

Coastal Submarine Canyons

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Abstract. Roughly 20% of the shelf edge between Alaska and the Equator is interrupted by steep, narrow and abrupt submarine canyons. Such canyons have long been of interest to geological and biological oceanographers. Physical oceanographers have suggested that mixing, internal wave activity, upwelling and cross-shelf/slope transport are enhanced within submarine canyons and that waves may be generated or modified by the canyon topography. These processes may significantly affect mass balances on regional and even larger scales. For example, the existence of submarine canyons along the Pacific shelf edge provides up to 30% more coastline over which upwelling and/or mixing can occur. The state of our knowledge with respect to such processes is described in this paper and critical research areas are identified.

Measurements in submarine canyons are among the most difficult in the ocean to make and, until recently, models of submarine canyon circulation and their effects on regional circulation have been few and highly idealized. Thus, understanding both the circulation within submarine canyons and the effect of canyons on the large-scale coastal circulation is yet a relatively immature field. Considerable progress has been made recently towards understanding the interaction of the steep topography of coastal canyons with time-dependent, stratified coastal circulation. This progress is due to the availability of measurements over canyon flanks (as opposed to simply along the axis) and to the development of models that include both realistically steep and abrupt topography as well as a canyon shape (as opposed to, e.g., a channel). Results indicate that for incident flow with the coastline on the left (upwelling-favorable), downwelling of shelf water occurs over the upstream wall of the canyon and upwelling typically occurs over the canyon axis and over the downstream wall. Upwelling water flows shoreward within the canyon and exits at the head and along its downstream wall. In the upper water column, with realistic stratification and inflow conditions, the flow is directed essentially straight over the canyon. Cyclonic relative vorticity occurs on the upstream side of the canyon near the rim and anticyclonic, over the canyon axis and on the downstream side. The cyclonic vorticity is associated with shelf water that has fallen into the canyon. Nonlinear effects tend to sweep spatial patterns downstream. The deeper circulation is cyclonic for upwelling-favorable incident flow (in the northern hemisphere), a result of layer stretching during upwelling. In the one canyon for which the data adequately resolve the spatial structure of the velocity field over the canyon, results suggest that a Taylor-cap-like circulation pattern occurs for Rossby numbers below about 0.25. Closed streamlines have not been observed in model results for the cases examined to date. Although models suggest that enhanced mixing due to internal wave focusing within canyons and wave generation and modification by canyons should be important, evidence for such processes is either extremely limited or nonexistent.

Numerous questions remain. For example, under what circumstances is the circulation within a canyon closed? How does an incident flow with an undercurrent interact with a canyon? How does the specific shape of a canyon affect its interaction with the regional flow field? Are particles preferentially retained within canyons? How does the presence of a canyon impact the local and regional marine ecosystem? What is the effect of a canyon on regional mass and momentum balances?

Background

The shelf edge of many continental margins is interrupted at irregular intervals by submarine canyons. A typical coastal submarine canyon has scales similar to that of the Grand Canyon: ~10-30 km wide and ~2 km deep. Canyons may cut across the shelf all the way to shore, or they may barely indent the outer shelf. Coastal canyons have long been of interest to geological and biological oceanographers.

Measurements in submarine canyons are among the most difficult in the ocean to make. This is because most coastal canyons have extremely steep slopes, making it challenging to safely obtain CTD profiles and to

accurately deploy moored arrays over the slopes. Fishing activities often are intense over these same slopes so that it is difficult to maintain moored arrays in the water for extended periods. Last, the lateral coherence scales are very small—typically 10 km or less even along the canyon axis for both the monthly mean and the subtidal flow—so that arrays must be very heavily instrumented in order to delineate spatially coherent signals. Until recently, models of submarine canyon circulation and of the effect of canyons on the regional circulation have been few and highly idealized. For these reasons, the understanding of both the circulation within submarine canyons and the effect of canyons on the regional scale coastal circulation is a relatively immature field.

Fear of the complicating effects of submarine canyons has induced most researchers to make measurements outside their suspected range of influence. This was the case in the early 1970s and 1980s on the U.S. west coast when wind-driven dynamics were the focus of attention. In spite of purposeful selection against three-dimensional features, researchers usually failed to find two-dimensional mass balance. Consequently, during the 1980s, even straighter shelf-edge topography was selected for most field studies. A few field studies of canyons took place during the late 1970s and early 1980s. However, these studies were performed either by or with geological oceanographers, with a mind-set towards axial processes in canyons; for example, turbidity flows (e.g., Shepard et al., 1979; Hickey et al., 1986; Noble and Butman, 1989). Therefore, instrumentation was placed primarily along canyon axes and below canyon rims. Recent studies indicate that much of the interesting canyon dynamics occurs over the flanks of a canyon and just above its rim (Hickey, 1995).

Realistically shaped canyons have been given little attention by modelers. This omission may be due in part to the widely held idea that theories developed for a hill (which are comparatively numerous) can be applied directly to a depression. This is not the case, however, because boundary layers are free to communicate at all depths within a depression; for a hill or a seamount, communication can occur only over the top of the obstacle. Whereas the height of a hill is of fundamental importance to the effect of the hill on the regional flow field, the depth of a coastal canyon (beyond a minimum depth that depends on incident flow conditions) has only a small effect on the disturbance to the regional flow field. Moreover, the presence of the coastal wave guide introduces north-south asymmetries into the canyon-flow interactions. The additional complexities of having one open boundary, steep slopes, and abrupt changes in isobath orientation, as well as the existence of the strong and time-variable forcing that generally occurs in coastal regions where canyons are most common, make the problem particularly difficult. Early analytical models that included canyon topography typically made the assumption that the canyon could be considered as a perturbation to the regional topography; i.e., the canyon was extremely wide (Allen, 1976). Regional numerical models to date have provided insufficient spatial resolution to address details of the interaction processes. However, such models have demonstrated that canyons affect the spatial patterns of regional upwelling; in particular, they suggest that upwelling is enhanced on the downstream side of a canyon (e.g., Hurlburt, 1974; Peffley and O'Brien, 1976).

In the first attempts at modeling canyon circulation and its interaction with shelf flow on more realistic scales, the canyon was simulated as a vertical-walled channel (i.e.,

without a closed end) (Klinck, 1988, 1989). In spite of the absence of a canyon headwall, the latter models provided the first useful insight into canyon/flow interaction. Two- and three-layer linear models were used to describe the steady state response of the canyon flow and density field for channel widths narrower, wider, and on the order of the Rossby radius. The incident forcing had a sinusoidal cross-shelf structure. With this model configuration, maximum upwelling occurred over the two walls and no north-south asymmetries were predicted. Cyclonic vorticity was observed within the canyon in the region where the incident flow was upwelling favorable.

Two recent models with realistically steep and abrupt topography have provided a major step forward in understanding the interaction of shelf flow with coastal canyons (Allen, 1995; Klinck, 1995). Results from these models are qualitatively consistent with the one set of spatially comprehensive observations that is available. These models as well as the spatially comprehensive dataset will be discussed further in the section on the current state of our knowledge in submarine canyons.

Why are Canyons of Interest?

In some coastal areas, submarine canyons occupy nearly 50% of the shelf edge. An example of such a coastline is shown in Figure 1. The interaction of fluctuating flows over the shelf and slope with abrupt topographies such as these, i.e., the nature of the circulation and mass balance within and in the immediate vicinity of a canyon, presents a fundamental and challenging problem for physical oceanographers. Moreover, canyons play an important role in regional ecosystems. A plethora of anecdotal information suggests that canyons are regions of enhanced species diversity and biological productivity. This productivity enhancement apparently extends all the way up the food chain to include birds and mammals. For example, The Gully, a 1200-m-deep, 12-km-wide submarine canyon off the Scotian shelf, is home to a non-migratory population of 200-300 endangered bottlenose whales (Faucher and Whitehead, 1992). Elevated chlorophyll and zooplankton density, as well as doming of temperature and salinity isopleths, have been observed over this canyon (Bohrer, 1995). The basic hypothesis invoked in most anecdotal accounts is that upwelling is enhanced near canyons and that this upwelling provides a nutrient source that increases phytoplankton and, hence, zooplankton density. Fish, birds, and mammals congregate in the area for the predictable and enhanced source of food. Most reports linking canyons to enhanced productivity have not been presented in the reviewed literature. The studies have not to date included specific efforts to link physical mechanisms and biological effects.

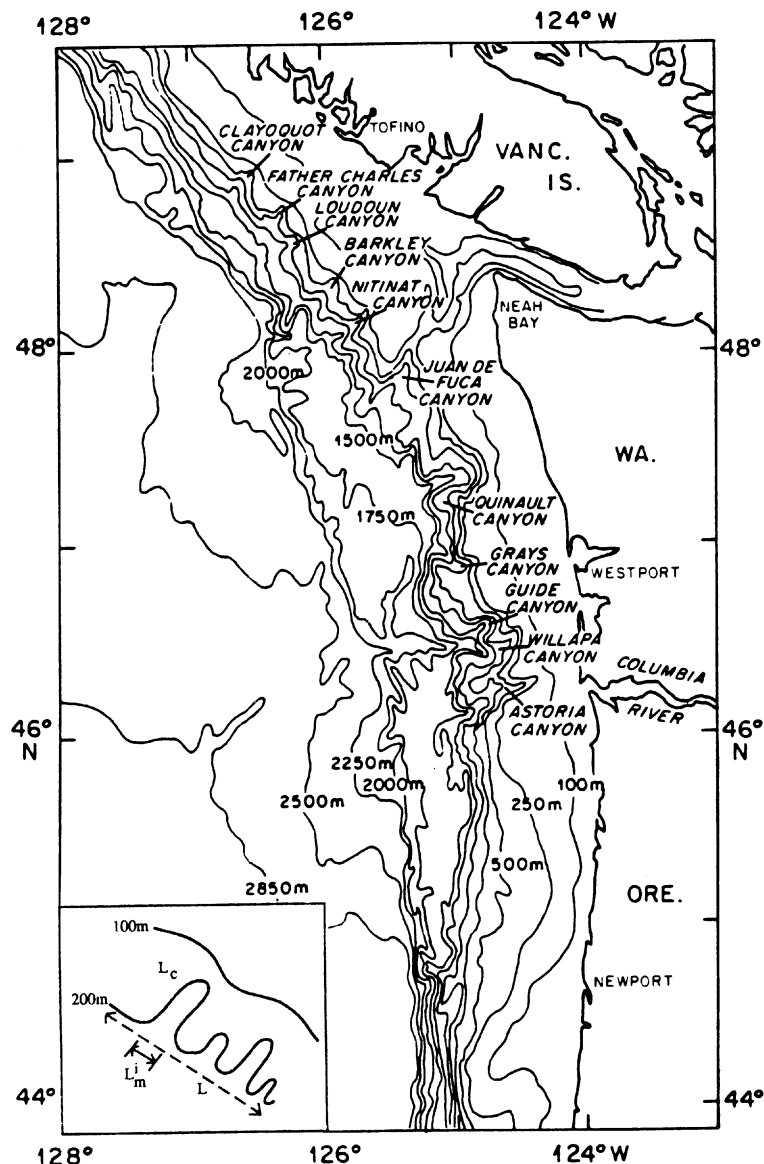


Figure 1. Bathymetric map of the Washington-Oregon coast illustrating the number and frequency of submarine canyons. The inset figure shows the method used for estimating the canyon shelf-edge enhancement factor.

Submarine canyons incising the continental shelf also play an important role in the ultimate fate of sediment in suspension or resuspended over the continental shelf. Many canyons incise the shelf sufficiently far to cut across and thereby interrupt the movement of river-supplied sediment along the shelf in the bottom boundary layer. For example, on the Washington shelf, sediments trend northward and offshore from their source, the Columbia River, intersecting several canyons along the outer shelf from Astoria to Juan de Fuca (see Figure 1) (Nittrouer, 1978). Baker and Hickey (1986) used sediment traps to demonstrate that particles are preferentially concentrated in a canyon following resuspension on the adjacent shelf. Water flowing *over* the canyon, as opposed to *around* the canyon, provides an opportunity for suspended sediment in the water column to settle out at depths deeper than would be otherwise possible. Gardner (1989) shows that

focusing of internal waves by canyon walls can elevate bottom currents and hence shear stress sufficiently to resuspend sediment along the canyon floor, after which it can move farther seaward in detached nepheloid layers.

On a regional scale, the presence of coastal submarine canyons can modify and/or enhance the effects of other physical processes. A number of possibilities are listed below. These effects have some basis in model studies. However, only a few have been studied in the field. The state of our knowledge in each of these areas will be reviewed briefly in the next section.

1. Internal Wave Generation and Modification. The topography of a canyon, with sloping bottoms on three sides, is likely to significantly modify the ambient internal wave field. In addition, bottom slopes within the canyon generally differ from those over the continental slope outside the canyon, and offer several angles, any one of

which might be favorable to generation of the internal tide.

2. Enhanced Mixing. Modification of the internal wave field, in particular, amplification and breaking, could lead to enhanced mixing within and around canyons. Enhanced mixing might also result from an increase in bottom shear stress as the flow is steered around the topography.

3. Wave Generation. The interaction of fluctuating shelf flow with the abrupt topography of canyons is likely to result in the generation of a spectrum of trapped and propagating waves.

4. Modification of Coastal-Trapped Waves. The energy of low mode coastal-trapped waves commonly found on continental shelves may be scattered into higher modes by the abrupt change in bottom topography.

5. Shelf/Slope Mass Exchange. Upwelling and downwelling rates and/or the total volume exchanged via these processes may be altered or enhanced by the presence of a canyon.

6. Modification of Regional Currents and Water Properties. For realistic ambient conditions, shelf flow does not simply follow isobaths around a canyon indenting the shelf break. Rather, flow crosses the isobaths into the canyon. The departure of streamlines from the isobaths is a function of many parameters (notably stratification and Rossby number of the incident flow) which vary in space and time. Also, water masses produced and/or modified by canyon processes are not constrained to remain in the vicinity of the canyon. Advection and mixing can move the canyon water downstream and inshore or offshore of the canyon from which it originated, thereby affecting regional salt, heat and mass balances in a fundamental way.

How important are any of the expected canyon transformations and enhancements in regional and global contexts? On the west coast of the U.S., the shelf break occurs generally in the vicinity of the 200-m isobath. To estimate cumulative canyon effects over one specific shelf region, we measured the overall length of the 200-m isobath (L), the length of the 200-m isobath indented by the mouths of canyons ($L_m = \sum L_m^i$) and the length of the 200-m isobath including canyons (L_c) for the Pacific coast from Alaska to the Equator (Figure 1). Distances were measured with a ruler whose least division is about 2 km. Results indicate that in this region, almost 20% of the shelf edge is interrupted by canyons; i.e., the mouths of canyons occupy 20% of the shelf edge ($100 L_m / L$). In addition, the presence of canyons increases the length of the shelf edge by roughly 30% ($100 L_c / L$). Thus, if canyons do indeed facilitate exchange between the shelf and the slope or enhance vertical mixing, this example suggests that presence of canyons is likely of first order importance to larger scale mass balances.

In the discussion below, the state of our knowledge with respect to mean flow and fluctuating flow in and around canyons will be presented. This will be followed

by a discussion of each of the potential canyon effects that were listed above.

The State of Current Knowledge

Mean Flow Within Submarine Canyons

Observations suggest that the mean flow along canyon axes within a few hundred meters of the canyon floor is predominantly up- or down-canyon. This axial canyon flow is of great interest to geological oceanographers, who view it as a mechanism for transporting sediment from the upper slope to the deep sea. Long term (several month) mean currents along canyon axes do not appear to correspond to any simple spatial pattern: they are sometimes up-canyon, and sometimes down-canyon, often within the same canyon. For example, Hunkins (1988) found mean down-canyon flow in Baltimore Canyon in the canyon head, but up-canyon flow farther seaward. Hickey (1989) found up-canyon flow in the head of Quinault Canyon. Shepard et al. (1979) conclude that of 69 measurements of axial flow, 43 were down-canyon and 26 were up-canyon. They also make the observation that canyons on the east coast of the U.S. (i.e., in a western boundary system) tend to have more up-canyon mean flow than West coast canyons (i.e., in an eastern boundary system). However, presently available data now suggest the opposite: Quinault (Hickey, 1989) and Juan de Fuca (Freeland and Denman, 1982, hydrographic data) suggest up-canyon flow at least at the head; whereas, Baltimore, Lydonia (Noble and Butman, 1989), and Wilmington (Church et al., 1984, from hydrographic data) all suggest down-canyon flow at the head. The observations have been made over different time periods and in different seasons, at different heights above the bottom and in different parts of canyons. Not surprisingly, therefore, no firm understanding of driving mechanisms for mean flow near the canyon floor has emerged. It is safe to say that at this point in time, the direction of the mean flow above the floor of a specific canyon cannot be predicted with any reasonable certainty. To what extent are the mean flows obtained repeatable from year to year? In the one case for which data exist (Quinault), the spatial pattern of the mean flow direction along the canyon axis was the same during two successive years (Hickey et al., 1986).

Few direct current measurements have been made over the canyon flanks: to my knowledge such data exist only for Astoria, Lydonia, and Baltimore. In all cases for which such data have been obtained, a cyclonic flow pattern is observed within the canyon over its edges. For example, data from the head of Lydonia Canyon provide evidence that the mean flow of that canyon is in opposite directions on the two sides and cyclonic (Noble and Butman, 1989). In Baltimore Canyon, the only available data are deep, but they too indicate cyclonic mean flow with flow in opposite directions on the two canyon walls (Hunkins, 1988). Data

in Juan de Fuca Canyon are consistent with a mean cyclonic circulation pattern (Cannon and Lagerloef, 1983). With the exception of the Juan de Fuca data, all examples were obtained for incident flow with the coastline on the right (i.e., downwelling-favorable). The data sets generally included at most one mooring near the shelf break upstream and downstream of the canyon and one in the canyon. With such sparse data it is not possible to determine whether the flow is conserving vorticity and simply following the isobaths around the canyon, or whether the water column has crossed isobaths into deeper water, thereby generating cyclonic relative vorticity as it is forced to stretch. This determination is easier in the case of flow incident with the coast on the left (i.e., upwelling-favorable). In such cases, if the flow is sufficiently slow to be able to follow the isobaths, the data that would result from two moorings on either side of the canyon would suggest an anticyclonic rather than a cyclonic flow pattern.

In the one data set that resolves flow over both the canyon axis and its slopes (Astoria) the flow crosses directly over the isobaths on the upstream side of the canyon to form a mean cyclonic eddy, with maximum velocities over the canyon walls (Hickey, 1995). Under strong incident flow conditions (Rossby number >0.25), the cyclonic eddy disappears from the canyon. This Taylor-cap-like feature decays vertically both above and below the canyon lip, with a scale roughly given by the vertical length scale appropriate for geostrophic flow, fL/N , where f is the Coriolis parameter, L is the canyon width and N is the Väisälä-Brunt frequency. Since the width of Astoria Canyon is less than half that of the local internal Rossby radius, the observed flow is unlikely to be completely geostrophic. In some locations where Astoria data were obtained, the canyon walls were only 3 km apart. For the cases for which appropriate data are available (Astoria, Quinault, Baltimore, Lydonia, and Carson), mean flow at some distance (~ 50 - 100 m) above the canyon over its walls was not measurably perturbed by the canyon: it was directed straight over the canyon following the curvature of the regional isobaths.

The only observations available on canyon floors have been made along canyon axes. Such flows are generally weak (<5 cm s^{-1}). Whether the flow over the canyon floors is unidirectional to some height off the bottom or whether the flow is in opposite directions over the canyon flanks right down to the canyon floor is presently unknown. Most canyons narrow continuously towards the bottom rather than being flat over a broad region (i.e., over several kilometers), so that at some distance from the sea surface the flow might be unable to follow isobaths around the edges. Although the depth at which the flow would transition to such a regime might be thought to depend on the local internal Rossby radius, flow has been observed to follow the isobaths around at least one canyon at distances much less than the internal Rossby radius

(Hickey, 1995). Model results also suggest that, in the absence of friction, flow can be oppositely directed on the two sides of a canyon for canyons much narrower than the Rossby radius (Klinck, 1988). It seems likely that bottom friction might play an important role in determining near-bottom canyon flow. The physics of the near bottom flow in deep canyons, and, in particular, the transition from around-canyon flow to axial flow (if such indeed occurs), has not been addressed to date with either models or observations.

Fluctuations in Canyon Currents and Water Properties

Statistics and forcing mechanisms of subtidal currents in deep submarine canyons (arbitrarily defined as those for which bottom depths exceed 200 m) have only been examined in four studies. In each case, horizontal coherence scales, both along and across the canyon axis, are remarkably small (less than 10-20 km) (Hickey, 1989; Noble and Butman, 1989). Typically, only a small fraction ($<25\%$) of the variance has been explained by conventional statistical analysis (Hickey, 1989; Noble and Butman, 1989). The cross-shelf/slope pressure gradient associated with the along-shelf/slope regional flow incident on or over the canyon is most frequently invoked in discussions of driving mechanisms, with an offshore increase in pressure being related to up-canyon flow, and vice versa for an onshore increase in pressure. For example, Cannon and Lagerloef (1983) illustrate out-canyon flow in the Juan de Fuca Canyon for downwelling-favorable flow conditions. Hickey (1989) demonstrates a statistical relationship between along-axis flow in Quinault Canyon at depths of about 1200 m from the surface (5-50 m above the bottom) and the along-shelf flow over the canyon (near the shelf edge). Noble and Butman (1989) illustrate that for these dynamics to apply to Lydonia Canyon, dissipation must be extremely high, consistent with estimates deduced from the large tidal currents that are present. For both Quinault and Lydonia Canyons, maximum coherence with the shelf forcing occurs at periods of about 3-5 days. In the shallow heads of some canyons or in shelf valleys such as the Hudson, wind set-up (and thus a cross-shelf pressure gradient force) has been related directly to down-canyon flow (e.g., Nelson et al., 1978; Hsueh, 1980). Coherence scales for such depressions might be expected to be larger than those for deep ("real") canyons, which lie below the depth of directly wind-driven shelf currents.

With adequate resolution on the canyon edges, results show that the fluctuating flow on the two sides of the canyon is often in opposite directions (Hickey, 1995; Kinsella et al., 1987). Consequently, the flow cannot be driven by a spatially uniform regional pressure gradient, as deduced from the several data sets which emphasize axial measurement sites. A sequential time series illustrating the changes in the velocity field during an upwelling event in Astoria Canyon is presented in Figure

2. Detailed analysis of the Astoria dataset demonstrates that during an upwelling event, up-canyon flow initially occurs below the canyon lip on both walls and over the axis. This flow is likely to be driven directly by the barotropic cross-shelf/slope pressure gradient associated with the overlying incident shelf flow, as reported in the other canyons (Hickey, 1995). Over the canyon walls, the up- (or down-) canyon flow that occurs at the onset of upwelling (or downwelling) is followed by an increase in cyclonic circulation (with flow in opposite directions on the two walls). This cyclonic circulation is consistent with stretching (or compression) of upwelled (downwelled) layers as these layers drop into the canyon. An example of layer stretching is illustrated in Figure 3. In this figure, recently upwelled layers of shelf water can be traced as a turbid layer across the canyon. The maximum in turbidity coincides with the maximum in stretching vorticity.

Deeper in the canyon, layer stretching due to the upwelling itself causes an additional increase in cyclonic vorticity (Figure 3). Note that the region of large positive vorticity near the rim of the canyon is sandwiched between two layers of strong anticyclonic vorticity, a result of layer compression by the regional upwelling. Current meter data in Carson Canyon off the coast of Newfoundland suggest a response to an upwelling event not unlike that in Astoria Canyon: a strong cyclonic circulation pattern is observed 2-3 days after the onset of upwelling. In this case, the direction of the flow at the shelf break on the two sides of the canyon is the reverse of that normally observed for mean conditions on this western boundary.

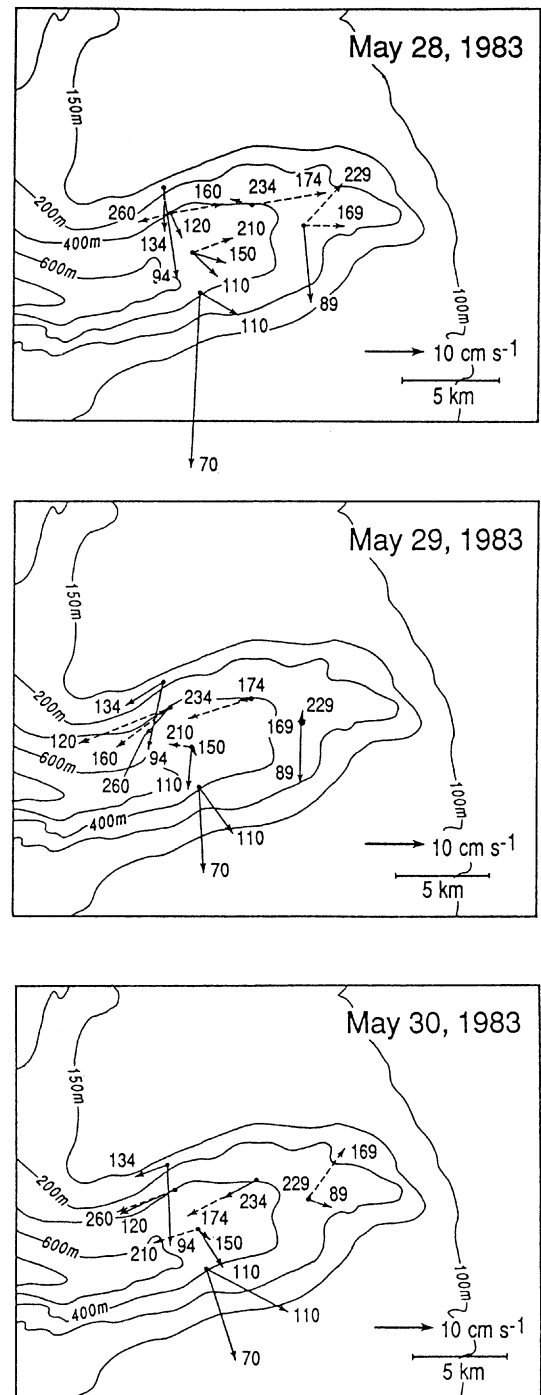


Figure 2. Sequential maps of subtidal vector velocities in Astoria Canyon during an upwelling event. Measurement depth in meters is indicated near the tip of each vector. Locations above (below) the depth of the canyon rim are shown as solid (dashed) arrows. From Hickey (1995).

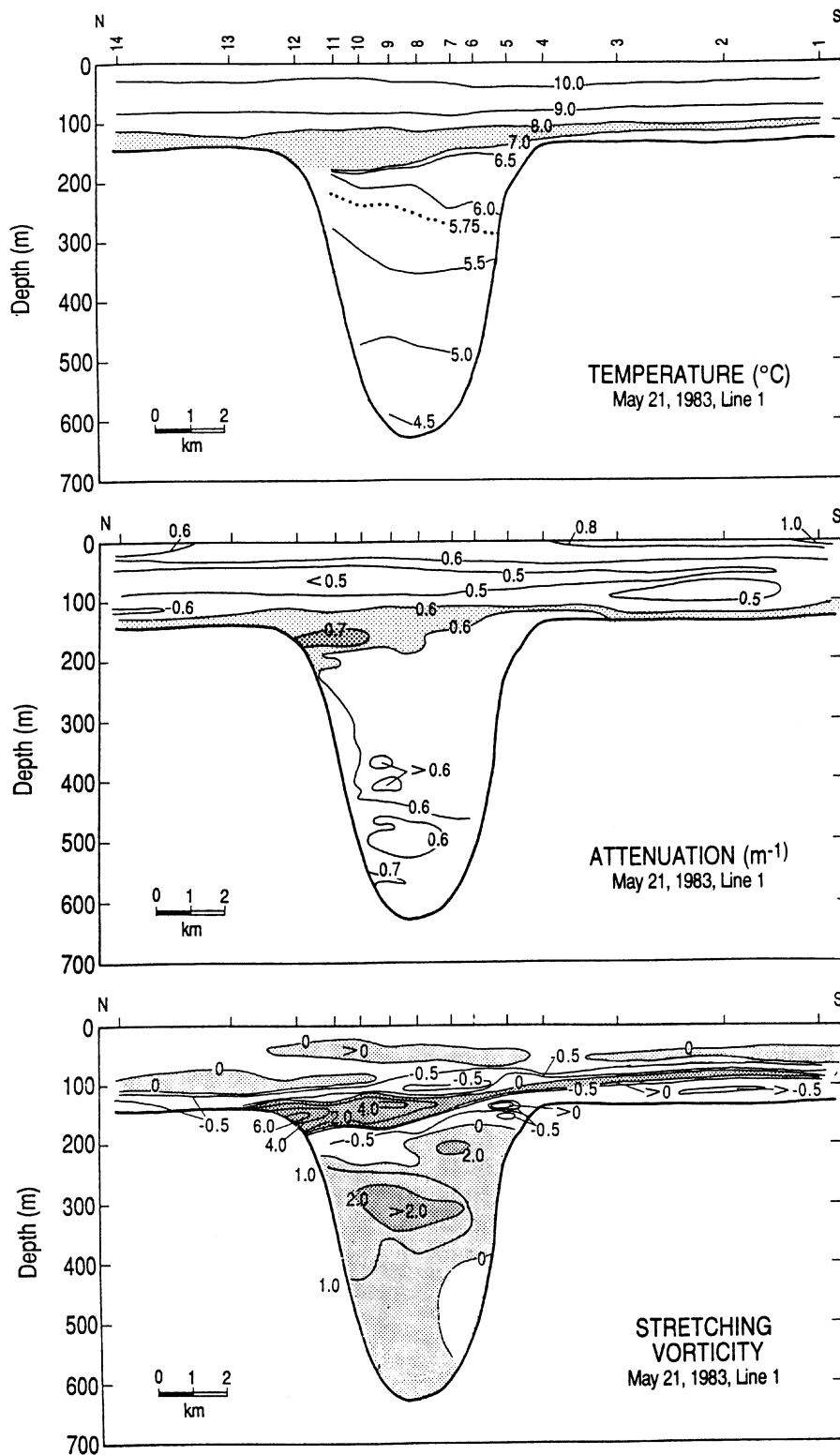


Figure 3. Contoured sections of temperature, attenuation and stretching vorticity on a section across Astoria Canyon during an upwelling event. The shaded region near the canyon lip traces the pathway of water that originated from the bottom boundary layer on the shelf or upper slope as it flows over and up the canyon. The deeper region of shaded vorticity is consistent with layer stretching during the upwelling event. Adapted from Hickey (1995).

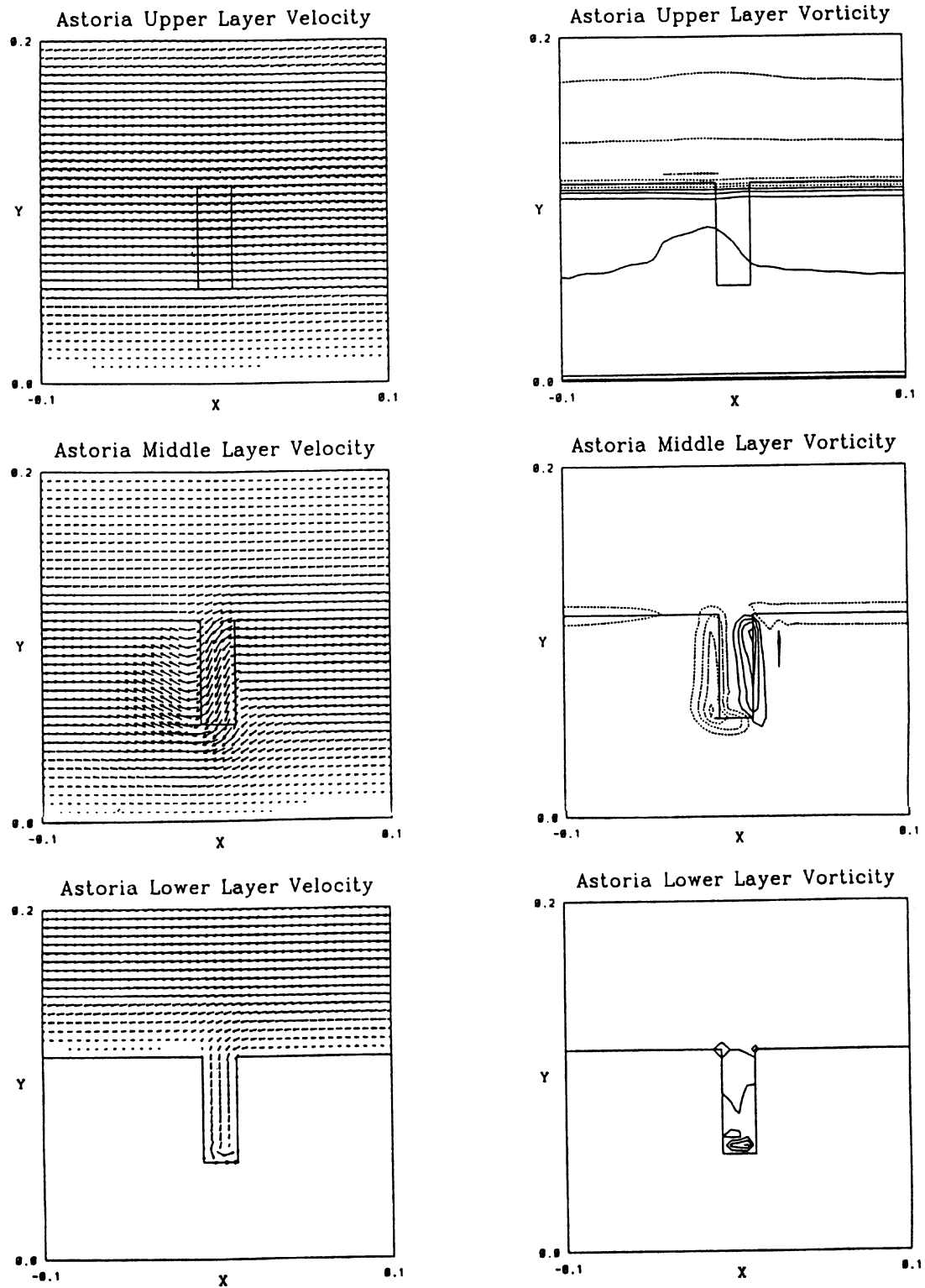


Figure 4. Modeled velocity and vorticity fields for upper, middle, and lower layers after one day of spin-up with a nonlinear numerical model. The model is forced with steady, upwelling-favorable, spatially uniform wind stress. Maximum velocities in the three layers are 47 cm s^{-1} (upper layer), 37 cm s^{-1} (middle layer) and 14 cm s^{-1} (lower layer). Vorticity is contoured from $-0.11 f$ to $0.062 f$ by $0.025 f$ (upper layer), $-0.43 f$ to $0.43 f$ by $0.12 f$ (middle layer) and $0 f$ to $0.19 f$ by $0.062 f$ (lower layer). From Allen (1995).

A recent study of submarine canyon dynamics includes both spin-up and steady state, linear and nonlinear models of a shelf/slope system in which a vertical-walled canyon incises the continental slope (Allen, 1995). One nonlinear, three layer model run was designed for the topography and stratification of Astoria Canyon. The relatively large incident velocity ($\sim 50 \text{ cm s}^{-1}$) approximates the high Rossby number flow observed in the Astoria field study during upwelling events. In the upper water column the flow is essentially straight over the canyon. In the middle layer, the flow turns shoreward over the canyon. Cyclonic vorticity occurs on the upstream side of the canyon near the rim and anticyclonic on the downstream side (Figure 4). The cyclonic vorticity is associated with shelf water which has fallen into the canyon, consistent with the field observations of Astoria Canyon (Figure 3). Cyclonic vorticity occurs over about 2/3 of the canyon due to the relatively large inflow velocity and the relatively important nonlinear effects, which tend to sweep spatial patterns downstream. The deeper circulation is cyclonic near the canyon head in the model results, consistent with the observations, a result of layer stretching during upwelling. However, modeled vorticity is generally weaker than that observed in the field study of Astoria Canyon (compare Figures 3 and 4). The model-observation discrepancy may be due to the fact that the model results are presented after only one day of spin-up, whereas the observations suggest that maximum cyclonic circulation is observed during spin-down.

Klinck (1995) uses a semi-spectral, primitive equation model (the "SPEM" or "Haidvogel" model) to model the steady state response of a Gaussian canyon (400 m deep and with a half-width of 5 km) to both upwelling and downwelling-favorable overflow events. Klinck uses stratifications corresponding to an internal Rossby radius on the order of the canyon width and three times the canyon width. The Rossby number of his incident flow is 0.1-0.2. The major result of his study is the demonstration that the direction of incident flow (i.e., whether upwelling-favorable or downwelling-favorable) has a stronger effect on the flow disturbance due to the canyon than does stratification. In particular, during upwelling events, downwelling of shelf water occurs over the northern flank of the canyon and upwelling occurs over the canyon axis and over the southern flank (Figure 5). Upwelling water is pumped from the canyon, exiting at the head and along its southern flank. These results are qualitatively similar to observations in Astoria Canyon, as discussed above (see Figure 3). For strong stratification, the canyon effects (including the downwelling) are observed well up over the adjacent shelves. Flow is directed over the canyon at the sea surface, but turns into the canyon at depths close to the canyon rim. Cyclonic vorticity occurs at depth within the

canyon due to layer stretching. For downwelling-favorable overflow, downwelling (on the upstream side) and upwelling (on the downstream side) are symmetric with the canyon topography and little water is lost from the shelf to the canyon (Figure 5).

Internal Wave Modification and Generation by a Submarine Canyon

Both models and laboratory experiments suggest that internal waves are focused and therefore amplified within canyons (Hotchkiss and Wunsch, 1982; Baines, 1983; Grimshaw et al., 1985). This result has been confirmed in several canyons, notably Hudson (Hotchkiss and Wunsch, 1982), Quinault (Hickey, 1989) and Monterey (Petrunco et al., 1994). Hotchkiss and Wunsch use statistical analysis of current meter data to illustrate the enhancement of the internal wave field toward the canyon head and toward its floor (Figure 6). The potential energy density averaged over the internal wave band increases roughly 100-fold toward the canyon head and 10-fold toward the bottom at most sites. The energy in the internal wave band is higher everywhere in the canyon where measurements were made than that predicted by the Garrett and Munk (1975) model (see values on Figure 6).

Petrunco et al. (1994) use a time series of shipboard ADCP data to demonstrate bottom enhancement of the semi-diurnal tide within Monterey Canyon. In this canyon, the slope of the canyon axis is near the critical slope for the semi-diurnal tide. This enhancement would not be expected on the much steeper adjacent continental slope. Their data also suggest that the internal tide undergoes significant alteration near the lip of the canyon. In general, the slopes of the canyon walls and the canyon floor can all differ from each other and from those on the adjacent continental slope, and so offer multiple opportunities to achieve the critical angle required for effective generation of internal tides.

Enhancement of Vertical Mixing by Submarine Canyons

Lueck and Osborn (1985) use turbulent velocity profiles to demonstrate that Monterey Submarine Canyon has an extremely turbulent bottom boundary layer. This turbulent layer was up to 170 m thick during their field study. The production of turbulent kinetic energy within a canyon could be related either to internal wave breaking or to bottom friction (or both). Hotchkiss and Wunsch (1982) use their energy analysis of the internal wave band to show that in Hudson Canyon, dissipation due to bottom friction is a factor of ten too small in the internal wave band to account for the influx of internal wave energy into the canyon. They suggest that internal

wave breaking and mixing likely occur near the canyon head. An example of mixing due to bores or wave breaking at internal tidal frequencies is presented by Gardner (1989). Time series of currents, temperature and beam attenuation within Baltimore Canyon are consistent with the hypothesis that bore-like features (breaking internal waves) resuspend sediment along the canyon bottom at tidal frequencies. The ratio of bottom slope to the slope of the internal tide characteristics is less than one, as required for internal wave breaking or bores, in the season in which the observed resuspension was most intense. Sediment-laden water moves up-canyon and then down-canyon, ultimately detaching from the bottom boundary layer and moving offshore as intermediate nepheloid layers. Maps of light transmission taken inside and outside Baltimore Canyon illustrate the resulting enhancement of suspended particle concentrations within the canyon in comparison with the open slope (Figure 7).

A recent study has shown that the thickness of the bottom mixed layer over the shelf off northern California is a function of stratification, current speed, and, most importantly, current direction (Lentz and Trowbridge, 1991). To the extent that this is generally the case, the height and structure of the bottom mixed layer in the vicinity of a canyon are likely to be strongly modified by canyon-related processes. For example, if the flow can follow the topography, conservation of mass would require an increase in velocity as the flow is channeled into the narrower shelf region inshore of the canyon. This would increase the bottom shear stress and, consequently, the structure of the bottom boundary layer and the height of the bottom mixed layer. The local density field, itself modified by the canyon effects on upwelling/downwelling and other regional processes, would also affect the structure of the bottom boundary layer and, hence, the bottom mixed layer. To my knowledge, there have been no field studies focused on boundary layer modification and mixing enhancement due to the presence of a submarine canyon for any frequency band.

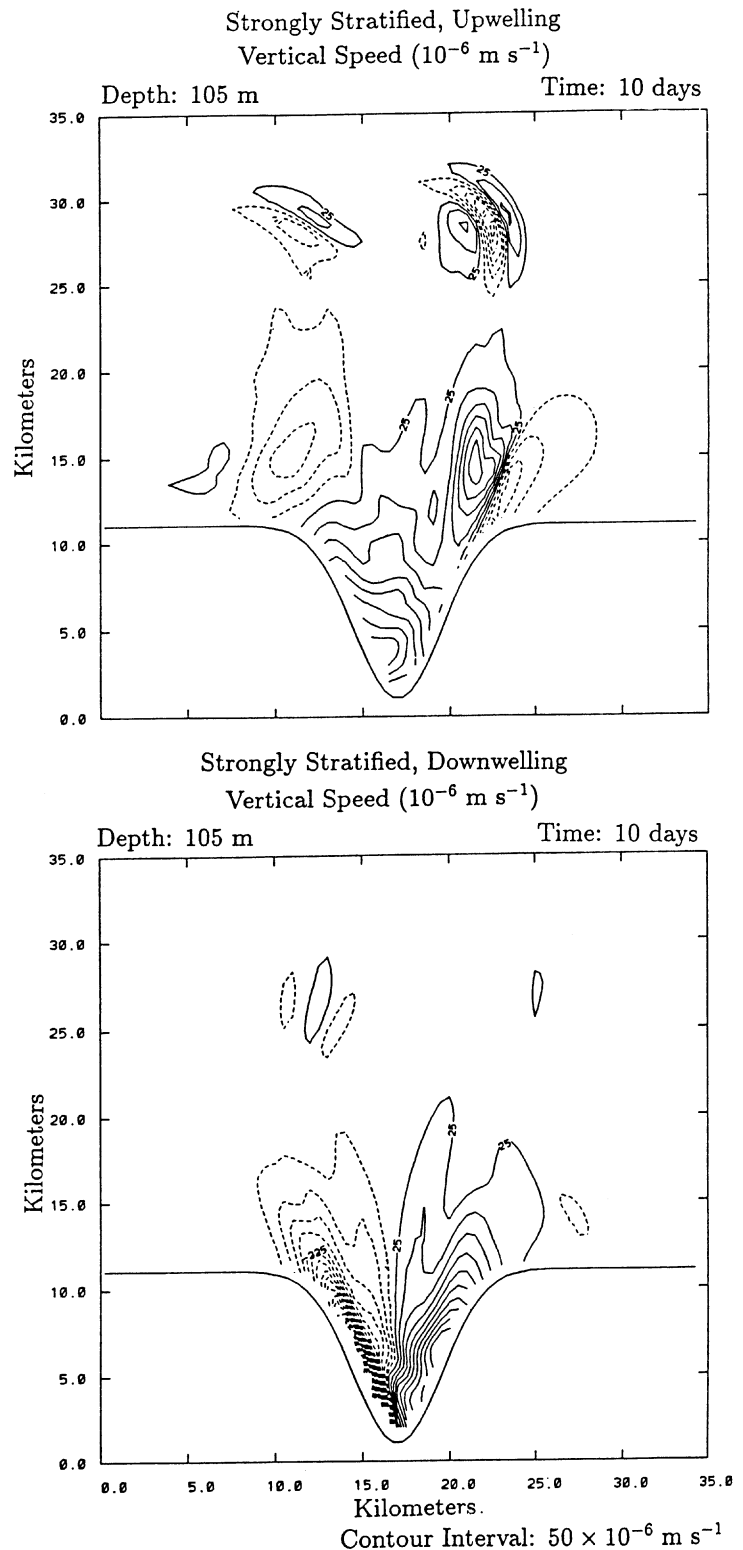


Figure 5. Modeled velocity for strongly stratified upwelling (upper panel) and downwelling (lower panel). The solid line indicates the top of the canyon and the shelf break. The vertical velocity is shown at a depth just below the shelf break (105 m). Solid contours indicate upward flow and dashed contours, downward flow. From Klinck (1995).

Canyons as Wave Makers and Wave Modifiers

The theoretical problem of variable shelf-slope topography was first addressed by Allen (1976). Along-shelf variations in topography were assumed to be greater than the shelf-slope width so that the motion could be treated in the long wave, non-dispersive limit. The resulting perturbation equations are those for barotropic, inviscid shelf waves. For a delta function applied wind stress (meant to model short time scale changes in stress), the flow adjusts through propagation of free shelf waves. For a Heaviside wind stress (meant to simulate steady stress, impulsively applied), Allen found a reduction of onshore flow over the canyon. This result is exactly the opposite of that found in recent models in which canyons are treated as abrupt topographic features (see below). Allen also showed that the energy in a shelf wave incident on a canyon is scattered into other modes.

Wang (1980) extended the study of the effects of a canyon on shelf waves by including finite amplitude topography and allowing waves to be dispersive. He presents numerical solutions for the case of a v-shaped canyon that indents the shelf all the way to the coastline, with a flat bottom seaward of the shelf. He concludes that wave diffraction leads to a reduction of long wave energy transmission (up to 70%), amplitude amplification near the canyon, and generation of strong localized disturbances in the vicinity of the canyon. Interestingly, the phase propagation upstream and downstream of the canyon is not significantly affected by the presence of the canyon. The scattering process transforms the large-scale alongshore motion into smaller-scale cross-shore motion associated with higher wave modes. Thus, Wang concludes that canyons effectively block much of the long wave transmission. We note that this would not likely be the case for submarine canyons that only partially indent the shelf. Perhaps more important, numerical studies of coastal-trapped wave modification by abrupt changes in shelf topography (Wilkin and Chapman, 1990) suggest that Wang's results would be altered dramatically by the inclusion of stratification. In the latter study, inclusion of realistic stratification eliminated all reflected waves and amplified the scattering process. Some upstream influences were produced by evanescent wave modes. No further numerical studies of wave modification by finite amplitude canyons have been presented since Wang (1980).

Generation of standing and radiating waves over and near a canyon at supertidal frequencies and at the inertial period has been examined for a homogeneous water column with a canyon treated as a channel (Klinck, 1988). Waves are generated during geostrophic adjustment to an impulsively imposed cross-shelf barotropic pressure gradient. The frequency of the resulting waves is a function of canyon depth and the width of the incident

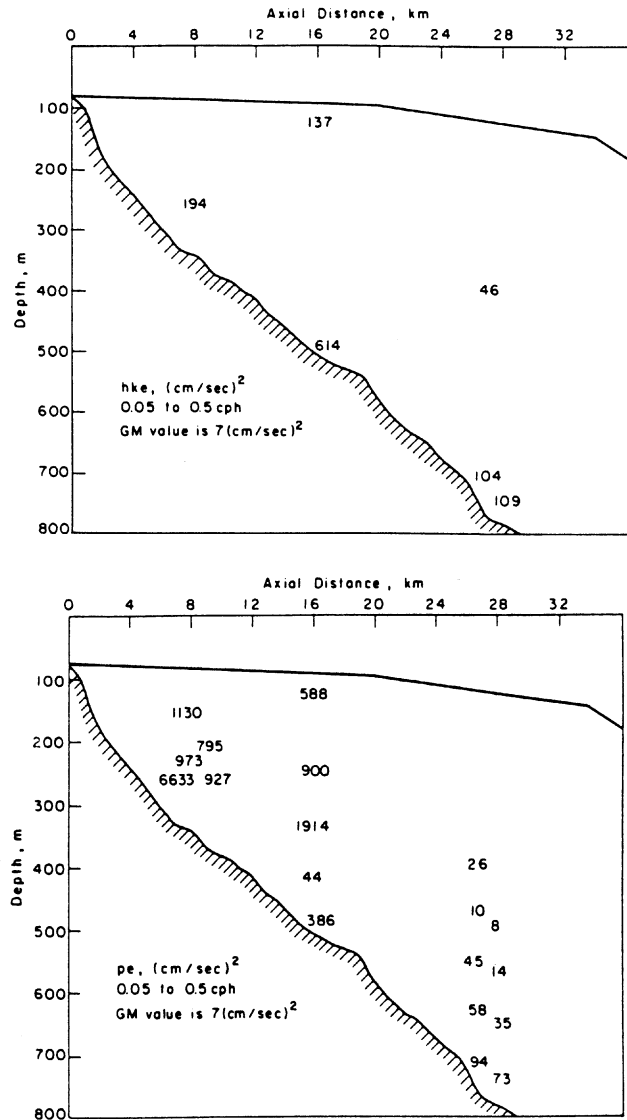


Figure 6. Horizontal kinetic energy density (upper panel) and potential energy density (lower panel) integrated over the internal wave band, shown as a function of location within the canyon. From Hotchkiss and Wunsch (1982).

flow. Strong localized disturbances at these higher frequencies would be expected in the vicinity of a canyon.

To my knowledge, no experiment has been designed to search for wave-like disturbances over a canyon and no experiments have been undertaken to study the modification of coastal-trapped waves by canyon topography. Although regional effects on coastal-trapped waves by small scale canyons may be negligible, the effect of broader canyons, which may cause an abrupt narrowing of the shelf for a distance of 20-100 km is unclear.

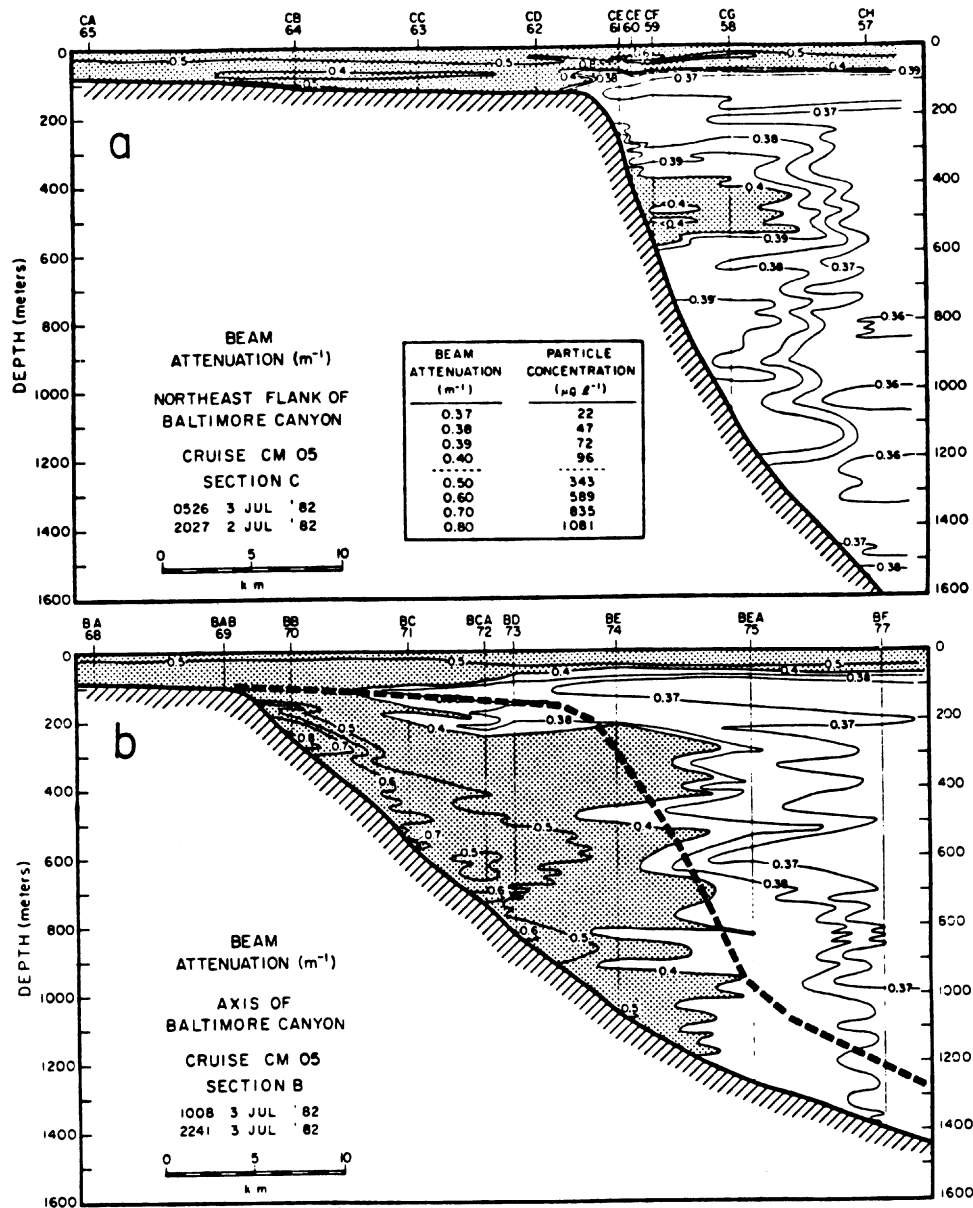


Figure 7. Contoured beam attenuation (m^{-1}) along sections northeast of Baltimore Canyon and along the canyon axis. Contour intervals are $0.1\ m^{-1}$ for values greater than $0.4\ m^{-1}$ (stippled area) and $0.01\ m^{-1}$ for values less than $0.4\ m^{-1}$. The heavy dotted line indicates the outline of the canyon walls. From Gardner (1989).

The Effect of Canyons on Shelf/Slope Mass Exchange

Church et al. (1984) conclude that shelf-slope exchange is modified by a canyon on the east coast of the U.S. Their data include hydrographic/nutrient/oxygen measurements obtained on a shipboard survey of the shelf and slope in a region including Wilmington Canyon. Their results suggest that the cyclonic circulation pattern observed at that time in the vicinity of the canyon promoted nutrient exchange and biological production. The authors suggest that more direct and time-dependent measurements would

be necessary to fully understand the nature of such interactions.

Regional models suggest that upwelling is enhanced on the downstream side of canyons (Peffley and O'Brien, 1976; Cushman-Roisin and O'Brien, 1983). The finer resolution models of realistic canyons described in the preceding section also suggest that upwelling is enhanced on the downstream side of a canyon (Allen, 1995; Klinck, 1995). Onshore flow and upwelling rates are as much as a factor of ten stronger within the canyon than over the nearby continental slopes (Allen, 1995) and the upwelled

water is lifted out of the canyon at the head and along the downstream edge (Figure 5). Little spatial asymmetry occurs in the case of downwelling, at least in the steady state model (Figure 5) (Klinck, 1995). Thus, one might expect to more readily observe dramatic canyon effects on regional water properties in areas and seasons in which upwelling is dominant. Klinck's (1989) model for the flow within a coastal channel suggests that strong density disturbances can occur even for canyons much narrower than the internal Rossby radius.

An example of enhanced upwelling on the downstream side of a canyon was obtained in the field study of Astoria Canyon (Figure 3). Data in Shaffer (1976) are also suggestive of localized upwelling near the head of a canyon off the African coast. Time series of temperature data within Quinault Canyon and on the nearby slope illustrate that the canyon upwelling is stronger during each individual upwelling event (Hickey, 1989). To my knowledge no such explicit examples have been presented for canyons in western boundary systems, on which wind-driven upwelling is less common.

Whether upwelled water actually breaks the surface above or near the canyon is a question of great interest, particularly to biological oceanographers. Localized upwelling of nutrient-rich water into the euphotic zone would provide an explanation for enhanced zooplankton biomass in the vicinity of some canyons. In Juan de Fuca Canyon, upwelled water reaches close enough to the surface to allow erosion by entrainment into the surface mixed layer (Freeland and Denman, 1982). However, the driving mechanism for this upwelling depends in part on the buoyantly driven coastal current associated with the effluent from the Strait of Juan de Fuca; this physical situation is unlikely to occur near most canyons. The majority of the data available as well as the recent model results for stratified situations suggest that upwelled water is likely confined to a bottom boundary layer in most cases. If a canyon cuts across the shelf sufficiently close to the coast to be within the coastal upwelling zone (a Rossby radius), water upwelled from the canyon might be upwelled further by upwelling near the coastal wall. Shaffer (1976) seems convinced that water upwelled from a canyon breaks the sea surface just shoreward of the canyon. However, the evidence as it is presented in his paper is far from conclusive.

Rosenfeld et al. (1994) have recently demonstrated that during at least one coastal upwelling event, the cold surface water observed in Monterey Bay came from water upwelled outside the bay that was advected laterally into the bay. The upwelling plume passed straight over the canyon and was not connected to either the local coastline or the canyon in any way. The prevailing idea prior to this study was that upwelled water within Monterey Bay was due to the presence of Monterey Canyon. This example demonstrates that studies of canyon effects should always be done within a regional context.

Modification of Regional Currents and Water Properties by Submarine Canyons

Regional circulation will attempt to follow the topography as it bends around the canyon at the shelf edge. How successfully it can do so will likely depend on stratification, vertical and horizontal structure of the incident flow, canyon width and the Rossby number of the incident flow. Canyon model studies to date have confirmed that the amount of steering is a function of both stratification and the Rossby number of the incident regional flow (Allen, 1995; Klinck, 1995). Steering of streamlines by canyon topography has been observed over a number of canyons. One example, obtained from hydrographic data off the coast of Spain, is shown in Figure 8 (Maso et al., 1991). The data illustrate that the degree of steering increases with proximity to the bottom. Likewise, over Astoria Canyon, direct current measurements show that whereas the flow 80 meters above bottom is not strongly affected by the canyon, the flow 50 meters above bottom is strongly affected by the topography (Hickey, 1995; and see Figure 3, this paper). A Rossby number dependence has been confirmed observationally by the Astoria data: the higher the Rossby number, the less the flow over the canyon turns to follow canyon isobaths (Hickey, 1995).

The abruptness of the canyon topography, i.e., the angle between the incident flow and the canyon isobaths, would also be expected to have a significant effect on the resulting interaction between the incident flow and the canyon. The greater than 90° bend in local isobaths on the upstream side of Astoria Canyon (see Figure 3) may provide an explanation for the semi-permanent cyclonic circulation pattern observed above that canyon. A similar situation may occur near Carson Canyon (Kinsella et al., 1987). In this case, the strongly bent isobaths are also on the upstream side of the canyon (for downwelling-favorable flow). The flow only 10 m above bottom passes directly across the local isobaths of Carson Canyon, making little attempt to follow the larger scale canyon curvature.

The enhancement of upwelling on the downstream side of canyons must also affect regional flow patterns and mass balances. In particular, during upwelling events, significant quantities of water are pumped out of a canyon. This water is advected downstream and also inshore of the canyon. On the west coast of North America, canyons provide about 15% additional shelf edge for upwelling (assuming that upwelling occurs only on the downstream side of each canyon). If the canyon upwelling rate is only a factor of two greater than non-canyon regions (a very conservative estimate based on model results to date), a total of 30% more water would be upwelled along the shelf break in this region due to the existence of the canyons. Moreover, the greater the upwelling rate within the canyon in comparison with that

outside the canyon, the greater will be the water property anomaly on the shelf in the vicinity of the canyon. Localized fronts must occur within the bottom boundary layer, and these fronts, in turn, would be expected to cause spatial variations in the quasi-geostrophic, baroclinic flow patterns downstream and somewhat inshore of the canyon. The structure of the bottom boundary layer, which is a function of stratification, would also be expected to be affected by a nearby canyon.

Another important feature of submarine canyons is that they can allow much deeper, nutrient-rich water to reach the nearshore zone than would otherwise be possible. If the canyon lies sufficiently close to the coast, the canyon-upwelled water might be further upwelled into the euphotic zone where it would become readily available to the biota.

Critical Research Areas

Considerable progress has been made within the last year in understanding the interaction of the abrupt and realistic topography of coastal canyons with time-dependent, stratified coastal circulation (Allen, 1995; Hickey, 1995; Klinck, 1995). For adequate verification in the field (Astoria Canyon), the effort required a combination of moored and shipboard surveys as well as the fortuitous occurrence of several strongly forced events during those surveys (Hickey, 1995). The models used appropriately steep and abrupt topography, realistic

stratification and incident flow conditions, and a canyon that included a headwall on its nearshore end. The results of these studies indicate that during upwelling-favorable incident flow conditions, downwelling of shelf water occurs over the upstream wall of the canyon and upwelling occurs over the canyon axis and over the downstream wall. Upwelling water flows shoreward within the canyon and exits at the head and along its downstream wall. In the upper water column the flow is essentially straight over the canyon. Cyclonic vorticity occurs on the upstream side of the canyon near the rim, and anticyclonic, on the downstream side. The cyclonic vorticity is associated with shelf water which has fallen into the canyon. For realistic incident flows over Astoria Canyon, cyclonic vorticity is observed over about 2/3 of the canyon due to the relatively large inflow velocity and the consequently important nonlinear effects, which tend to sweep spatial patterns downstream. The deeper circulation is cyclonic, a result of layer stretching during upwelling. The data for Astoria Canyon suggest that a Taylor cap-like circulation pattern exists over this particular canyon for Rossby numbers below about 0.25. Closed streamlines have not been observed in model results for the cases examined to date.

The research to date has addressed some straightforward questions, and qualitative agreement between models and observations has been obtained for simple incident flow and simple canyon shapes under strong forcing. Numerous questions remain. For example,

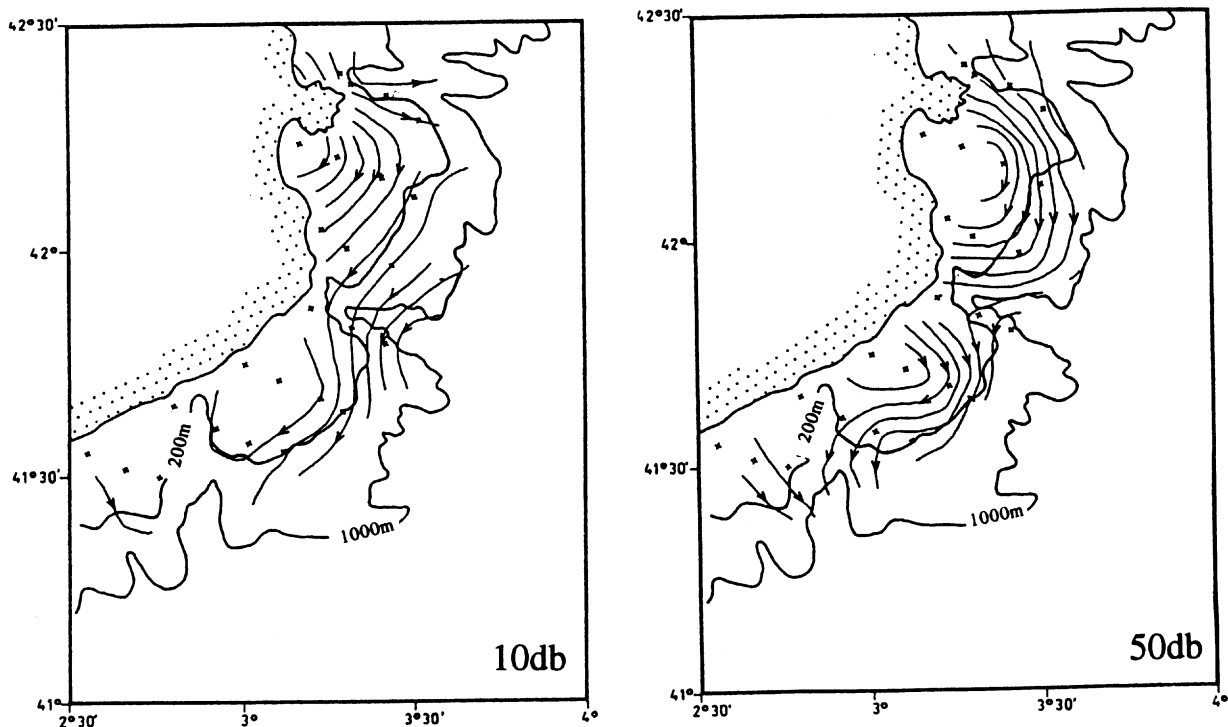


Figure 8. Dynamic topography relative to 100 db in the vicinity of several submarine canyons off the coast of Spain. From Maso et al. (1991).

as the canyon narrows towards its floor, does the flow change from primarily around the canyon walls (quasi-geostrophic) to primarily up and down its axis (quasi-frictional)? What is the role of side wall friction at various depths within the canyon? Model studies suggest that canyons may be energy sinks for barotropic shelf waves. How does a canyon affect wave scattering under stratified conditions?

The extent to which a canyon can trap particles is particularly important to many interdisciplinary problems. Under what conditions does a vortex occur *over* the topography of a canyon? Under what conditions is the circulation *within* the canyon completely closed? How does a two layer flow (e.g., a coastal jet with an undercurrent over the slope) or a stratified flow interact with a steep canyon? The only spatially and temporally comprehensive data set is that for Astoria Canyon. To what extent is Astoria Canyon unique? The more than right angle bend in the shelf break isobaths north of this particular canyon may funnel the incident flow offshore near the apex of the bend. This could lead to a steady cyclonic vortex under all incident conditions as observed. In the real ocean, canyons have many shapes, depending on the geology of their formation. How does the shape of a canyon affect the details of its interaction with the coastal flows? These and other aspects of canyon circulation and canyon-flow interactions are the subject of ongoing research.

Finally, we note that there is strong evidence to suggest that submarine canyons have an important effect on marine ecosystems. The effects include the entire food chain, from phytoplankton to marine mammals. The exact mechanisms for such effects have not been addressed to date. Future efforts in canyon studies would benefit greatly from an interdisciplinary approach.

Acknowledgments

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