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CASCADIA SUBDUCTION ZONE: NEOTECTONICS OF THE ACCRETIONARY WEDGE AND ADJACENT ABYSSAL PLAIN OFF OREGON AND WASHINGTON

Contract 14-08-0001-G1800

Principal Investigator: LaVerne D. Kulm*
Co-Principal Investigator: Robert S. Yeats**
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Newly discovered WNW-trending strike-slip faults and associated fold structures deform the youngest sediments of the seafloor on abyssal plain, continental slope and shelf off Oregon. They project toward several coastal bays of Oregon where sudden subsidence events are interpreted as manifestations of large earthquakes associated with large-scale rupture of the Cascadia subduction zone. Alternatively, these transverse faults and local folds could be the nucleus of less severe mainshock earthquakes which cause small-scale deformation of individual bays. This study will help evaluate the seismic potential of these offshore WNW-trending faults and their possible seismic hazards to coastal communities.

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Investigations

The overall objective of this project is to characterize and determine the timing of deformational events in the subducting Juan de Fuca plate (abyssal plain) and deformation front (accretionary wedge) of the Cascadia convergence zone off Oregon and Washington. A neotectonic map was constructed of the subducting oceanic plate, accretionary wedge, and adjacent continental shelf basins off Oregon to identify the styles and areal extent of deformation. We are trying to identify and date discrete strike-slip deformational events and relate them to the distribution of earthquakes on the subducting oceanic plate and in the subduction zone.

Computer Hardware and Software Facilities

We have recently upgraded our computer facilities in the Neotectonics Laboratory through funds supplied by another federal agency. These facilities include: (1) a SUN SPARC IV IPX computer workstation and external Fujitsu 1GB hard drive, (2) a Calcomp digitizing table, (3) Microstation Mac V3.6 CAD software and other graphics software for use on the Macintosh computer, (4) and TECPLOT for rendering 3-D mesh and shaded relief images on the SUN computer. The computers are linked to a College-wide micronet and Ethernet network with centralized SUN fileservers, tape drives and output devices. The Oregon neotectonics map described below is being produced in layers with the Microstation CAD software for publication through the Oregon Department of Geology and Mineral Industries. We are requesting that NEHRP support the purchase (with existing funds) of additional imaging processing software that will allow us to analyze and visualize both the extensive SeaBeam swath bathymetry, GLORIA long-range sidescan sonar, and high-resolution SeaMARC-IA sidescan sonar digital data sets that are now available for the Oregon margin. These data will be analyzed in our 1992 NEHRP project as well as the GLORIA data and conventional bathymetry data currently available for the Washington margin; the latter data set will be the main focus of our 1992 work.

Results

Abyssal Plain

Three WNW trending left-lateral strike-slip faults (A,B,C) occur on the abyssal plain off central and northern Oregon and have been under investigation during the past two years (Fig. 1). During the past six months, detailed studies of the sedimentary deposits and seismic stratigraphy of the abyssal plain surrounding these faults reveal the amount of fault separation and the rate of slip of the most prominent fault (A). These active transverse features extend from the plain across the plate boundary and into the folds and thrusts of the accretionary wedge. First discovered in 1986 using SeaMARC 1A sidescan sonar, these faults were imaged extensively in a follow-up 1989 narrow swath, high resolution survey (Fig. 2; Appelgate et al., 1991). In migrated multichannel seismic reflection (MCS) profiles on the Juan de Fuca plate, all three faults offset the entire 3-4 km thick sedimentary section, as well as the oceanic basement (Fig. 3A, 4; MacKay et al., 1991; Goldfinger et al., 1991a). A prominent magnetic anomaly occurs across at least two faults. Magnetic modeling of fault A (Wecoma fault) and reflection profiles both indicate about 75-100 m of vertical separation of the basaltic basement, NE block up (Appelgate et al., 1991). Sidescan coverage of the abyssal plain indicates that displacement on fault A dies to nearly zero 17-20 km seaward of the deformation front. At its western tip, fault A is greatly diminished in surface expression, and the westernmost MCS crossing shows modest displacement in comparison to crossings near the deformation front. Two other seismic records located 3.7 and 5.5 km to the west show the fault does not extend west of 125° 41' W. Faults A and B both cut or have generated N to NNW plunging anticlines near their intersections with the deformation front. Faults B and C extend at least 7-8 km seaward into the abyssal plain based on sidescan images and seismic records, and their terminations will be constrained by one of our N-S MCS lines, located 15 km seaward of the deformation front, when it is processed.

SeaMARC 1A sidescan imagery shows that fault A offsets left-laterally a late Pleistocene distributary channel on the Astoria submarine fan as well as a slump scar and escarpment crossing the fault (Figs. 2,5). A horizontal displacement of about 120 m was measured on the channel (designated OC, Fig. 2) in the youngest sediments of the seafloor (Appelgate et al., 1991; Goldfinger et al., 1991b). This crosscutting relation can be used to obtain an estimate of the slip rate during latest Pleistocene and Holocene time. The channel is blocked 18 km to the north by slump debris from a 32 km^3 bedding-plane slump from the leading accretionary thrust ridge (Fig. 5). We estimate the age of this slump to be 10-24 ka, based on a calibrated ^{14}C date from a gravity core (10,300 yrs bp) taken on top of one of the slump blocks and on onlapping relations on a high resolution seismic record. The slump debris rests directly on the seafloor reflector with no visible sediment onlap or ponding around the slump blocks. Using a composite late Pleistocene-Holocene sedimentation rate derived from data in Nelson (1968) and Goldfinger et al. (1991a), we estimate that sediment accumulation by turbidity currents following the slump could not exceed about 24 ka without depositing a thick enough turbidite unit to be detectable on the MCS profile, thus setting a maximum age for the slump (Goldfinger et al., 1991a). The calculated latest Pleistocene-Holocene slip rate ranges from 5-12 mm/yr using the 120 m of left-lateral offset on the channel.

Pre-faulting sedimentary units of the fan and abyssal plain sequences, which strike mostly N-S and thicken uniformly eastward, were used to calculate the net slip on the Wecoma fault since its inception. Sediment thickness changes across the fault are pronounced. The youngest seismic unit (Astoria Fan, Unit 1) is thicker on the south (downthrown) side, while successively older units 2 and 3 (abyssal plain) are thinner on the south side (Figs. 3A, 4). We attribute the abrupt thinning across the fault as the result of strike-slip juxtaposition of the eastward thinning wedges comprising these two units. Isopachs of these wedge-shaped pre-fault sedimentary units give a piercing-point horizontal offset of 5.5±0.8 km (Fig. 3B). Neglecting the 100 m of vertical separation, we believe the 5.5 km value represents the best estimate of the net slip on the Wecoma fault near the deformation front. Stratigraphic correlations suggest that growth of the plunging anticline (called a pressure ridge in our interpretation) was approximately coeval with dip slip on fault A. Faulting began at about 600 ± 50 ka, based upon the age of strata that separate pre-faulting and syn-faulting parts of the section, assuming that dip-slip and strike-slip motion began concurrently (Goldfinger et al., 1991a). The estimated age of 600 ±50 ka is derived from high resolution biostratigraphy, sedimentation rates, and tentative correlation of the base of the Astoria submarine fan section with strata drilled and dated at DSDP site 174, about 70 km to the southwest (Fig 1 inset) which is tied to the fault with a connecting seismic line (Kulm et al., 1973; Goldfinger et al., 1991a). Stratigraphic thinning over the crest of the pressure ridge and thickening on the downthrown side of the fault are pronounced in the syn-faulting section (Fig. 4). This range of ages and net slip yields a slip-rate of 7 to 10 mm/yr, which is similar to the latest Pleistocene-Holocene rate (5 to 12 mm/yr).

Intersection of Transverse Faults with Deformation Front

SeaMARC 1A sidescan and seismic records of the deformation front, where fault A intersects the initial thrust ridge, show a complex embayment with individual blocks within a positive flower structure, forced upward and westward as pop-ups as they impinge on the deformation front (Figs. 4, 5). Several splays cut upslope on the initial thrust ridge and continue into the structural basin to the east. The embayment is bounded by linear gullies that cut upslope into the initial thrust ridge, and other such gullies lie within the embayment. Rock samples collected with the submersible ALVIN from the seaward gully sites consist of sheared siltstones, sandstones and pebble to cobble conglomerates (Sample et al., 1991; Tobin et al., 1991) with multidirectional slickensided surfaces and mullions. These accreted Astoria Fan deposits have been re-cemented with a secondary carbonate cement (Kulm and Suess, 1990). The carbonate cement, derived from fluids venting from the shear zones, commonly bonds the sheared sedimentary fragments into an angular breccia filling the bottoms of the gullies. Stable oxygen and carbon isotopic analyses of these pore-fluid derived carbonate cements show that they probably represent deep fluid sources within the subducting plate (Sample et al., 1991). Current activity on fault A is suggested by the presence of active fluid vents supporting live chemosynthetic clam and tube worm communities (Moore et al., 1990) along the fault zone (Appelgate et al., 1991) and especially where the fault cuts the the initial accretionary thrust sequence.

On the initial thrust ridge, a seaward-vergent thrust segment occupies the area between the splays of fault A in an overall landward vergent thrust setting, which suggests that a local reversal of vergence is induced by the interaction of the thrust and the strike-slip fault (Fig. 1). Fault B also coincides with a reversal of thrust vergence at its intersection with the deformation front (MacKay et al., 1991). Faults B and C do not have the same detailed MCS coverage but they are left-lateral faults on the basis of sidescan records and stratigraphic mismatches similar to those of fault A in the abyssal plain (Goldfinger et al., 1991a). Faults B and C offset the deformation front (i.e., bathymetric break in slope between abyssal plain and accretionary wedge) 3.7 and 2.2 kilometers, respectively, in a left-lateral sense (Fig. 1). This offset of bathymetric contours may result from strike-slip, dip-slip (up to the north) or oblique-slip motion. The active frontal accretionary thrust, on the other hand, does not appreciably offset the traces of the strike-slip faults where they cross the plate boundary. These relationships suggest that the strike-slip faults may actually be part of the plate boundary, coeval with the frontal accretionary thrusts.

Continental Slope and Shelf

Several WNW-trending left-lateral strike-slip faults have been mapped on the continental slope and shelf off central and northern Oregon (Fig. 1). We have tentatively correlated three throughgoing strike-slip faults on the mid to upper slope with faults A, B, and C on the abyssal plain using GLORIA long-range sidescan, SeaBeam swath bathymetry, and a network of industry, academic and U.S.G.S. seismic profiles. At least one of the strike-slip faults (A) on the subducting plate clearly crosses the deformation front into the accretionary wedge. The connection of faults B and C is still unresolved. Several other WNW-trending faults on the slope have, as yet, no documented abyssal-plain extensions. The recognition of these faults in the structurally complex accretionary wedge is more difficult than on the abyssal plain because of the lack of high-resolution sidescan data, the complex structure, and the high topographic relief of the wedge. However, we do recognize them in GLORIA imagery and SeaBeam bathymetry on the basis of offset and sigmoidal bending of fold axes and linear WNW-trending scarps (Goldfinger et al., 1991a). Where offsets are observed, they are left-lateral. On individual seismic reflection profiles, these faults sometimes branch upward into positive flower structures from a single vertical trace.

In northern Oregon, the continental slope consists of upper and lower terraces separated by a major landward-dipping thrust fault and a coincident break in slope (Fig. 1, labeled SB). Seaward of this boundary, thrusts and folds of the accretionary wedge trend north-south, subparallel to the continental margin. Landward of the boundary, folds of the upper slope and shelf, with the exception of outer shelf submarine banks, trend mostly NNW to WNW, oblique to the margin. In the structural province traversed by faults A, B, and C, a small set of folds is subparallel to the principal strike-slip faults. Most of the folds trend WNW to NNW (Fig. 1). While the genetic relationship between these young strike-slip faults and oblique folds is not yet known, we postulate that they both developed in the regional stress field related to oblique Juan de Fuca subduction, possibly as manifestations of partitioned components of oblique subduction strain. Although many folds on the continental shelf and upper slope involve older rocks ranging in age from Eocene to Pliocene (Kulm and Fowler, 1974), Pleistocene and Holocene strata are also deformed. Active folds commonly have associated flexural-slip faulting which is observed in a few seismic records on the Oregon shelf. Continued activity on older folds and faults on the shelf has resulted in scarps of probable Holocene age on the sea floor (Goldfinger et al., 1991b; Clarke, et al., 1985; Snavely et al., 1977).

Clockwise Crustal Rotation

We postulate that deformation of the Oregon-Washington forearc region by clockwise tectonic rotation accommodates a significant portion of the tangential plate convergence along the Cascadia subduction zone (Goldfinger et al., 1991b). Several models for upper crustal rotation between blocks bounded by strike-slip faults have been proposed to explain well-documented paleomagnetic rotations in the Transverse Ranges of southern California (Jackson and Molnar, 1990), the Coast Ranges of Oregon and Washington (Wells and Coe, 1985) and several other strike-slip dominated settings. The discovery of three confirmed and many more possible left-lateral faults creates the geometric requirement that the blocks bounded by these faults must rotate clockwise (Freund, 1974). Onshore in Oregon and Washington, clockwise rotations have been documented paleomagnetically in rocks as old as early Eocene, and as young as middle Miocene. England and Wells (1991) show that clockwise rotations in Columbia River Basalt of middle Miocene age (12 and 15 Ma) exhibit a clear increase in rotation from east to west, and infer that such rotations probably continue to the present. The tangential motion between the Juan de Fuca and North American plates is inferred to have caused the quasicontinuous deformation of westernmost North America by rotation of small blocks of unspecified size (England and Wells, 1991). We postulate that clockwise rotations of this type should occur in the submarine forearc, and the east to west increase in rotation should reach a maximum near the plate boundary. We feel that submarine mapping of these faults is the best method to study the structural mechanisms responsible for this distributed deformation.

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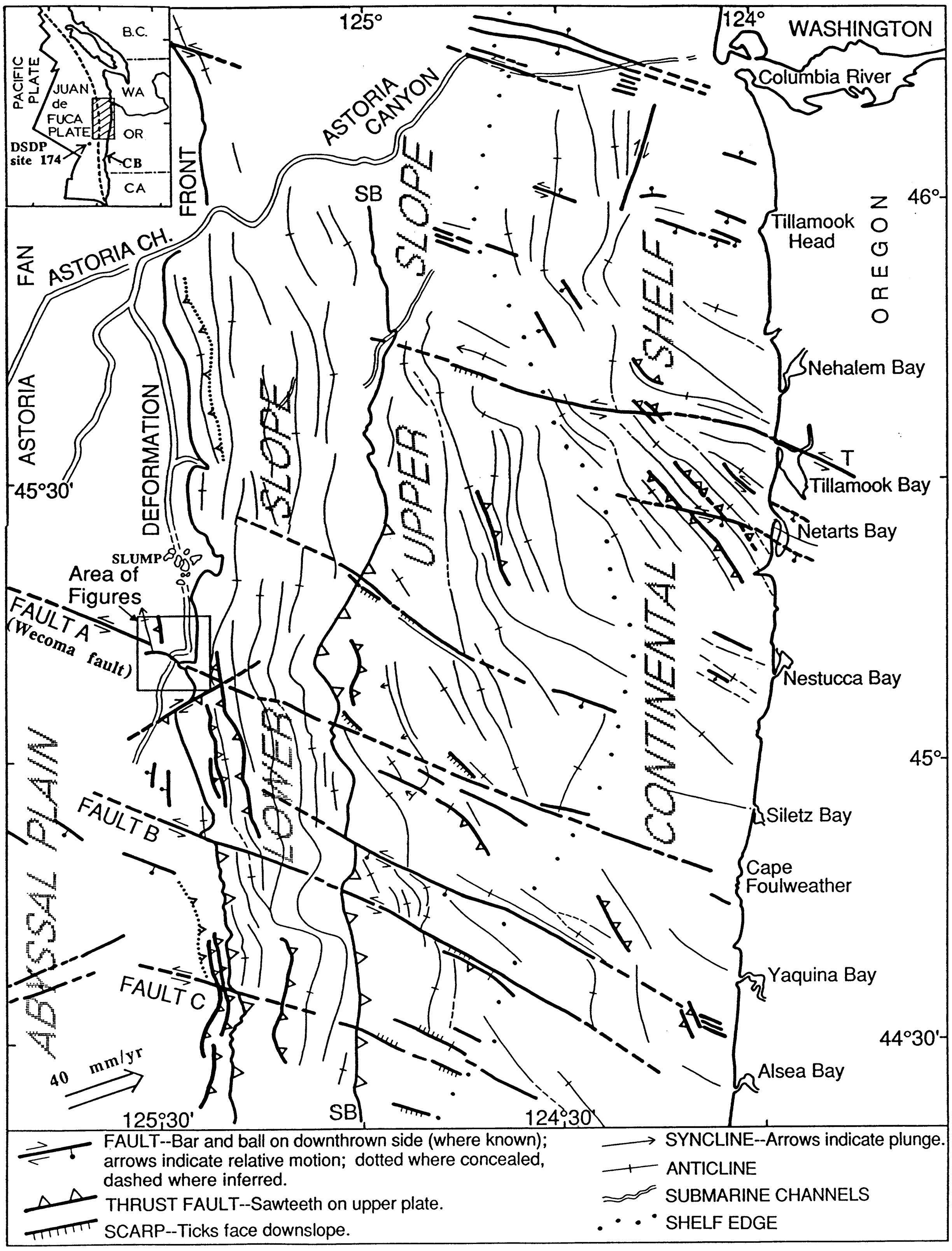

Figure 1. Structure map of the northern and central Oregon margin. Map emphasizes active features; most structures shown cut or deform the sea floor. Deformation front is a thrust fault south of Fault B, and the base of a seaward dipping ramp north of Fault B. SB = slope break; T = Tillamook Bay fault. Inset shows Juan de Fuca plate and DSDP Site 174.

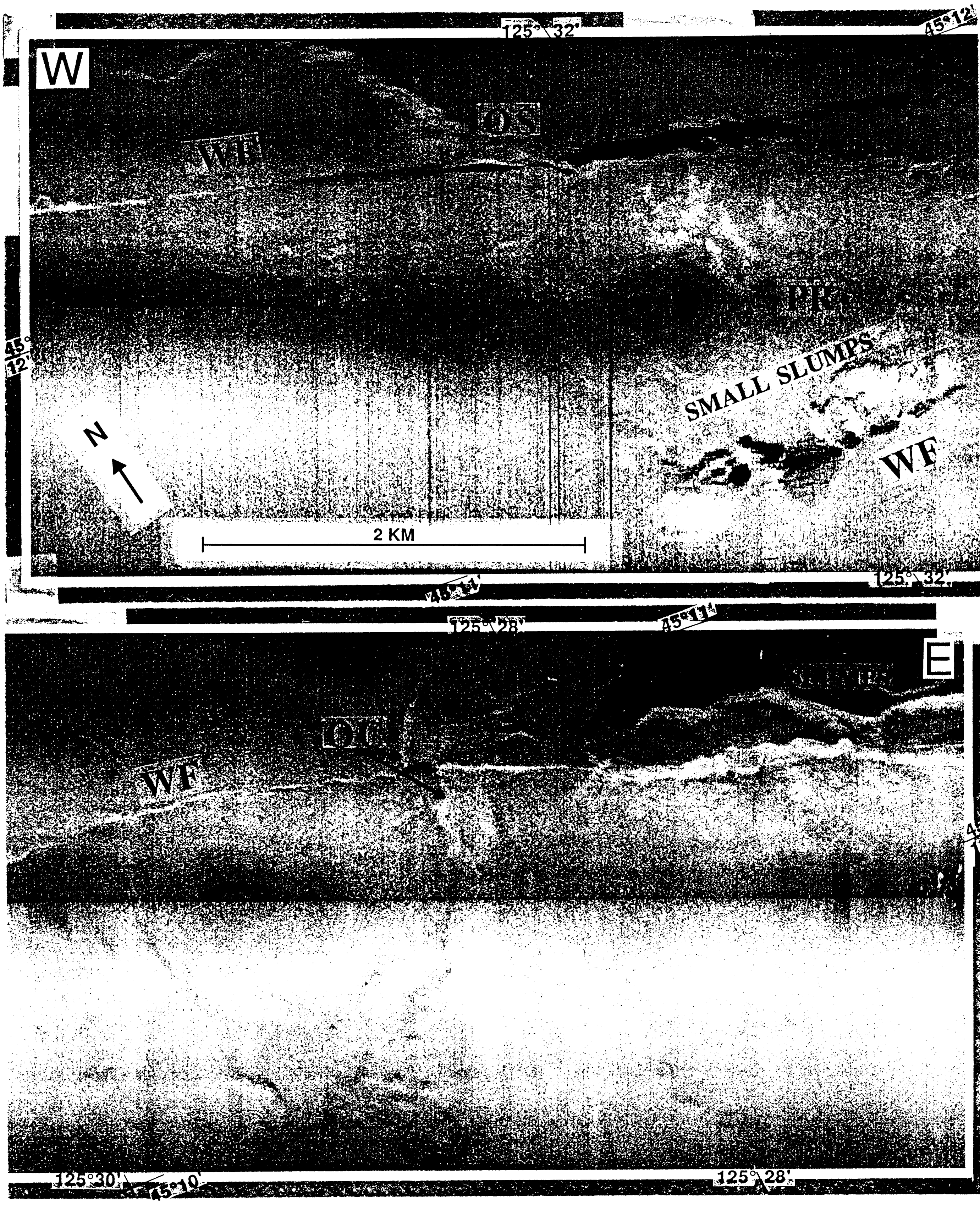

Figure 2. High resolution 2 km swath along the Wecoma fault (fault A on the abyssal plain). Note right step in trace of the Wecoma fault. PR = Pressure ridge; OC = offset channel shown by arrows; OS = offset slump scar. Note large scarp at eastern end of northern fault strand is a surficial normal fault.

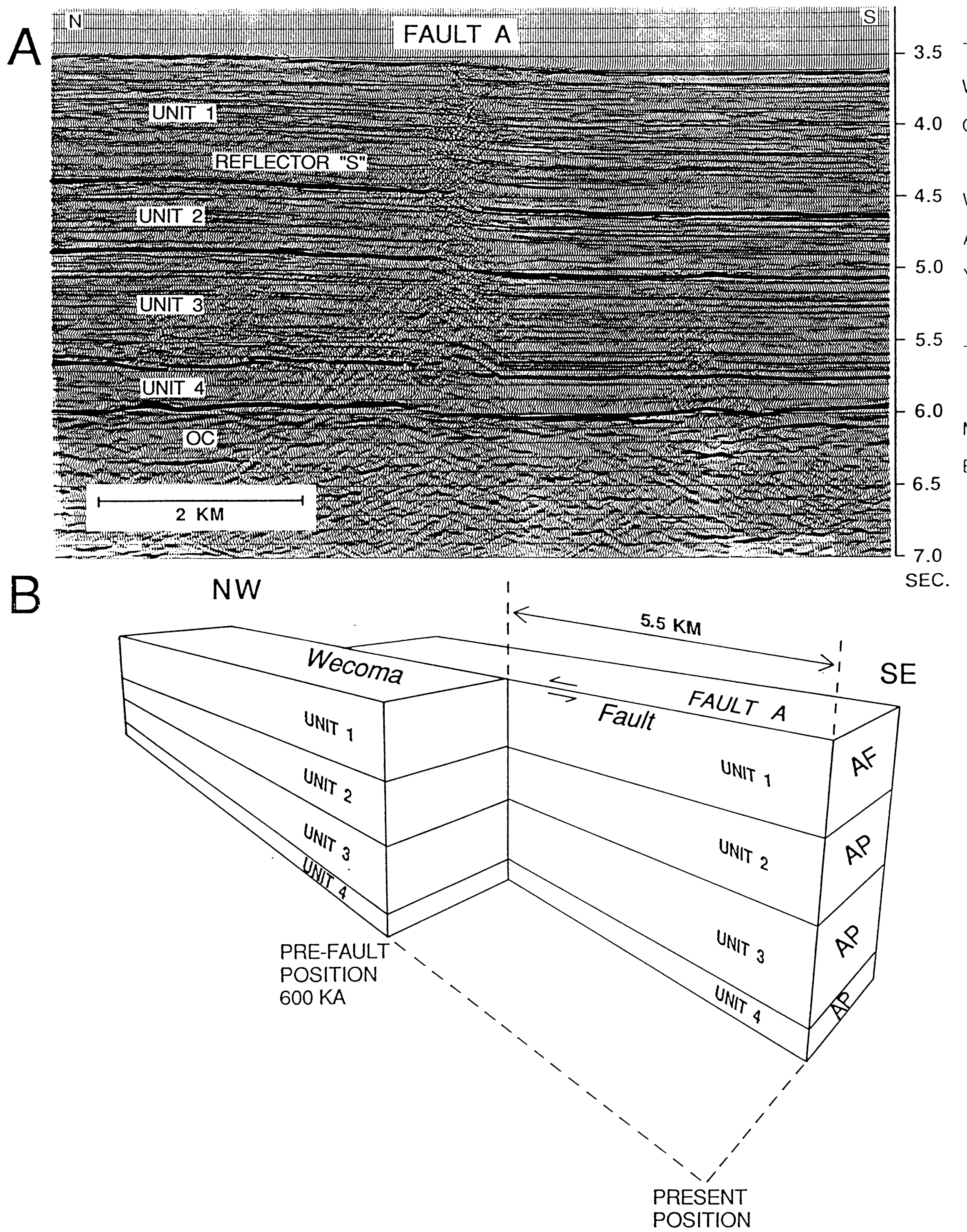

Figure 3. A) Multichannel seismic line crossing Wecoma fault (fault A) between pressure ridge and deformation front. V.E. 2:1. B) Cartoon illustrating the method used in fault A reconstruction. Fault motion was reversed until eastward thickening sediment wedges of units 2 and 3 matched, resulting in a separation of 5.5 ± 0.8 km. AF = Astoria Fan and AP = Abyssal Plain sedimentary deposits.

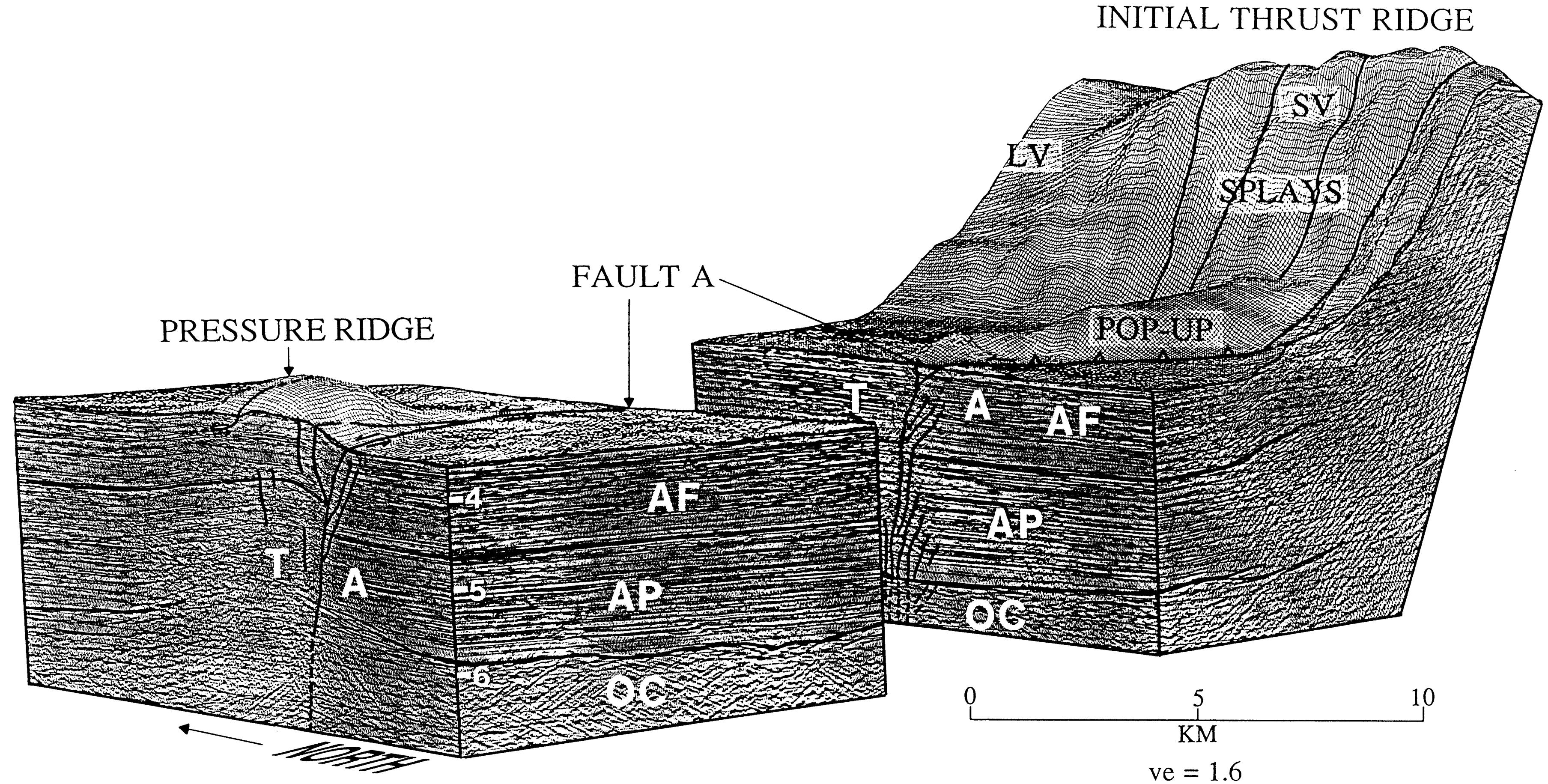

Figure 4. Composite block diagram of pressure ridge area and intersection between Fault A and the deformation front, viewed from southwest. Seismic sections (two way time) shown with selected reflectors enhanced. AP = abyssal plain section; AF = Astoria fan (note thickening across the fault and thinning over the pressure ridge); A = away ; T = toward ; SV = seaward vergence; LV = landward vergence; OC = oceanic crust.

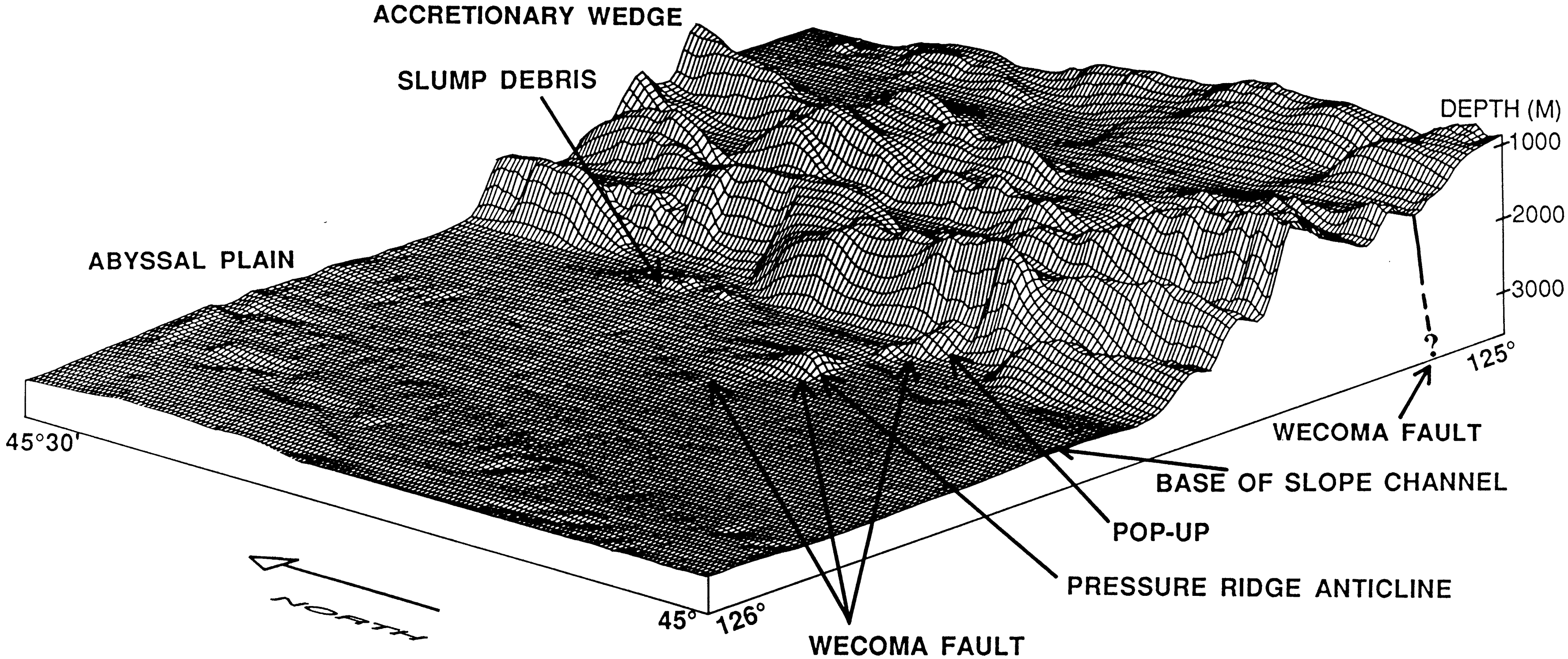

Figure 5. 3-D Perspective view of SeaBeam bathymetry from the southwest showing the physiography of the abyssal plain, and accretionary wedge in the vicinity of the Wecoma fault. Note slump debris blocking base of slope channel at foot of large slump scarp on deformation front.