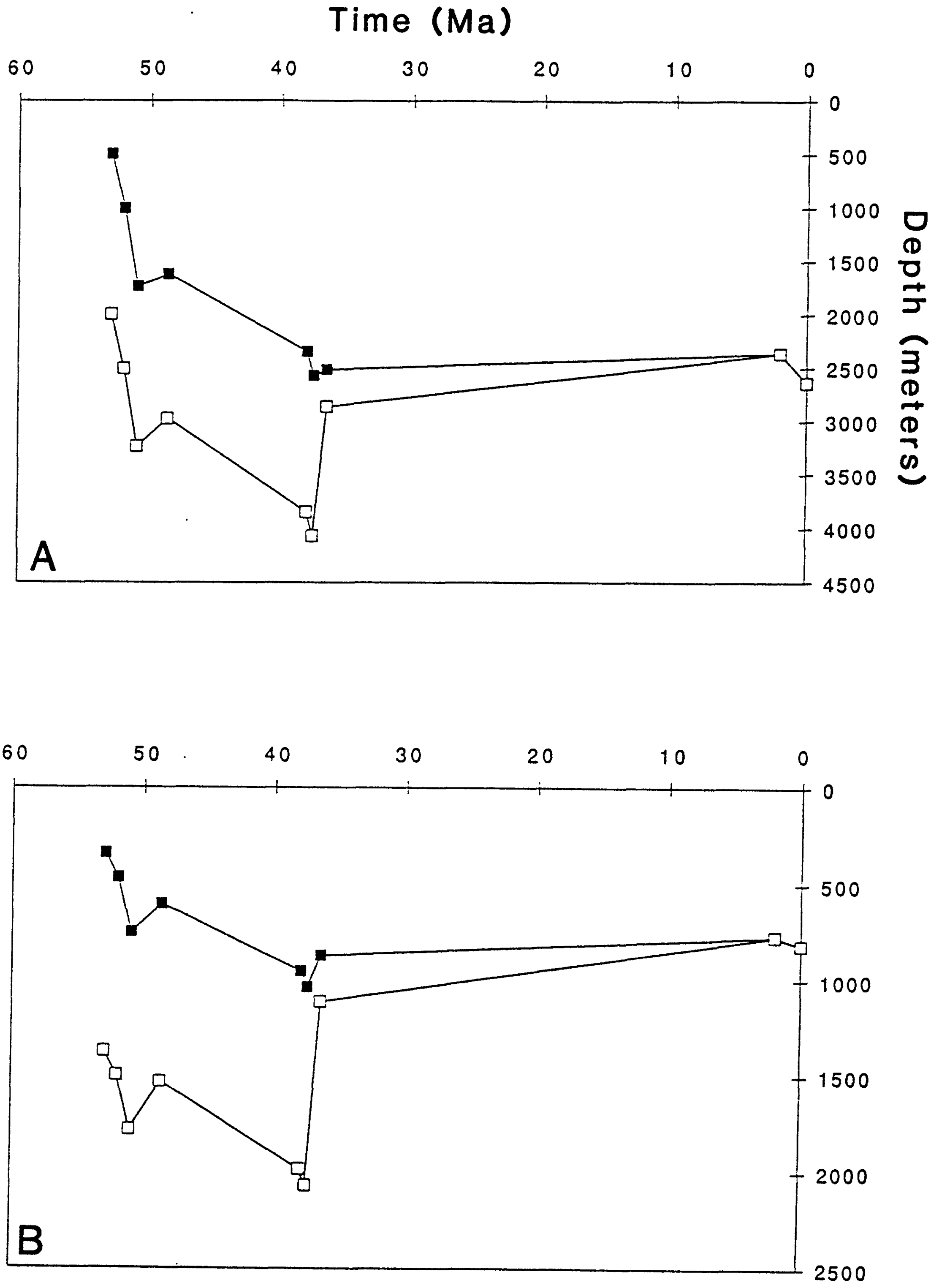

Figure 3. Graphs showing (A) total subsidence and (B) tectonic subsidence of the Mobil Kingston #1 borehole. Dark squares show data points using minimum paleobathymetric estimates; open squares show data points using maximum paleobathymetric estimates. See text for discussion.

two Refugian intervals descried above are assigned ages of 38 to 37.5 Ma, and 37.5 to 36.5 Ma, coinciding with the lower half of the Refugian stage (Prothero and Armentrout, 1985).

Western part of the Seattle basin

The western part of the Seattle basin is located between the structurally high Kingston arch on the north and the Seattle fault (Gower and others, 1985; Yount and Gower, 1991) on the south (fig.1). The basin is outlined by a major gravity anomaly and contains a thick fill of sedimentary rocks (Danes and others, 1965). The subsidence history of the Seattle basin is difficult to constrain because the sedimentary fill of the basin has not been drilled and is absent, covered, or poorly exposed on the basin margins. Analysis of marine seismic reflection profile 46-69 (provided by Mobil Exploration and Producing U.S. Inc.), which extends down the axis of Puget Sound (fig. 1), however, allows stratigraphic horizons to be traced from a projection of the Mobil Kingston #1 borehole (fig. 1) southward into the western part of the Seattle basin (fig. 4). Projection of the Mobil Kingston #1 stratigraphy onto the north-south line (fig. 4) is based on analysis of two additional marine seismic profiles that cross line 46-69 and extend to within 1,700 m and 2,400 m of the Mobil Kingston #1 borehole site, and analysis of four short (< 8,000 m) onshore seismic profiles from the Kingston area. The presence of a local, low-angle unconformity at the top of the Crescent Formation viewed on line 46-69 (fig. 4) is a key element in correlating the stratigraphy to the Kingston borehole.

Assigning correct thicknesses to the stratigraphic horizons in the western Seattle basin is problematic because of the lack of deep (below about 3,500 m) sonic logs or other precise information on seismic velocity gradients from the region. For estimating thicknesses in this study, a time-depth plot (fig. 5) for interpretation of the seismic profile was derived using relevant sonic logs and other geophysical data. The sonic log from the Standard Engstrom Community #1 borehole (TD of 2,226 m) on Whidbey Island (fig. 1) was used for generating the shallower part of the plot. This borehole penetrated a thick Quaternary and Oligocene section. Because the western part of the Seattle basin must contain a thick section of Oligocene and younger strata (fig. 4), the Standard Engstrom Community #1 borehole provides a better analog for the western part of the Seattle basin (fig. 4) than the more nearby Mobil Kingston #1 borehole, which extends lower into the stratigraphic section and is characterized by faster velocities. Below 2,226 m on the time-depth plot, the velocity structure of the Phillips State #1 borehole (southeast of Seattle, fig. 1) between 610 and 3,476 m (TD) was used. This borehole is also more useful than the Mobil Kingston #1 borehole because it penetrated a much thicker section (Eocene rocks, deformed and uplifted in the Miocene) and therefore provides a better indication of regional velocity trends in deeply buried sedimentary rocks. The approximate velocity measured at 610 m in the State #1 borehole (~3,200 m per second) is only slightly greater than that measured at 2,226 m (~3,050 m/sec) in the Engstrom Community well. Velocities between about 2,134 and 2,439 m in the State #1 borehole are anomalously high because of interlayered volcanic rocks. Rather than incorporating these high values in the composite time-depth plot (fig. 5), a steady velocity increase was assumed for this interval.

Analysis of the seismic data suggest that the top of basement (Crescent Formation) in the deepest part of the western Seattle basin is at 4.3 seconds. For the time-depth plot (fig. 5), this value was assigned depths of both 9,000 and 10,000 m. The 10,000 m estimate for the depth of basin fill was obtained from a gravity model by Danes and others (1965). This estimate is reasonably consistent with seismic tomographic studies of Lees and Crosson (1990), who suggested that the low-velocity anomaly represented by the Seattle basin had little expression below 9 km. Each of these estimates is consistent with expected increases in seismic velocity with depth (fig. 5). Mean velocities for the entire basin fill are 4,651 m/sec and 4,186 m/sec for assumed depths of 10,000 m and 9,000 m, respectively.

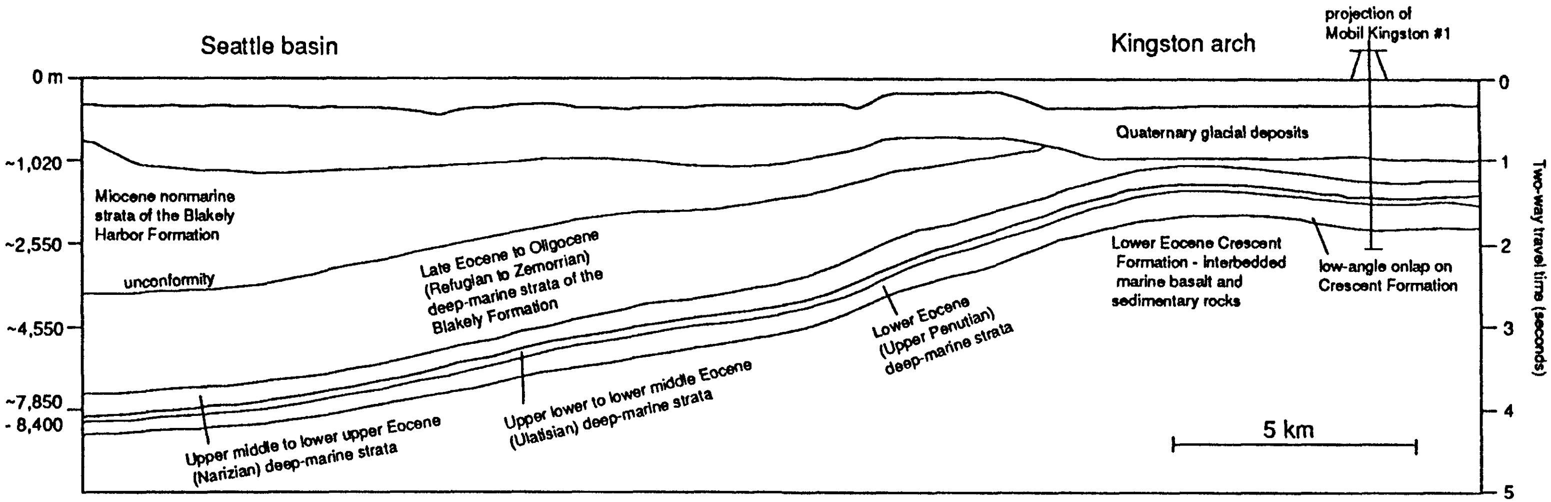

Figure 4. Interpretation of Mobil seismic reflection profile 46-69. Line of profile shown on Figure 1.

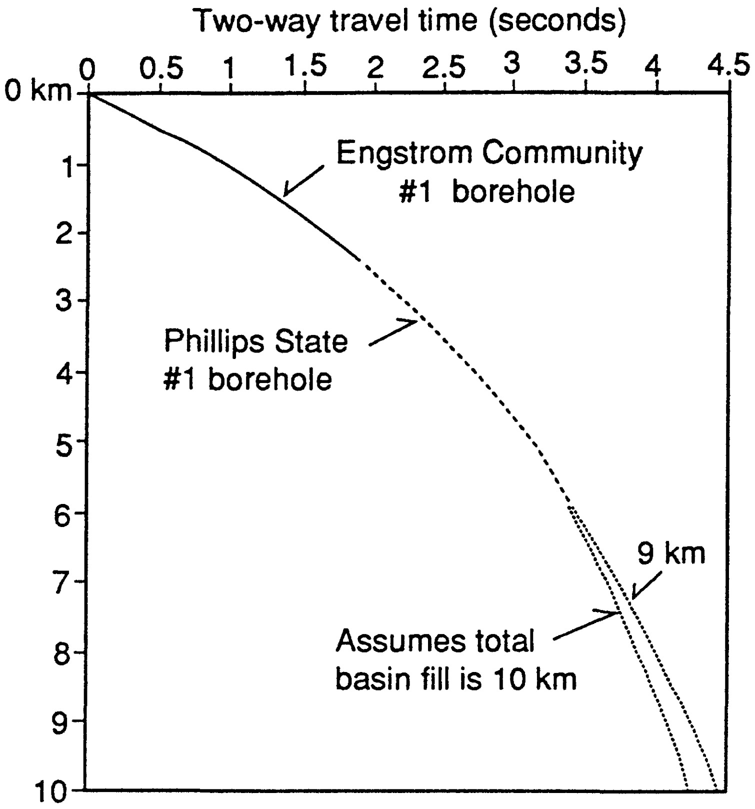

Figure 5. Time-depth plot used for calibrating the stratigraphy in the western Seattle basin. See text for details on how the plot was constructed.

The thicknesses for the stratigraphic units traced on the seismic reflection line (fig. 4) from the projection of the Mobil Kingston #1 borehole are thus based on the time-depth plot (fig. 5) and other rationale discussed below. Stratigraphic information for the western part of the Seattle basin is summarized in Table 1 and the subsidence models are shown in Figures 6 and 7. Variations in thicknesses for the Penutian through Zemorrian section shown in Table 1 reflect the different estimates from the time-depth plot (fig. 5) based on the two estimates of total basin fill. Lithologic compositions and depositional environments (i.e., paleobathymetry) are assumed to be the same as in the Mobil Kingston #1 well for the Penutian through Narizian part of the section.

The Refugian to Zemorrian section in the Seattle basin occurs between the top of the Narizian section and a low-angle unconformity interpreted as the contact between Zemorrian marine sedimentary rocks and Miocene nonmarine sedimentary rocks (fig. 4; see below). The Refugian and Zemorrian section could not be subdivided on the seismic reflection profile and is treated as one interval, approximately 3450 to 3990 m thick, for subsidence analysis (table 1; figs. 6, 7). An incomplete section of the Refugian and Zemorrian Blakely Formation (2184 m thick) has been described by Fulmer (1975) and McLean (1976) from the Seattle fault zone on the southwestern basin margin. These rocks provide an important analog for the correlative section in the western Seattle basin and were used to assign values for age, lithology and paleobathymetry (table 1). Foraminiferal stages identified by Fulmer (1975) in these outcrops extend to the late Zemorrian (to 24.5 Ma), providing the upper age limit for this interval used in the subsidence reconstructions. Foraminiferal assemblages (Fulmer, 1975) suggest lower middle bathyal deposition when compared to tables of Ingle (1980), consistent with the sedimentologic interpretations of McLean (1976). Refugian to Zemorrian strata consist of sandstone, siltstone, shale, and conglomerate.

The Blakely Formation outcrops on the south flank of the west Seattle basin are unconformably overlain by nonmarine sandstone, conglomerate, and siltstone of the Blakely Harbor Formation (Fulmer, 1975). The contact between the Blakely and Blakely Harbor Formations is probably a west-trending fault that extends up Blakely Harbor, but could also be an unconformity. On the seismic profile (fig. 4), this contact is placed at a low-angle truncation surface that marks a change from subparallel, low-amplitude, discontinuous reflectors (representing deep-marine deposits) below the contact to hummocky, variable-amplitude, discontinuous reflectors (representing coarse-grained alluvial deposits) above the contact. Fulmer (1976) suggested that the outcrop section of the Blakely Harbor Formation could be as thick as 1,040 m, but the section is cut by faults and neither base or top are exposed. The seismic data indicate the Blakely Harbor Formation is about 3,010 m thick in the western Seattle basin. The Blakely Harbor Formation is unconformably overlain by approximately 600 m of Quaternary sediments along a low-angle unconformity (fig. 4). The age of the Blakely Harbor Formation is not precisely known. The stratigraphic relationships described above place it between 24.5 and 2 Ma. A more limited age range of 20 to 4 Ma was used in the subsidence analysis (figs. 6, 7) in order to allow time for the underlying and overlying unconformities to develop. The outcrops of the Blakely Harbor Formation lie along tectonic strike (along the southern margin of the Seattle basin) with a thinner section of Miocene strata to the east in the Newport Hills area (fig. 1; table 1), for which an age of 15 to 6 Ma was inferred (see above) based on isotopic dates.

DISCUSSION

For the purpose of comparison, Figure 8 shows total and tectonic subsidence for the four separate areas. For each area and subsidence plot, the midpoint of the paleobathymetric range was used. Figure 8 includes two plots for the western Seattle basin based on inferred basin-fill thicknesses of 9,000 and 10,000 m. Eocene subsidence (57 to 37 Ma) was most rapid and pronounced in the Tiger Mountain-Newport Hills area, despite the major uplift recorded by the transition from the Raging River Formation to the Tiger

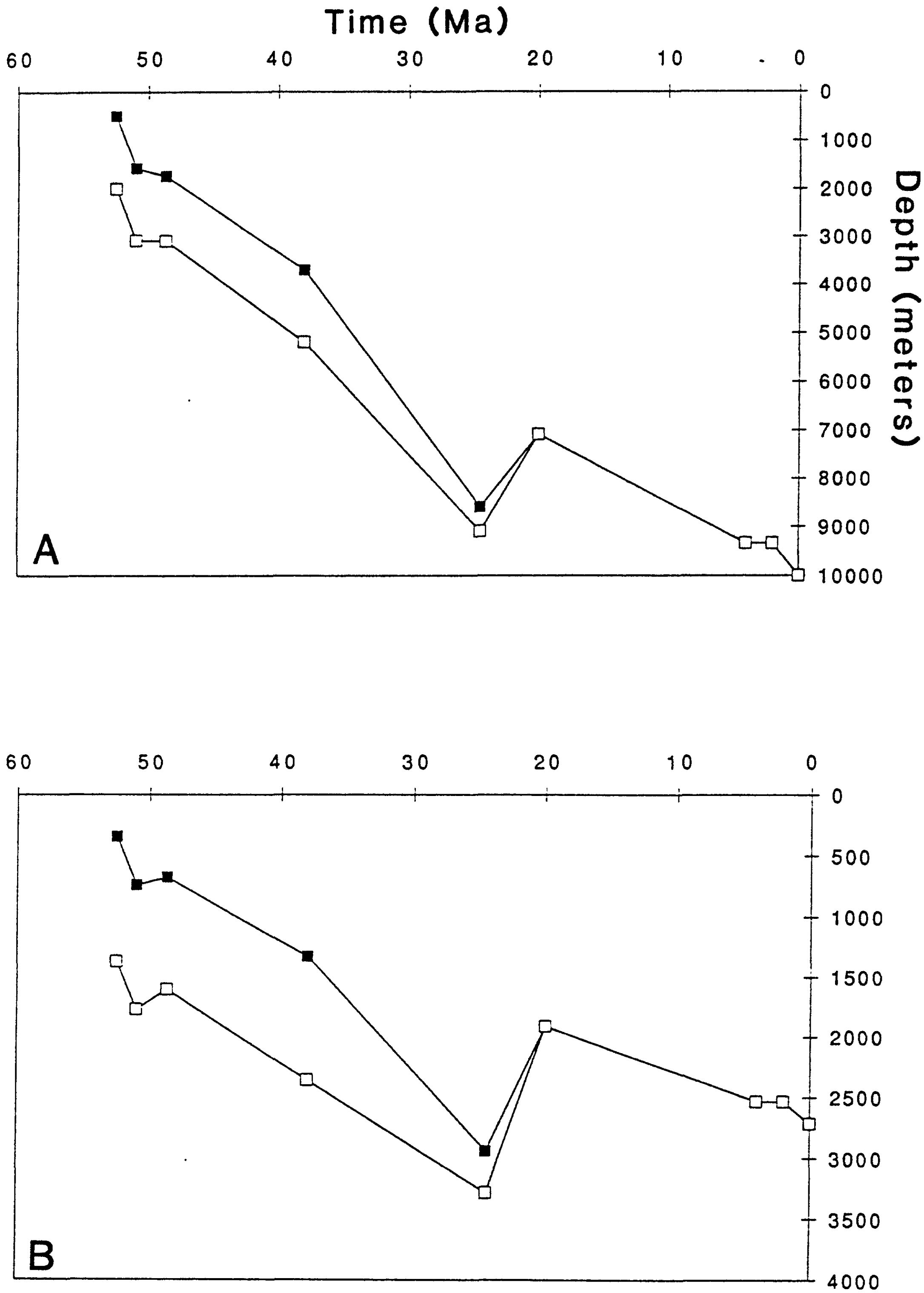

Figure 6. Graphs showing inferred (A) total subsidence and (B) tectonic subsidence of the western Seattle basin assuming a total basin fill of 10,000 m. Dark squares show data points using minimum paleobathymetric estimates; open squares show data points using maximum paleobathymetric estimates. See text for discussion.

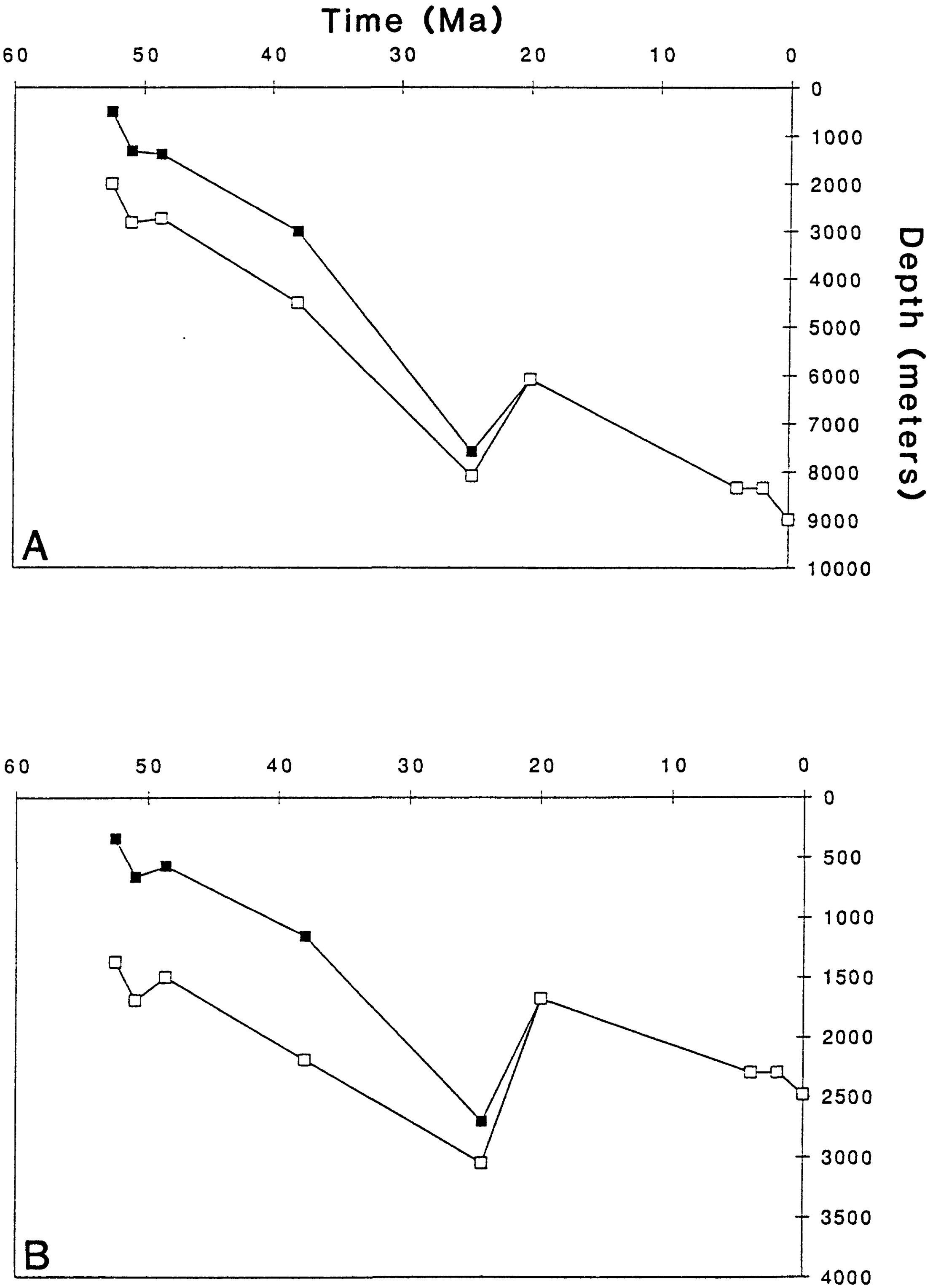

Figure 7. Graphs showing inferred (A) total subsidence and (b) tectonic subsidence of the western Seattle basin assuming a total basin fill of 9,000 m. Dark squares show data points using minimum paleobathymetric estimates; open squares show data points using maximum paleobathymetric estimates. See text for discussion.

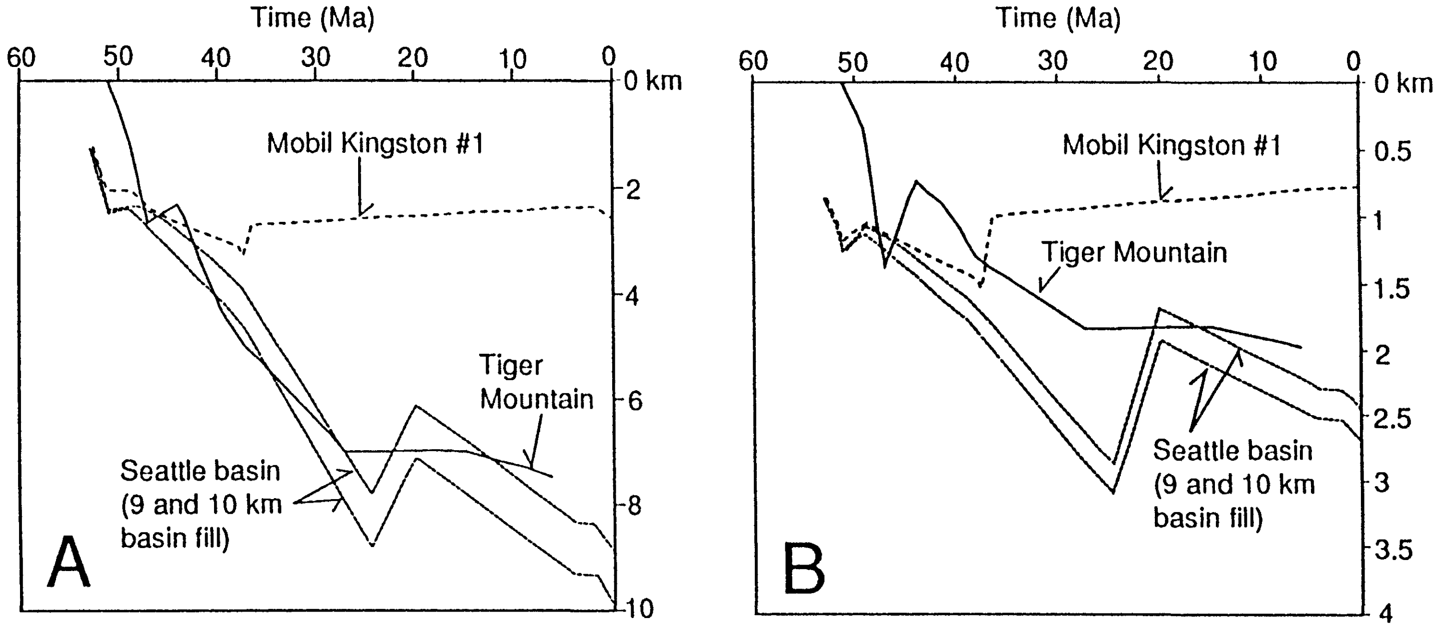

Figure 8. Graphs showing (A) total subsidence and (B) tectonic subsidence for the Tiger Mountain-Newport Hills area, the Mobil Kingston #1 borehole, and the western part of the Seattle basin (fig. 1). Graphs based on mean estimates of paleobathymetry.

Mountain Formation. Slower Eocene subsidence characterized the western part of the Seattle basin and the "Kingston arch". Oligocene subsidence was greater in the western Seattle basin and in the Tiger Mountain-Newport Hills area than at the northern Mobil Kingston #1 site.

In the Miocene, uplift and erosion occurred at the northern Mobil Kingston #1 site (fig. 1), and subsidence characterized each of the two localities to the south. The plots suggest higher subsidence rates in the western Seattle basin than in the Tiger Mountain-Newport Hills area. It should be noted, however, that the inferred thickness of Miocene strata in the western Seattle basin (3,010 m) was based on the seismic reflection data; outcrop data on the southern margin of the western part of the Seattle basin would indicate a thickness of only 1,040 m. To the east on strike, the thickness for Miocene strata in the Newport Hills (700 m; table 1) is based on outcrops in the Seattle fault zone. The thickness of Miocene strata in the subsurface of the eastern part of the Seattle basin is probably much greater.

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