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Fluid flow along a strike-slip fault at the toe of the Oregon accretionary prism: Implications for the geometry of frontal accretion

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ABSTRACT

Sediment offscraping and accretion takes place predominantly by landward-vergent thrusting along most of the Oregon accretionary prism north of latitude 44°50′N. This indicates very low basal shear stress, probably due to near-lithostatic fluid pressure on the décollement horizon. Recent multichannel seismic and sidescan sonar studies have demonstrated the existence of an oblique, basement-involved, left-lateral strike-slip fault, termed the Wecoma fault. It cuts abyssal plain sediments and oceanic basement of the subducting plate. Where the Wecoma fault intersects the wedge thrust front at 45°09′N, accretion to the wedge occurs through an anomalous seaward-vergent thrust. Linear, fault-parallel erosional gullies, which trend obliquely across the slope on the seaward flank of the frontal anticline in the accretionary wedge, are interpreted as marking the surface traces of splays of the Wecoma fault. Data collected during six *Alvin* dives on and around these gullies demonstrate that fluid expulsion from the deforming sediments is preferentially concentrated along the fault traces. Evidence includes the presence of chemosynthetic biological communities, pervasive veining and fracturing of the rock, and extensive carbonate cementation, all forming preferentially within the gullies. This strike-slip fault apparently acts as a high-angle fluid escape conduit, channeling fluids from deep within the wedge to the surface. We propose that this fluid conduit causes the local inversion of thrusting to seaward vergence by allowing the escape of highly overpressured fluids from the incipient décollement horizon. The consequent increase in basal effective normal stress favors the development of a seaward-vergent thrust. The discovery of this strike-slip fault acting as an efficient fluid conduit to the surface of the wedge emphasizes the generally unappreciated importance of strike-slip (and normal) faults in dewatering accretionary prisms. Such dewatering features may significantly influence the development of large-scale structures, and they have broad applicability to other tectonic settings, including collision zones and continental fold-and-thrust belts.

INTRODUCTION

It has become increasingly clear that fluid pressure and fluid flow are inextricably linked to structural development in areas of crustal shortening ranging from oceanic to continental (Hubbert and Rubey, 1959; Davis and others, 1983; Cloos, 1984). In most geologic settings, fluid flow and the interaction of fluids with faults can only be inferred from indirect evidence left in the rock record by past flow through the rocks and now-inactive faults. Submarine accretionary prisms, being young, water-saturated, and exhibiting high strain rates, provide an excellent setting in which to study present-day active fluid flow. Furthermore, the relative simplicity of structure near the toe of most accretionary prisms and the increasingly high quality of seismic imaging permit the interpretation of cause and effect relationships between fluid flow and structural geometry. In this study, we are able to discern the effect of a major strike-slip fault on the evolution of frontal accretion in one region of the Oregon accretionary prism by combining the powerful tools of sea-floor geologic mapping, sidescan sonar, and multichannel seismic (MCS) reflection profiling. The results have broad applicability not only in the setting of early sediment accretion, but also to more-evolved fore-arc settings, collision zones, continental fold-and-thrust belts, and regions of strike-slip tectonics.

Recent studies have shown the pervasive interdependence of fluid flow and structural development at all levels in accretionary prisms. Sediments transported to the deformation front on the downgoing plate start out with porosities in excess of 50%, but compact to about 10% porosity during incorporation into the wedge of accreted sediments (Bray and Karig, 1985), with concomitant expulsion of pore fluids. These fluids take varied pathways depending on position in the wedge, depth of burial, and structural evolution. Because fluid pressure is an important control on thrusting processes through the concept of effective stress (Hubbert and Rubey, 1959; Davis and others, 1983), structural development of the accreting sediments is, in turn, strongly influenced by fluid flow (Seely, 1977). Recent studies of the Barbados and Cascadia accretionary margins have outlined the major pathways fluids may take as sediments dewater (for example, J. C. Moore and others, 1990; Brown and Westbrook, 1988). MCS data and previous submersible studies of the Oregon margin by J. C. Moore and others (1990) suggest that pore water expulsion initially occurs along the most permeable stratigraphic horizons. They argue that this early flow exploits intergranular permeability but is replaced by focused flow along faults within 5 km landward of the deformation front. Apparently, faults become the dominant fluid conduits at an early stage in the

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accretion of sediments, even in such relatively high permeability sediments as are typical of the Cascadia accretionary complex. Hydrogeologic modeling by Screaton and others (1990) of the Barbados Ridge Complex required fault permeability three to five orders of magnitude higher than surrounding wall rocks to generate the overpressuring in the décollement observed during ODP Leg 78A drilling (Biju-Duval and others, 1984).

In accretionary prisms, thrusting takes place in a predominantly compactive regime, which should reduce rather than enhance permeability (Karig, 1990). Evidence outlined above, however, indicates that faults commonly become fluid conduits in the toe of accretionary prisms.

How is this fault-parallel permeability developed? Decreased tortuosity along fault-parallel structures may play a role (Arch and Maltman, 1990). Also, dilation of fractures is a likely mechanism for generating enhanced permeability (K. M. Brown and J. C. Moore, 1992, personal commun.). Sibson (1981) and Behrmann (1991) both argued that fault-parallel permeability develops due to hydraulic fracturing resulting from the build-up of fluid pressure in excess of hydrostatic pressure, which might generate stress conditions suitable for *simultaneous* shearing and hydraulic opening of fractures. The pore pressure required to open tensile fractures during shearing is approximately equal to the least principal stress (σ_3) (Sibson, 1981); the orientation and magnitude of this stress depends on the mode of faulting (Anderson, 1951). Faults with σ_3 oriented in a near-horizontal plane (normal or strike-slip faults) may generate associated fractures under much smaller excess pore pressures than those with σ_3 in a near-vertical plane (thrust faults). Thus, normal or strike-slip faults are more likely to undergo significant hydrofracturing and are thereby more likely than thrusts to develop into significant fluid conduits (Behrmann, 1991).

In this paper, we present results from a series of *Alvin* submersible dives conducted at the deformation front of the Oregon continental margin. We focus on a region where an active major abyssal plain strike-slip fault intersects the thrust front of the accretionary wedge. By combining structural and fluid seepage data from the dive sites with MCS and SeaMARC IA sidescan sonar data, we interpret the structural evolution and fluid flow regime near the deformation front. This study illustrates several major and potentially important effects strike-slip faults may have on fluid flow, state of stress, and structural development in accretionary wedges.

TECTONIC SETTING AND STRUCTURAL FRAMEWORK OF THE DIVE AREA

We focused on a region of ~12 km^2 at the base of the central Oregon continental slope at 45°08′N latitude, just on the southern edge of the Astoria fan (Fig. 1). The Oregon subduction complex is characterized in this region by young subducting oceanic crust (ca. 9 Ma) converging at a rate of 39 mm/yr along a vector of 069° (calculated from NUVEL-1 relative motion poles of DeMets and others, 1990). Owing to copious clastic sediment influx from the mouth of the Columbia River and the Oregon coastal mountains, and the relative youth of the subducting crust, the central Oregon subduction boundary lacks a distinct bathymetric trench and is at maximum water depths of only 2,500–2,900 m. At the deformation front, the downgoing slab is covered by 3.5 to 4 km of hemipelagic and trench turbidite sediments (Kulm and others, 1984).

The initial offscraping and accretion of sediment in the Cascadia subduction zone occurs in broad domains of either landward- or seaward-vergent thrusting (Silver, 1972; Kulm and others, 1973; Carson, 1974; Snavely and others, 1986). We use "vergence" to refer to the direction of transport of the overriding thrust sheet, following the usage of Seely (1977) and MacKay and others (1992). Most of the southern part of the Oregon margin is dominated by the seaward-vergent thrusting typical of most accretionary wedges (Snavely and others, 1986; MacKay and others, 1992). Beginning ~30 km south of our study area, however, a major and abrupt shift along strike to dominantly landward-vergent thrusting takes place (MacKay and others, 1992). This landward-vergent style has developed for tens of kilometers along strike to the north, and recurs along the northern Oregon and Washington margins (Silver, 1972; Carson, 1974; Seely, 1977). Approximately 100 km west of the Oregon coast, at 45°N latitude, accretion is very well imaged by new MCS data (Fig. 2). On MCS line OR-26 (Fig. 2A), landward-vergent thrusting appears to sole into a décollement level close to the top of oceanic crust (within ~0.25 s, or ~400 m, above basement), much deeper than in the seaward-vergent domain to the south; thus, in the landward-vergent area, nearly all of the ~4 km of sediment is frontally accreted to the wedge (MacKay and others, 1992). The cross-strike structure shown in Figure 2A is typical of the region in that the most seaward two or three thrust sheets are coherently landward vergent, show little internal deformation, and have developed two to three successive anticlinal ridges, with an average spacing of ~10 km.

MacKay and others (1992) found no clear evidence that changes in sediment thickness or type, basement character or dip, or other features explain the sudden change of dip direction of the thrusts in this region. The origin of coherently developed landward-vergent thrusting, as discussed by Seely (1977), remains enigmatic. He proposed that a necessary—though not *sufficient*—condition for the development of landward vergence is very low basal shear stress caused by near-lithostatic fluid pressure at the potential décollement horizon, sufficient to reduce the effective normal stress to near zero. Evidence from basinal sediments suggests that rapid deposition of trench sediments is capable of generating this overpressure (Hunt, 1990); lateral tectonic compression also may play a significant role. This low shear stress condition would, however, result in the development of both conjugate faults: that is, neither landward nor seaward vergence would be favored. In the absence of a more complete explanation, landward vergence is at least considered strong evidence for the presence of highly elevated fluid pressures on the décollement. Without such elevated pressure, shear stress at the incipient décollement level would introduce an asymmetry to the conjugate pair of potential thrust faults, favoring motion on the more gently inclined landward-dipping (seaward-vergent) fault (Seely, 1977).

The inference that high pore pressure exists in accretionary wedge décollement faults is supported by several observations, including, wedge taper (Davis and others, 1983); direct observations by drilling at Barbados (Biju-Duval and others, 1984); and reversed polarity reflections in seismic data, also from Barbados (Bangs and Westbrook, 1991).

In addition to thrusts and associated anticlines, a distinctive system of oblique structures is developed in the region of the deformation front off central Oregon. In SeaBeam bathymetry and MCS data, MacKay and others (1992) found two distinct sets of near-vertical strike-slip faults, one northeast-striking and the other northwest-striking. The northeast-striking faults, which have right-lateral offset, are confined to the deforming sediments of the overriding plate and are apparently tear faults, bounding areas of differential displacement (MacKay and others, 1992). In contrast, the northwest-trending, steeply northeast-dipping strike-slip faults deform lower plate sediments and basement, extend

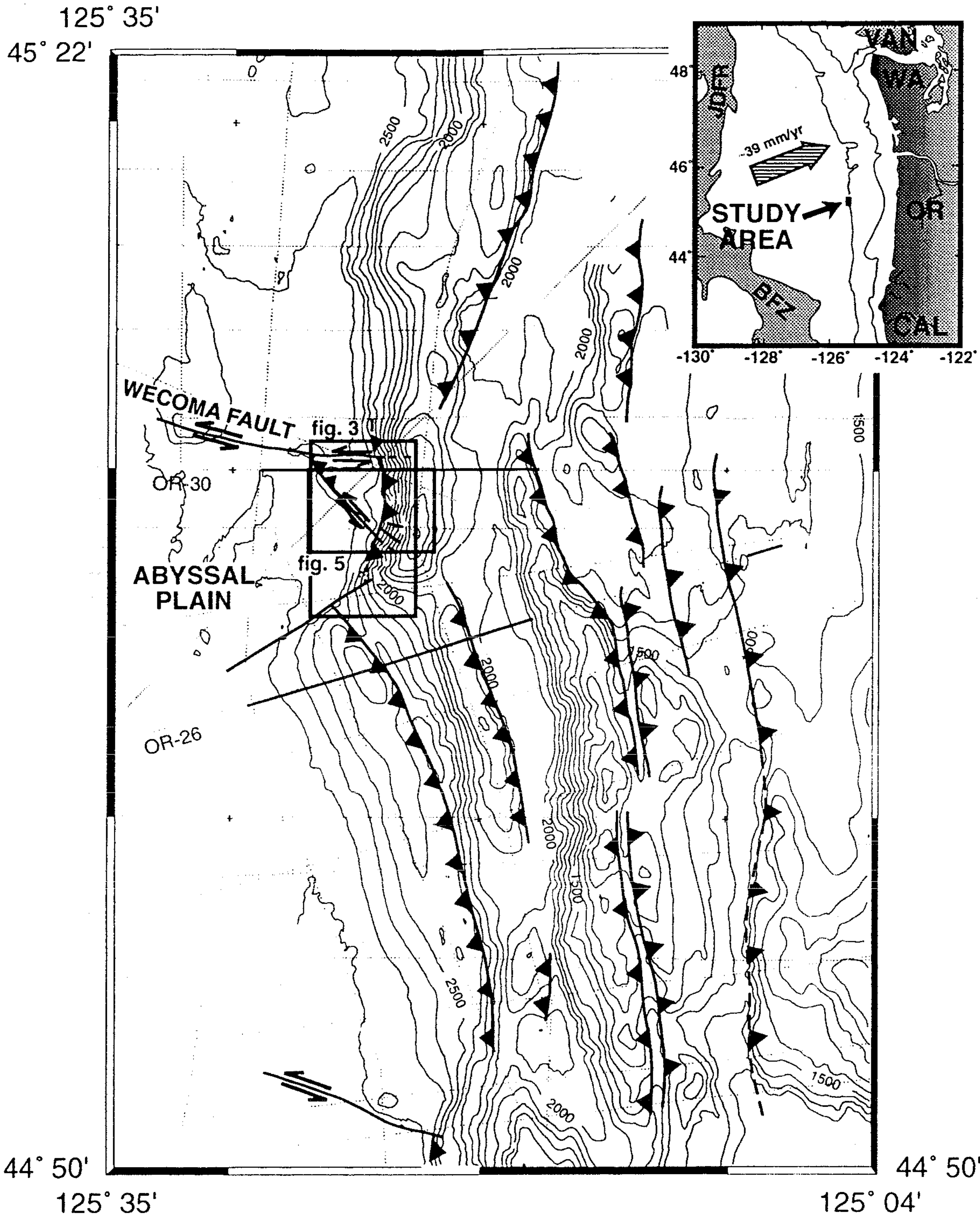


Figure 1. Map of the toe of the Oregon accretionary wedge in a region dominated by landward-vergent thrusting, showing SeaBeam bathymetry (in meters), major thrust faults, location of seismic lines in Figure 2, and the locations of Figures 3 and 5. Note the thrust-vergence reversal where the Wecoma fault intersects the thrust front (see Fig. 5). JDFR = Juan de Fuca Ridge; BFZ = Blanco Fracture Zone. Stippled lines show multichannel seismic (MCS) tracklines.

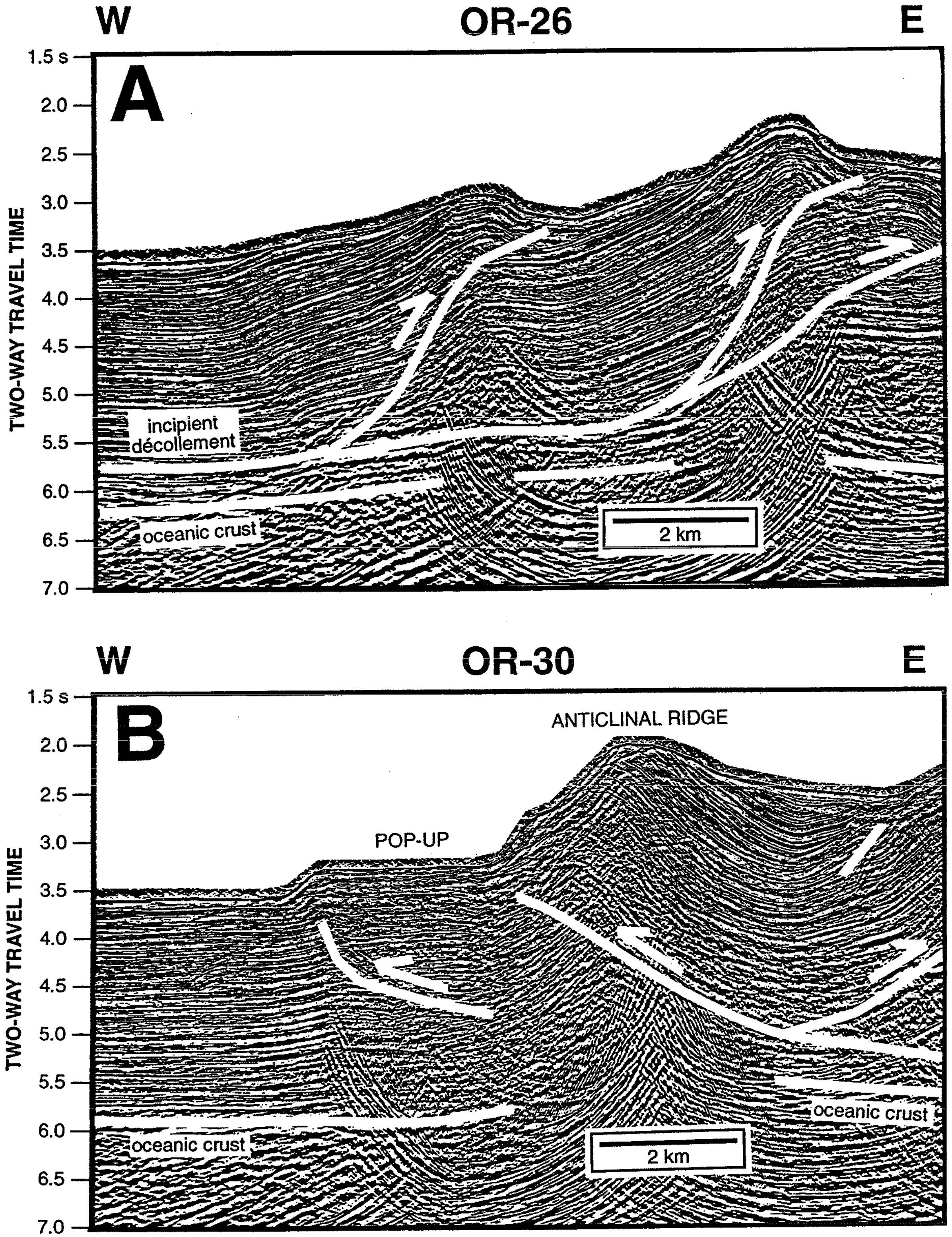


Figure 2. Migrated MCS data showing accretionary styles at the central Oregon margin. Vertical exaggeration at sea floor is 2×. (A) Line OR-26, exhibiting landward-vergent accretion near deformation front, is typical of the northern Oregon margin (see Fig. 1). Frontal thrust soles into a décollement at ~0.25 s above oceanic crust. Landward vergence implies low basal shear stress and high fluid pressure at the décollement horizon. (B) Line OR-30, showing development of seaward-vergent thrusting where the Wecoma fault intersects the deformation front.

tens of kilometers seaward of the present-day deformation front, and are presently active with components of sinistral and contractile displacement (Goldfinger and others, 1992). The northernmost of these faults, the Wecoma fault, has been the subject of a detailed sidescan study (Applegate and others, 1992). It intersects the continental slope at 45°08′N latitude (Fig. 1). This fault extends at least 18 km seaward of the present deformation front, cuts to the base of the sedimentary section, and offsets oceanic crust in the soon-to-be subducting slab. The Wecoma fault also offsets sea-floor features such as submarine channels, indicating Holocene activity. Seaward by 3 km of the thrust front, the Wecoma fault splays into two diverging active traces (Fig. 1). These two traces bound a pop-up wedge, visible in bathymetry and the SeaMARC image (Goldfinger and others, 1992).

The SeaMARC image (Fig. 3) also has several northwest-trending, parallel, small canyons, or "gullies," developed across the seaward flank of the first anticlinal ridge, within a large circular embayment in the ridge slope. These gullies are in an area bounded by the extension of the two major traces of the Wecoma fault. The gullies typically extend hundreds of meters obliquely across the steep slope of the ridge. Because they do not trend directly downslope and are predominantly parallel to each other and the regional trend of the Wecoma fault, we conclude that these canyons are structurally controlled. Following Goldfinger and others (in press), we interpret these gullies as the probable surface traces of splays of the Wecoma fault that have been incorporated into the hanging wall of the frontal thrust.

On MCS line OR-30 (Fig. 2B), the main frontal thrust is seaward vergent where the Wecoma fault intersects it, in contrast to the regions along strike to both north and south where frontal accretion is uniformly landward vergent (Fig. 1). This distinct structural domain of seaward-vergent frontal thrusting is developed for ~7–8 km along strike. The transitions to landward vergence on the northern and southern ends of this thrust are somewhat defined by the bathymetry and MCS data. Between 2 and 10 km to the north of line OR-30, the seaward-vergent thrust appears to die out into a symmetric anticlinal fold, beyond which landward vergence resumes. Approximately 5 to 6 km to the south of line OR-30, the sea-floor morphology and MCS lines suggest that a northeast-trending dextral tear fault forms a sharp boundary to the domain of anomalous reversed vergence (Fig. 1). This region, where the surface traces of the fault splays are apparently exposed in the embayment, and where anomalous seaward-vergent thrusting takes place, was the focus of the 1990 *Alvin* dive series undertaken for this study.

ALVIN DIVE PROGRAM

Six *Alvin* dives were conducted in the study area (Figs. 4 and 5). Four of these dives concentrated on documenting fluid expulsion and structure in and around the gullies trending parallel to the strike-slip fault trend, one dive (2274) investigated the strike-slip fault seaward of the frontal thrust, and one dive (2278) traversed upslope 1 km to the north of the gully region, in a region lacking evidence for fault splays. Evidence for active and recently active fluid flow at the surface of the wedge (Figs. 6 and 7) includes (1) biological communities associated with fluid seepage (Fig. 6A: *Calyptogena* sp. and *Solemya* sp. clams, vestimentiferan tubeworms *Lamellibrachia barhami*, and bacterial mats; Suess and others, 1985), (2) carbonate crusts or pavements (Figs. 6C and 7B: Ritger and others, 1987; Kulm and Suess, 1990), and (3) carbonate veins in exposed outcrops (Figs. 6B and 7).

Clam shells observed on the sea floor were partially dissolved, and the sandstone outcrops exhibited cavernous weathering, suggesting calcite dissolution. All dive sites are probably below the local calcite compensation depth due to coastal upwelling (Karlin and others, 1992). Thus, the precipitation of carbonate derives solely from methane-enriched fluids expelled from the wedge (Kulm and others, 1986).

During *Alvin* dives, we collected structural data, mainly bedding attitudes and fault and fracture orientations. Outcrop exposure in the study area is good, with numerous vertical and blocky exposures as much as 20–30 m high interspersed with areas covered by hemipelagic drape. We measured attitudes using hand-held compasses inside the submersible. Analysis of errors in orientation measurement due to magnetic and/or optical effects suggests that the strikes and dips are good to within about 5° (see J. C. Moore and others, 1990). To test accuracy, we made several orientation measurements on bedding using a digital compass placed directly on bedding surfaces using the mechanical arm of the submersible. These orientations were within 3° of our handheld ones at the same sites. We were able to locate structural data and seepage sites accurately on SeaBeam bathymetric maps with *Alvin*'s bottom transponder navigation. By integrating the geological and fluid-seepage information with the MCS data, we interpreted the structure and seepage geometry of the study area, illuminating the relationship between fluid expulsion and the development of anomalous seaward vergence.

STRUCTURAL DATA AND EVIDENCE FOR FLUID FLOW

A. Structural Data

We measured 128 structural attitudes during the six dives; however, only the 53 orientations for which we have a high degree of confidence are shown in Figure 5. The orientations measured from *Alvin* exhibit a clear change in structural style from dive 2278 into the gullied zone to the south, evident in the stereograms of poles to bedding. Bedding at dive 2278 strikes parallel to the slope, thus parallel to the strike of the frontal (seaward-vergent) thrust. At levels below about 1,700 m (two-thirds of the way up the slope), bedding dips 10°–40° landward. Above this level, dips are consistently 15°–25° seaward with similar strike. This geometry is best explained by imbrication along a piggyback thrust within the hanging wall of the main frontal thrust (Fig. 8). Bedding has ramped up on the frontal thrust, causing the eastward dips on the lower slope. The westward dips on the upper slope are explained by another thrust (perhaps a splay of the lower one), forming a fault-propagation anticline of which the seaward limb is now exposed by erosion of the slope.

The strike of bedding becomes less uniform in the gullied region to the south, but it progressively rotates into a northwest-southeast trend, parallel to the strike-slip fault (Fig. 5). Dips are consistently to the southwest within the gullied area, varying between 16° and 45°. The pattern of bedding attitudes in this region suggests that the simple thrust-related folding style developed to the north has been disrupted. The shift in attitudes coincides with the location of the gullies; furthermore, strikes appear to become progressively more parallel to the Wecoma fault trend with increasing distance south in the gullied area. These observations indicate that significant deformation has taken place along the trend of the strike-slip fault in the hanging wall. There is a rotation of 23° ± 6.9° (at 95% confidence) between the average poles to bedding of the northern and southern dive areas (Fig. 5).

Several alternative sequences of deformation are consistent with the observations. (1)

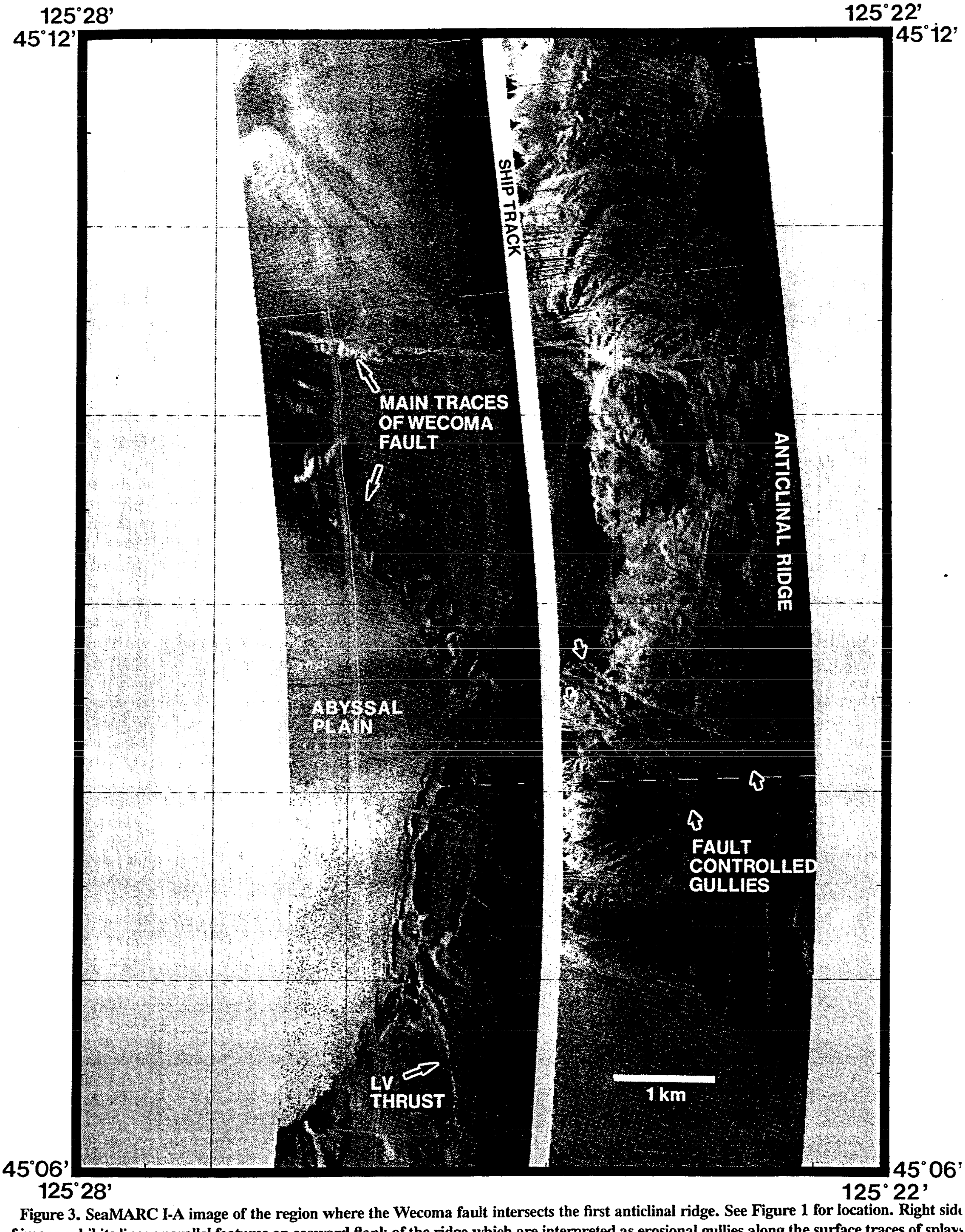


Figure 3. SeaMARC I-A image of the region where the Wecoma fault intersects the first anticlinal ridge. See Figure 1 for location. Right side of image exhibits linear parallel features on seaward flank of the ridge which are interpreted as erosional gullies along the surface traces of splays of the Wecoma fault. *Alvin* dives discussed in this paper concentrated on these gullies.

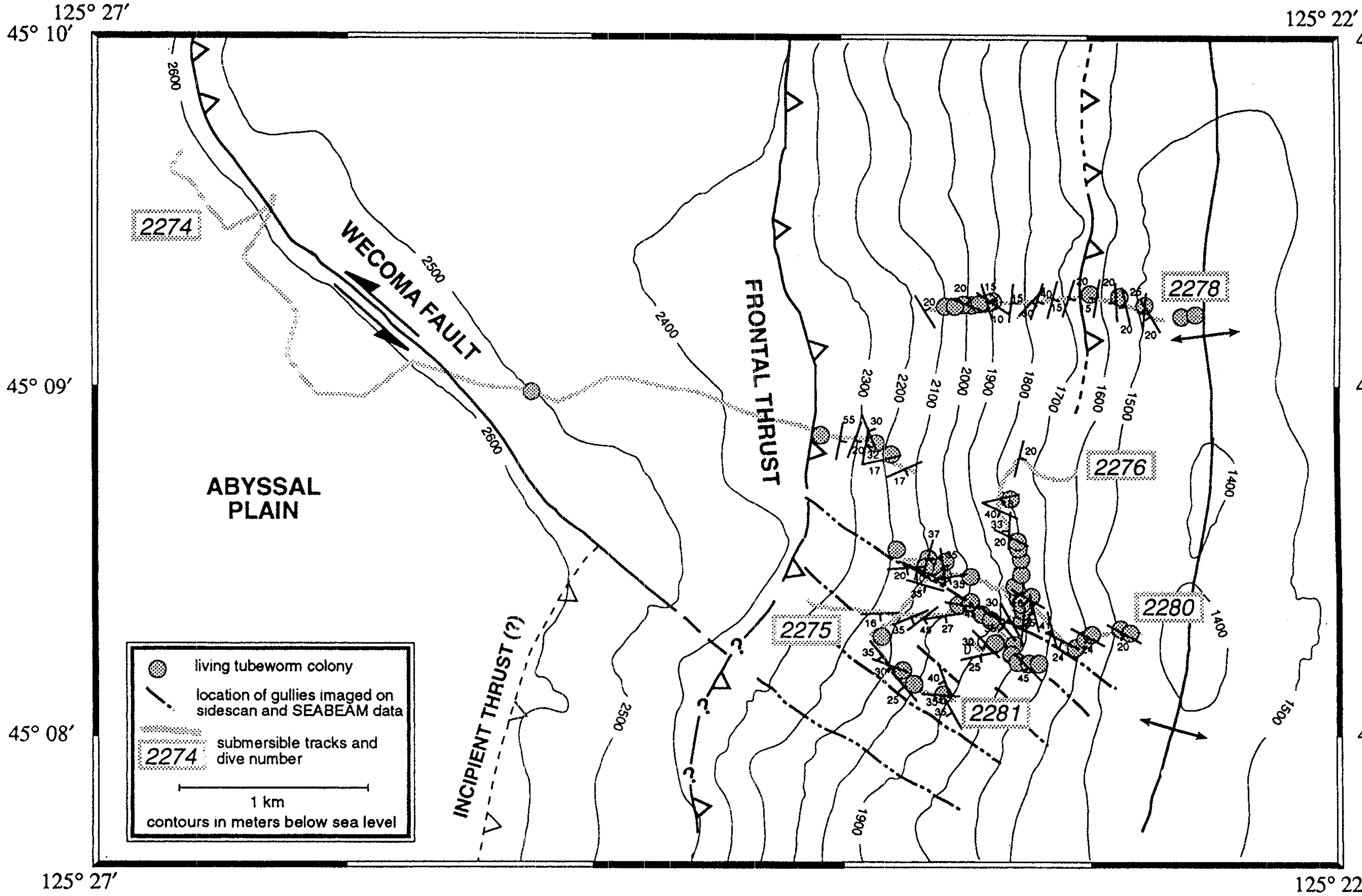


Figure 4. Map of dive tracks, biological communities associated with active fluid seepage, and geologic data collected during all *Alvin* dives. Base map is SeaBeam bathymetry. Each stippled circle represents a tubeworm colony ± clams with chemosynthetic symbionts.

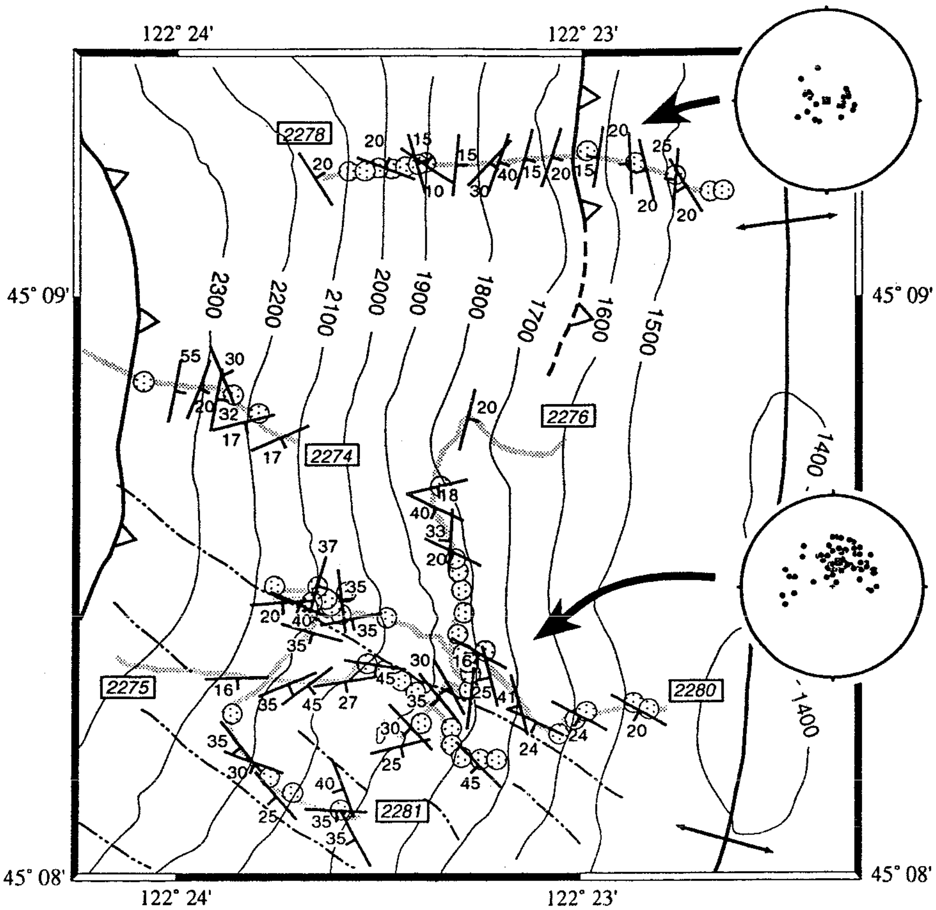


Figure 5. Detail of Figure 4 with selected bedding attitudes in the dive areas. Some data are not shown for clarity. Stereograms are equal-area, lower-hemisphere projections depicting poles to bedding (circles) and best-fit mean pole (filled square) for *all* measured orientations split into two domains: the strike-slip fault area, and the northern transect area, which includes dives 2278 and 2274.

Bedding that strikes north-south due to backtilting by thrusting has been subjected to drag folding in right-lateral shear along the Wecoma fault trend. (2) Bedding is backtilted as above, then subjected to oblique or vertical motion on steeply dipping faults in the gully area, with a down-to-the-south sense of motion. (3) Initially flat-lying sediments are thrust southwest up an oblique lateral-ramp thrust. We favor alternative 2; it is the simplest and agrees best with regional structure and bathymetry. The Wecoma fault is clearly left-lateral on the abyssal plain (Appelgate and others, 1992), so that significant right-lateral displacement on the ridge appears unlikely. The bathymetric ridge formed by the anticline above the frontal thrust dies out to the south, starting at the gullied zone, forming a pronounced saddle or depression in the bathymetry (Fig. 1). This feature is consistent with down-to-the-south normal or high-angle reverse faulting. Outcrop-scale faults observed on dives in the gullies consistently exhibit apparent normal displacement.

The evidence cited above strongly suggests that the strike-slip–fault splays deform not only the downgoing plate, but also the hanging wall of the frontal thrust. It is not clear whether this deformation is indicative of throughgoing left-lateral faulting or, alternatively, reactivation of an inherited existing plane of weakness with oblique or vertical motion during and/or after incorporation into the hanging wall. Whichever is true, the splays clearly continue to be active structures after accretion. Attitudes collected on these dives thus define two distinct structural domains, which we will hereafter refer to as the "northern area" and the "strike-slip–fault area" respectively.

B. Fluid Seepage Features

Mapping of sites where fluid actively seeps from the wedge surface reveals a distinctive pattern with respect to the structural framework. All observed sites of living, in-place, chemosynthetic biological communities are mapped in Figure 4; these observations are only what we can see from the very limited vantage of the submersible (visibility is ~10 m to either side) and are thus sporadically sampled. Nevertheless, the overall distribution of seepage sites, including their conspicuous absence in some locations, delineates a clear variation between the two structural domains defined in the previous section. In the northern area (dive 2278), seepage sites may be divided into two subsets: respectively, the lower- and upper-slope groups. The lower-slope group includes nine distinct seep communities with tubeworms and clams present, as well as frequent observations of individual scattered clam shells. These seep communities are rooted directly into outcrop exposures of sandstone and seem to be preferentially located where massive, relatively coarse-grained sand crops out and where the slope is steepest, that is, where there is the least slope cover on the outcrop. The lack of seep communities upslope of ~1,950-m depth on dive 2278 appears to coincide with a transition to a finer and more thinly bedded rock, suggesting local stratigraphic control of the fluid flow. Above this barren zone, the upper cluster of five observed seeps is located at and above the abrupt transition from east-dipping to west-dipping strata. These biological communities are more scattered and less numerous than those downslope.

The only other evidence of fluid seepage observed on the northern transect (dive 2278) was intermittent occurrences of carbonate crusts (not shown in Fig. 5) and the presence of calcite veins in two localities (at ~2,040-m and 1,968-m depth), both directly associated with seep communities (Fig. 6A). Besides folding, evidence for fault-related deformation, such as pervasive vein-filled fractures or outcrop-scale faulting, was completely absent on this dive. These observations are consistent with a pattern of fluid flow to the surface of the wedge controlled by stratigraphic conduits, perhaps combined with flow along the plane of the upper thrust.

The evidence of fluid flow in the strike-slip–fault area to the south presents a significantly different pattern. First, we observed fluid seep communities at all bathymetric levels on the slope, in contrast to the presence of the barren zone from 1,900 to 1,650 m in the

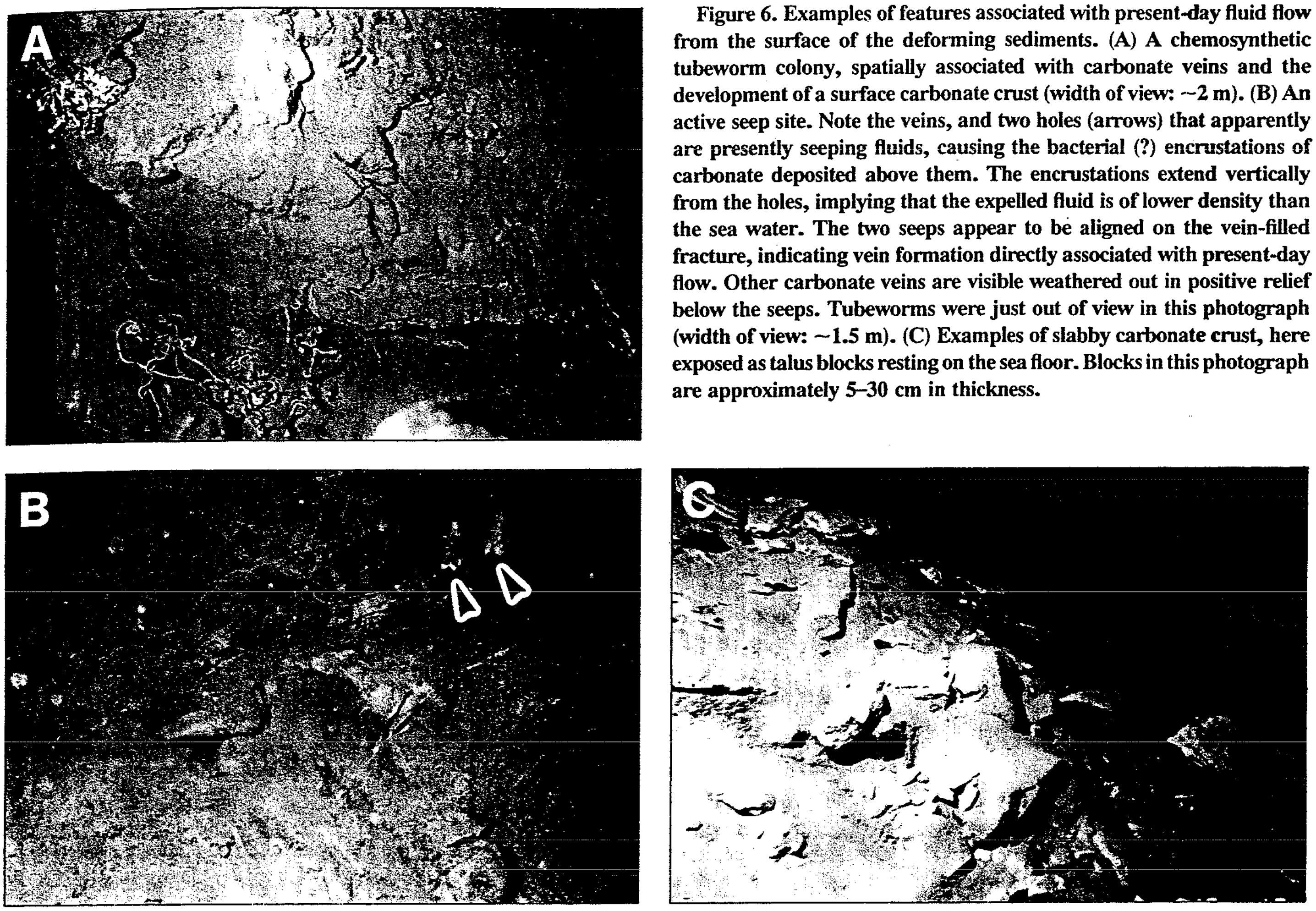
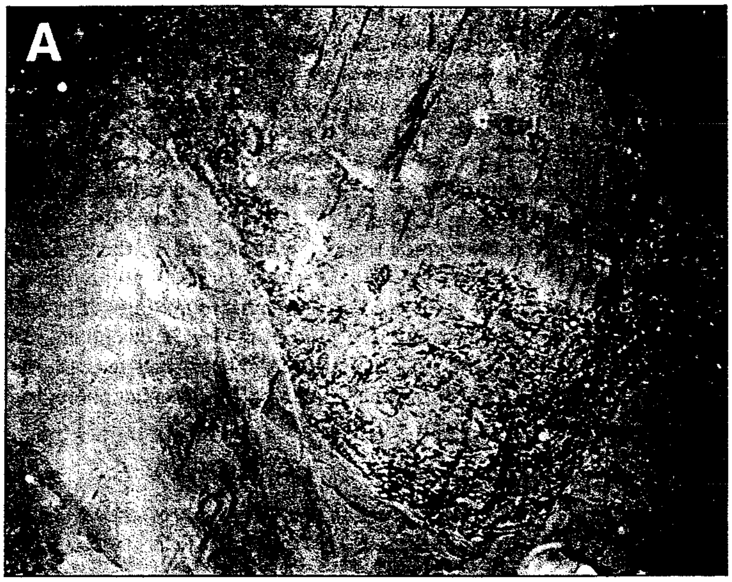


Figure 6. Examples of features associated with present-day fluid flow from the surface of the deforming sediments. (A) A chemosynthetic tubeworm colony, spatially associated with carbonate veins and the development of a surface carbonate crust (width of view: ~2 m). (B) An active seep site. Note the veins, and two holes (arrows) that apparently are presently seeping fluids, causing the bacterial (?) encrustations of carbonate deposited above them. The encrustations extend vertically from the holes, implying that the expelled fluid is of lower density than the sea water. The two seeps appear to be aligned on the vein-filled fracture, indicating vein formation directly associated with present-day flow. Other carbonate veins are visible weathered out in positive relief below the seeps. Tubeworms were just out of view in this photograph (width of view: ~1.5 m). (C) Examples of slabby carbonate crust, here exposed as talus blocks resting on the sea floor. Blocks in this photograph are approximately 5–30 cm in thickness.

northern area. More individual active sites are present in the strike-slip-fault region than anywhere outside of it, even when normalized per 500-m intervals of dive track to correct for the varying number of dives devoted to each region (Figs. 9A and 9B). Thus, the concentration of biological communities is denser in areas in, or proximal to, the gullies than it is on areas of the slope distal to the gullies. Figures 5 and 9 also show the difference in the degree of clustering of seep sites within, and outside of, the strike-slip–fault zone. In the strike-slip–fault area (Fig. 9A), only one 500-m length of dive track lacks biological communities; but outside the fault area (Fig. 9B), five out of ten of the intervals lack communities. Out of all the dive tracks outside the strike-slip–fault region, one 500-m interval accounts for 9 out of 21 sites. Within the strike-slip–fault area, seep sites are more pervasively distributed; outside this area, sites are more concentrated into one or two specific areas.

For comparison, in Figure 9C we include data from another seaward-vergent section 50 km to the south which has not experienced strike-slip faulting (J. C. Moore and others, 1990). It has very few fluid seep sites on the eroded seaward flank of the first anticlinal ridge; seepage is concentrated in a few large, well-developed (compared to those of the present study) sites on the landward flank. The number of seep sites on the anticlinal ridge is thus much less in this "control area" (even though the volume of fluid expelled regionally may be about the same).

Fluid seepage from the strike-slip–fault zone is associated with structural and geomorphic features indicative of faulting. Four major observations support this interpretation. (1) In nearly all cases, the evidence of seep communities is found in the bottoms or walls of the gullies, rarely on the sea-floor slopes or local ridges between them. All tubeworm colonies observed in this region root into the gully walls or floor. (2) Observations of steeply inclined vein-filled fractures are typically associated with the locations of well-developed seep biological activity. Outcrop observations indicate intense vein formation (Figs. 6B and 7B) and evidence of fracturing and development of cataclastic shear zones in the gully exposures. By contrast, these features are rarely developed at seep sites to the north. Evidence of intense veining or fracturing was observed at only 1 of the 14 seep sites on the northern transect. (3) In several locations seeps in the gullies are associated with observed outcrop-scale minor faults with apparent normal offsets. (4) Carbonate crust precipitates are pervasively developed in the south, present both in the gullies and on the ridges and slopes between them. These crusts (Fig. 6C) are composed of a micritic carbonate, predominantly Mg-calcite (J. C. Sample, 1992, personal commun.), which probably formed just below the sediment-water interface where methane and CO_2-charged fluid rising through the sediments react with sea water to form $CaCO_3$ (Ritger and others, 1987). The resistant crusts typically are a few to a few tens of centimeters thick. Accumulations of talus blocks of the carbonate crust are in, and downslope of, all of the gullies we investigated (Figs. 6C and



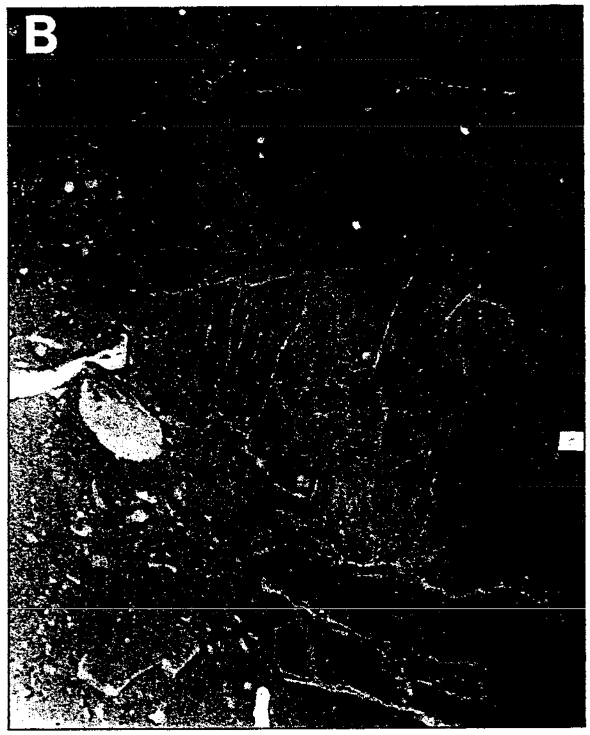


Figure 7. Examples of the association of fluid flow with structural features. (A) Gully wall exposure of minor fault offset in pebble conglomerate lenses. Fault surface appears to have carbonate fill, and vein-filled fractures branch off from the main fracture plane (width of view: ~3 m). (B) Regular system of vein-filled fractures exposed in a gully wall. Camera orientation looks down and forward at the rock surface. Left side of the view is the talus-filled gully floor; right side is the bedrock wall (width of view: ~2 m).

7B). At least two of the gullies we studied exhibit apparent *in situ* formation of the carbonate precipitate on the gully floor at the present-day surface, cementing the talus pebbles and blocks into a well-indurated conglomerate, which clearly extends along the trend of the gully and is confined to a narrow (1–2 m) zone on the floor. The crusts are closely associated with regions where biological communities are most strongly developed, indicating that both are associated with active seepage. The association of biological communities, carbonate precipitates, and carbonate veins in the same locations demonstrates the ongoing nature of fluid flow and relative stability of these sites.

The intensity, structural association, and surface pattern of fluid expulsion varies mark-

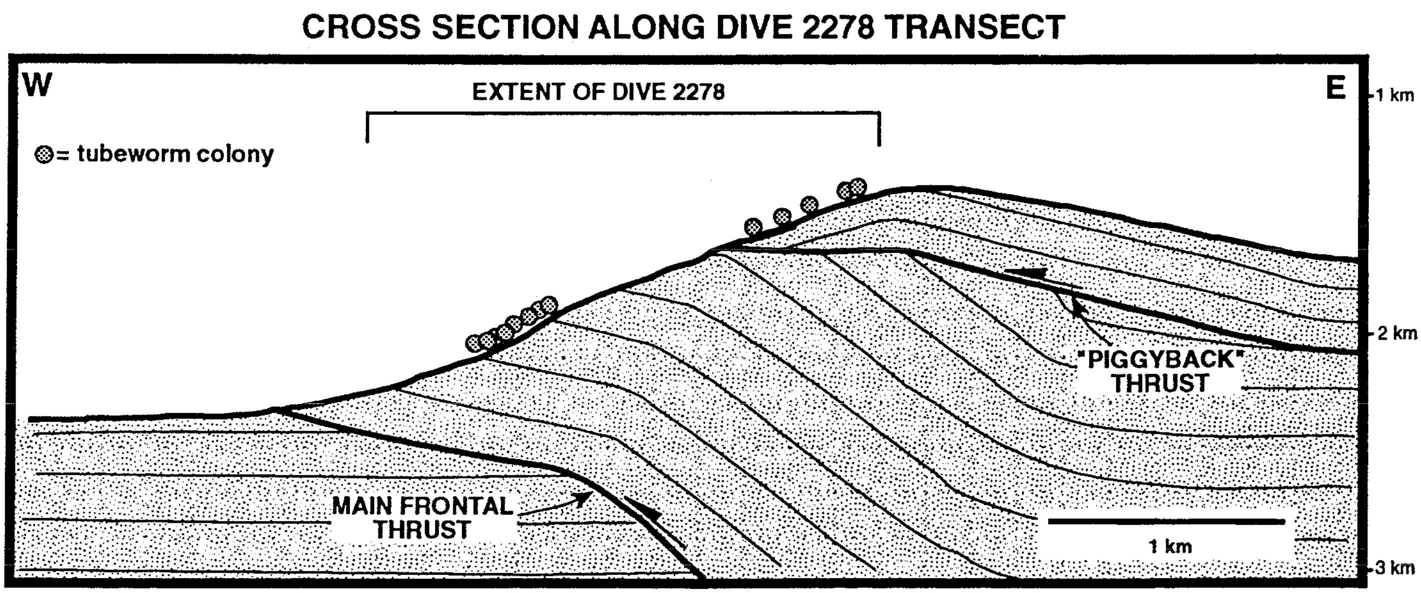


Figure 8. Interpretive cross section of structure along the track of dive 2278, based on attitudes measured during the dive, and interpretation of nearby seismic data. Vertical scale is depth below sea level. Locations of tubeworm colonies on the section suggest stratigraphic and thrust-bounded fluid seepage. Dive 2274 suggests that seepage may also take place on and above the frontal thrust, which was not visited on 2278.

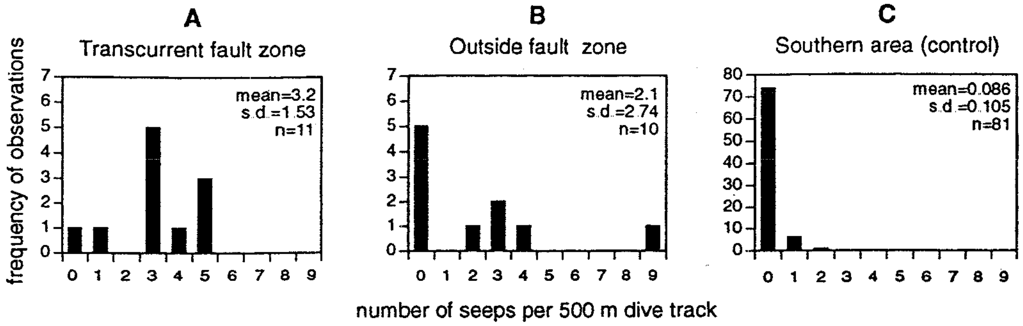


Figure 9. Histograms depicting the distribution and relative frequency of seep biological communities (A) within and (B) outside the system of gullies associated with the Wecoma fault, and (C) in a seaward-vergent region 50 km to the south investigated in previous studies (data from J. C. Moore and others, 1990), used here as a control. The dive tracks have been broken into 500-m intervals. "Frequency of observations" is the number of 500-m intervals containing a given number of communities. Note the wider distribution of seeps in the fault zone, as opposed to the higher degree of clustering of seep sites outside the fault zone. Also note the change in scale in C, where seepage is concentrated into a few sites.

edly between the two structural domains. We conclude that the strike-slip fault zone forms a significant conduit for fluid flow to the surface of the wedge, replacing the otherwise prevalent mode of fluid expulsion along stratigraphic conduits and thrust faults with a new one dominated by fluid escape through high-angle faults associated with the Wecoma fault system.

DISCUSSION

A. Generation of Fault-Parallel Permeability

The two main mechanisms that have been proposed to explain the enhancement of permeability in fault zones are reduced tortuosity of flow paths due to the alignment of phyllosilicates (Arch and Maltman, 1990) and the generation of fracture permeability preferentially in the plane of the fault, with associated sealing perpendicular to the fault plane due to the smearing of clay mineral grains (K. M. Brown and J. C. Moore, 1992, personal commun.). Brown and Moore have obtained experimental evidence that only fracture permeability is capable of enhancing permeability sufficiently to focus fluid along faults. The generation of fracture systems in a fault plane is not sufficient to enhance permeability by several orders of magnitude; the fractures also need to dilate, enhancing fracture porosity.

Sibson (1981) and Behrmann (1991) presented a mechanism whereby simultaneous shear failure and extensional opening by hydraulic fracturing could occur under low effective stress conditions in sediments with low (but non-zero) cohesion and tensile strength, typical of accretionary wedge sediments. The development of tensile fractures by hydraulic opening of fractures is an efficient means of enhancing permeability by orders of magnitude.

Conditions for hydrofracture are given by

$$p = \sigma_3 + t$$

where p is the pore pressure, σ_3 is the least principal stress, and t is the tensile strength of the rock. Thus, the magnitude of principal stresses determines the fluid pressure necessary to either cause hydrofracture in intact rock or reopen existing fractures. We assume that one of the principal stresses is vertical, reasonable for faulting near a free surface. The magnitude of the least principal stress varies systematically in the three different Andersonian faulting regimes owing to the forces generating the stresses (Anderson, 1957). For example, in a thrust-mode stress regime, σ_3 is vertical, and σ_1 is near horizontal. Thus σ_3 is equivalent to the lithostatic overburden load, whereas σ_1 is a tectonic compressional stress. By contrast, in a normal-fault stress regime, the vertical overburden stress is σ_1, and σ_3 is by definition less than the lithostatic stress. Strike-slip faults represent the intermediate case, where σ_1 and σ_3 are horizontal and σ_2 is vertical.

By combining the Coulomb equations for hydrofracture and those for shear failure in each of the three Andersonian principal stress orientations, the fields of potential hydrofracture during shearing can be delimited (see Sibson, 1981, for development of the equations). This relationship is depicted in a graph of depth versus λ (Fig. 10), where λ is the overpressure ratio, or pore pressure/lithostatic pressure. To produce this graph we have modified Sibson's (1981) equations to account for realistic variations in cohesion and tensile

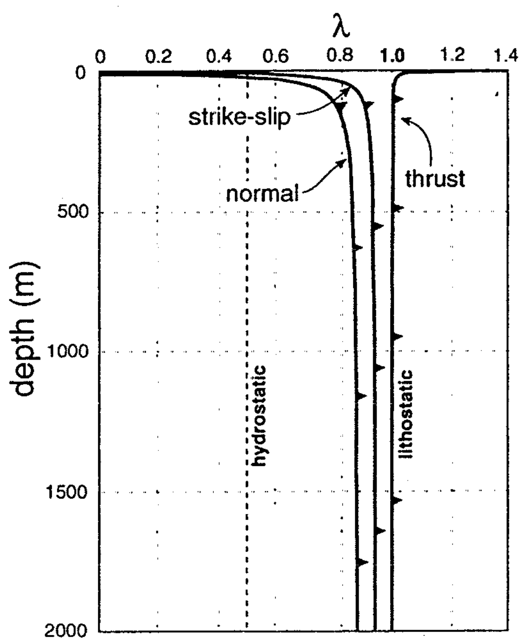


Figure 10. The fields of potential hydrofracture for each faulting mode as a function of pore pressure ratio (λ) versus depth below the surface of the wedge. Barbs on the curves point to fields where simultaneous hydrofracture and shear failure will occur. These curves are modified from Sibson (1981), applying empirical values (from Nankai wedge) for cohesion, tensile strength, coefficient of friction, and density for trench turbidites in early stages of accretion. Note that the normal and strike-slip mode curves approach a lower critical pore pressure at depth than does the thrust mode curve. Lithostatic pore pressure is not required for hydraulic fracture of a strike-slip fault at any depth. See text for values and further discussion.

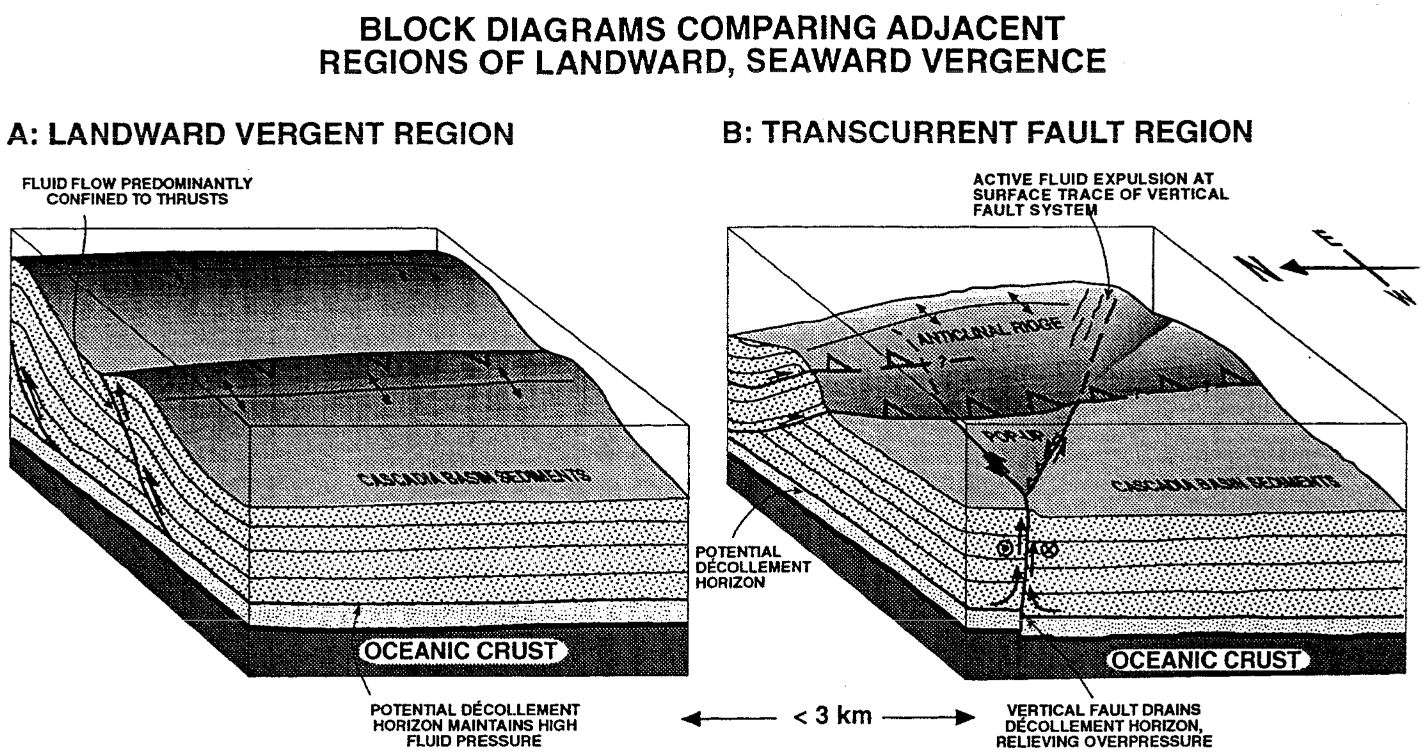


Figure 11. Schematic block models illustrating the change in structural development caused by the effect of the Wecoma fault as it interacts with the thrust front. Block A illustrates the landward vergence typical of the region. Abnormally elevated (near lithostatic) fluid pressure develops in the rapidly accumulated trench sediments and is maintained in the décollement horizon as thrust deformation begins. In block B, the strike-slip fault provides a favorable fluid conduit to the surface, perhaps due to the strike-slip stress regime, which allows tensile fracturing due to the high fluid pressure deep in the wedge. The "draining" of built-up fluid pressure on the décollement, in turn, increases basal effective shear stress and forces the development of a seaward-vergent thrust.

strength in the trench wedge sediments being incorporated into the accretionary wedge. We allow cohesion to vary linearly with depth, using the relation experimentally derived by Karig (1986) from cores of DSDP site 583 in the Nankai trough, such that $C_0 = 70 + 0.85z$ (C_0 is cohesion in kPa, z is depth in meters). Sand also dominates in the Nankai sediments, which represent the nearest analog for which data on mechanical properties are available. The Oregon sediments may differ significantly due to greater cementation. Tensile strength t was arbitrarily fixed at 10% of cohesion on the assumption that t of fractured rock would be very small compared to cohesion (Sibson, 1981).

It is evident from Figure 10 that for thrust mode faulting, λ must be > 1 for all depths and stress magnitudes in order for hydrofracture to occur at all. In other words, in order to cause tensile failure in this stress regime, the pore pressure *must* exceed lithostatic; however, for a strike-slip fault, σ_3 is less than the overburden stress (σ_2). Thus, λ may be significantly <1, and hydrofracture may occur under pore pressures closer to hydrostatic. At burial depths to 2 km and greater, hydrofracture could occur with $\lambda = 0.93$.

The net result is that tensile fracture dilatancy is much more likely in normal or strike-slip systems than in thrust systems. Note that this argument does not require true hydrofracture opening in the optimally oriented plane perpendicular to σ_3 but could dilate existing fractures at an angle to the principle stresses if these fractures are sufficiently weaker than the intact rock. Thrust faults can maintain higher λ ratios without dilation of fractures, thus they are able to sustain high pore pressure, low effective stress conditions. Platt (1990) argued, from combined Griffith and Coulomb mechanics, that pore pressure in accretionary wedge faults must inevitably rise to lithostatic levels then be effectively buffered just below the tensile (hydrofracture) failure criterion under thrust stress orientation. Any rise in fluid pressure would cause hydrofracture and release of pressure, whereas a drop in pressure would seal fractures, preventing escape and thereby elevating pressure. Since normal and strike-slip faults may form tensile fractures under lower λ ratios, any near-lithostatic overpressuring developed in these faults would tend to be efficiently tapped and flow toward the surface along the fractures (Behrmann, 1991). If Platt's (1990) argument is correct, then inspection of Figure 10 leads to the conclusion that hydraulic fracturing *must* occur at the intersection of a strike-slip fault and the incipient décollement or frontal thrust.

In a strike-slip fault the tensile fracture planes would be aligned and vertically oriented due to the horizontal σ_3, providing a strongly preferred flow path in the plane of the fault. Thus fracture permeability is created in an orientation that strongly favors migration of fluid upward toward the surface of the wedge. These vertically oriented fractures would propagate toward the surface, with resistance to hydrofracture decreasing as depth decreases. Even as pressure drops during ascent, near-surface fracturing could occur given pressures as low as hydrostatic ones (Fig. 10).

We propose that this mechanism accounts for the observed fluid flow at the intersection of the Wecoma fault and the thrust front. Landward vergence is well developed regionally, indicating fluid pressure at the developing décollement horizon at or near lithostatic. The Wecoma fault has been shown to cut through the décollement horizon and probably into oceanic basement (Appelgate and others, 1992). If near-lithostatic pore pressures exist at the décollement horizon, then hydrofracture is bound to occur in the stress field associated with the Wecoma fault. Fluids being expelled at the surface thus may have a source at or below the décollement level, although fluid from shallower sources may also be incorporated.

A recent study of isotopic signatures preserved in carbonate cements sampled during these four dives in the strike-slip fault zone (J. C. Sample, 1992, personal commun.) supports the interpretation that fluids expelled from the gullies have deep sources. Sample obtained $\delta^{18}O$, $\delta^{13}C$, and $^{87}Sr/^{86}Sr$ ratios exhibiting coupled depletion in ^{18}O and high radiogenic strontium, ruling out detrital marine carbonate or shallow, normal sea-water sources for the fluids. The results strongly indicate that the fluids that precipitated the cement had experienced temperatures of as much as 100 °C, consistent with a minimum source depth of 2 km below the surface of the wedge (J. C. Sample, 1992, personal commun.).

B. Mechanism for Localized Thrust-Sheet Vergence Reversal

We propose that the presence of the Wecoma fault as an efficient fluid conduit out of the wedge causes the local inversion of thrust geometry around this fault intersection (Fig. 11). The structure has been somewhat simplified for clarity in these block models. Landward vergence (Fig. 11A) requires near-zero effective stresses on the incipient décollement horizon, probably due to high fluid pressure generated by rapid sedimentation in the trench (Seely, 1977; Hunt, 1990), perhaps augmented by lateral tectonic compression. In the thrust stress regime, this overpressure is effectively maintained in the fault plane.

Figure 11B illustrates how the Wecoma fault alters the fluid pressure and stress regime, thereby altering the conditions for thrust development. The interval of strike-slip–faulted sediment converges on the deformation front. Overpressured fluid from the developing décollement thrust causes fracture dilatancy in the high-angle fault system, and fluid is expelled toward the surface. The overpressure is reduced by the presence of this "drain," causing a local increase in effective basal shear stress. The incipient landward-vergent thrust ceases to move and a seaward-vergent one develops that dominates the accretion of the sedimentary section. Upon intersecting the deformation front, the strike-slip fault may gain a component of oblique or dip slip, but it continues to actively deform and expel fluid from deep sources. The resulting fluid-pressure reduction apparently affects the décollement level for ~4 km along strike in either direction, corresponding to the total extent of the seaward-vergent frontal thrust. Beyond this limit, to both north and south, the regionally normal landward vergence develops. The facilitated fluid expulsion we have demonstrated in the Wecoma fault thus appears to invert the geometry of frontal accretion at its intersection with the thrust front.

SUMMARY AND CONCLUSIONS

Off central Oregon, a significant change in the pattern and volume of fluid flow out of accretionary-wedge sediments occurs in a region where a basement-involved, near-vertical strike-slip fault in the abyssal plain sediments intersects the thrust front. MCS and bathymetric data indicate that this fault intersection is associated with the presence of an anomalous seaward-vergent thrust in a region dominated by landward-vergent accretion. Surface fluid seepage in the region of fault intersection occurs in and around a system of sea-floor gullies that we interpret as the surface expression of splays of the strike-slip fault. On the basis of mapping of the location of biological seep communities, veins, and carbonate precipitation, we find that this fluid expulsion is greater in volume than, and differs in surface pattern from, fluid flow out of nearby regions of the anticlinal ridge that are removed from strike-slip faulting. Seepage is directly associated with outcrop evidence for deformation in the strike-slip fault regime. On the other hand, fluid expulsion on the frontal ridge outside the strike-slip fault area is less extensive, is confined to stratigraphic and thrust-fault conduits, and is not associated with outcrop-scale fracturing or veins.

We believe that this high-angle fault zone acts as a preferred conduit for fluids, most likely due to the development of fault-parallel fracture permeability by hydrofracture and because its vertical orientation creates a short path to the surface. We argue that the development of a vertical plane of tensile fractures in this fault zone acts as a "drain" on the overpressured décollement horizon, tapping off that overpressure and allowing fluid to escape to the surface. If correct, this model suggests a mechanism for the local reversal of thrust vergence. The draining of fluid pressure from the basal sedimentary section would increase the effective normal stress, thereby increasing the basal shear stress. This change in stress condition would rotate σ_1 to favor the development of seaward vergence. The along-strike extent of the seaward vergence—only about 3–9 km—may indicate the area over which this pressure-reduction effect takes place. Although the development of landward vergence remains an enigma, these results define a sufficient condition to inhibit it, thus providing evidence that basal fluid pressure is a critical parameter governing the development of landward vergence.

This study provides the first direct evidence of a potentially important and previously unappreciated mechanism of efficient venting of pore fluids from sediments in the initial stages of accretion—the role of strike-slip faults, which are commonly developed in accretionary thrust systems. Strike-slip faults provide a more favorable environment for the development of enhanced fracture permeability than do thrust faults. Not only does this have far-reaching effects on the permeability structure, but also, as we have shown, potentially on the overall structural development of the wedge through the interdependency of fluid pressure, permeability, and effective stress. An analogous situation is likely in other fold-and-thrust settings. Future field studies on land in collision zones and continental overthrust belts would benefit from attention to evidence for past fluid flow and its relationship to structural development and geometry.

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