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Seamounts: a review of physical processes and their influence on the seamount ecosystem

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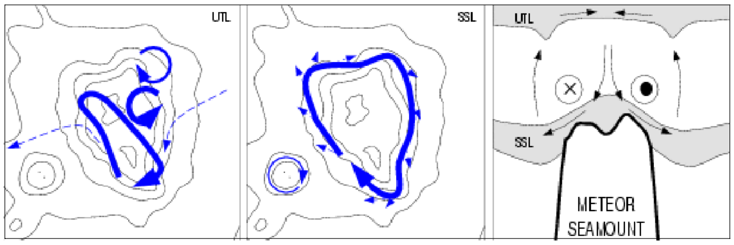

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OASIS report

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Cover graph: The flow regime at Great Meteor Seamount derived
from model experiments (after Mohn and Beckmann, 2002)

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1 INTRODUCTION

Seamounts are large topographic features, which extend a great vertical distance from the seafloor of the world's oceans. They are defined as having a vertical elevation of more than 1000 m with limited extent across the top summit region. Smaller features, similar in characteristics, but with elevations of 500-1000 m, have been termed knolls, and those less than 500 m hills. In recent years, a large number of seamounts have been discovered, and there are now over 30000 features over 1000m in vertical extent known in the Pacific alone (see Rogers (1994) for references to above).

Seamounts may have various shapes – conical, circular, elliptical, or elongated seamounts often known as Guyots and are usually volcanic features. The water depth at which the summit reaches may be important. Shallow seamounts may be thought of those reaching into the euphotic zone, intermediate seamounts with summits below the euphotic zone but within the upper 400 m layer and deep seamounts with peaks below 400 m depth (Genin, 2004).

This report reviews the many physical oceanographic processes that occur at seamount features and describes the effect these processes may have on the bio-geochemistry of seamount ecosystems. Section 2 reviews the basic dynamical concepts and models of these processes are described in section 3. Section 4 describes the observations of the different physical processes that have been identified. The interaction between the physical processes and bio-geochemistry are discussed in section 5 and a synthesis summary is presented in section 6. A map showing the location o f the principal seamounts mentioned in this review is given below in Fig 1.

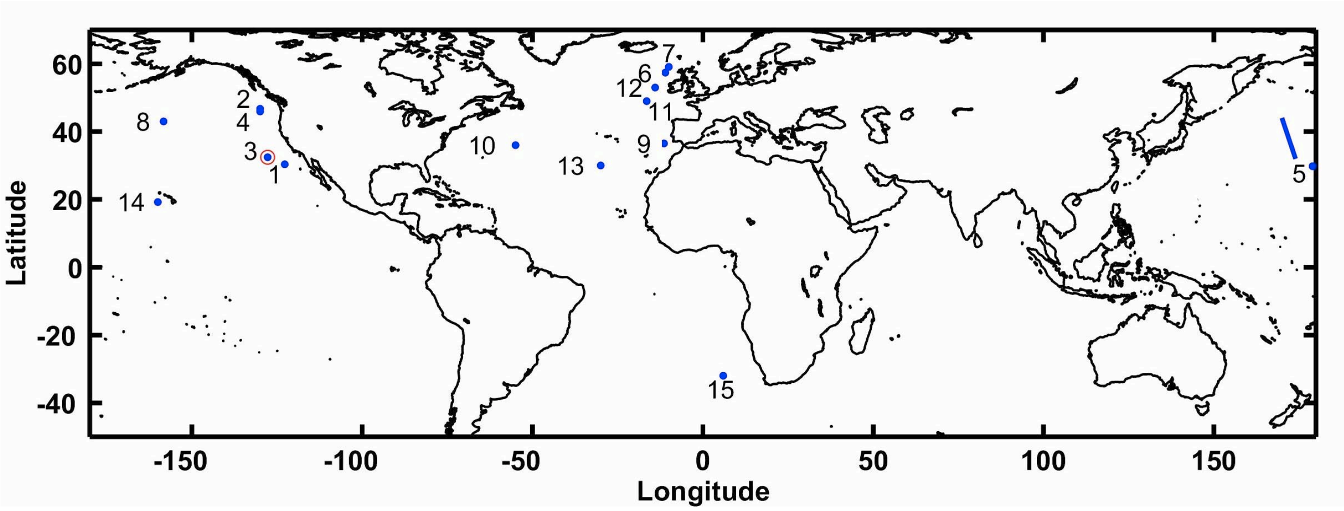

Fig 1. Location of principal seamounts discussed in the review: 1 – Jasper, 2 – Cobb, 3 – Fieberling Guyot, 4 – Axial, 5 – SE Hancock, 6 – Anton Dohrn, 7 – Rosemary Bank, 8 – Cross, 9 – Gorrainge Bank, 10 - New England, 11 – Porcupine Abyssal Plain Knoll, 12 – Porcupine Bank, 13 – Great Meteor Seamount, 14 – Horizon and 15 – Vema Seamount. The blue line shows the approximate position of the Emperor seamount chain.

2 BASIC THEORETICAL CONCEPTS

2.1 Taylor columns and caps (steady forcing)

One of the basic theoretical concepts relevant to fluid dynamics at isolated topography was introduced by Taylor (1917) and Proudman (1916) and is known as the Taylor-Proudman-Theorem: They showed that a flow in perfect geostrophic balance (steady, linear, inviscid) cannot cross isobaths. Hence, if such a flow encounters an isolated topographic obstacle (e.g. a seamount) an anticyclonic circulation following the isobaths is generated and any fluid inside is trapped in a stagnant area above the obstacle. This flow pattern is commonly known as Taylor column.

In the real ocean nonlinearity, unsteadiness, stratification and viscous processes will break the constraint for an ideal Taylor column flow. A more complex picture evolves mainly depending on the strength of the impinging flow, the geometry of the obstacle and the strength of the oceanic background stratification. In the case of a steady current encountering and crossing a seamount upwelling on the upstream side and downwelling on the downstream side of the obstacle is generated. If the steady current is weak or frictional effects are large, this dipole pattern of vertical motion is stationary and accompanied by two counter-rotating cells of locally enhanced horizontal currents (see Fig. 2a) and isopycnal doming. Stronger steady currents lead to the generation of a Taylor cap (Chapman and Haidvogel, 1992), a generalization of Taylor columns in stratified fluids (see Fig. 2b). Undisturbed Taylor columns/caps can only exist in regions of strong mean flows and weak tidal variability. These restrictions are valid only for a few regions in the world ocean, thus a combination of effects induced by steady and tidal forcing can be expected for many seamounts and submarine banks.

2.2 Resonant amplification of seamount trapped waves and rectified flows (periodic forcing)

The second approach considers the theory and properties of freely propagating trapped waves at isolated topography (Chapman, 1989; Brink, 1989; 1990). These waves exist only for sub-inertial frequencies and are the special form of coastally trapped waves adapted to the geometry of seamounts and submarine banks. The restoring force of seamount trapped waves is the potential vorticity gradient related to changes in water depth. The properties of these waves strongly depend on the relative importance of stratification and topographic form (Huthnance, 1978; Brink, 1989). The gravest wave modes are dipoles rotating about the seamount in an anticyclonic sense (Fig. 2c) and show a tendency for bottom-trapping with increasing stratification. Lower frequency wave modes are not generated due to frictional damping (Brink, 1990). A continuous excitation of seamount trapped waves at or near their characteristic frequency through resonance with ambient tidal currents can lead to a strong response with substantial amplification factors (Chapman, 1989).

As a consequence of resonant amplification of seamount trapped waves a time-mean residual flow may be generated through non-linear rectification, a process that is associated with time-mean deviations of the non-linear wave solutions from the initial state. This time-mean rectified flow is comparable to a Taylor cap flow for steady forcing and marked by an anticyclonic along-isobath circulation pattern and a corresponding doming of isopycnals (Fig. 2d). The residual flow can reach substantial amplitudes with strong implication for the dispersion of biological and chemical tracers as well as for sediment dynamics.

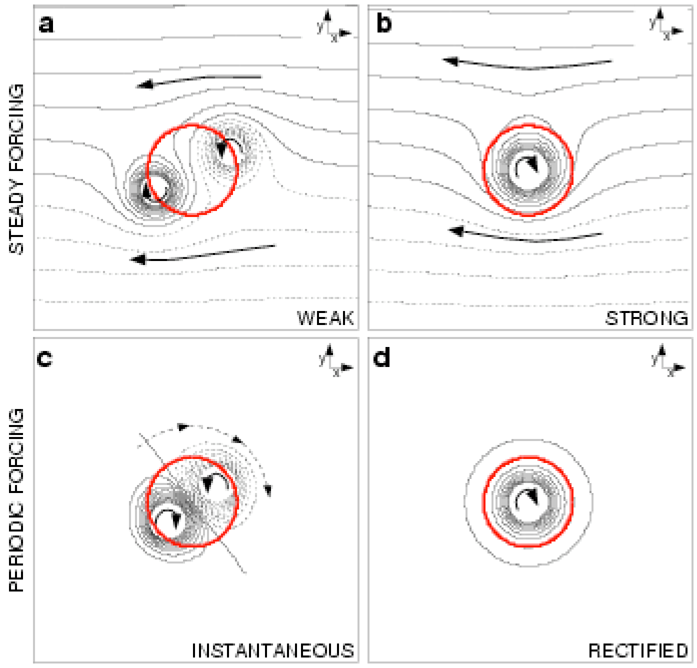

Fig.1: Principle flow pattern at a circular seamount (red circle) on the northern hemisphere: a) stationary dipole pattern for weak steady inflow, b) Taylor column/cap for strong steady inflow, c) rotating dipole pattern as a transient response to periodic forcing, d) time-mean rectified flow due to seamount-trapped waves (Beckmann and Mohn, 2002).

2.3 Parameter dependencies

In this subsection the relative importance of important geometrical and environmental parameters and their variation in parameter space for the generation and response of Taylor columns/caps and seamount-trapped waves are highlighted. The current knowledge of the influence of these factors on the residual flow at seamounts and submarine banks mainly results from theoretical and model studies.

2.3.1 Topographic irregularities

A set of idealized model experiments addressing the question how the height of a Gaussian shaped seamount relative to the strength of an impinging steady flow is affecting Taylor column/cap occurrences was carried out by Chapman and Haidvogel (1992). They identified the seamount height as the critical factor: True Taylor caps, i.e. permanently trapped fluid parcels, will only develop above a certain seamount height (Chapman and Haidvogel, 1992).

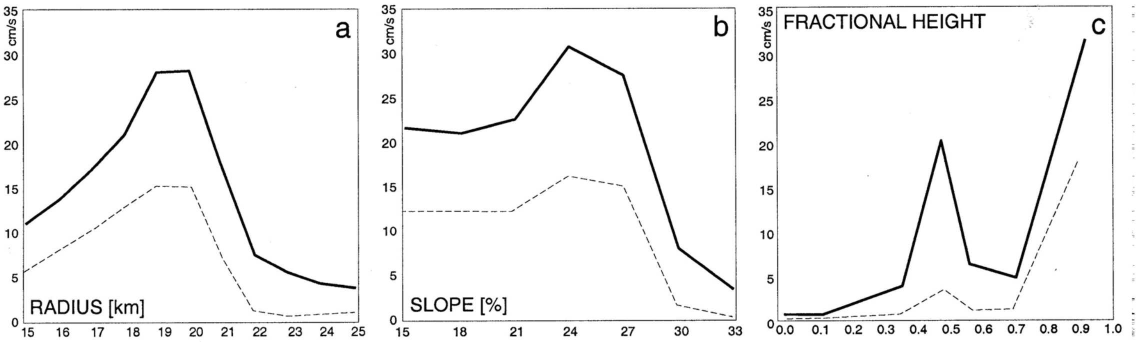

Fig. 3: Resonant amplification (solid line) and mean flow generation (dashed line) for periodic forcing as a function of seamount radius (a), slope (b) and height (c) at a tanh-shape seamount (Beckmann,1999).

Beckmann (1999) presented sensitivity studies extended to periodic forcing and variations of seamount radius, slope and height for an idealized tanh-shape seamount representing a more realistic seamount geometry with a flat summit (Fig. 3). Results of the variation of the seamount radius revealed a maximum resonance and rectified mean flow for a radius of 20 km. The resonance and strength of the mean flow weakens for wider and narrower seamounts: Wider seamounts do not support a sufficient interaction between the seamount trapped wave lobes, whereas narrow seamounts seem not to be able to establish an effective resonance mechanism (Fig. 3a). Variations of the seamount slope showed a strong resonance peak at 24% and a strong drop for slopes steeper than 30%. Steeper slopes seem to have a limited ability of wave trapping and mean flow generation (Fig. 3b). Finally, the seamount height was found to be also important for periodic forcing. The strongest amplification occurred for intermediate and tall seamounts whereas a corresponding maximum of the rectified mean flow was only observed for tall seamounts (Fig. 3c).

2.3.2 Stratification, rotation and forcing

The generation of a Taylor column/cap circulation through steady forcing and a rectified mean flow through periodic forcing is mainly influenced by the strength of the stratification and the impinging flow as well as the topographic scaling of the obstacle and the Coriolis parameter f (see above). The relative importance of these effects is expressed by the Burger number (e.g. Hogg, 1973; Huthnance, 1978)

$$B = N^2 H^2 / f^2 L^2 \qquad (1)$$

where N is the buoyancy frequency, H is the water depth, f is the Coriolis parameter and L the horizontal topographic scale. Small values of B indicate that the effect of stratification on the Taylor column/cap flow is less important in relation to the topographic scales. In the case of a weak stratification (, where $Ro = U / fL$ is the Rossby number) the formation of a Taylor column/cap is only possible below a critical Rossby number;

$$Ro_c = 0.5\delta(1 - 0.5\delta) \qquad (2)$$

where δ is the fractional height of the seamount (Johnson, 1978). If the stratification increases the isopycnal doming above a seamount decreases exponentially from the summit depth towards the surface to a water depth (Owens and Hogg, 1980);

$$h_e = \frac{Lf}{N} \qquad (3)$$

In general, stratification changes with latitude have to be considered: Stronger effects on the flow can be expected at higher latitudes due to the generally weaker stratification and convective overturning events in periods of intense surface cooling (Beckmann, 1999; Dooley, 1984).

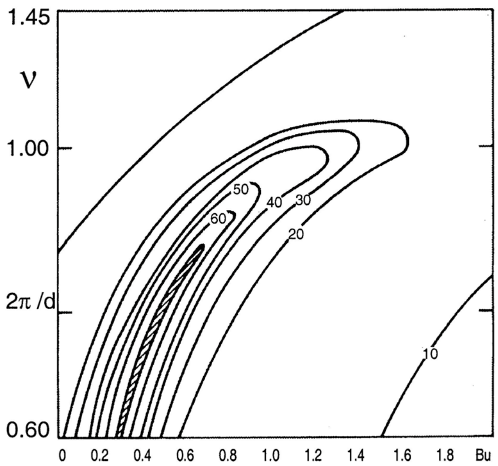

Fig. 4: Resonant amplification as a function of the Burger number and the forcing frequency (Haidvogel et al., 1993).

Similar considerations can be applied to periodic forcing (Brink, 1989; Haidvogel et al., 1993). Haidvogel et al. (1993) conducted a series of model experiments to investigate the resonant amplification of seamount trapped waves as a function of Burger number and forcing frequency at a Gaussian shaped seamount (Fig. 4). Their results show that amplification occurs not only for one particular situation but for a wide range of sub-inertial forcing frequencies and Burger numbers.

Hence, resonant amplification of seamount trapped waves of substantial amplitude is possible for forcing frequencies closely matching the frequency of the trapped wave. However, an important assumption is the limitation to sub-inertial frequencies w < f (e.g. trapped waves of diurnal period can only exist poleward of 30º N).

3 MODEL STUDIES

3.1 Properties and patterns of the flow at seamounts and submarine banks

Over the past decades a number of model strategies have been applied to study and verify the observations at specific sites as well as to understand and explain the principle physical mechanisms, their interaction and relative importance. The applications range from process studies with idealised topography and forcing, to scenarios at realistic seamounts and environmental conditions.

3.1.1 Idealised process studies

One of the first efforts using numerical ocean modelling to describe processes at isolated topographic features was made by McCartney (1975) using the quasi-geostrophic vorticity equations. He considered the problem of a steady flow over a short, cylindrical seamount in a stratified ocean on a b-plane (variation of the Earth's rotation with latitude). He showed that the structure of a Taylor cap over large seamounts strongly depends on the direction of the impinging flow due to the generation of Rossby waves. Eastward flow generates an anticyclonic eddy upstream of the seamount, and a stationary wave pattern downstream acting as a major source of oceanic variability. In the case of westward inflow, a Taylor cap centred above the summit, and the flow is up/downstream of the seamount is symmetric (see Fig. 5)

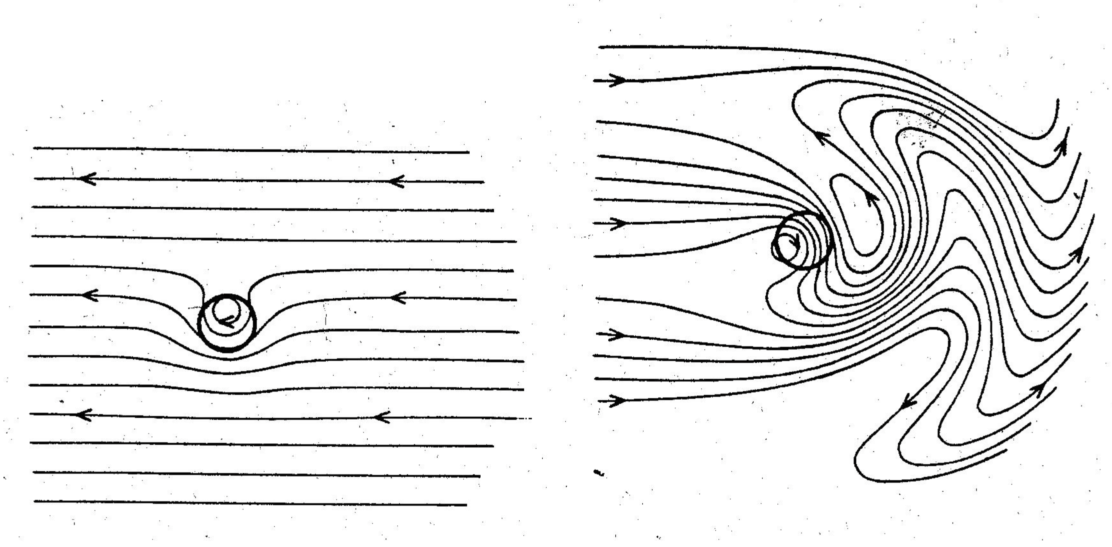

Fig. 5: Quasi-geostrophic flow past a cylindrical seamount on a beta-plane for westward flow (left) and eastward flow (right), after McCartney (1975).

Verron and Provost (1985) and Verron (1986) also used the quasi-geostrophic approach in the presence of lateral friction to discuss the evolution of flow perturbations above a short seamount through a steady inflow of variable strength and the effects of an oscillating inflow. The transient response of the flow regime strongly depends on the strength of the incoming steady flow. The initial state is marked by the generation of two counter-rotating cells above the seamount, rotating around the seamount as the inflow progresses. For strong inflows the advection dominates the eddy interaction and the cyclonic eddy is swept away with the incoming flow. For weak inflows the eddy interaction dominates and both eddies stay in the vicinity of the seamount. A temporally varying inflow tends to shed both eddies away from the seamount as a result of increased vorticity dissipation. Under such conditions seamounts may act as locations of permanent eddy generation with significant impact on the oceanic far field (see Fig. 6).

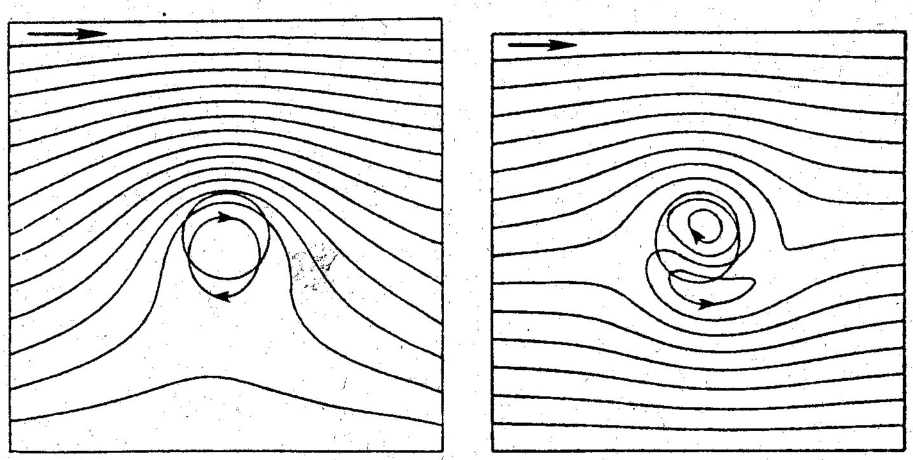

Fig. 6: Flow perturbations at a cylindrical seamount: Trapped anti-cyclonic vortex for strong advection (left), two counter-rotating eddies for weak advection (right), after Verron and Le Provost (1985).

Due to the limitations of the quasi-geostrophic approach (small amplitude topography and weak non-linearity) the three-dimensional primitive equation system was introduced to discuss questions associated with tall seamounts in strongly stratified oceanic regions and high non-linearity. A first series of experiments was carried out by Huppert and Bryan (1975), who considered the interaction between temporally varying currents and the bottom topography at an idealised seamount of moderate height motivated by observations of strong eddy activity at Atlantis II seamount in the North Atlantic (Vastano and Warren, 1976).

A first comprehensive model study on the formation of Taylor caps over a tall isolated Gaussian seamount in a stratified ocean was presented by Chapman and Haidvogel (1992). They took full advantage of a new representation of the vertical coordinate. The so-called sigma-coordinate replaces the classical z-coordinate by applying a transformation into topography-following vertical levels to get a more accurate treatment of near-bottom processes in areas with steep topography (Haidvogel et al., 1991). The study concentrates on the effects introduced by different seamount heights and varying steady inflow in a stratified ocean. Based on a systematic analysis the authors were able to separate different regimes for which Taylor caps may occur or not occur as well as to define situations of temporary Taylor caps (see Fig. 7)

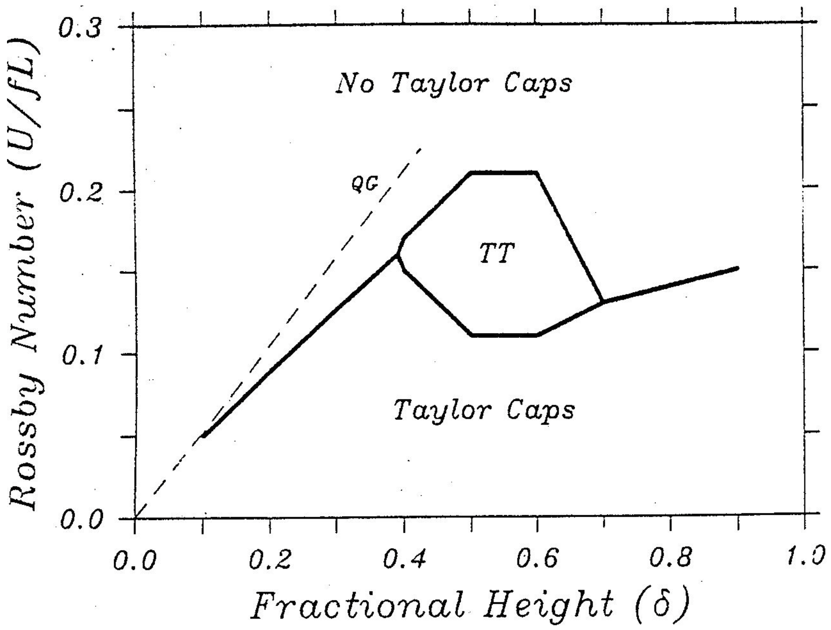

Fig. 7: Gaussian seamount regimes for steady, stratified flow based on the model results of Chapman and Haidvogel (1992).

Motivated by Brink's (1989, 1990) studies on seamount-trapped waves, Haidvogel et al. (1993) introduced periodic forcing to a set of numerical model simulations to investigate the resonant excitation of freely propagating seamount–trapped waves and the non-linear rectification of a time-mean flow at a Gaussian shaped seamount (see subsection 2.3.2).

The aspect of internal tide generation by seamounts and ridges was addressed by Holloway and Merrifield (1999). Using real stratification and tidal forcing representing realistic conditions for the Hawaiian Ridge they were able to show that weak semidiurnal tides are able to interact with the steep topography to generate an energetic internal tide. The signal strength, however, depends crucially on the shape of the topography. Symmetric seamounts produce only a weak internal tide, whereas at ridges (elongated seamounts) the internal tidal signal strength increases by almost one order of magnitude. The authors also emphasise that an effective generation of internal tides is also influenced by the relationship between the topographic slope and the slope of the internal wave characteristics, i.e. the propagation path of the wave energy. This relationship leads to a classification of critical (important for internal tide generation) and sub-critical slopes.

Another aspect of numerical process studies at seamounts are processes at quasi-isolated topographic features like shelf-break banks. Gjevik and Moe (1994) analysed the barotropic and baroclinic flow around isolated shelf-break banks applying varying current directions and orientations of the bank. For a northward inflow with the shelf edge at the eastern boundary, an enhanced shelf edge current develops forming an anti-cyclonic recirculation above the bank. In contrast, a southward flow with a shelf edge on the western boundary generates a stationary shelf wave pattern downstream of the bank. Mohn and Beckmann (2002) investigated possible mechanisms of flow amplification at an isolated shelf-break bank considering idealized tidal and steady forcing under different stratification conditions. This work was motivated by repeated hydrographic surveys at Porcupine Bank west of Ireland where a strong anti-cyclonic flow associated with uplifting of the isopycnals was observed in the vicinity of the bank. They found that the observed perturbations mainly arise from flow rectification through resonant amplification of diurnal seamount trapped waves. The structure and intensity of the residual flow strongly varies with the strength of the background stratification. Increasing stratification causes strong damping and bottom trapping of the flow (see Fig. 7).

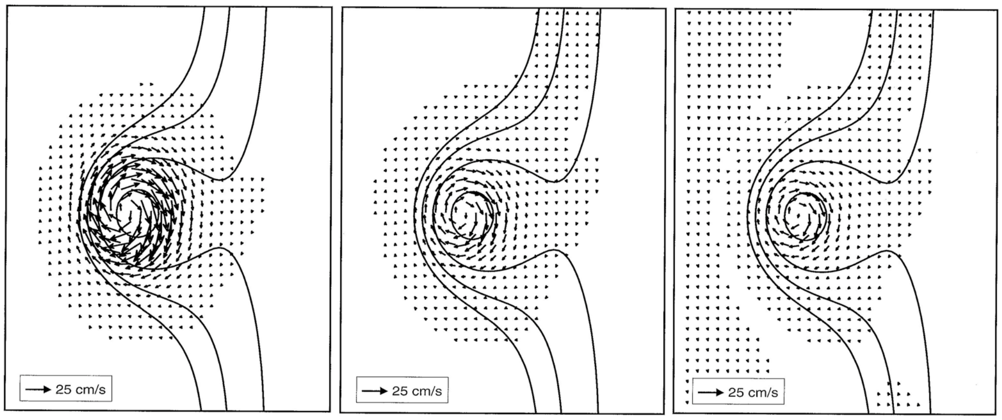

Fig. 7: Rectified residual flow over a shelf-break bank (adapted to Porcupine Bank) for weak (left), moderate (middle) and strong stratification (after Mohn and Beckmann, 2002).

3.1.2 Realistic scenarios

An early study of physical processes at a seamount and submarine banks was carried out by Loder and Wright (1985). They used a depth-dependent tidal rectification model (Wright and Loder, 1985) and a diagnostic frontal circulation model (Garrett and Loder, 1981) to predict the residual circulation associated with tidal rectification and the stratification at Georges Bank. Georges Bank is a large, north-east elongated shelf-break bank forming the southeastern boundary of the Gulf of Maine at the Northwest Atlantic continental margin. It rises from depths greater than 2000 m up to a wide plateau with an average water depth of 50 m. It was shown that the process of tidal rectification contributes significantly to the residual circulation at Georges Bank. Predicted winter and summer conditions were compared with observations and found to be in good agreement for the along-isobath component of the flow. Poor agreement, however, was found for the cross-isobath component probably due to the idealizations of the model setup (a dominant single tidal constituent and weak nonlinearity were assumed). Residual currents were predicted to be stronger in summer than in winter due to reduced wind stress and enhanced stratification. The circulation at Georges Bank was subject to further intensive studies (both observational and modelling) as part of different projects and initiatives addressing different problems associated with the variability and stability of the flow (e.g. Lynch et al., 1992; Naimie et al., 1994; Naimie, 1996).

A detailed numerical simulation study of the flow at Fieberling Guyot was carried out by Beckmann and Haidvogel (1997). The main aim was to reproduce the observed flow features and to identify the dominant physical mechanisms associated with it. Fieberling Guyot is the largest isolated feature in a group of seamounts in the northeast Pacific. It is an almost axis-symmetric seamount extending from bottom depths of 4000 m up to approx. 700 m below the sea surface. Fieberling Guyot was the target area of a detailed multidisciplinary programme to study the physical, biological and chemical properties of oceanic waters near steep and isolated topography. The forcing and initialization of the model was chosen to match typical values frequently observed in the area. The authors were able to reproduce the observed currents both qualitatively and quantitatively. The diurnal tidal currents were strongly amplified (20 times the tidal flow away from the seamount) generating a trapped anticyclonic time-mean vortex above the seamounts with current velocities up to 10 cm s^{-1}. A comprehensive characterisation of the three-dimensional circulation was given by the authors, clearly identifying up- and downwelling areas and the magnitude of the time-mean density perturbation. The secondary circulation is marked by an almost closed overturning cell (downward motion over the seamount summit, a radially outward flow along the upper seamount flanks and a recirculation farther away).

An interesting aspect of the interaction of seamounts and the surrounding ocean was considered by Beckmann et al. (2001). They investigated the role of seamounts in the formation and evolution of sea ice in the vicinity of Maud Rise with a couple ice-ocean model. Maud Rise is a large seamount in the Weddell Sea covering an area of approx. 300 by 400 km near 65ºS at the Greenwich Meridian. It rises from 3500 m at the seafloor to depths of 1700 m. The study was motivated by the occurrence of the so-called Weddell Polynya, an almost completely ice-free area between 64ºS and 69ºS near the Greenwich Meridian in the winters of 1974-1976 (Carsey, 1980). The model was forced and initialized with realistic tidal constituents, a steady mean flow and stratification typical for the region in winter. The authors showed that the mixed layer above the seamount can be modified as a response to steady and tidal forcing favouring a delay and decrease in the sea-ice formation throughout the winter. This sea-ice anomaly spreads and moves away from the seamount with the steady flow seamount affecting a large area outside the direct vicinity of the seamount (see Fig. 9).

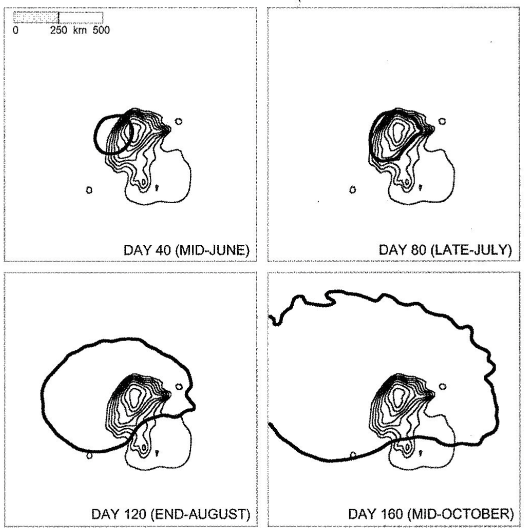

Fig. 8: Snapshots of the evolution of the sea-ice anomaly above Maud Rise in the Weddel Sea (Beckmann et al., 2001)

Another multidisciplinary seamount study was carried out recently focussing on the Great Meteor Seamount in the subtropical North Atlantic (Mohn and Beckmann, 2002). Great Meteor Seamount is one of the largest isolated submarine features in the Atlantic Ocean. It is centred at 30ºN and 28.5ºW in the subtropical North Atlantic extending from 4000 m up to 300 m water depth. Great Meteor Seamount is the main feature of a complex of two additional smaller seamounts nearby. Observations of hydrography and currents were combined with a three-dimensional ocean model to investigate the physical situation and some of the consequences for the marine ecosystem (see below). Realistic steady and tidal forcing and the background stratification were taken from observations during an accompanying field programme and from historical observations of Meincke (1971). Several physical aspects made this seamount worth studying, e.g. critical latitude effects and interaction with ancillary seamounts. It was found that both sub- and superinertial forcing is important for the flow, since the seamount intersects the critical latitude for the main diurnal tidal constituent. The model results revealed a substantial tidal amplification through a wider band of tidal frequencies leading to a high level of sub-mesoscale variability in the area. The isopycnal doming and the rectified time-mean flow were predicted to be comparatively weak. The semi-diurnal tide was found to have a major influence within the near-surface thermocline layer leading to two different flow regimes above the seamount: an upper thermocline layer, mainly influenced by the semi-diurnal tides, and a seamount summit layer showing a weaker anti-cyclonic recirculation due to the leakage of diurnal tidal energy and the interaction with the steady background inflow (see Fig. 9). Interactions with the smaller ancillary were not detected in the model; they exhibit there own flow regime but do not interfere with each other. Discrepancies between the model and observations were particularly obvious in the seamount areas south of 30ºN.

Fig. 9: The flow regime at Great Meteor Seamount derived from model experiments (after Mohn and Beckmann, 2002)

4 OBSERVATIONS OF PROCESSES

4.1 Introduction

The importance of isolated topographic features as a possible source of meso-scale and large-scale flow variability and instability has been discussed and emphasised in a large number of observational studies. In his overview Roden (1987) pointed out that the interaction of the seamount topography with impinging oceanic currents under the influence of stratification and rotation give rise to a large spectrum of effects and processes which may also have a substantial influence on the surrounding ocean. Some of the most important aspects are listed below:

- Strong amplification of tidal currents (e.g. Meincke (1971) at Great Meteor Seamount in the subtropical North Atlantic, Huthnance (1974) at Rockall Bank in northern North Atlantic, Hunkins (1986) at Yermak Plateau in the Arctic Ocean, Loder (1980) at Georges Bank in the Northwest Atlantic and Genin et al. (1989) at Fieberling and Horizon Guyot in the North Pacific).
- Resonant excitation of seamount trapped waves through tidal forcing (e.g. Eriksen (1991) at Fieberling Guyot, Codiga and Eriksen (1997) at Cobb Seamount and Mohn et al. (2002) at Porcupine Bank in the Northeast Atlantic).
- Perturbation of the oceanic mass field and closed anticyclonic circulation cells generated by stratified Taylor column/cap formation (e.g. Owens and Hogg (1980) at a small seamount in the Gulf Stream system, Roden and Taft (1985) at the Emperor Seamount chain and Roden (1994) at the Fieberling Guyot in the North Pacific).
- Baroclinic instabilities and eddy generation (e.g. Vastano and Warren (1976) at Atlantis II Seamount in the North Atlantic, Cheney et al. (1980) in the Kuroshio system and Booth (1988) in the Rockall Trough).
- Enhanced vertical mixing, turbulence and internal wave generation (e.g. Noble and Mullineaux (1989), Kunze and Toole (1997) and Eriksen (1998) at Fieberling Guyot).

4.2 Mean Flow and Mesoscale Variability

4.2.1 Large Scale Interactions

Roden (1987) has shown how perturbations in the dynamics around the Emperor Seamount chain (Pacific) can be revealed from the changes in the geo-potential height anomaly. The Emperor Seamount chain is 100 km wide and 2400 km long, hence provides a substantial topographic influence to flow. Geo-potential height anomalies, up to 3 J kg^{-1} in magnitude, equivalent to a sea surface change of 30 cm, were found in the vicinity of the seamounts (sea surface relative to a level of 1500 m. Currents varied between 15- 35 cm s^{-1} within the seamount chain, and eddy generation and deflections of the Kuroshio Current were apparent. Furthermore, Roden (1991) has shown similar processes at work at the Fieberling Chain in the eastern Pacific Ocean. Current jets, about 20-30 km wide were observed between the seamounts, with associated currents of between 20-50 cm s^{-1} and pairs of eddies 10-20 km in diameter. Associated with these features was dynamic height variability of 3-8 cm, in the form of ridges and troughs around the region of the seamount chain. Roden (1987) also quotes other examples from previous work, e.g. the deflection of the Gulf Stream by the New England Seamount Chain, as revealed by drifter tracks (Vastano and Warren; 1985).

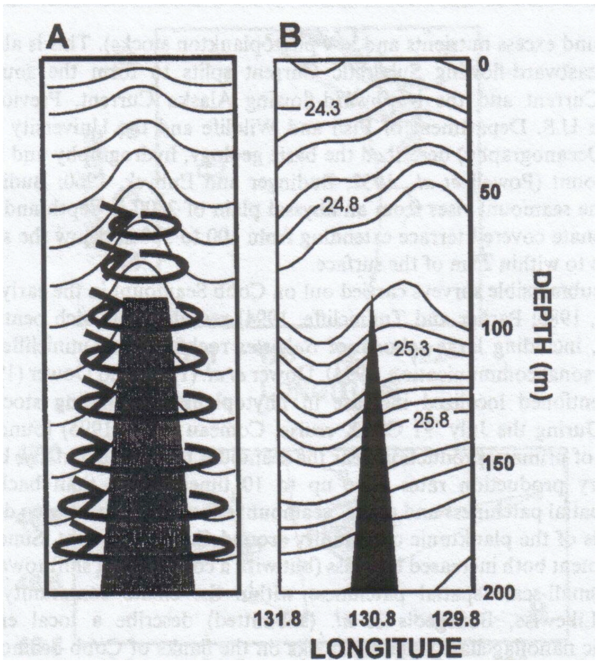

Fig 10. (a) Theoretical isopycnal doming over Cobb seamount from the model of Freeland (1994) and (b) measured doming by Dower and Mackas (1996). Taken from Dower and Mackas (1996).

Owens and Hogg (1973) have described hydrographic observations around a 400 m high seamount in deep water (4800 m) in the region of Gulf Stream re-circulation. Uplifting of isotherms of vertical scale 3km was observed. Amplitude of the isotherm deflections was 400 m above the seamount summit, and decreased to 100 m at 3000 m depth. Vorticity in the seamount region was estimated between $-6.5x10^{-5}$ s^{-1} or 0.1f. This value was in line with the expected vortex compression caused by the flow over the seamount which gave a scale height of 4 km, similar to that observed for the scale of isotherm uplifting. Mohn et al. (1999) has observed isotherm doming over the Porcupine Bank, a large submerged bank partly connected to the Irish continental slope. The doming was observed to persist for several months (White et al.; 1998). A comparison of theoretical isopycnal doming (as suggested by Freeland, 1994) and that measured over Cobb seamount by Dower and Mackas (1996) is shown in Fig 10.

As large topographic features, seamounts may interact with the prevailing oceanic circulation to generate eddies, or eddies themselves may advect across seamount features. Stationary eddies may be generated in the vicinity of seamounts due to the Taylor cap/column formation. Under certain dynamical conditions these eddies may be shed from the seamount or topographic feature. Booth (1988) has observed a series of cyclonic eddies in the Rockall Trough which appeared to be associated with the Anton Dohrn seamount. Isotherm doming, and analysis of historical current meter records, indicated that an anti-cyclonic circulation exists around the Anton Dohrn seamount, and dynamical conditions were consistent with a Taylor cap formation. Booth (1988) also argued, based on scaling arguments and the time varying character of the background Rockall Trough flow, why more than one cyclonic eddy was present close to Anton Dohrn. Only occasionally would the background currents would be strong enough to advect eddies away from the seamount. Royer (1978) has shown that eddies were generated downstream of seamount chains by the flow of the North Pacific current. The eddies, of length scale 37 km, were observed in a CTD transect and Royer suggested their generation provides a source of energy dissipation within the North Pacific current in the region.

An example of eddy-seamount interaction has been presented by Dower et al. (2004, web.uvic.ca/~dower/dowerlab/PICES.pdf), observed by Crawford (2002), and modelled by Di Lorenzo et al. (2004). In the NE Pacific eddies known as 'Haida' eddies, have been reported to exist, and which interact with the numerous seamounts found in that region. Haida eddies are formed at the continental margin region through the interaction of the water masses with the canyon and island present there. Smaller eddies coalesce into a larger anti-cyclonic Haida eddy, standing up to 30 cm higher than the surrounding water and with a typical radius of 60-75km (Crawford, 2002), and which may extend down to 1000m depth (Lorenzo et al., 2004). Dower (web.uvic.ca/~dower/dowerlab/PICES.pdf) has shown that Haida eddies track WSW from their generation point and intersect with the seamounts found offshore. About 15 of these eddies have been observed off the continental shelf since 1992. The seamount chain includes the Bowie Seamount, which rises to 25m depth, where one eddy became stuck for a period of 3 months. The linkage of these eddies, which transport water from the continental shelf to the offshore seamounts, and fisheries populations are currently under investigation (Dower, 2004, web.uvic.ca/~dower/dowerlab/PICES.pdf). Another example of an eddy-seamount interaction was provided by Bower et al. (1995), who tracked the movement of Meddies generated by the

Mediterranean outflow SW of Portugal. One if these Meddies was shown to impinge on the nearby Gorrainge Bank which appeared to affect the subsequent propagation direction of the Meddy (Fig 11). Similar occurrences are possible at the Seine seamount, an OASIS study site.

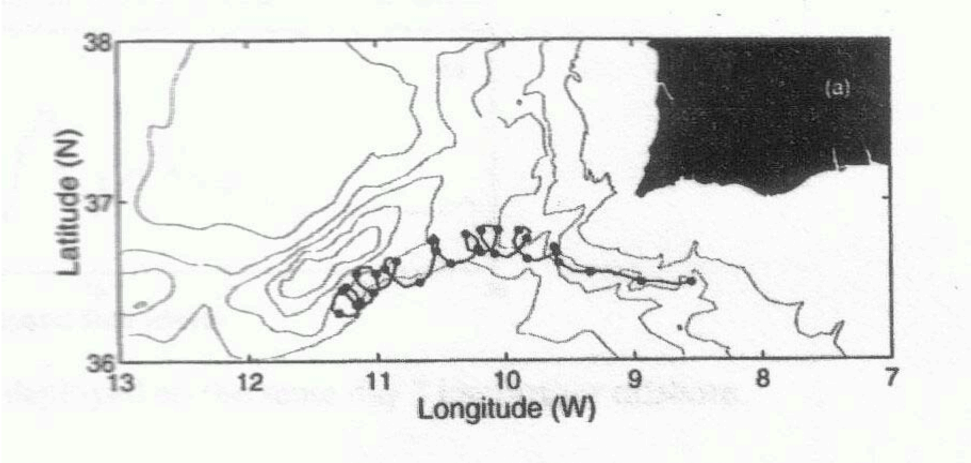

Fig 11. Track of subsurface buoy, drifting at Mediterranean Outflow Water level, showing the effect of Gorrainge Bank (centred at 36.5N, 11.5W) in deflecting the Meddy into which the float was seeded. Figure is taken from Bower et al. (1995).

4.2.2 Mean flow patterns

Lavelle et al. (2003) collected long timeseries measurements of currents at the Axial Volcano seamount, located on the Juan de Fuca Ridge. The volcano rises to a depth of 1400 m above the Ridge which itself is at 2500m depth, hence the seamount intercepts the flow at a level above the ridge. An anticyclonic circulation was observed around the seamount with a maximum residual current of 6.6 cm s^{-1} recorded at the rim of the seamount about 7 km radial distance from the summit, but at a depth level above the summit. Whilst there was no measured change in the M2 semi-diurnal tidal amplitude, relative to the far field away from Axial Volcano, the S2 and diurnal tidal components K1 and O1 were amplified at the seamount. A 10fold amplification of energy in the weather band (period centred at 4 days) was found between the depths 100m above the summit to 400m below the summit, which also varied seasonally. Spectral analysis and comparison to a simple model indicated that a topographic resonance of period between 1-2 days existed, with weaker, longer period resonances also present. This long period resonance aspect of the circulation at Axial Volcano has not been reported for other locations where long timeseries measurements have been made.

Genin et al. (1989) have made short term observations at Fieberling and Horizon Guyot which have highlighted the difference that seamount topography can make to the amplification of different period tidal forcing. Fieberling Guyot is a circular seamount with a summit at 500 m depth, whilst Horizon Guyot is more elongated and has a summit at 1500m. Measurements at both sites were made at the summit and on opposite sides at the seamount flanks. At Fieberling Guyot, an anticyclonic circulation was measured with bottom intensified diurnal period motions present in the record and current amplitudes were amplified from far field tidal currents. A vertical trapping of the motion within 50 m of the seabed was inferred with associated isotherm uplifting. At Horizon Guyot, semi-diurnal currents were predominant, but overall currents at the seamount were less than at Fieberling Guyot.

Short (6-13 day) time series made at Cobb seamount by Freeland (1994) on three separate occasions have revealed anti-cyclonic flow (mean currents up to 12 cm s^{-1}) 50 mab (m above seafloor), with weaker currents found closer to the seabed (10 mab) that also had a mean offslope component (Fig 12). Analysis of underway ADCP data indicated that flow in the surface 100 m was largely unaffected by the seamount, despite the fact that the seamount had a peak at 24 m depth. This summit was a sharp pinnacle and the main upper flat summit region of Cobb Seamount was at 200 m depth. The ADCP data revealed that the upper extent of the enclosed circulation measured by 50 mab was likely 80-100 mab. Observations did not fit into a simple theory of a Taylor Cap generation in this case, which predicted a bottom enclosed circulation reaching only 40 m from the seabed. A combination of Taylor Cap generation and tidal rectification was suggested as driving forces for the currents measured.

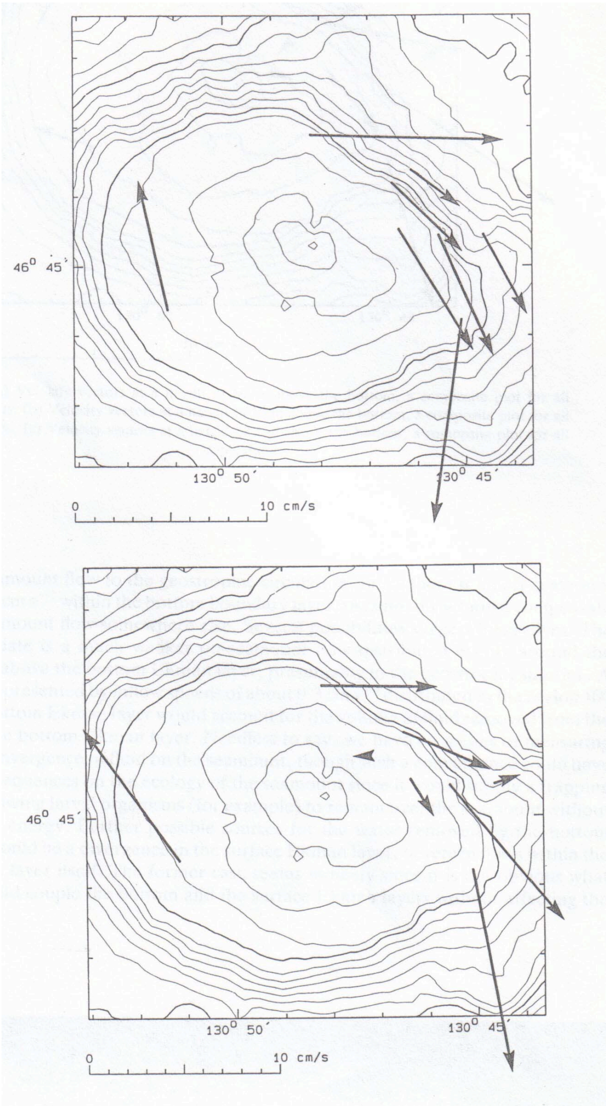

Fig 12. Mean current vectors from a composite of 3 measurement periods at (top) 50 m above seabed and (b) 10 m above the seabed at Cobb seamount, as described in Freeland (1994).

4.3 Diurnal Tide Amplification and Trapped Waves

Poleward of the latitude for the cut off period for freely propagating waves, wave motions of longer period may be trapped at topographic features, including seamounts. These motions may be forced by the background wave motions, including the diurnal tides. Brink (1995) has described the presence of such trapped waves at Fieberling Guyot from a set of year long current measurements. The trapped waves were of diurnal period and had maximum amplitude at 450 m depth, above the seamount summit and outward over the seamount flank. Amplification of 11x the far field diurnal tidal current amplitude was estimated, whilst a model predicted an amplification factor of 18. The action of the waves was to rectify the flow such that a mean anti-cyclonic circulation was measured around the Guyot, with maximum flow at 50 mab at the Guyot flank. The mean flow amplitude was modulated on a fortnightly period supporting the idea that the mean flow was generated by the tidal rectification and amplification at the seamount. In addition, the M2 semi-diurnal tide was also amplified, while the S2 component was not. It was suggested that the reason was because the M2 tide was the sum of the principal diurnal tidal components, O1 and K1 and hence was influenced by the diurnal amplification. Lower frequency current amplitudes were also amplified, from a background flow of about 1 cm s^{-1} to 10 cm s^{-1} near the seamount, although not bottom trapped. The low frequency variability was driven by the ambient background flow fluctuations.

Noble et al. (1994) have also recorded amplification of the diurnal tide over Fieberling Guyot from a short time series of currents and inferred that the amplification occurred over a narrow bandwidth. Eriksen (1991) also measured large (20-40 cm s^{-1}) mean anticyclonic currents above Fieberling summit. Other measurements at Fieberling Guyot and Cobb seamount also indicate a mean anticyclonic flow pattern around the topographic features driven by amplification and trapping of the diurnal tidal forcing (e.g. Genin et al. 1989, Freeland, 1994). Huthnance (1974) have shown that diurnal trapped waves exist at the Rockall Bank, and have been identified in current meter measurements on the lower flank of the bank by White (unpublished data), who has inferred a bottom trapping within 150 m of the seabed. Kunze and Toole (1997) have shown that the diurnal motions at Fieberling Guyot can produce large current shear and mixing, with inferred vertical diffusivities of up to 10 cm^2 s^{-2} at the seamount flanks.

4.4 Internal Waves

There has been much attention paid to the reflection of internal waves from a sloping seabed, and the resultant change in energy spectrum and vertical turbulent mixing the reflection process may generate (e.g. Eriksen, 1982; Thorpe, 1987; Garret and Gilbert, 1988; Eriksen, 1998). When internal waves reflect from a boundary, the vertical wavenumber changes and hence the energy density and vertical current shear produced by the internal wave. This may lead to wave overturn and/or turbulent mixing. The angle at which the internal wave energy propagations is dependant on the vertical stratification

(N), Coriolis parameter (f) and wave frequency (s). When this angle is matches the seabed slope, a critical condition results when linear theory predicts an infinite increase in energy density as the vertical wavenumber vanishes. At depths where this matching occurs, large currents and turbulent mixing may be expected. Topographic features such as seamounts, therefore, can act as energy sinks for internal wave energy and cause perturbations in the deep ocean internal wave spectra, which otherwise is remarkably uniform (Munk, 1981).

From observations on Muir seamount, Eriksen (1982) observed spectral enhancement near the critical wave frequency within 100 m of the seabed and polarisation of the near seabed currents. Further long term observations at Fieberling Guyot by Eriksen (1998), have revealed non linear aspects to the internal wave breaking process. Whilst many aspects of the linear internal wave theory could account for many of the characteristics in the dynamics measured around the Guyot, departures from the theory were evident. In particular, wave reflection was observed as far away as 750 m from the seabed. The linear theory did not predict the broader spectral enhancement around the critical frequency for wave reflection that was measured, or the amplitude of the enhancement which was greatest for the on-slope current component. Spectral enhancement was observed to occur in a waveband which extended $\pm$ 20% either side of the critical frequency for internal wave reflection (Fig 13). Wave reflection caused numerous density inversions implying a large deal of turbulent mixing with an estimated vertical diffusivity of 2-6 cm^2 s^{-2} for the bottom few hundred meters.

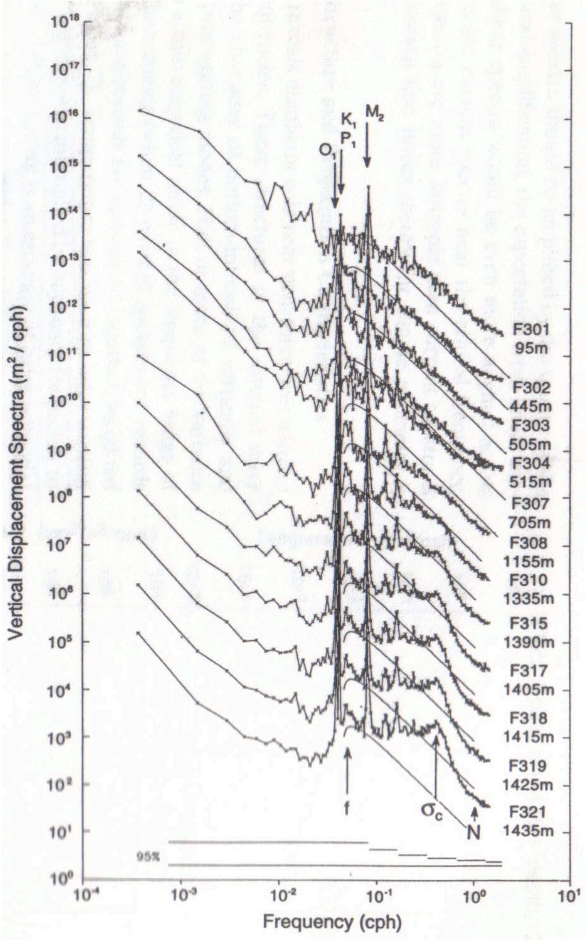

Fig 13. Spectra of vertical displacement, inferred from temperature measurements, at Fieberling Guyot for different depths above the seabed. Data taken from Eriksen (1998) and is 3 spectra in his Figure 3. Note the broad spectral peak at the internal wave critical frequency apparent near the seabed (lowest current meter is 20 mab) which decays with height from seabed. The thin line drawn with each spectrum is the predicted deep ocean internal wave spectra (Munk, 1981).

Noble and Mullineaux (1988) have observed internal wave motions at Cross Seamount, 300 km SW of the Hawaiian Islands, from a relatively short (46 day) current meter record from the summit of the seamount. The current record was dominated by semi-diurnal fluctuations, which accounted for 28% of the variance in the time series. Interestingly the S2 tidal component was 1.5x larger than the M2 component, with a tidal amplitude that varied between 4-9 cm s^{-1}. Noble et al. (1988) also found a 400% increase in tidal amplitude of currents at the flanks of Horizon Guyot relative to the deep water tides in the far field region away from the Guyot.

4.5 Vertical mixing

The role of seamounts in the vertical mixing of heat and momentum has recently become of interest, due to the increased surface seabed area that seamounts provide in the deep ocean. From theoretical and modelling arguments, a vertical turbulent eddy diffusivity of $K_v = 1$ cm^2 s^{-1} is required to maintain the steady state balance of heat and salt in the global ocean (e.g. Munk, 1966). This diffusivity is needed to balance the mean upwelling of 10^{-7} m^2 s^{-1} of the deep cold water in the interior ocean, part of the thermohaline circulation process. Direct measurements of K_v in the ocean interior, however, have yielded values of only 10% of the required diffusivity. Attention has turned to the ocean boundaries, therefore, as the source of the extra vertical mixing needed to provide the necessary mixing for the interior ocean to balance the heat budget (e.g. Garrett, 1979).

In the most simplistic terms, if a diffusivity of K, acting over an ocean basin of surface area, A, is required to balance the heat budget, this may be accomplished by mixing in the bottom boundary region at the ocean margins with diffusivity K_v over a boundary surface area A_b, i.e.

$$A \,.\, K = A_b \,.\, K_v \quad \text{or} \qquad K_v = K \,.\, [\, A_b / A]$$

This assumption excludes arguments about mixing efficiency, transfer of boundary mixing to the interior and the effect of mixing in an already mixed boundary layer (Armi, 1978; Garrett and Gilbert, 1988).

Seamounts provide an increased bottom boundary layer where enhanced vertical mixing may take place (see later sections for mechanisms), and this is particularly significant with the discovery of many more seamounts in the oceans than previously thought. Enhanced mixing has been observed at a number of seamount locations. Ledwell et al. (2000), for example, inferred increased vertical mixing and diffusivity over rough topography in the Brazil Basin from tracer experiments. At mid depth in the interior Brazil Basin, a vertical diffusivity of 0.1 cm^2 s^{-1} was estimated. In the water 500m above the hills and knolls of the eastern basin, the diffusivity rose to 2-4 cm^2 s^{-1} and increased further to 10 cm^2 s^{-1} in the bottom boundary layer. Ledwell et al. (2000) show that the diffusivities inferred would be sufficient to close the heat budget for the Brazil basin, based on the volume transport of cold deep water in to the basin and the resultant upwelling required to keep the vertical temperature profiles in a steady state. Furthermore, Lueck and Mudge (1997) have measured a 100-100000x increase in energy dissipation over Cross seamount, a shallow (25m depth summit) seamount in the N Pacific ocean. The peak dissipation and vertical mixing occurred at the seamount rim. The authors estimate, based on similar scaling arguments presented above, that the mixing at the Cobb seamount rim was equivalent to a diffusivity of 0.1 cm^2 s^{-1} over 100,000 km^2 in the interior of the Pacific. Toole et al. (1997) found similar results for the Fieberling Guyot in the eastern N Pacific, although in that case, the mixing there was only 10% as effective as at Cobb seamount. Vertical diffusivities of 0.1 cm^2 s^{-1} was found in the far field from the Guyot and increased to 1-5 cm^2 s^{-1} near the flanks. These results indicate the potential for seamounts to provide a significant contribution to the vertical mixing in the deep ocean that is a core component of the global ocean overturning cycle.

5 BIO-GEOCHEMICAL IMPLICATIONS

5.1 Sediment Distribution

The regular and predictable residual circulation pattern around seamounts, generated by the Taylor Cap formation or other topographic effects, has been used to explain the sediment distribution around some seamounts (e.g. Turnewitsch et al., 2004; Roberts et al., 1974; von Stackelberg et al., 1979). Roberts et al. (1974) describe a moat and ridge structure around two seamounts in the northern Rockall Trough – the Anton Dohrn seamount and Rosemary Bank, both rising from about 200m water depth to a summit at about 500m depth. The sedimentary deposits were asymmetrically distributed around both seamounts, being thinner on the eastern flanks. The predominant flow is southward of overflow waters from the Norwegian Basin. Acceleration of the impinging flow would be on the eastern side of the seamounts, therefore, and probably cause the erosion or lack of sediment deposition on that flank of the seamounts. Turnewitsch et al. (2004) show that the topographically controlled flow around a small scale (5x10 km area, 900 m height) knoll in the Porcupine Abyssal Plain, NE Atlantic, produce asymmetries in the sediment distribution there. As with the example discussed by Roberts et al. (1974), the flow near the knoll is predicted to accelerate to the left of the knoll, looking down flow. In this case the enhanced flow was on the western side of the knoll for a northward directed mean flow but no Taylor Cap or topographically trapped waves would be generated by the flow. Inventories of sedimentary excess ^{210}Pb with ^{210}Pb input from the water column indicated a lower sediment-derived ^{210}Pb flux, relative to the water column fluxes, on the western side of the knoll where flow would be accelerated. Lower excess water column-derived ^{210}Pb fluxes or a balance of fluxes, where measured on the northern and western side of the knoll respectively where the currents were expected to be somewhat weaker. The sedimentary patterns, combined with knowledge of the ^{210}Pb half lives, indicated that a reasonable steady flow pattern had existed over the region for about a century. Von Stackelberg et al. (1979) have shown similar asymmetric sediment distribution patterns around the Gt Meteor Seamount in relation to the impinging Antarctic Bottom Water (AABW) flow. Again sediment deposition was found to the right of the seamount in relation to the northward flowing AABW. Cores representing different geological ages showed different amounts of asymmetry which highlighted the climatic variability in AABW flow.

5.2 Material Retention around seamounts

It would seem that the residual circulation patterns that may be generated, by either tidal rectification or Taylor Column formation, may be conducive to isolate water from the surrounding ocean. This may have a pronounced influence on the retention of planktonic or other organic material in the vicinity of a seamount. Goldner and Champman (1997) have conducted model studies for simplified flow and seamount topography to quantify the role of seamount generated circulation on the local advection of particles in the seamount vicinity. The model was of an idealised Gaussian shaped seamount of horizontal scale of 25 km, extending from 4500m water depth to a summit of 4050m depth, in a rotating, stratified ocean, forced by both steady flow and diurnal period tidal forcing. In their experiments, Goldner and Chapman (1997) released particles to trace particle advection at the start of the model run including the ramping up of the current forcing (either steady flow or tidally driven), unlike experiments conducted in fully developed steady state flows. A consequence of this is that the particle advection (or retention) is dependent on details of initial particle location relative to seamount and also how quickly/strongly the current forcing is applied. This is partly reflective of realistic conditions for seamounts located in regions with mesoscale variability in the oceanic flow.

For the case steady flow only impinging on the seamount, a Taylor Cap was formed with flow intensification to the left of the seamount looking downstream. After 30 days of model run, advected particles fall into 3 groups, dependant on their fate. Most particles are carried around seamount and do not cross the seamount. Some particles within a narrow upstream region are carried onto the seamount and retained there for at least 5 advection timescales (Fig 14), defined as flow speed (u) / seamount length scale (L), i.e. u/L). Some particles initially released over the seamount are advected away from the seamount. Higher retention was found for particles close to the seabed (50 m above seabed) relative to those at the 400m depth level (summit peak at 450m depth). For tidally forced flow only, trapped waves are generated around the seamount, intensified close to the seabed, and generating a rectified mean anti-cyclonic circulation around the seamount. Instantaneous currents are amplified by 50-100x the initial forcing amplitude and also displace particles vertically 100-300 m during a diurnal period.

The combination of advection and vertical displacement causes a mean change in depth level for the particles over the course of the 30 day model run. The majority of the particles released at 400m depth, exhibited a mean downward drift (Figure 14) and this was more pronounced for those particles released near the seabed. Most of the particles that had a net upward drift were released from the same region. When both steady and tidal forcing was applied, the particle motions were essentially a superposition of the two individual responses. This was due to the different spatial scales of the resultant flow patterns with the trapped waves confined close to the seamount with the Taylor Cap generated vortices found further away from the seamount summit. In general, the tidal forcing does not affect the retention caused by the mean flow and the steady flow does not effect the net vertical displacement of particles released at 400 m depth. Those particles released near the seabed, however, were retained for a significantly longer time due to the combined effect of the Taylor column and tidally rectified anti-cyclonic flows found there (Figure 15). The authors conclude that the retention of particles by the seamount circulation was dependant on the speed of the ramp up of the forcing motion and that particles close to the region of maximum residual current would be retained longer. In addition, fluid replacing that lost over a seamount comes from a relatively narrow band upstream of the seamount so dispersion of particles is heavily dependant on the mean flow direction and the time scale of directional changes in the mean flow.

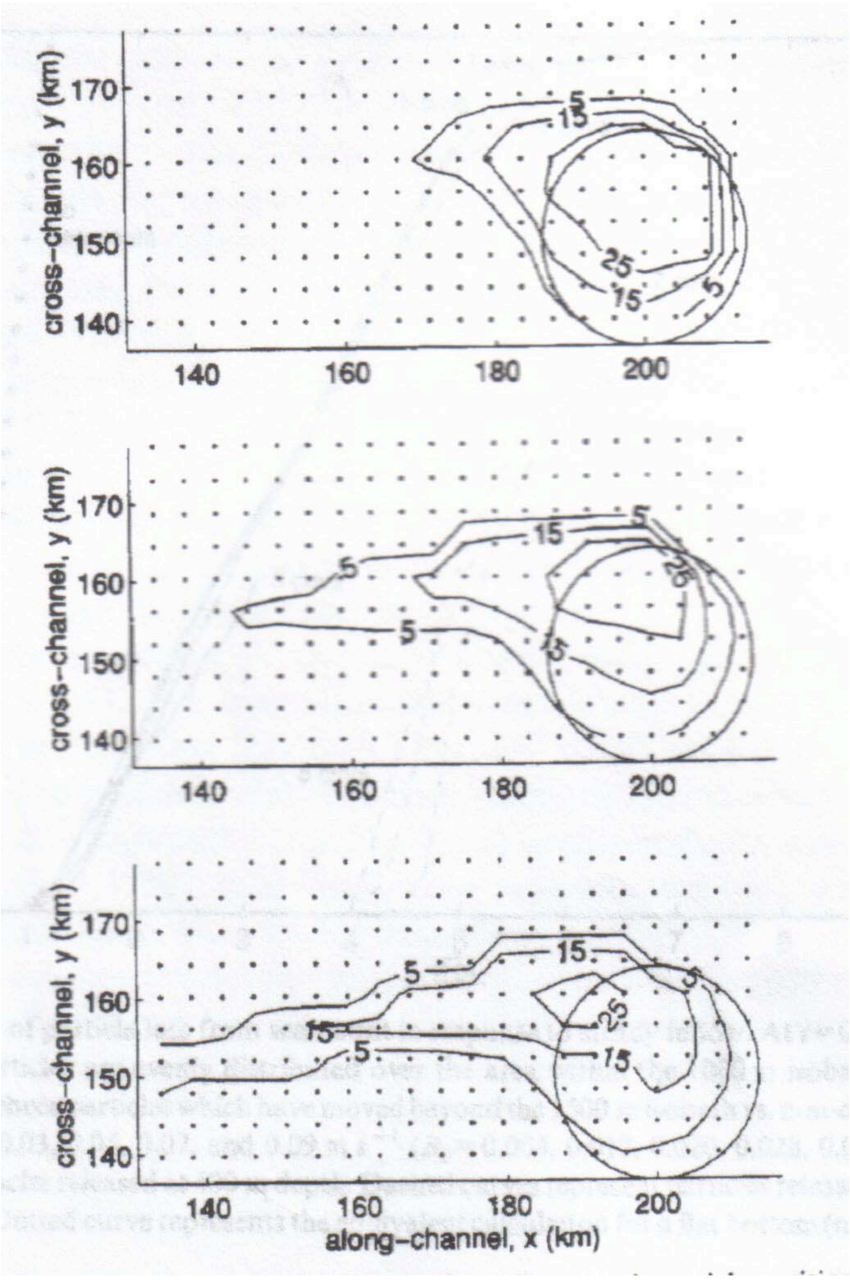

Fig 14. Contours of days spent by particles over an isolated seamount, represented by the 1500 m isobath (black circle) during 30 day model run with steady forcing impinging on the seamount. The initial particle positions are given by the dots and the 3 plots represent different inflow speeds of (top) 3 cm s-1, (b) 5 cm s-1, and (c) 7 cm s-1. Figure shows how the maximum particle detention by the seamount flow occurs for a small area at the upper right seamount edge. Figure from Goldner and Chapman (1997).

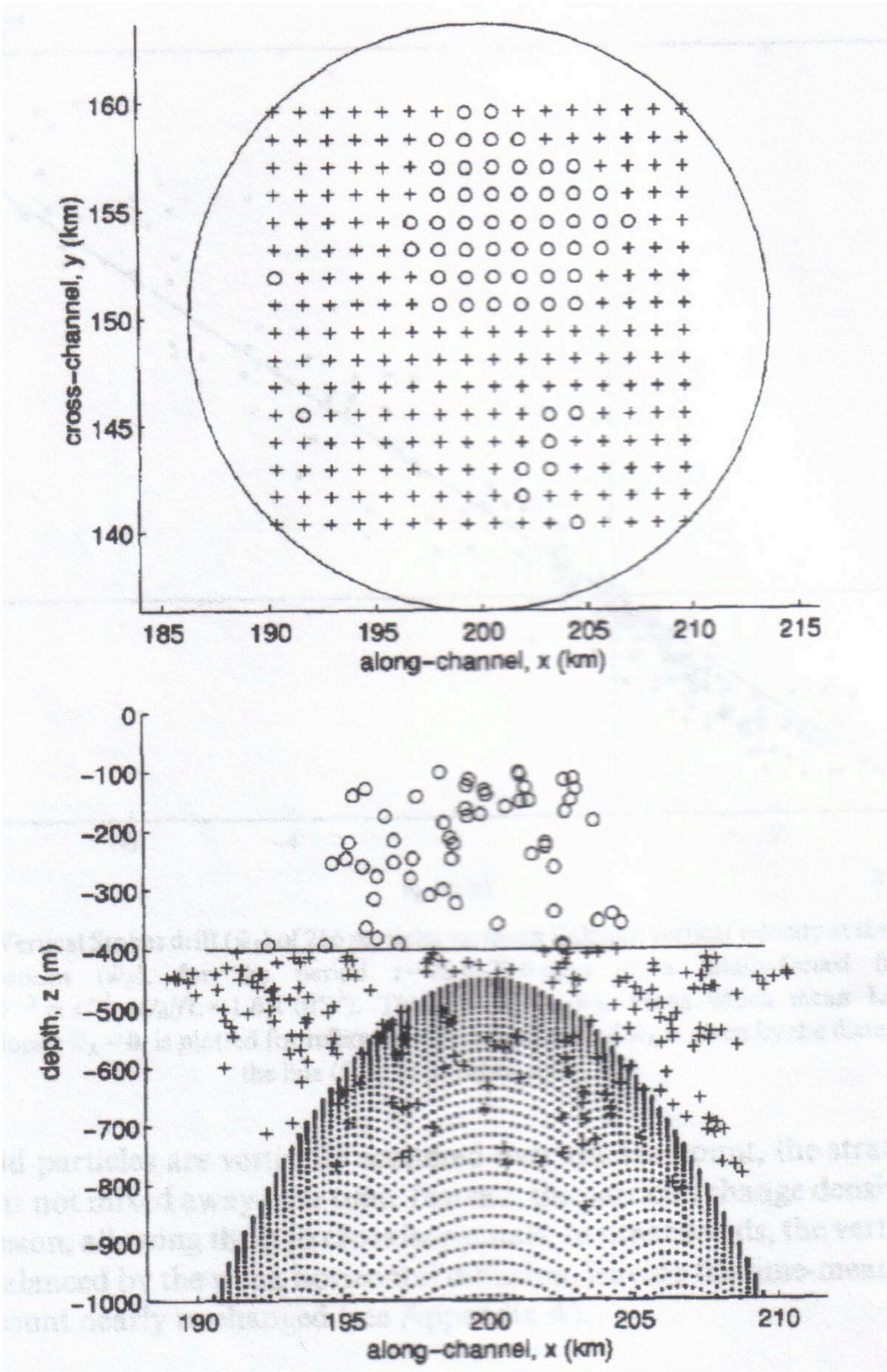

Fig 15. The scattering of particles as a result of tidal forcing at an isolated seamount after 30 days model run. The upper figure shows the initial positions of the particles located at 400 m depth (50 m above summit depth) and the circle represents upward net drift over 30 days and crosses downward net drift. Figure from Goldner and Chapman (1997).

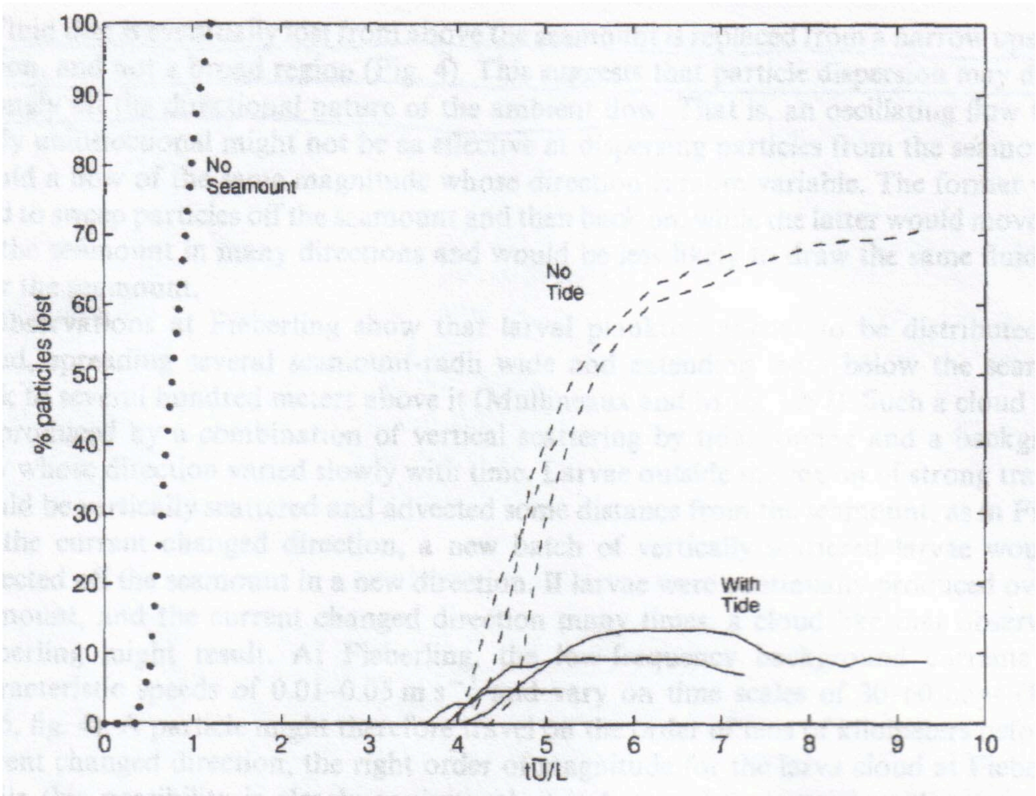

Fig 16. Rate of particles lost with (non-dimensional) time from the region around an isolated seamount forced by a steady (dashed) and both steady and tidal flow (line) for particles released at a depth equivalent to 50 m above the summit depth. Figure from Goldner and Chapman (1997). The dotted line shows the advective loss in the absence of a seamount, i.e. all particles loss in 1 non-dimension time unit (i.e. velocity / width of seamount).

A test of a larval retention hypothesis for a seamount has been attempted by Mullineaux and Mills (1997) from measurements at Fieberling Guyot. Both currents and benthic invertebrate larvae distribution were measured to ascertain what type of circulation pattern was set up and if the circulation was conducive to retain larvae. A typical bottom intensified anti-cyclonic residual circulation, maximum at the seamount rim, was set up around Fiberling Guyot, generated by tidal rectification, rather than a Taylor Cap generation. The background (far field) circulation was too variable in direction for a persistent Taylor Cap to be maintained over the seamount, and was often found to be in different directions on opposite sides to the Guyot. Instead, diurnal tidal currents near the seabed over the Guyot were amplified 11x the far field amplitude. A resultant circulation cell was found from the measurements with a strong current, flowing out from the seamount rim, measured at the seamount rim and strong inferred downwelling over the seamount summit. The circulation cell was closed by a weak flow from the far field towards the seamount in the depth layer immediate above the summit (of 500 m depth).

Planktonic larval abundances, however, showed only some definitive patterns in their distribution. Larval abundances were marginally higher over the summit regions and generally lower over the seamount flanks. Different species showed somewhat different patterns and this was attributed to the combination of different spawning times and the fact that the meso-scale variability in the background flow would result in different advection pathways as proposed by Goldner and Chapman (1997). The broad distribution pattern, however, was consistent with retention within the circulation cell generated over the seamount and measured by the current meter records (Fig 17). Measurement of the number of Hydriod Colonists on specially deployed settlement plates close to the current meters, however, did show a clear distribution pattern, consistent with the circulation cell present. Highest abundance of colonists (over a 1 year period) on the plates were found at the seamount rim, but were also found in a narrow depth range between 450-650m as far as 40 km from the summit. This depth range coincided with that expected for the outward flow from the seamount rim as predicted from model studies.

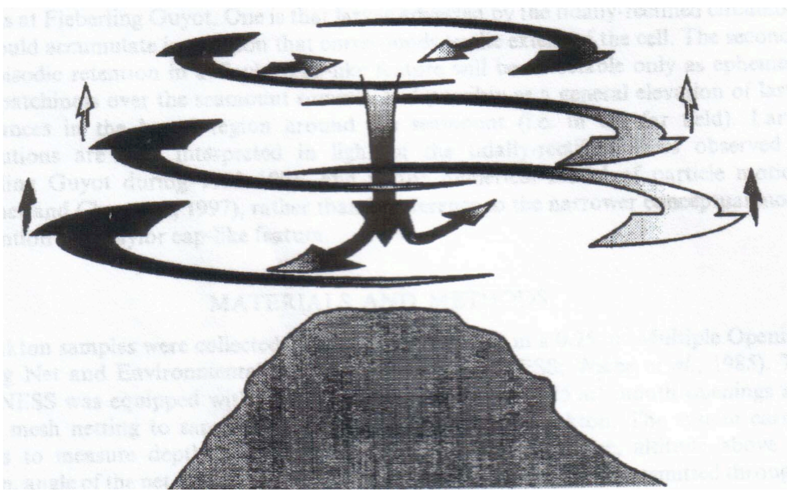

Fig 17. Idealised flow pattern over seamount with outward radial flow at the seamount rim, decreasing in magnitude from with height above the seamount, and a slow return flow towards the summit region and associated downwelling over the summit. From Mullineaux and Mill (1997).

5.3 Colonisation from the far field

Some what opposite to retention of larvae around seamounts is the idea that currents impinging on seamount structures may bring larvae to the seamount, and hence may be one method of seeding an isolated seamount located in the deep ocean. Lutjeharms and Heydoorn (1981) have suggested such a process for the recruiting mechanism of the rock lobster *Jasus tristani* on Vema seamount in the southern Atlantic. This species has a wide distribution in the southern Atlantic, and it is thought that colonisation of the isolated Vema seamount occurs from the island of Tristan de Cunha over 1000 miles away to the SW. Drifting buoy tracks have indicated flow paths from Tristan de Cunha to Vema seamount with a transit time of about 5-7 months, similar to the larval development time of the lobster (9 months) before becoming benthic. The nature of the recruitment to the seamount is likely to be sporadic, however. This is supported by the fact that the lobster was fished out of the seamount some 15 years prior to the buoy observations and that the lobster population had not recovered at the time of the observations.

This sporadic nature of recruitment to isolated seamounts may be common. For example, the Haida eddies in the NE Pacific are thought to transport larvae of yelloweye rockfish (*Sebastes ruberrimus*) to the Bowie and other seamounts located offshore of the NW US continental shelf (Dower; 2004, see section 4.2.1) Generally, adult specimens were not found offshore, but the age population on Bowie seamount showed few fish younger than 15 years old. The inference is that recruitment to the seamounts by the Haida eddies is very episodic.

5.4 Productivity

It has been suggested that the dynamic conditions at seamounts may favour enhanced productivity. This may be due to the isotherm/isopycnal doming that occurs over the seamount which may bring deeper, higher nutrient content, water above the seamount where it may be utilised if other conditions, such as light and water column stability, are suitable. Dower et al. (1992) have observed a 2-5x increase in chlorophyll levels over the shallow (26m peak) Cobb seamount which persisted for up to the 3 weeks during the survey period. This time scale was long compared to the likely advection timescale of 4 days for material to be transported away from the seamount. Retention of the chlorophyll for long periods is important if the productivity is to be transferred into higher trophic levels. The authors report that the presence of a high biomass benthic community over the seamount. At the same location, Comceau et al. (1995) have measured a 10fold increase in production over the summit region, whilst the chlorophyll and light levels remained fairly uniform in an area extending 30 km out from the summit. The increased productivity was thought to be the result of the increased water column stability over the summit region due to the small isotherm lifting above the summit. Mourino et al. (2001) also found increased chlorophyll levels, carbon incorporation rates associated with the Great Meteor Seamount relative to the far field. A 21 day residence time for water over the Great Meteor seamount was deduced from a variety of current observations. Mourino et al. (2001) suggested that the increased chlorophyll levels may have been associated with a stagnant region caused by a Taylor Column feature. Enclosed or retentive circulation characteristics of seamounts may be important for the retention of primary production to allow exchange of energy to higher trophic levels. Observations to date, however, have not been conclusive as to whether retention does occur, as in studies which show short term high chlorophyll values resident over a seamount (e.g. Genin and Boehlert, 1985). It may be that fast growing opportunist species of zooplankton may be favoured at seamount locations, as suggested by Dower and Mackas (1996).

At higher latitudes the deep winter mixing of surface waters may reach the summits of relatively shallow seamounts and submerged banks, and may have a significant impact on the nutrient dynamics over the seamount. White et al. (1998) have observed the presence of nutrient rich, cold water masses over the Porcupine Bank, NE Atlantic, initially attributed to Taylor Column formation, but more likely formed by deep winter mixing which easily extends beyond the 200-400 m depth of the shallow portion of the bank. White et al. (2004) have shown that increased chlorophyll levels, relative to the surround deep water and also matching nearby continental shelf values, are present over the bank for periods > 1 month. White et al. (2004) have suggested that the nutrient rich domes may fuel this increased plankton biomass.

5.5 Zooplankton Dynamics

Genin (2004) has recently reviewed the effects of the bio-physical coupling that cause aggregations of zooplankton and fish over different abrupt topographic features including seamounts, canyons and the continental shelf edge. Genin (2004) identifies 5 mechanisms which may cause micronekton aggregations: (i) upwelling, (ii) daily formation of accumulations when topography blocks the descent of zooplankton, (iii) depth retention against upwelling (i.e. active downward swimming), (iv) depth retention against downwelling, and (v) when strong currents, amplified at abrupt topography, augment suspended food fluxes. Of these 5 mechanisms, Genin suggests that the enhanced food fluxes, topographic blockage is important at seamounts, and that both counter upwelling depth retention and upwelling may be important if timescales are long enough (see above discussion on productivity) and the seamount summit region is shallow. There is a depth dependency for the processes that cause zooplankton accumulations to be important. Topographic blockage and counter upwelling depth retention are important for intermediate depth seamounts, i.e. those with a summit above 400 m depth but below the euphotic zone.

Genin (2004) suggests that the enhanced horizontal food flux process is depth dependant, whilst upwelling would be important for shallow seamounts with summits lying within the euphotic zone. In addition, the idealised enclosed circulation pattern for seamounts, described by Brink (1995), may also help in retaining delivering suspended matter to the seamount summit region. The out-welling from the seamount summit rim is compensated by a return flow towards the seamount above the level of the seamount. This suggests that there must be downwelling above the summit region. This may bring enhanced vertical fluxes of organic material to the seamount benthic layer. In combination with enhanced horizontal fluxes caused by flow acceleration, due to bottom trapping of tidal waves and other local topographic effects, dynamic conditions over seamounts may generate large organic fluxes in the benthic boundary layer and help support the suspension feeding community there. Genin et al. (1986) have related the distribution of suspension feeding fauna over the multiple peak Jasper seamount to the locations where local topographic acceleration of flow was measured or predicted. White et al. (2004) have suggested that enhanced vertical/horizontal fluxes of material over the Porcupine Bank is the reason for the favourable development of the deep water coral ecosystems found at the flanks of the bank.

Currents at seamounts may also act to advect zooplankton, despite the mobility of zooplankton. Wilson and Boehlert (2004) has shown, from combined plankton hauls and acoustic surveys, that vertically migrating micronekton at Southeast Hancock seamount (N Hawaiian Ridge) were transported downstream through the night. The displacement distances, however, were less than the distances that current could potentially transport the micronekton, suggesting that the migrating species were actively resisting the advective loss from the seamount.

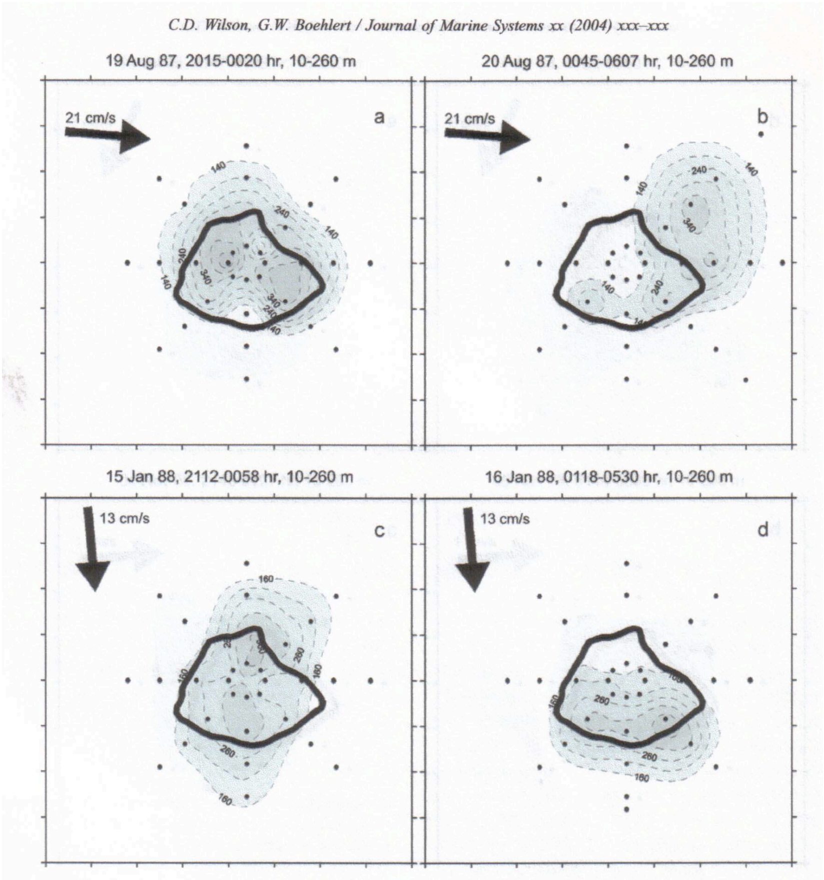

Fig 18. Advection of the relative acoustic abundance (from sound scattering layer) across South Hancock Seamount during the night for two measurement times – (a & b) summer and (c & d) winter surveys. The arrows indicate the mean current flow strength/direction and the solid line is the 300 m isobath. Data is figure 6 presented in Wilson and Boehlert (2004).

Gaps in the zooplankton distribution may form when the seamount blocks the descent of the vertically migrating migration. The zooplankton may be trapped by the residual circulation around the seamount, and can then be eaten by resident predators or advected off seamount (Genin et al., 1994). Haury et al. (2000) have tested this and other related hypothesis from measurements at 4 different Pacific seamounts. One related hypothesis is that the fine scale patchiness of the zooplankton distribution may be enhanced downstream of the seamount summit as lateral current shear acts to smear and mix water with higher zooplankton abundance into the gap regions. Another is that increased predation at seamounts should result in a larger number of crustacean carcasses over the seamount. Results suggested that when gaps were present, then increased downstream patchiness and crustacean carcasses were generally found. No increased patchiness or carcass abundance found when zooplankton gaps were not present suggesting a linkage between the 3 phenomena.

6 SUMMARY

The dynamics around seamounts is obviously a highly complex set of interactions depending on many processes or seamount characteristics. The seamount structure influence depends on the many different topographic variables – seamount height and extent, summit depth, geographic location (latitude and distance from continental shelf) and slope. In addition, there are many physical processes at work – stratification, far field flows (stable or variable flow direction/strength) as well as biological processes. It appears, therefore, that it is hard to classify seamounts easily and that most seamounts require individual classification as to what processes may be important.

Some basic principles do apply, however. For example basic flow patterns are controlled by two basic processes – the rectification and amplification of tidal motions, particularly of diurnal period, and by the Taylor Column processes for steady flows impinging on the topographic feature. There is some influence by together processes. These include large scale current deflections, generally involving a chain of seamount features, which produce jets and eddies. Eddies themselves may interact with a seamount, which can cause exchanges of water, stripping away water previously resident on the seamount, or transient up/downwelling at the seamount flanks. The degree to which either of the two main processes will dominate can reasonably be deduced from models, but the models have not always had success in predicting the degree of tidal amplification and mean rectified flow speeds that have been measured on different seamounts.

The affect of the physical dynamics on the bio-geochemical processes are becoming well known, although some questions remain. Retention of material over a seamount is still an area to address. With a few exceptions, observations of chlorophyll distribution over seamounts have generally suggested that the primary producers are advected off the seamount although particle tracer models appear to suggest that material should remain over the bank. Retention of primary production over seamounts would appear important to the energy transfer to higher trophic levels and the discrepancy between the two may be resolved from longer timescale measurements (Boehlert and Genin, 1987). Modelling studies have shown that the retention of material over a seamount depends significantly on how quickly the currents change strength and direction as well as the initial position of the particles relative to the seamount. These characteristics may be important in terms of the optimum location for fish spawning over topographic features and their resultant retention or advection away. Kloppmann et al. (2001) have speculated that retention of Blue Whiting larvae over the Porcupine Bank is associated with retention by a Taylor Column and that separation of larvae transport paths away from the bank may result in separate stock development. In addition, disruption of the Taylor Column circulation, for example by strong wind mixing events, may result in poorer retention of larvae over the bank in any particular year. Whether the downwelling associated over seamount summits (e.g. Freeland, 1994), or that opportunist species of zooplankton (Dower and Mackas, 1996) play a major role in the flux of organic material is still open to question. In addition, tidal modulation of passive tracers in producing net up/downwelling fluxes requires further quantification (Goldner and Chapman, 1997), as does the possibility that definite zooplankton distribution patterns might be generated by the phase locked interaction of diurnal vertical migration and diurnal tidal modulation (biological processes not withstanding).

Other advection effects, combined with biological processes such as vertical migration and predation, are also highly significant at seamounts (e.g. Genin, 2004; Wilson and Boehlert, 2004; Haury et al., 2000). Biophysical coupling may cause both large aggregations of zooplankton and the patchiness in zooplankton distribution around a seamount. These characteristics imply that it may be hard to characterise biomass over the seamounts, unless high spatial/temporal resolution measurements are made. In addition, there are circulation patterns, either the well defined enclosed circulation cell due to tidal rectification, or a more diffuse pattern caused by far field flow which has high mesoscale variability. Both these features appear to act over a distance of some 20-40 km from the seamount centre, typically 1 or 2 seamount diameters. Such a scale appears to define the major sphere of influence of the seamount, although other effects may be apparent further away.

Dynamics at Sedlo and Seine Seamounts.

The two chosen sites for the OASIS study are Sedlo and Seine seamount, which have slightly different topographies and which have received essentially no attention in the past. Sedlo seamount has a summit at a depth of around 750 m, and has a number of peaks, somewhat resembling Fieberling Guyot. Seine seamount, however, has a broad summit, at around 150 m depth close to the euphotic zone (similar to Cobb seamount dimensions). This difference is of likely importance, particularly if the physical dynamical regime is similar. Indeed the forcing mechanisms at both seamounts are likely to be somewhat similar. Table 1 summarises the basic scaling factors as discussed in section 2. The Burger No (B) is similar for both seamounts and the stratification at the main thermocline and seamount summit are also of similar magnitude.

Table 1. Summary of dynamical parameters for Sedlo and Seine seamount.

Parameter	Sedlo	Seine
Length scale L	20 km	30 km
Summit Depth (m)	750 m	150 m
H (height above thermocline depth of 800 m)	50-100 m	650 m
d (fractional height of summit above thermocline)	0.06-0.1	0.85
Stratification (rads/sec)	0.0035	0.004
Burger Number	1.5	1.7
Rossby Number (Ro) for flow 5 cm/s	0.025	0.02
Rossby Number (Ro) for flow 10 cm/s	0.05	0.04
Critical Ro	0.03-0.05	0.24
Taylor Cap or not?	Taylor Cap	Taylor Cap
Decay height of Taylor Cap	250 m	400 m

The topographic scales are different in terms of the seamount extension from the main thermocline depth of 800 m, however. This causes a difference in the critical Rossby number for the trapping of a Taylor cap over the seamount. The critical value is much larger for Seine seamount, which means that the Rossby No for the flow at Seine for any likely inflow speed is likely to be less than the critical value and trapping is always likely. Furthermore the vertical scale for the isopycnal doming over the seamount is relatively large and hence doming of isopycnals may well extend into the euphotic zone. At Sedlo seamount, however, the Rossby Number is less than the critical value for mean inflow current speeds of about 5-7 cm s-1. Whilst the mean surface flows are weak, there is a possibility that Taylor Caps may not be trapped over Sedlo. There is one interesting point to note in regard to the mean flows impinging on the two seamounts. IN regard to surface flows the Canary current impinging on Seine seamount may produce a reasonably steady background flow which is likely absent at Sedlo. At Sedlo, however, the summit depth of 750 m is close to the depth for the Mediterranean Outflow Water flow and hence the currents interacting with the upper flanks of the Sedlo seamount may well be quite strong. It would seem, therefore, that as the dynamical forcing at the two seamounts is similar, the main influence on the biology at the two sites will be determined by the difference in topographic shape and position in relation to the Euphotic zone.

7 REFERENCES

Armi, L., 1978: Some evidence for boundary mixing in the deep ocean. J. Geophys. Res., 83, 1971-1979.

Beckmann, A., and D.B. Haidvogel, 1997: A numerical simulation of flow at Fieberling Guyot. J. Geophys. Res., 102, 5595-5613

Beckmann, A., 1999: Dynamical processes at isolated seamounts. Habilitation thesis, Carl-von-Ossietzky University Oldenburg

Beckmann, A., R. Timmermann, A.F. Pereira, C. Mohn, 2001: The effect of flow at Maud Rise on the sea-ice cover – numerical experiments. Ocean Dyn., 52, 11-25

Beckmann, A. and C. Mohn, 2002: The upper ocean circulation at Great Meteor Seamount. Part II: Retention potential of the seamount-induced circulation. Ocean Dyn., 52, 194-204.

Boehlert, G. W., and Genin, A., 1987: A review of the effects of seamounts on biological processes. In: Seamounts, Islands and Atolls. Geophysical monograph vol 43, American Geophysical Union. (Eds. B. H. Keating, P. Fryer, R. Batiza, G. W. Borhlert).

Booth, D.A., 1988: Eddies in the Rockall Trough. Oceanol. Acta, 11, 213-219.

Bower, A. S., Armi, L. and Ambar, I., 1995: Direct evidence for meddy formation off the southwestern coast of Portugal. Deep Sea Res., 42, 1621-1630.

Brink, K.H., 1989: The effect of stratification on seamount-trapped waves. Deep Sea Res., 36, 825-844

Brink, K.H., 1990: On the generation of seamount-trapped waves. Deep Sea Res., 37, 1569-1582.

Brink, K. H., 1995:

Carsey, FD, 1980: Microwave observations of the Weddell Polynya. Mon. Weath. Rev. , 108, 2032-2044

Chapman, D.C. and D.B. Haidvogel, 1992: Formation of Taylor caps over a tall isolated seamount in a stratified ocean. Geophys. Astrophys. Fluid. Dyn., 64, 31-65

Cheney, R.E., P.L. Richardson and K. Nagasaka, 1980: Tracking a Kuroshio ring with a free drifting buoy. Deep Sea Res., 27, 641-654

Codiga, D.L. and C.C. Eriksen, 1997: Observations of low-frequency circulation and amplified subinertial tidal currents at Cobb Seamount. J. Geophys. Res., 102, 22993-23007.

Comeau, L. A., Vezina, A. F., Bourgeois, M., and Juniper, S.K. 1995: Relationship between phytoplankton production and the physical structure of the water column near Cobb Seamount, northeast Pacific. Deep Sea Res., 42, 993-1005.

Crawford, W., 2002: Physical characteristics of Haida eddies. J. Phys. Oceaogr., 58, 703-713.

Di Lorenzo, E., Foreman, M.G. G. and Crawford, W. R., 2004: Modelling the generation of Haida Eddies. Unpublished manuscript.

Dower, J., Freeland, H. and Juniper, K. 1992: A strong biological response tp oceaninc flow past Cobb seamount. Deep Sea Res., 39, 1139-1145.

Dower, J. and Mackass, D. L., 1996: “Seamount effects” in the zooplankton community near Cobb Seamount. Deep Sea res., 43, 837-858.

Eriksen, C.C., 1982: Observations of internal wave reflection off sloping bottoms. J. Geophys. Res., 87, 525-538.

Eriksen, C.C., 1991: Observations of amplified flows atop a large seamount. J. Geophys. Res., 96, 15227-15236.

Eriksen, C.C., 1998: Internal wave reflection and mixing at Fieberling Guyot. J. Geophys. Res., 103, 2977-2994.

Freeland, H., 1994: Ocean circulation at Cobb seamount. Deep Sea Res., 41, 1715-1732.

Garrett, C. 1979: Mixing in the ocean interior. Dyn. Atmos. Oceans, 3, 239-265.

Garrett, C. and Gilbert, D., 1988: Estimates of vertical mixing by internal waves reflected off a sloping bottom. In, Small-scale turbulence and mixing in the ocean, Proceedings of the 19th International Liege Colloquium on Ocean Hydrodynamics, edited by J.C.J. Nihoul and B. M Jamart pp. 405-424, Elsevier, New York.

Garrett, C.J.R. and J.W. Loder, 1981: Dynamical aspects of shallow sea fronts. Phil. Trans. R. Soc. Lond. A, 302, 563-581.

Genin, A. 2004: Bio-physical coupling in the formation of zooplankton and fish aggregations over abrupt topographies. In press: J. Marine Systems.

Genin, A., and Boehlert, G. W., 1985: Dynamics of temperature and chlorophyll structures above a seamount: An oceanic experiment. J. Marine Res., 43, 907-924.

Genin , A., Dayton P. K. Lonsdale, P. F., and Spiess, F. N., 1986: Coral on seamount peaks provide evidence of current acceleration over deep-sea topography. Nature, 322, 59-61.

Genin, A., M. Noble and P.F. Lonsdale, 1989: Tidal currents and anticyclonic motions on two North Pacific seamounts. Deep Sea Res., 36, 1803-1815.

Genin, A., Green, G., Haury, L., Wiebe, P., Gal, G., Kaartvedt, S., Meir, E., Fey, C., and Dawson, J., 1994: Zooplankton patch dynamics: daily gap formation over abrupt topography. Deep Sea res., 41, 941-951.

Gjevik, B. and H. Moe, 1994: Steady and transient flows around banks located near a shelf edge. Cont. Shelf Res.,14, 1389-1409

Goldner, D.R. and D.C. Chapman, 1997: Flow and particle motion induced above a tall seamount by steady and tidal background currents. Deep Sea Res., 44, 719-744

Haidvogel, D.B., J.L. Wilkin and R.E. Young, 1991: A semi-spectral primitive equation ocean circulation model using vertical sigma and orthogonal curvilinear horizontal coordinates. J. Comput. Phys., 94, 151-185

Haidvogel, D.B., A. Beckmann, D.C. Chapman and R.-Q. Lin, 1993: Numerical simulation of flow around a tall isolated seamount. Part II: Resonant generation of trapped waves. J. Phys. Oceanogr., 23, 2373-2391.

Haury, L., Fey, C., Newland, C. and Genin, A., 2000: Zooplankton distribution around four eastern north Pacific seamounts. Progress in Oceanography, 45, 69-105.

Hogg, N.G., 1973: On the stratified Taylor column. J. Fluid Mech., 58, 515-537

Holloway, P.E. and M.A. Merrifield, 1999: Internal tide generation by seamounts, ridges and islands. J. Geophys. Res., 104, 25937-25951

Hunkins, K., 1986: Anomalous diurnal tidal currents on the Yermak Plateau. J. Mar. Res., 44, 51-69.

Huppert, H.E. and K. Bryan, 1976: Topographically generated eddies. Deep Sea Res., 23, 655-679.

Huthnance, J.M., 1974: On the diurnal tidal currents over Rockall Bank. Deep Sea Res., 21, 23-35

Huthnance, J.M., 1978: On coastal trapped waves: analysis and numerical calculation by inverse iteration. J. Phys. Oceanogr., 8, 74-92

Johnson, E.R., 1978: Trapped vortices in rotating flow. J. Fluid Mech., 86, 209-224.

Kloppmann, M., Mohn, C., and Bartsch, J., 2001: The distribution of blue whiting eggs and larvae on Porcupine Bank in relation to hydrography and currents. Fisheries Res., 50, 89-109.

Kunze, E, and Sanford, T. B., 1997. Tidally driven vorticity, diurnal shear and turbulence atop Fieberling Seamount. J. Phys. Oceanogr., 27, 2663-93.

Lavelle, J. W., Baker, E. T. and Cannon, G. A., 2003: Ocean currents at Axial Volcano, a northeastern Pacific seamount. J. Geophys. Res., 108, 3020-3038.

Ledwell, J. R., Montgomery, E. T., Polzin, K. L., St. Laurent, L. C., Schmitt, R. W. and Toole, J. M., 2000: Evidence for enhanced mixing over rough topography in the abyssal ocean. Nature, 403, 179-182.

Loder, J.W., 1980: Topographic rectification of tidal currents on the sides of Georges Bank. J. Phys. Oceanogr., 10, 1399-1416

Loder, J.W. and D.G. Wright, 1985: Tidal rectification and frontal circulation on the sides of Georges Bank. J. Mar. Res., 43, 581-604.

Lueck, R. G. and Mudge, T. D., 1997: Topographically induced mixing around a shallow seamount. Science, 276, 1831-1833.

McCartney, M., 1975: Inertial Taylor columns on a beta-plane. J. Fluid Mech., 68, 71-95

Meincke, J., 1971: Observations of an anti-cyclonic vortex trapped above a seamount . J. Geophys. Res., 76, 7432-7440

Mohn, C., J. Bartsch and J. Meincke, 2002: Observations of the mass and flow field at Porcupine Bank. ICES J. Mar. Sci.,

Mohn, C. and A. Beckmann, 2002: Numerical studies on flow amplification at an isolated shelfbreak bank, with application to Porcupine Bank. Cont. Shelf Res., 22, 1325-1338

Mohn, C. and A. Beckmann, 2002: The upper ocean circulation at Great Meteor Seamount. Part I: Structure of density and flow fields. Ocean Dyn., 52, 179-193.

Mourino, B., Fernadez, E., Serret, P., Harbour, D., Sinha, B., and Pingree, R., 2001: Variability and seasonality of physical and biological fields at the Great Meteor Tablemount (sub tropical NE Atlantic). Oceanologica Acta, 24, 1-20.

Mullineaux, L. S. and Mills, S., 1997: A test of the larval retention hypothesis in seamount-generated flows. Deep Sea Res., 44, 745-770.

Munk, W. H., 1966: Abyssal recipes. Deep Sea Res., 13, 207-230.

Munk, W. H., 1981: Internal waves and sall scale processes. In Evolution of physical oceanography, scientific surveys in honor of Henry Stommel, edited by B Warren and C. Wunsch, pp 264-291. MIT press, Cambridge, Mass.

Naimie, C.E., J.W. Loder and D.R. Lynch, 1994: Seasonal variation of the three-dimensional circulation on Georges Bank. J. Geophys. Res., 99, 15967-15989

Naimie, C.E., 1996: Georges Bank residual recirculation during weak and strong stratification periods – Prognostic model results. J. Geophys. Res., 101, 6469-6486.

Noble, M. and Mullineaux, L. S., 1989: Internal tidal currents over the summit of cross seamount. Deep Sea Res., 36, 1791-1802.

Noble, M., Cacchione, D. A. and Schwab, W. C., 1988: Observations of strong mid-Pacific internal tides above Horizon Guyot. J. Phys. Oceanogr., 18, 1300-1306.

Owens, W.B. and N.G. Hogg, 1980: Oceanic observations of stratified Taylor columns near a bump. Deep Sea Res., 27, 1029-1045.

Roberts, D. G., Hogg. N., Bishop, D. G. and Flewellen, C. G., 1974: Sediment distribution around moated seamounts in the Rockall Trough. Deep Sea Res., 21, 175-184.

Roden, G.I., 1987: Effects of seamounts and seamount chains on ocean circulation and thermohaline structure. In: B. Keating, P. Fryer, R. Batiza and G. Boehlert, (Eds.), Seamounts, Islands and Atolls. Geophysical Monograph, 43, AGU, Washington D.C., 335-354

Roden, G.I. and B.A. Taft, 1985: Effect of the Emperor seamounts on the mesoscale thermohaline structure during the summer of 1982. J. Geophys. Res., 90, 839-855

Roden, G.I., 1994: Effects of the Fieberling seamount group upon flow and thermohaline structure in the spring of 1991. J. Geophys. Res., 99, 9941-9961.

Royer, T. C., 1978: Ocean eddies generated by seamounts in the north Pacific.Science, 199, 1063-1064.

Thorpe, S. A., 1987: On the reflection of a train of finite-amplitude internal waves from a uniform slope. J. Fluid Mech., 178, 279-302.

Toole, J. M., Schmitt, R. W. and Polzin, K. L., 1997: Near-boundary mixing above the flanks of a mid latitude seamount. J. Geophys. Res., C102, 947-959.

Turnewitsch, R., Reyss, J-L., Chapman, D. C., Thomson, J. and Lampitt, R. S. 2004: Evidence for a sedimentary fingerprint of an asymmetric flow field surrounding a short seamount. Earth Plan. Sci. Let., in press.

Vastano, A.C. and B.A. Warren, 1976: Perturbation of the Gulf Stream by Atlantis II seamount. Deep Sea Res., 23, 681-694

Verron, J., 1986: Topographic eddies in temporally varying oceanic flows. Geophys. Astrophys. Fl. Dyn., 35, 257-276

Verron, J. and C. Le Provost, 1985: A numerical study of quasi-geostrophic flow over isolated topography. J. Fluid Mech., 154, 231-252

Von Stackelberg, U., von Rad, U. and Zobel, B., 1979: Asymmetric sedimentation around Great Meteor Seamount (North Atlantic). Marine Geology, 33, 117-132.

White, M., C. Mohn and M. Orren, 1998: Nutrient distributions across the Porcupine Bank. ICES J. Mar. Sci., 55, 1082-1094.

White, M., Mohn, C., de Stigter, H., and Mottram, G. 2004: Deep water coral development as a function of hydrodynamics and surface productivity around the submarine banks of the Rockall Trough, NE Atlantic. In press: Deep water corals and ecosystems. Procs 2nd International symposium on deep water corals, Erlangen, Germany. Eds. A. Freiwald and M. Roberts.

Wilson, C. D., and Boehlert, G.W. 2004: Interaction of ocean currents and resident micronekton at a seamount in the central North Pacific. In press: J. Marine Systems.

Wright, D.G. and J.W. Loder, 1985: A depth-dependent study of the topographic rectification of tidal currents. Geophys. Astrophys. Fluid. Dyn., 31, 169-220