

Inferring physical processes from seafloor bedforms around
Brothers and Rumble III volcanoes in the Kermadec Arc

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Abstract

The objective for this project is to determine the contribution of physical processes, such as turbidity currents and bottom currents, to the transport and distribution of sediments around the underwater volcanoes known as Brothers and Rumble III of the Kermadec Arc off the coast of New Zealand. This project, conducted during March of 2009, tests the hypothesis that currents from the East Cape Eddy (ECE) produce the most significant contribution to sediment transport in this area, based on previous studies which indicated a consistency between substrate winnowing and relatively shallow water movement of the ECE (Wright, 2001). Research includes analyzing seafloor bedforms using a towed camera system and determining the magnitude, direction, and type of bottom stresses based on the shape of sediment waves and the size of the sediment particles. This data was compared to direct local current measurements to evaluate trends in water movement along different timescales. Utilizing data from a satellite altimeter will examine broad-scale current information from maps of sea surface height. Sedimentology inference of ocean currents allows for an interpretation about the history of volcanic rock. So far, it has been determined that unidirectional flows occur in about 55% of the sediment ripple photographs at Brothers and 70% at Rumble III. The other flow patterns observed at both volcanoes indicate the presence of internal waves. Correlations between multiple methods of current analysis further indicate that unidirectional currents are more significant to sediment transport than oscillatory currents, but longer-term trends in currents are likely occurring.

Non-Technical Summary

This project was designed to understand the way ocean currents move along the seafloor by studying their effect on the sediment of underwater volcanoes which includes mud, silt, sand, and ash. If the dominant physical process controlling the distribution of sediment grains can be determined, this may reveal useful information in interpreting volcanic rock deposits in addition to increasing the general knowledge of deep ocean currents and how other small particles within the water column, such as some larval species, can be affected by the physical environment. During March of 2009 aboard the R/V Thompson, sediment ripples around Rumble III and Brothers volcanoes of the Kermadec Arc were studied. Data was collected at each volcano for 2 and 4 days respectively. If the water is flowing in one direction, the sediment will create a pattern of asymmetrical ripples along the seafloor. However, if the water moves back and forth along its path, the sediment will settle in a symmetrical pattern. The intensity of wave motion has been calculated based on features such as the distance between ripples and the size of particles. Photographs show that both patterns exist at each of the volcanoes of interest. Since there were more images of asymmetrical ripples at both sites it is likely that unidirectional currents are a greater source of particle movement than oscillatory flows. Currents were also mapped by satellites at the surface and by an ADCP to a depth of about 700m for comparison to the information yielded from the sediments. Correlations between these methods of current analysis further indicate that unidirectional water movement is more significant than wave-like patterns for sediment transport, but longer-term trends in currents are likely occurring.

The Kermadec Arc is the largest submarine arc in the world where oceanic crust of the Pacific plate is subducting under continental crust of the Australian plate resulting in relatively unique chemical and geological features (de Ronde et al., 2007). It consists of many underwater volcanoes and hydrothermal vents between about 200m and 1700m. Off of the East Cape region and South Westland, the sediment supply to the New Zealand coast is among the highest rates in the world (Bradford-Grieve et al., 2006).

Studying the movement of water masses provides information valuable to anyone interested in the relationships between those features and where they are located. Sediment ripples may contain a record of water movements that provide a different perspective from traditional current measurements like ADCP, the geostrophic method, and satellite altimetry. Such information has applications in relating surface current patterns to deep current movements, as well as evaluating the relative accuracy of various deep current measurement techniques; knowing how currents affect sediment distribution helps geologists interpret the volcanic rock record. This research project focuses on these aspects. In addition, ecological impacts may result from correlating larval dispersal to the same sediment carrying currents as well as distribution of any of the various species sensitive to sediment grain size; this study does not investigate the biological aspects applicable from this project, but others could use the work for future studies in this area of research.

Possible controls of sediment transport include tides, surface currents that induce deep currents, localized deep currents, and internal waves. Tides have been shown to contribute significantly to the movement of water around New Zealand. They are

largely dominated by moon cycles and tend to form a trapped Kelvin wave with a 360 degree rotation around the islands in response to the forcing of amphidromes (Walters et al., 2001). It is also possible that localized currents around the volcanoes, which are generated by tidal fluxes, dominate sediment transport (Lavelle 2006). There exist currents that depend on the seafloor topography around New Zealand, rather than with tides or surface waves, with definite periods (Heath 1985). Other studies exploring circulation patterns suggest that eddies affect current flow around Brothers volcano and that internal tides cause tidal current differences contributing to general flow patterns through the water column (Lavelle et al., 2008).

Sedimentology has been used to infer current movements from seafloor bedforms in the Kermadec Arc assuming unidirectional current flow (Wright 2001). Wright took sediment samples along tow-cam track lines, sorted the grain sizes and calculated the magnitude and vertical profile of currents around Kermadec volcanoes, particularly around Rumble IV where the samples could be correlated with the photography. The threshold of sediment movement can be calculated if the sediment size and density, as well as the fluid density, shear stress, and viscosity are known (Miller et al., 1977). Results in Wright's experiment indicated a high correlation between East Cape Eddy current flow and seafloor bedform data.

Following up on areas where similar research has been conducted and a basic idea of the sediments and their related currents has been established, research for this study has been done at the Brothers volcano and Rumble III volcanoes of the Kermadec Arc in New Zealand. Comparing bedforms to a broader array of data on currents such as ADCP information and satellite altimetry of surface currents show different timescales

and depths for recording currents. This research is important for its applications in developing geological, physical, biological knowledge around subduction zones and underwater volcanoes. Inferring currents from sediment data reveals information about the history of post-eruptive volcanic processes on a timescale much longer than direct current measurements. Comparing various methods of evaluating currents provides insight to various timescales of current movement and their affects on sediment transport. Understanding how physical processes influence transport of sediment may be applied to the transport and distribution of larval species in later research.

Methods

This project was conducted along the Kermadec Arc off the coast of New Zealand aboard the R.V. Thompson during March of 2009. It began with approximately four days of research at Brothers volcano and proceeded to Rumble III for an additional two days of study. Data collection consisted of taking photographs of the seafloor substrate from a towed camera system, dredging for sediment, and continuous measurement of currents using a 75 kHz hull-mounted ADCP. The TowCam was oriented such that it would face the same direction that the ship was moving and the direction of currents could be estimated from the photographs based on the angle of deviation between sediment wave orientation and TowCam heading. Current velocities were calculated from the sediment sample data and components obtained from photographs.

Details of analysis are based largely on Wright (2001), who used similar methods in the same areas for analyzing bedforms. Direction and magnitude can be calculated

using threshold flow formulas for an assumed unidirectional flow which rely on sediment and fluid data (Miller et al., 1977).

$$\theta = \tau / ((\rho_s - \rho) gD) = \rho u_*^2 / ((\rho_s - \rho) gD) = f(u_* D / \nu) = f(D / \delta) \quad (1)$$

Where θ is the entrainment function or dimensionless shear stress, τ is the critical shear stress, ρ_s is the density of the sediment, ρ is the density of seawater which is equal to 1.027 g cm^{-3} at 1500m depth (Wright, 2001), g is the acceleration of gravity which is 979.8 cm s^{-2} at 36°S , D is the sediment grain diameter, u_* is the friction velocity, δ is the thickness of the viscous sublayer given by $\delta = 10\nu/u_*$, and ν is the fluid viscosity. The function f is given by a Shields diagram that has been determined experimentally (Miller et al., 1977). This experimental relationship determines u_* which is used to calculate the bottom stress. Bottom stress can be related to velocity from:

$$U_{100} = (1/k)u_* \ln(z/z_0) \quad (2)$$

Where U_{100} is the velocity measured 100cm above the bed, k is the von Karman's constant, z is the height above the bed, and z_0 is the roughness length of the bed given by $z_0 = H^2/(2\lambda)$. H represents bedform height and λ is the wavelength of the sediment ripples.

Oscillatory waves can exert a stress on sediment grains in back and forth directions which yield more symmetrical substrate patterns and smaller ripple heights

than a unidirectional flow (Komar and Miller, 1975). The threshold of particle movement for oscillatory flow can be determined by:

$$\rho u_m^2 / (\rho_s - \rho) gD = 0.30 (d_o/D)^{(1/2)} \quad \text{for } D < 0.05\text{cm} \quad (3a)$$

$$\rho u_m^2 / (\rho_s - \rho) gT = f_2 (d_o/D) \quad \text{for } D > 0.05\text{cm} \quad (3b)$$

Where u_m is the near-bottom velocity, d_o is the orbital diameter of wave motion, T is the wave period and the function f_2 has been determined experimentally (Komar and Miller 1973). Data on orbital wave motion was not collected directly, so d_o is estimated from its relationship to λ (Komar, 1976).

One sediment sample was collected from a dredge at Brothers volcano after failed attempts to use a van-Veen grab sampler mounted to and deployed from the camera sled. Because of field constraints, sediment data for the entirety of this experiment is confined to this sample. To analyze this sediment, the sample was first dried in an oven for approximately 24 hours at 60 C. Next, the total sample was weighed and sieved for about 10 minutes with sieve sizes ranging from 0.063 to 1 mm. The sediment found in each sieve was then weighed and plotted as a histogram (Fig. 1). For velocity calculations, the mean of the histogram was used to determine the value of D . Sediment density was determined by measuring the volume and mass of de-ionized water, adding the sediment sample and measuring the volume and mass again, then dividing the differences in weight by the differences of volume.

During interpretations of seafloor substrate, careful discrimination was made between features that are relevant to physical processes and those that are not. Sediment

ripples can be confused with sediment deformation features unrelated to water currents, but there are criteria to distinguish these characteristics in the seafloor such as creep folds and extension faults in sediment waves, among several others (Wynn and Stow, 2002). To determine which physical process contributes the most to the transport of particles correlations between sediment ripples to other water movement data were examined in addition to calculating current flow from the substrate. All of the photographs along a single TowCam track line where sediment ripples were believed to have been observed were examined. Photographs were either critically analyzed or discarded if it was determined that they did not appear to exhibit distinguishable ripple features. Relative abundance of oscillatory and unidirectional flows was determined by separating symmetrical ripple images from asymmetrical ripples and finding a ratio between the number of images that represent areas of those ripple patterns along a track line. Analysis of the images investigated ripple symmetry, direction of propagation, and wavelength. Height of asymmetrical sediment ripples could not be determined from photographs because the TowCam lacked an adequate altimeter and it cannot be calculated without already knowing the speed of the current that generated it. Symmetrical ripples did not require H for calculating current speed because d_o can be calculated from its relationship to either H or λ (Komar, 1976).

Current analysis from sediment distributions was compared to other forms of examining water movement which include mapping shallow currents with the shipboard ADCP and satellite altimeter data (Lavelle et al., 2008). This comparative data was analyzed with MATLAB for both volcanoes. The comparison itself exists to gauge the effectiveness of my use of sediment ripples as a means of calculating currents as well as

providing additional data about how physical processes may be influencing the system. For example, internal waves may be contributing oscillatory water movement around the summits of the volcanoes and their possible effects will be considered if I encounter inconsistencies in the assumption of unidirectional flow (Lavelle et al., 2008).

Results

Satellite altimetry showed a consistent pattern of surface currents during the days of study. Surface currents were oriented towards the southwest near Brothers and northwest near Rumble III (Fig. 2). The currents surrounding the volcanoes follow a general clockwise circulation indicating that the ECE may have been centered on the volcanoes during the time of study. Towards the southwest of this site is an anti-cyclonic eddy pattern which could be the actual ECE since that eddy is within close proximity to, and propagates in the same direction as, previous observations of the ECE (Wright, 2001; Lavelle et al., 2008). Directions of surface currents from satellite altimetry were consistent with currents measured with the ADCP between 500 and 600m depth (Figs. 3-4).

For Brothers volcano, neither the oscillatory or unidirectional current patterns correlated to the direction of the current directions measured by the ADCP (Figs. 3, 5-6). Unidirectional currents flow towards the northwest and the northeast according to the sediment ripple data (Fig. 5). Oscillatory currents flowed along a northwest and southeast trajectory (Fig. 6). The average magnitudes of velocity calculated from oscillatory currents in the sediment data and from the ADCP vector map were about 12 and 16 cm/s respectively which is a difference of 25% (Figs. 3, 6).

There was an array of current directions at Rumble III among the sediment data. Unidirectional currents generally flowed in both southwest and northeast directions which did not correspond to the general northwest orientation of currents indicated by ADCP and satellite data (Fig. 7). Oscillatory currents indicated by sediment ripples were observed to flow in northwest and southeast directions just as the ADCP and satellite altimetry indicated, but the angle at which they propagate is not precisely correlated with those other forms of measurement (Figs. 2, 4, 8). The average velocity calculated from sediment data and from the ADCP vector map were about 10 and 15 cm/s such that magnitude of oscillatory currents were about 66% than the overall current magnitude (Figs. 4, 8). Overall, there was little correlation between the sediment ripple data to the ADCP and satellite altimetry. In addition, though oscillatory ripple directions were oriented as northwest and southeast at both Brothers and Rumble III, neither their angles nor magnitudes of velocity were correlated.

The average eastward and northward velocities were extracted from the ADCP data for both of the volcanoes. Westward velocity of Rumble III decreased with depth from about 17.5 cm/s at the surface to 5 cm/s at depths near 600m. Rumble III's velocity also changes from about 17.5 cm/s northward near the surface to 4cm/s southward at around 650m depth (Fig. 9). At Brothers, the westward magnitude of velocity generally increases and the southward velocity decreases slightly with depth. Westward velocity at Brothers has a maximum of approximately 11.5 cm/s at 600m depth and a minimum of about 2cm/s near the surface. The southward velocity of currents at Brothers decreases from 10 to about 7.5 cm/s between the surface and maximum depth capacity of the

ADCP and fluctuates through the water column with a minimum of about 6cm/s at approximately 330m depth (Fig. 10).

Patterns indicating the presence of oscillatory flow could be observed at Rumble III and at Brothers through the remaining ADCP data. Given a single moment in time, an alternation between high and low magnitudes of velocity can be observed with varying depths at both volcanoes (Figs. 11-12). That alternating pattern is also seen at a single depth as time changes. At Brothers, both the northward and eastward velocity maximums appear to form diagonal lines across the time and depth varying graph (Fig. 12).

Photographs of the seafloor yielded a comparison between the occurrence of oscillatory and unidirectional flows based on the symmetrical or asymmetrical patterns observed. Approximately 55% of the photographs at Brothers and 70% at Rumble III were asymmetrical. These frequencies are estimated from photographs that showed clear evidence of sediment winnowing from which wavelength and deviation from heading could be calculated. Examples of both symmetrical and asymmetrical sediment ripples for Brothers and Rumble III are shown in Figure 15.

Discussion

Based on Wright's study in 2001, sufficient bedforms for this experiment can be found between depths of about 300-1600 meters around Rumble III and over the full relief of Brothers to a depth of about 1900 meters including the caldera floor. These sediment ripples become smaller and less distinct with increasing distance from the source of sediments, so there exist distances where it is ineffective to observe the substrate for these features. While there was evidence of winnowing across the Brothers

volcano caldera and on the northwest caldera wall, the site where the presence of sediment ripples could actually be interpreted was the Extinct Site of the southeast caldera wall because other bedform deformations were either indistinct or had the potential of being derived from non-current sources as determined from the photographs. The exact locations of sediment ripple occurrence have not yet been mapped. When the directions and magnitudes of water velocity are graphed from ADCP and sediment image data, the sources of current generation can be determined by examining the correlations between the observations and the source information. Such sources include tides, the ECE, and internal waves.

The two types of flow patterns that can be propagated through and observed from the water column are unidirectional and oscillatory. Unidirectional currents immediately north of New Zealand can be derived from surface currents such as the ECE or the East Auckland Current; the ECE is the most likely source of these flow patterns around Rumble III and Brothers volcanoes because it is typically centered within their proximity (Wright, 2001). Oscillatory currents can be generated by internal waves that were created by water flowing over parts of the Kermadec Ridge or by tides which rotate in an anti-cyclonic pattern around New Zealand (Walters et al., 2001).

Previous studies in New Zealand have observed significant correlation between the ECE and deep current movements (Wright, 2001; Lavelle et al., 2008). The unidirectional current directions observed in sediment ripple analysis were not consistent with the ADCP and satellite altimetry data corresponding to the locations of each volcano which suggests that the observed real-time data does not represent longer term trends in deep water circulation. If the ECE was located further south than the surface current

circulation above the volcanoes during the time of study, the inconsistency between data sets does not exclude the possibility of the eddy's influence on the system. With few other sources of unidirectional currents, the ECE could be contributing to sediment transport over longer time-frames than the brief presence of currents observed during the cruise not produced by that eddy. There is also a chance that the TowCam was not oriented in the same direction as the ship during times when the ship was turning which created error in evaluating the true direction of currents. As long as the ship was moving in a straight line, however, the direction of the TowCam and the sediment ripple directions derived from its images should be accurate.

It is important to recognize the flaws in the sediment data before completing analysis for current velocities shown by seafloor bedforms. Unfortunately, logistical constraints prevented the addition of both a precise altimeter to measure ripple height directly and a compass which could accurately record the direction of the TowCam and sediment ripples within each image. For the latter problem, current flow was estimated with the assumption that the camera sled is in fact oriented to face in the direction of the ship movement. Error was reduced by not including images in the analysis where the ship was not moving and thus not making the further assumption that the camera maintained the same heading as the ship. For the former problem, the height for sediment ripples in a unidirectional flow cannot be estimated from velocity calculations without already knowing the velocity. Therefore, only sediment ripples indicating oscillatory flow were evaluated for magnitude of the currents. Also, it is a large assumption that the one sediment sample is representative of all areas on both volcanoes so the D and ρ_s of all those calculations may not be entirely accurate (Fig. 1).

A comparison can be made between the directions of sediment ripples and of currents changing with depth as seen by the ADCP (Figs. 5-10). At Rumble III, the deep currents seen in the ADCP are correlated to the direction of many of the asymmetrical sediment ripples, but not the symmetrical ripples which indicates that the source of oscillatory currents does not produce a strong signature in the general movement of deep currents relative to unidirectional currents at that volcano. The magnitude of currents calculated from symmetrical sediment ripples at both volcanoes were greater than 50% of the velocity magnitudes measured by the ADCP which may be counterevidence to the proposed weaker contribution of oscillatory currents, but the implications are difficult to ascertain without also having the magnitudes given by asymmetrical ripples (Figs. 3-4, 6, 8). Deep currents measured by the ADCP at Brothers did not correlate to the direction of either ripple type even though the ADCP current directions were averaged over four days. This implies that the range of the ADCP was inadequate to measure the deeper currents of this volcano as opposed to being an issue of not recognizing the affects of longer-term affects of currents.

Another interesting thing to note with respect to sediment ripple direction is the lack of consistency between the locations of Brothers and Rumble III. Symmetrical ripple directions were oriented to the northwest and southeast at both Brothers and Rumble III, neither their angles nor magnitudes of velocity were correlated similarly oriented which suggests a different source of oscillatory currents (Figs. 6, 8). Asymmetrical ripples were oriented in almost opposite directions, with the exception of a few, which could be explained by assuming either a different source or the same source. If unidirectional currents have different sources among these volcanoes, it's not particularly surprising that

they would be oriented differently. However, if their common source is the ECE, then the different course of sediment ripples could be a result of the eddy producing current which flows towards one direction at Brothers and another direction at Rumble III.

Signatures of oscillatory currents were identified in both ADCP and sediment ripple data (Figs. 11-13). Symmetrical ripples seen at both volcanoes were arranged such that oscillatory current flow was consistent with the expected anti-cyclonic tidal current direction. Alternating patterns of maximum and minimum velocities did not always occur at the same times along a range of depths which suggests the presence internal waves as oppose to just a tidal oscillatory effect (Figs. 11-12). Relative contributions of tides and internal waves are not yet known because the research was constrained by not being able to measure internal waves directly. From the image analysis, it is observed that unidirectional flow patterns occur with greater frequency than oscillatory flows at both volcanoes. This means that the sources of unidirectional flows contribute more to the transport of sediment transport than those of oscillatory flow. However, oscillatory patterns occur with a great enough frequency that their contribution to water and sediment transport is non-trivial composing about 45% of the observed ripples at Brothers and 30% at Rumble III. Since unidirectional currents were more abundant than oscillatory currents, the source of those unidirectional currents likely makes the most significant contribution to water movement and sediment transport.

Conclusions

This paper has established that internal waves and tides influence the transport of sediment around the underwater volcanoes to a significant, but lesser extent than unidirectional currents based on their relative abundances and the correlation between one of the ADCP deep current measurements to asymmetrical sediment ripples. Relative tidal and internal wave contributions to sediment transport have not been evaluated. It is difficult to determine much from the velocity determined from sediment ripples because the magnitudes of unidirectional flow could not be calculated. The magnitude of oscillatory waves, however, was easily over 50% of the velocity measured by the ADCP implying a strong influence on general current movement. The contribution of the ECE to the propagation of unidirectional current flow has neither been confirmed nor denied through this research, but there is evidence that it is the source of these currents because of the inconsistency of sediment data to surface currents that are probably not derived from this eddy and the lack of other sources in the area. Since the directions of deep currents measured by the ADCP did not typically correlate to sediment inferences of currents, longer-term trends in the contribution of sediment transport are likely taking place and were not observed in the few days during which the project took place.

References:

Bradford-Grieve, J., K. Probert, K. Lewis, P. Sutton, J. Zeldis, and A. Orpin. 2006. New Zealand shelf region, p. 1451-1492. *In* A.R. Robinson and K.H. Brink [eds.], *The Global Coastal Ocean: Interdisciplinary regional studies and synthesis*. Academic.

De Ronde, C.E.J., ET Baker, GJ Massoth, JE Luptin, IC Wright, RJ Sparks, SC Bannister, ME Reyners, SL Walker, RR Greene, J Ishibashi, K Faure, JA Resing, and GT Lebon. 2007. Submarine hydrothermal activity along the Kermadec Arc, New Zealand: Large-scale effects on venting. *American Geophysical Union* **8**: 1525-2027

Heath, R.A. 1985. A review of the physical oceanography of the seas. *New Zealand Journal of Marine and Freshwater Research* **19**: 79-124

Komar, P.D., and M.C. Miller. 1973. The threshold of sediment movement under oscillatory water waves. *Journal of Sedimentary Research* **43**: 1101-1110

Komar, P.D., and M.C. Miller. 1975. The initiation of oscillatory ripple marks and the development of plane-bed at high shear stresses. *Journal of Sedimentary Research* **45**: 1101-1110

Komar, P.D. 1976. The transport of cohesionless sediments on continental shelves, p. 107-124. *In* D.J. Stanley and D.J.P Swift [eds.], *Marine sediment transport and environmental management*.

Lavelle, J.W. 2006. Flow, hydrography, turbulent mixing, and dissipation at Fieberling Guyot examined with a primitive equation model. *Journal of Geophysical Research* **111**: C07014 1-21

Lavelle, J.W., G.J. Massoth, E.T. Baker, and C.E.J. de Ronde. 2008. Ocean current and temperature time series at Brothers volcano. *Journal of Geophysical Research* **113**: C09018 1-10

Miller, M.C., I.N. McCave, and P.D. Komar. 1977. Threshold of sediment motion under unidirectional currents. *Sedimentology* **24**: 507-527

Walters, R.A., D.G. Goring, and R.G. Bell. 2001. Ocean tides around New Zealand. *New Zealand Journal of Marine and Freshwater Research* **35**: 567-579

Wright, I.C. 2001. InSitu modification of modification of modern submarine hyaloclastic/pyroclastic deposits by oceanic currents: an example from the Southern Kermadec arc (SW Pacific). *Marine Geology* **172**: 287-307

Wynn, R.B., and D.A.V. Stow. 2002. Classification and characterization of deep water sediment waves. *Marine Geology* **192**: 7-22

Figure Legends

Figure 1: Sediment grain size ranging between 0Φ and 4Φ where $(\Phi) = -\log_2(D/1\text{mm})$

Figure 2: Satellite Alimetry- The blue square shows an anti-cyclonic pattern which may represent the ECE. The red square shows a cyclonic pattern centered on the area of study

Figure 3: ADCP velocities at Brothers shown as vectors along the ship's course

Figure 4: ADCP velocities at Rumble III shown as vectors along the ship's course

Figure 5: Brothers asymmetrical sediment ripple vector map showing direction of ripples along the ship's path. Vector's do not represent magnitude of velocity.

Figure 6: Brothers symmetrical sediment ripple vector map showing direction of ripples along the ship's path.

Figure 7: Rumble III asymmetrical sediment ripple vector map showing direction of ripples along the ship's path. Vector's do not represent magnitude of velocity.

Figure 8: Rumble III symmetrical sediment ripple vector map showing direction of ripples along the ship's path.

Figure 9: Rumble III velocity through water depth at an average time

Figure 10: Brothers velocity through water depth at an average time

Figure 11: Rumble III velocity at varying times and depths

Figure 12: Brothers velocity at varying times and depths

Figure 13: Examples of symmetrical sediment ripples at both volcanoes. The green line represents the 10cm scale for evaluating wavelengths. Red arrows indicate the direction of propagation. A) Brothers, symmetrical ripples; B) Brothers, asymmetrical ripples; C) Rumble III, symmetrical ripples; D) Rumble III, asymmetrical ripples

Figures:

Figure 1

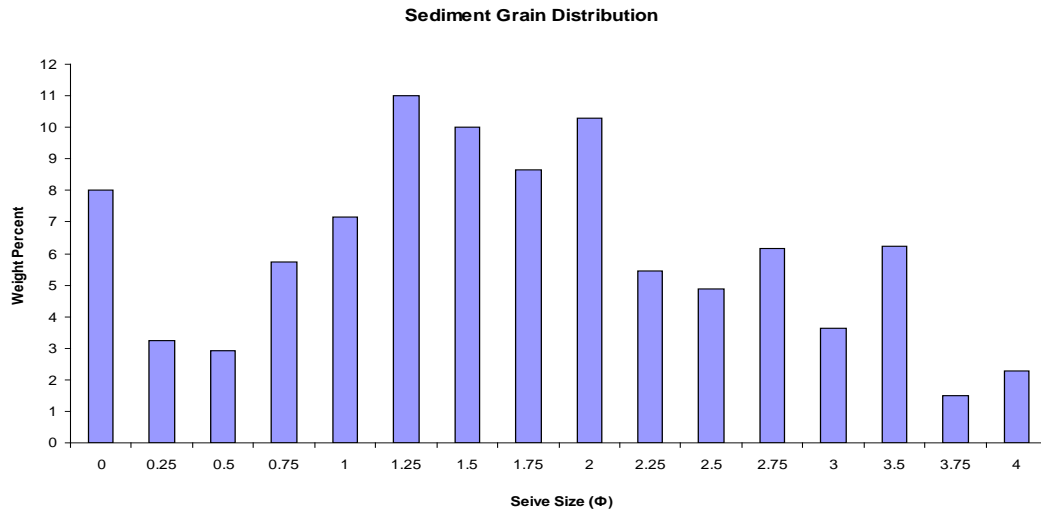


Figure 2: Satellite Altimetry

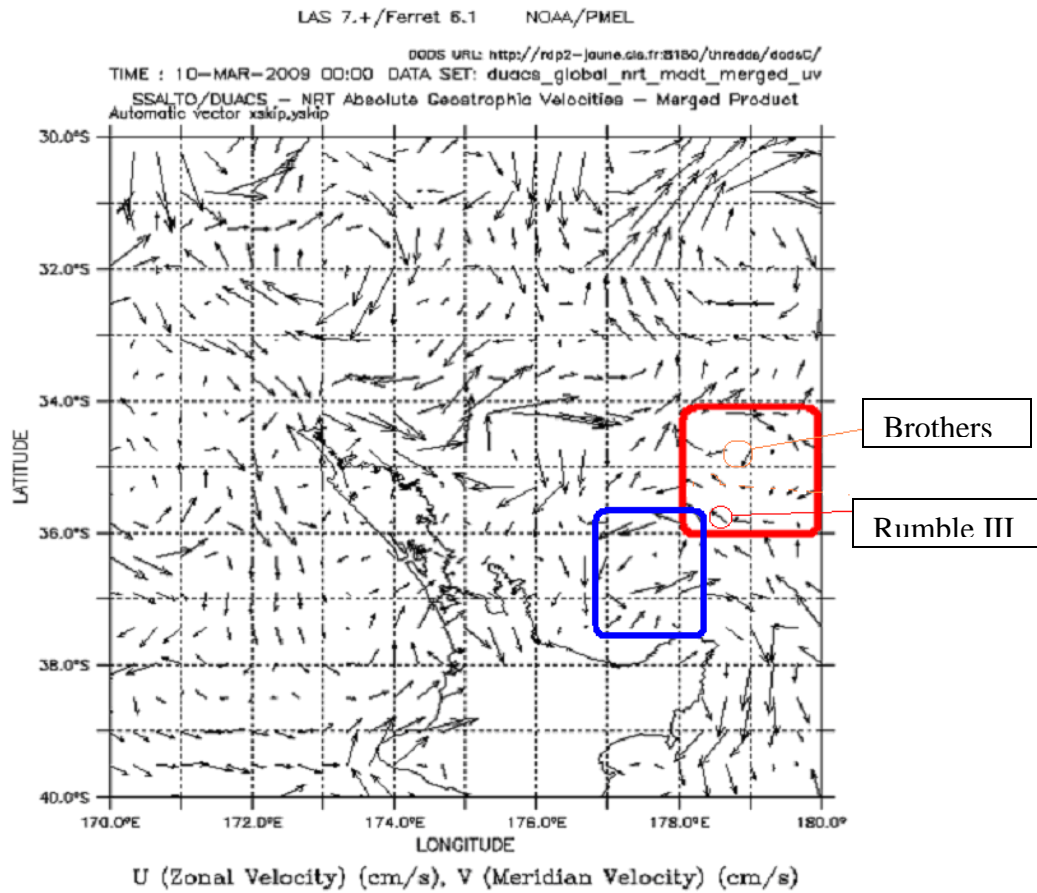


Figure 3

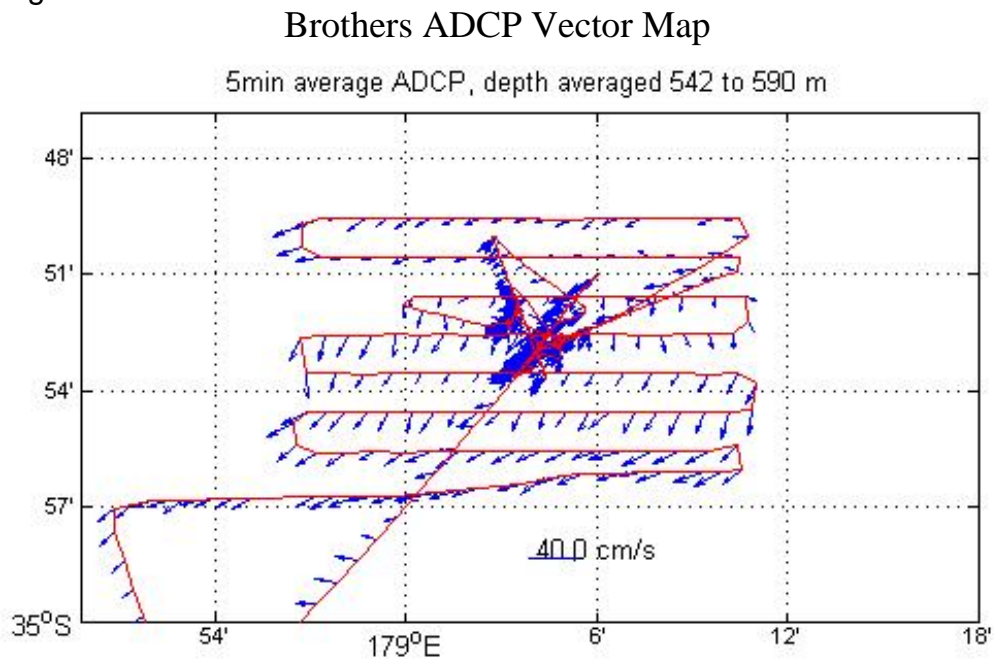


Figure 4

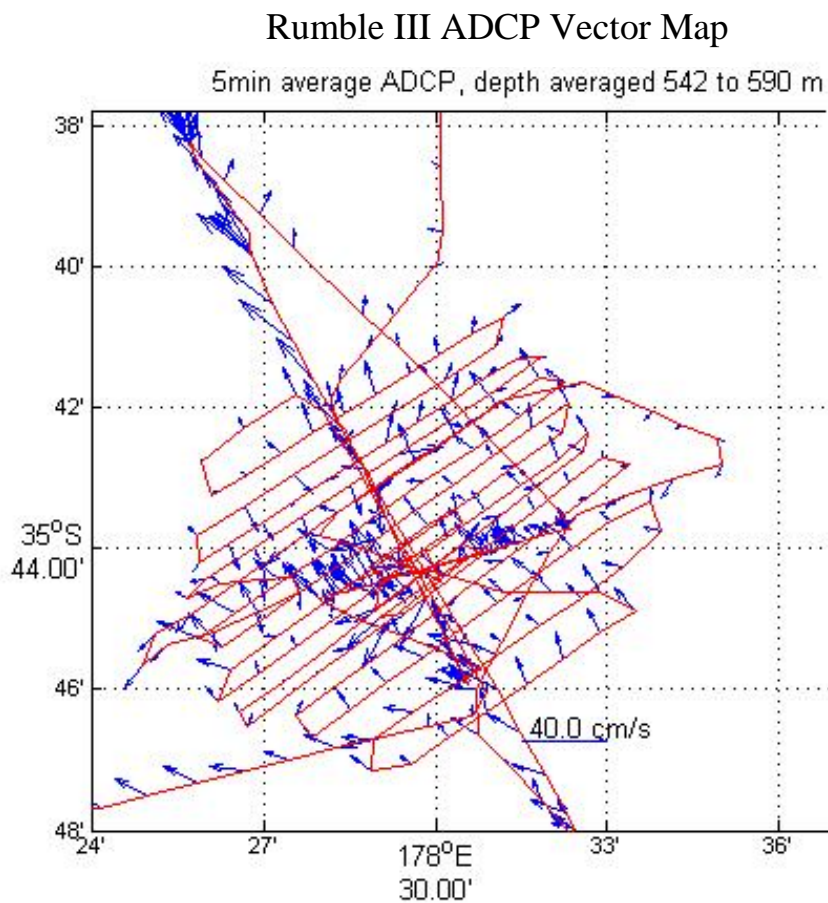


Figure 5: Brothers Asymmetrical Sediment Ripple Vector Map

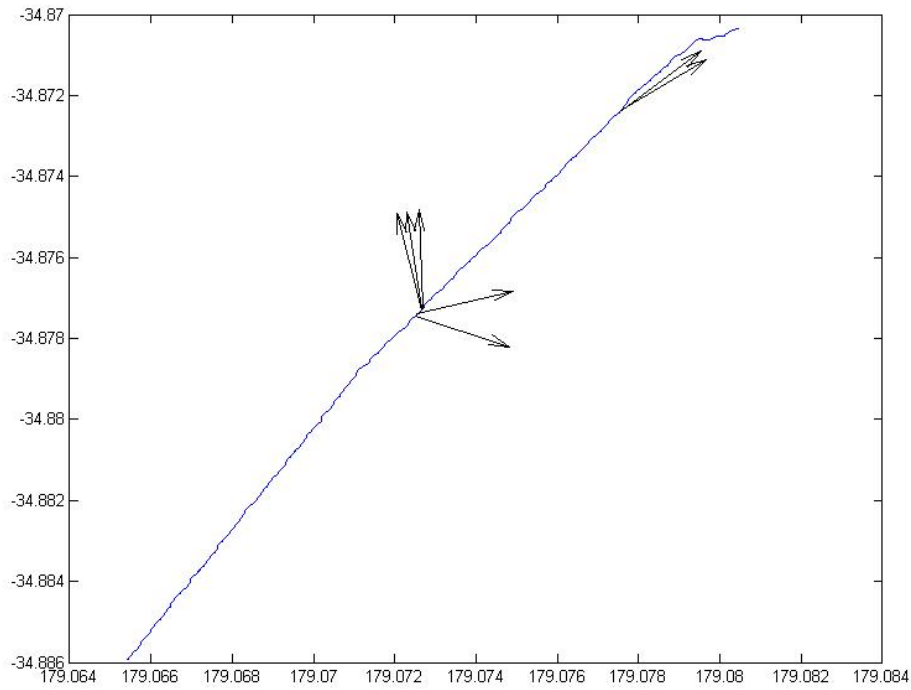


Figure 6: Brothers Symmetrical Sediment Ripple Vector Map

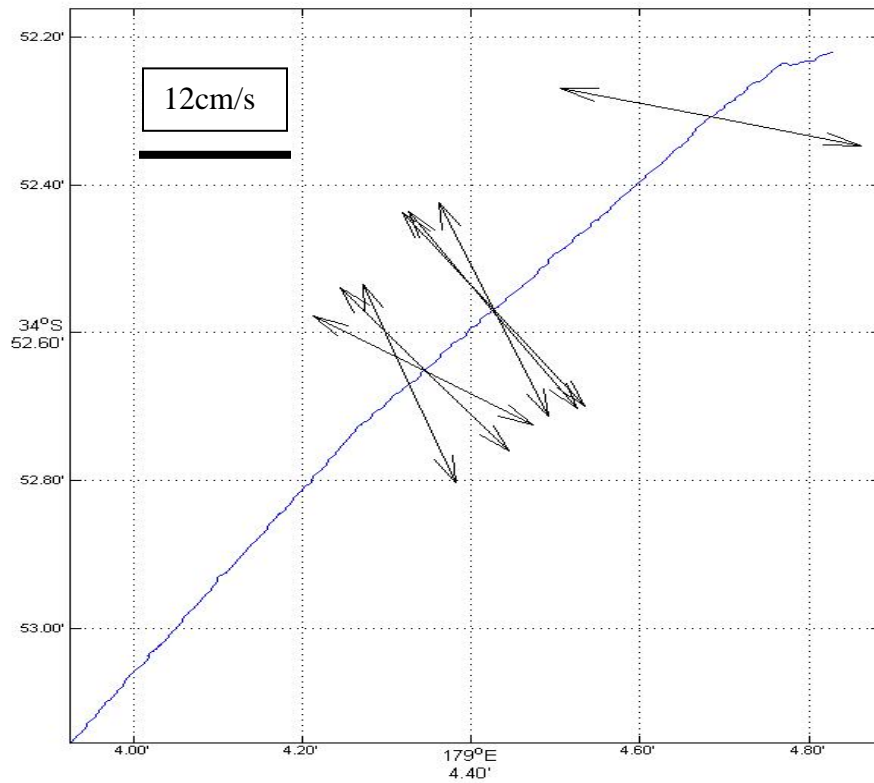


Figure 7: Rumble III Asymmetrical Sediment Ripple Vector Map

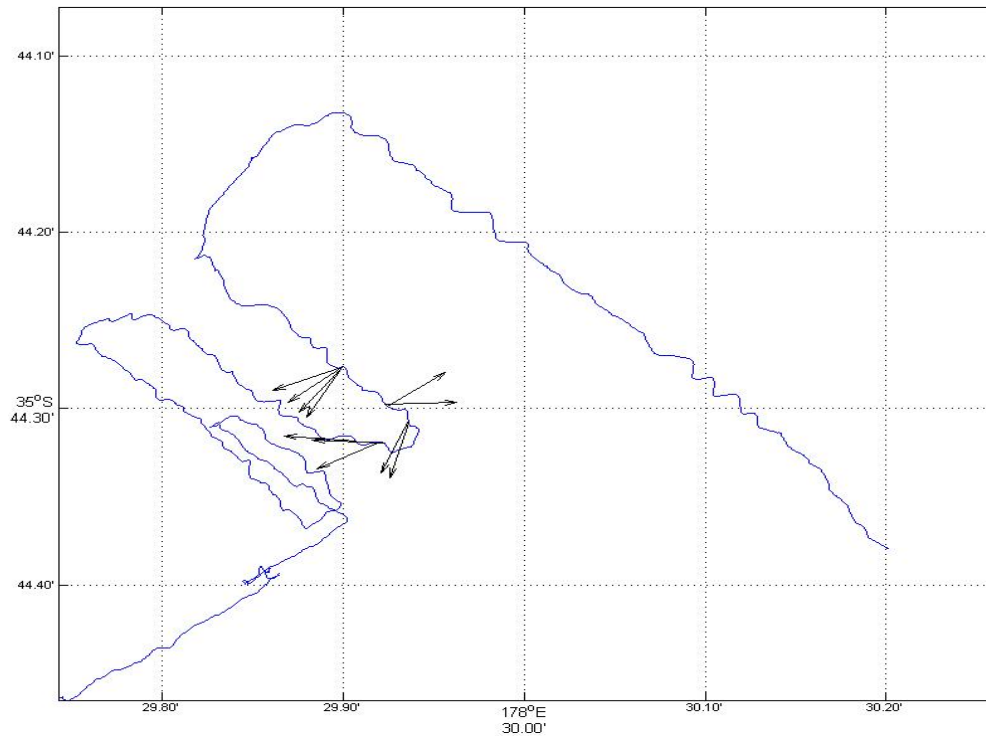


Figure 8: Rumble III Symmetrical Sediment Ripple Vector Map

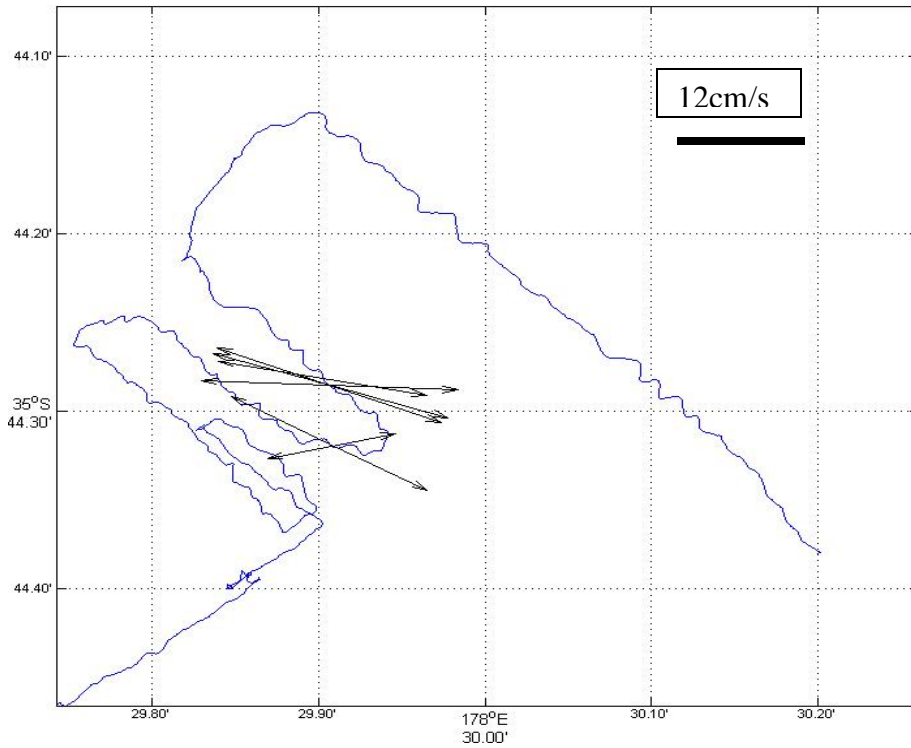


Figure 9: Rumble III Time Average

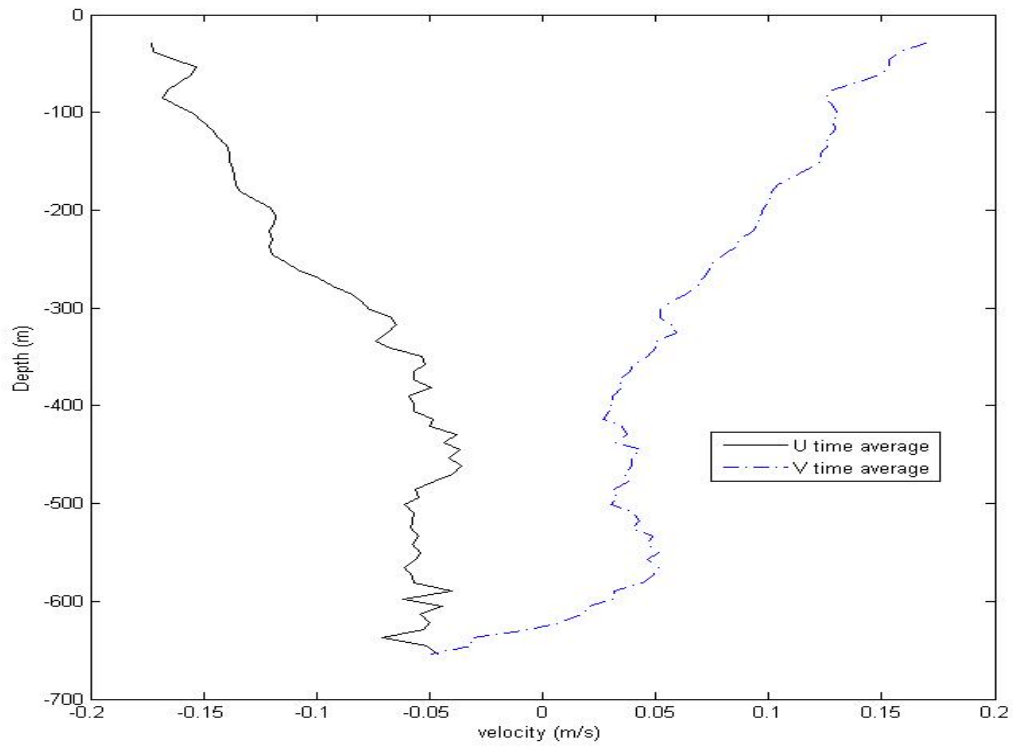


Figure 10: Brothers Time Average

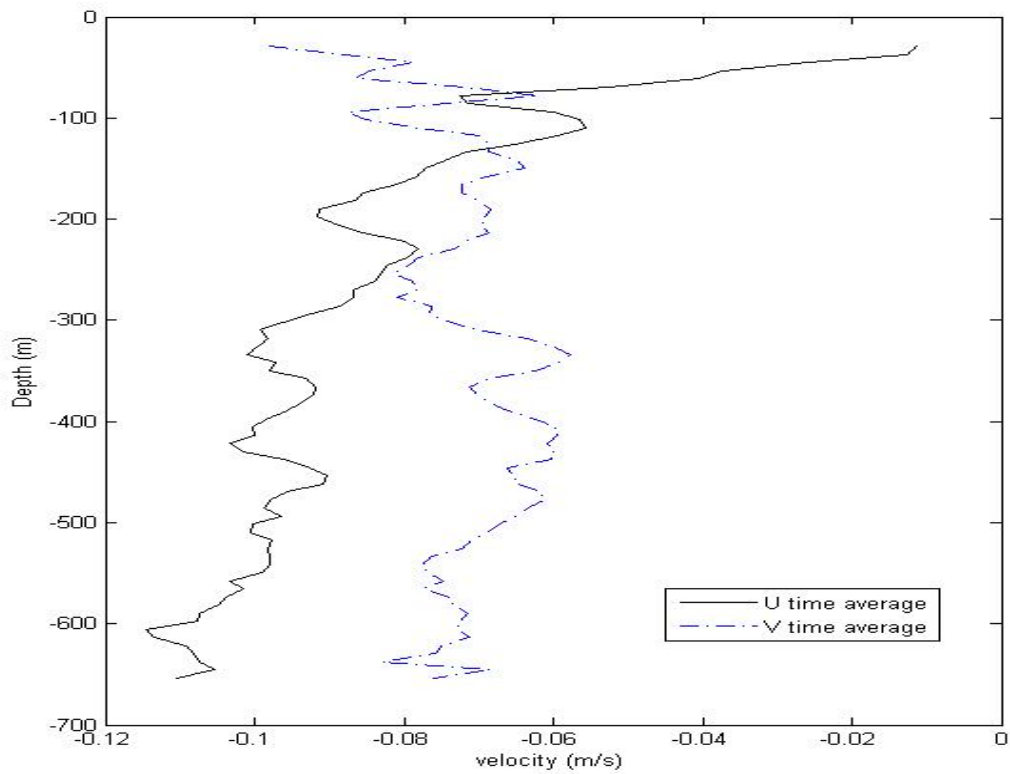


Figure 11: Rumble III

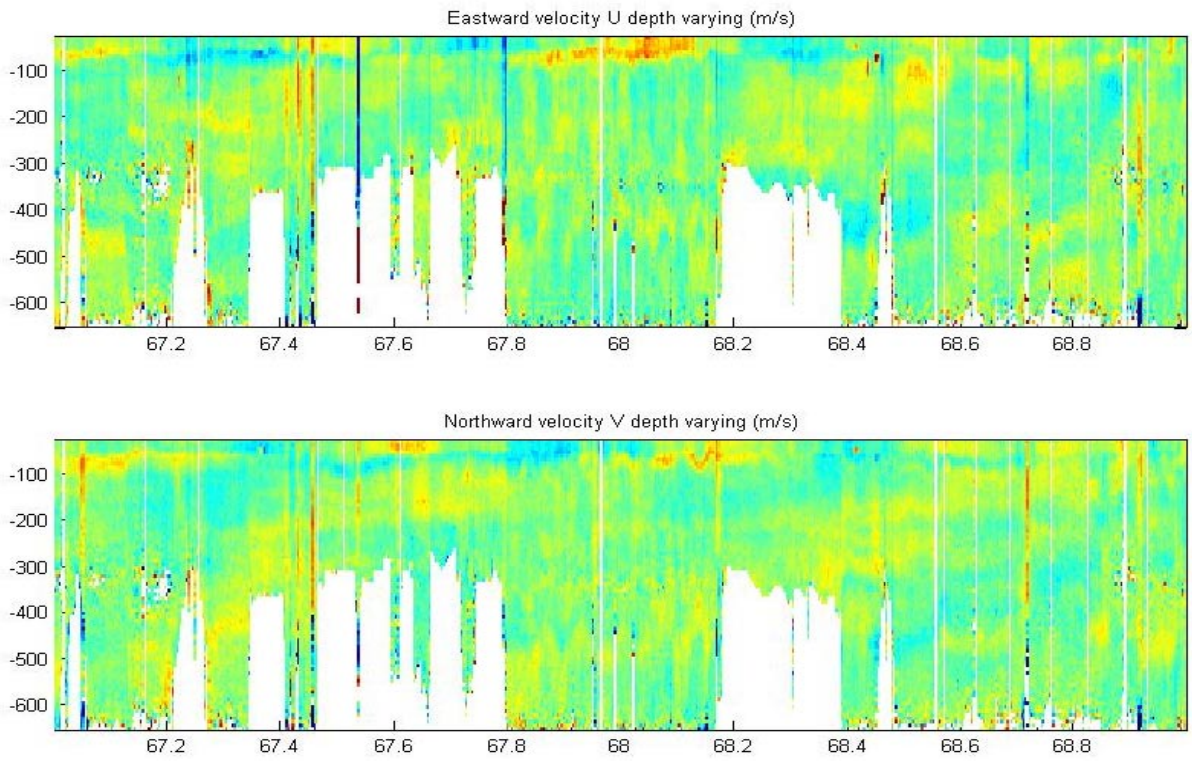


Figure 12: Brothers

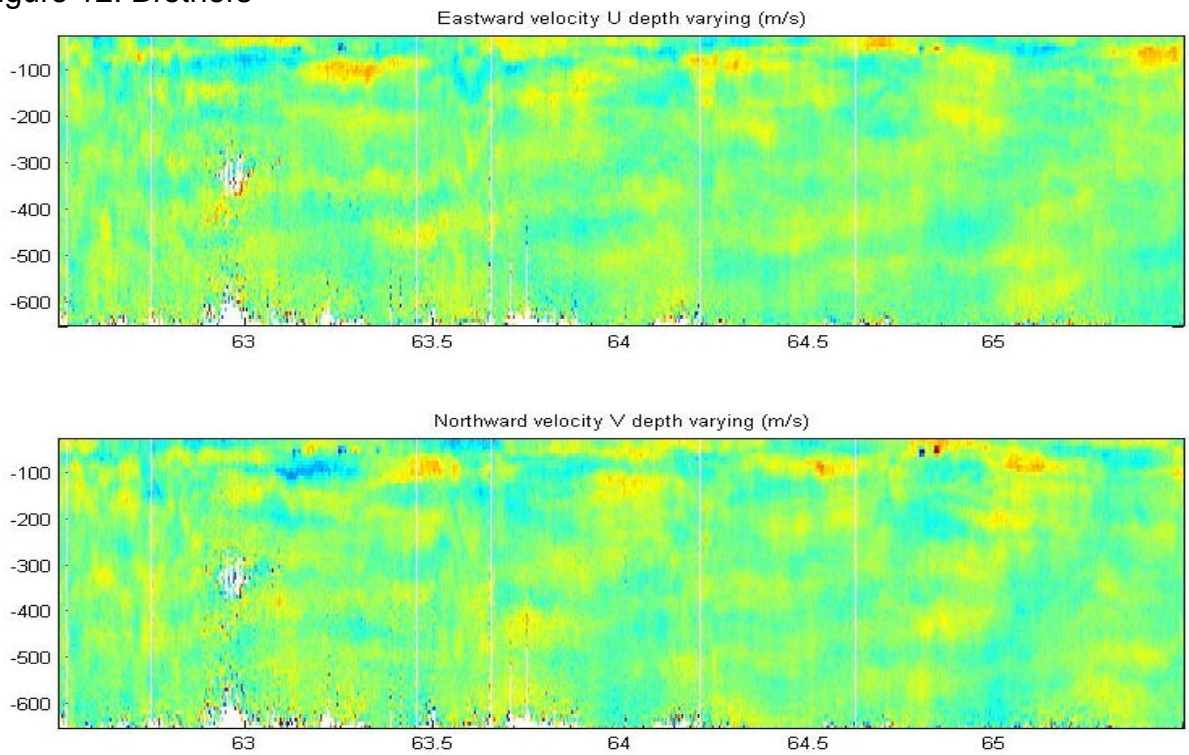


Figure 13:

