Dependence of multiple-attenuation techniques on the geologic setting: A case study from offshore Taiwan

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This paper presents multiple-attenuation strategies for most of the geologic environments encountered around the island of Taiwan.

The choice of the right multiple-attenuation technique is still a matter of trial and error, but ranking of the multiple-suppression techniques in terms of computing time can save considerable work. Unfortunately, our results show that there is no best multiple-suppression technique that works everywhere. In some instances, simpler techniques yield much better results than more sophisticated ones.

Our purpose is to present the advantages and weaknesses of different multiple-attenuation techniques. Our results are based on a reflection seismic data set recorded in 1995. The survey consists of 2980 km of 160-channel seismic reflection lines. The marine geologic environments range from passive to active margins and from shallow to deep water (Figure 1). The setup of the experiment is typical for deep crustal seismic reflection surveys conducted in academia today. Therefore and because of the many different environments, we hope that this case study will be useful for many upcoming projects.

Multiples in marine reflection data can be divided into sea-floor multiples, peg-leg multiples, and water-surface multiples (ghosts). The peg-leg multiples and ghosts in our data had low energy and could be neglected without impact on our goal to image the shallow and deep crustal structure. Sea-floor multiples, however, are a very severe problem. Since the sea floor usually causes a major increase in acoustic impedance, these multiples can have considerable energy which makes meaningful interpretation impossible.

The techniques to suppress multiples are extensive. Some are based on partial moveout (e.g., mutes, frequency-wavenumber [in the following called *f-k*] filters and Radon filters); others are based on the periodicity of multiples (e.g., deconvolution methods); and still others are based on the wave equation.

This paper does not discuss the technical details of all these methods but presents combinations of the methods devised to attack multiples in different geologic environments. In this respect, our term "working processing flow" implies that after processing, new coherent energies are visible where previously multiple energies (identified by traveltime, dip, and amplitude characteristics) dominated.

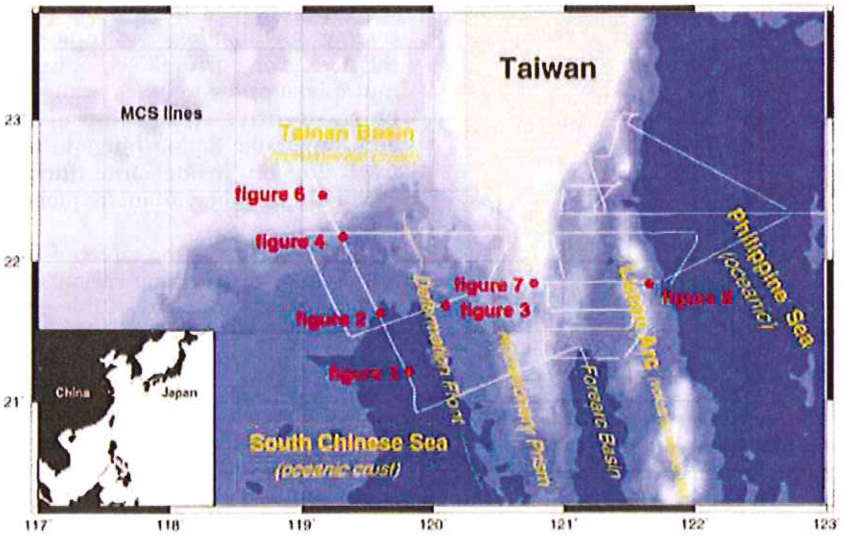

Figure 1. Our survey was conducted south of Taiwan. The yellow lettering indicates the geologic environments in the area. The red dots locate the seismic sections in the other figures.

Horizontally stratified layers in deep waters. Southwest and east of Taiwan, water depths range from less than 100 m to more than 5000 m. In deep water, the suppression of multiples is not difficult because of strong partial moveout.

Finding the right processing flow is more a matter of computing performance than a question of how to accomplish multiple attenuation.

We found that the best way of attenuating multiples in these areas is an *f-k* filter in the common midpoint (CMP) domain after application of a normal moveout velocity that overcorrects the primaries and undercorrects the multiples. Hence, the multiples will map in the positive wavenumber domain and the primaries in the negative wavenumbers. Muting the negative wavenumber in the *f-k* domain, transforming the remaining energy back, and subtracting it from the original data set will attenuate the multiples to a large degree. The difference section in Figure 2 shows the energy that was filtered. In a second step, we mute the near offset where primaries and multiples have the same moveout and *f-k* filtering does not work as well. This removes most multiples.

When the signal-to-noise ratio is lowered (e.g., by higher "wave-generated" noise), it is better to use a Radon filter instead of the *f-k* filter.

Unlike the latter, the Radon filter is able to use energies in the near offset for attenuating multiples because it models the entire moveout of both the primaries and multiples. The Radon filter has two drawbacks, however. First it is far less efficient in terms of computing time, and second it introduces strong high-frequency noise. In places where we had to use the Radon filter, we applied it only in the time window affected by the multiples and not on the whole section. Furthermore we used the Radon filter to compute the multiples and subtract these from the original data instead of muting the multiples in the tau-p domain and retransforming the section. A direct muting of the multiples in the tau-p domain and retransformation of the whole section gives the section a "wormy" appearance. The reason for this might be aliasing.

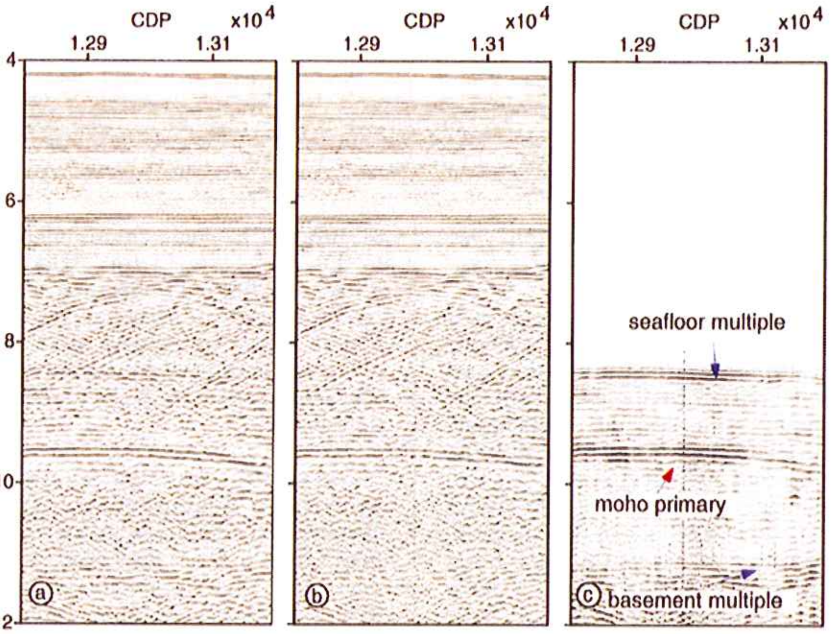

Figure 2. In deep water with relatively horizontal strata, the application of *f-k* filters to common midpoint gathers can remove most sea-floor multiples. (a) Typical stacked section after application of a time-variant filter; (b) after application of an *f-k* filter; (c) the difference of (a) and (b). Note that the gain is different for this section in order to show the whole range of attenuated energy. Blue arrows indicate removed multiple energy and red arrows removed primary energy. All vertical axes are two-way traveltime in seconds.

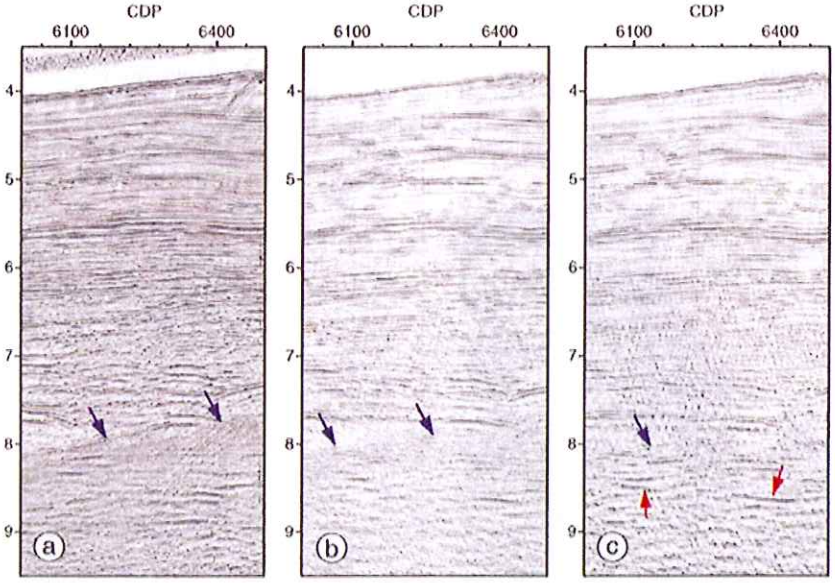

Figure 3. The effect of three different kinds of demultiple techniques and their interplay. (a) Multiples are only attenuated by inside mutes. The near-offset still has a lot of strong multiple energy at 8 s. (b) After application of an *f-k* filter and a Radon filter to the CDP gather. The *f-k* filter was applied to the whole section, and the Radon filter was only applied to the multiple-affected time window. Note the high-frequency content of the remaining multiples. (c) Final result after multiple-attenuation and migration. Red arrows = primaries, and blue arrows = multiples.

A time-variant frequency filter proved helpful for attenuation of high-frequency noise introduced by the Radon filter.

At a depth of 3000 m, multiple-suppression based on *f-k* modeling of the wavefield (wave-equation multiple rejection) proved much less effective than differential-moveout-based techniques. This technique requires a correct pick of the water bottom, the correct water velocity, and attenuation estimates to correctly predict the arrival time and the amplitudes of multiples. (The latter is particularly difficult to predict.) A reliability plot, in which difference sections for different processing flows are plotted in different colors on top of each other, shows the attenuated energy does not overlap for the *f-k* filtered data set and the section to which wave-equation multiple rejection was applied.

Moderately dipping events in intermediate depths. The second domain is characterized by water depths of 2000-4000 m, sedimentary sea floor, and moderately dipping events. Figure 3 shows a detail from the frontal thrust zone south of Taiwan. For this line segment, computing performance was of minor importance compared to a superior imaging, and we experimented to find the processing flow that best accomplishes this task. For our data set, optimal multiple suppression was achieved by consecutive application of *f-k* and hyperbolic Radon filters in the CMP domain, inside mute during stacking, and time-variant frequency filters.

Figure 3 shows the effect of the Radon filter and the time-variant frequency filter at the end of this processing flow. We emphasize that the order in which *f-k* filter, partial prestack migration (DMO), and Radon filter are applied is important. The *f-k* filter reduces coherent noise, but the Radon filter generates some high-frequency noise. Hence it is advantageous to apply the *f-k* filter before DMO and the Radon filter after DMO.

Again, we only apply the Radon

filter in the time window affected by multiple energy. The high-frequency noise generated by the Radon filter is suppressed by a time-variant frequency filter after stack, limiting the bandwidth to ranges as low as 6-28 Hz. The time-variant frequency filter is not only suppressing the noise from the Radon transformation but also the multiple noise. This is because primaries have increasingly lower frequency content due to three reasons: The P-wave velocities are higher at greater depth, the absorption of the signal is frequency dependent, and due to the dispersion characteristics of the earth lower frequencies arrive earlier than high frequencies. At the same time, multiples keep almost the same high-frequency content as the primaries from the same reflector.

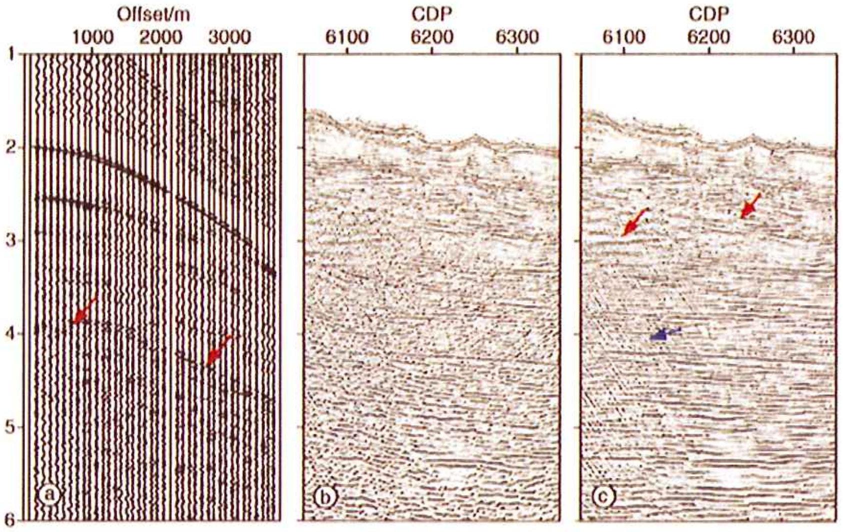

Figure 4. The continental slope is characterized by a lack of prominent multiple energy which can only be identified in prestack data (a). Attenuation by two *f-k* filters increases the signal-to-noise ratio and makes the reflections more continuous in the migrated version (b) and the *f-k* filtered and migrated version (c). Imaging improves above the sea-floor multiple-affected time window because, after *f-k* filtering, the migration does not project multiple energy in the shallow data (red arrows). However, some additional noise is introduced by the *f-k* filters (blue arrows).

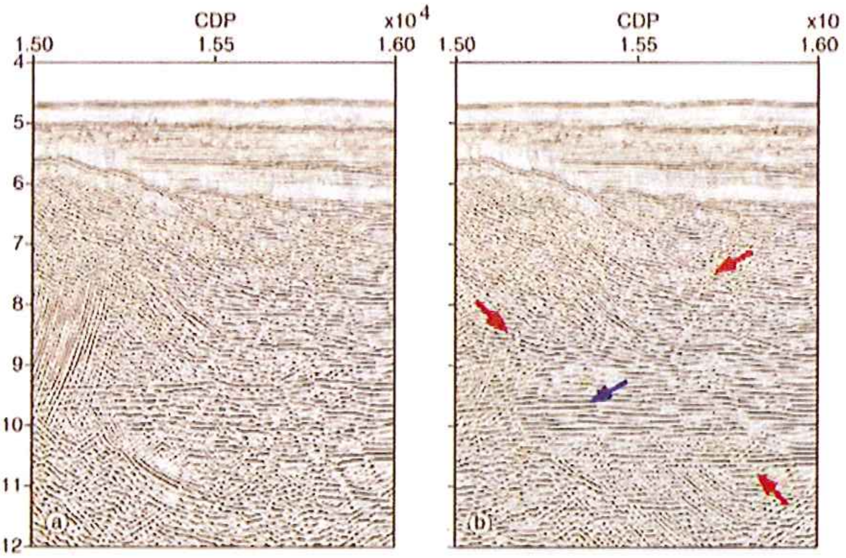

Figure 5. This section shows a buried volcanic edifice (basement undulation). Although the sediments are horizontally stratified, the sharp edges and steep slopes of the volcanic structure cause a lot of diffractions that are difficult to differentiate from multiple energy. We applied two *f-k* filters and a time-variant frequency filter with a small low pass for the deeper time windows. Red arrows indicate primary events, and the blue arrow marks the remnants of the sea-floor multiple. Note that the imaging above the multiple is improved because the section is migrated. At the depth of the sea-floor multiple, horizontal events are emphasized, but it is still difficult to distinguish multiples and primaries.

This processing flow yields good results as long as the strata are more or less horizontal, there are no strong diffractions, and water depth is more than 350 m. At depths less than 350 m, the differential moveout is smaller than an empirical 30 ms-threshold necessary for the Radon filter to work properly. Under this threshold, the data are contaminated by aliasing.

The time spent on multiple suppression with Radon filters is about three times more than that for simple *f-k* filtering. This is caused by the computing-intensive Radon filter, by the necessary Radon analysis, and the picking of the corresponding time gates.

Strongly dipping events in deep water. The attenuation of multiples of dipping events and diffractions is more complicated because strong dips do not allow a differentiation of primaries and multiples based on their differential moveout.

Offshore Taiwan we encountered two environments with this problem: the continental slope southeast of Taiwan and a volcanic sea mount covered by sediments in the South China Sea.

While the multiples in the deep sea environment are clearly visible, they are hardly distinguishable as coherent events in a stacked section of the slope environment. In a shot gather, however, the multiples with steeper dip than the primaries are easily identified (Figure 4a), and removal of these multiples enhances the data quality significantly. The signal-to-noise ratio becomes higher, and reflections are more continuous. To cope with these multiples, we used two *f-k* filters, one in the shot domain and one in the receiver domain. *F-k* filtering works better for slopes against the ship's travel direction, because the dip of the hyperbolas is emphasized. By resorting the traces into receiver gathers we simulated a pass in the other direction for the portions of the line where the ship's travel direction was along deepening sea floor.

Relatively weak *f-k* filters were applied to leave the diffraction intact for the migration. Figures 4b and 4c demonstrate that even in areas with no obvious multiple noise, demultiple processing is advantageous.

In the area of the buried volcanic feature (Figure 5), water depth is approximately 3500 m, and the crustal structures hidden by the multiple are at approximately 9 s two-way traveltime (which corresponds to a depth of at least 10 km).

Usually, deep crustal primary reflections dip moderately, because steeply dipping reflectors at these depths do not in general produce any recordable reflections. Therefore, good results can be obtained by applying strong *f-k* filters in the CDP domain in the multiple-contaminated time window, suppressing the multiple and leaving the horizontal primaries untouched.

This technique has to be used with care, however, since horizontal multiple energy also will be emphasized, and it is possible to generate artifacts.

Due to the great reflection depth, the primaries have much lower frequency content than the multiples. Therefore, in this environment, it is particularly effective to use a time-variant frequency filter to distinguish and eliminate the multiples.

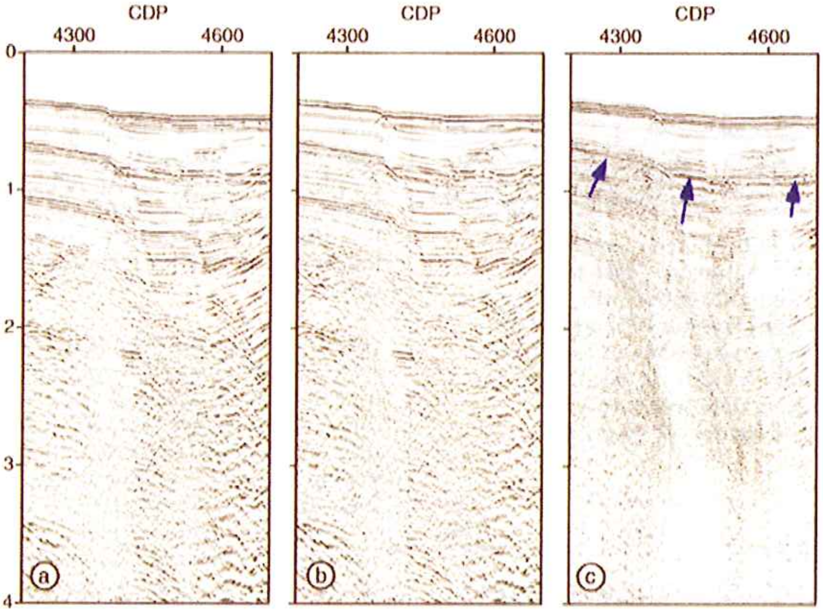

Figure 6. In the shelf area southwest of Taiwan, we successfully applied wave-equation multiple rejection. (a) A block faulted area at the shelf margin; (b) the same section after multiple suppression; and (c) the difference of (a) and (b). Blue arrows mark rejected multiple energy.

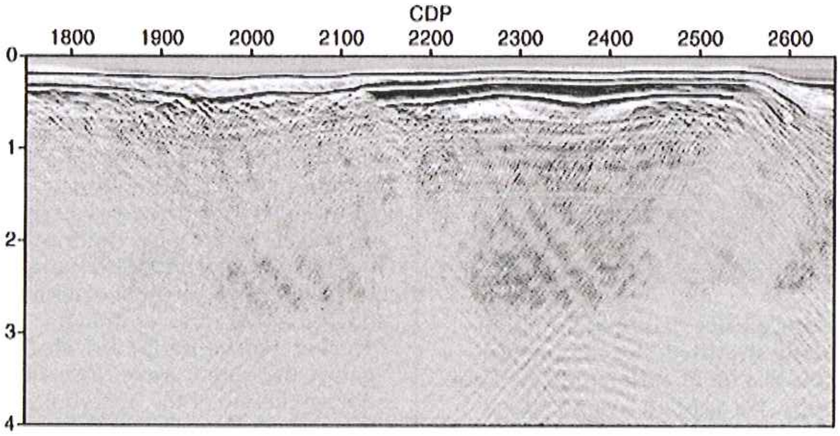

Figure 7. Section from southern tip of Taiwan which shows disturbed sediments of the collision zone. The crust of the South China Sea is being obliquely subducted under the Philippine Plate, and the whole subduction zone is colliding with the Asian continent. We spent considerable time trying to improve this image but without success.

Stratified layers in shallow water. For multiple attenuation in shallow water (e.g., on the shelf southwest of Taiwan), we successfully employed sea-floor multiple prediction in the *f-k* domain—a wave-equation-based multiple-suppression strategy (Figure 6).

We used time-variant frequency filters, but the shallow water causes the frequency content of multiples and primaries to be only slightly different.

The difference section demonstrates that this technique does not take only sea-floor multiples into account (blue arrows) but also peg-leg multiples. The appearance of the seismic section becomes clear, and primaries are more continuous.

Heavily disturbed sediments in shallow waters. We spent considerable time in researching a demultiple technique for shallow waters and disturbed sediments (Figure 7). We examined deconvolution techniques, *f-k* filters, Radon filters, and wave-equation multiple removal. Most of these depend in some way on the velocity function. However, primary velocities are not available due to the lack of continuous reflections in the strongly disturbed underlying sediments. Furthermore, the methods depend on sufficient partial moveout which might not be given in these shallow waters and the slowly increasing velocities with depth. Therefore, these techniques should not be expected to perform too well. But it should be possible to find appropriate deconvolution operators to use the inherent periodicity of the multiples. However, we were not successful in this. We do not know why wave-equation multiple removal does not yield a better result. The recording parameters are the same as those used in the adjacent Tainan Basin where this method worked well. We offer two possible explanations for this poor performance. First, because wave-equation multiple suppression as well as predictive deconvolution depend on a stationary waveform, the interference of out-of-plane energy with the direct wave can cause both processes to become unstable. Second, it is also possible that the processes work but that there are no strong reflectors underneath the sea floor because this area is heavily disturbed by the collision of the

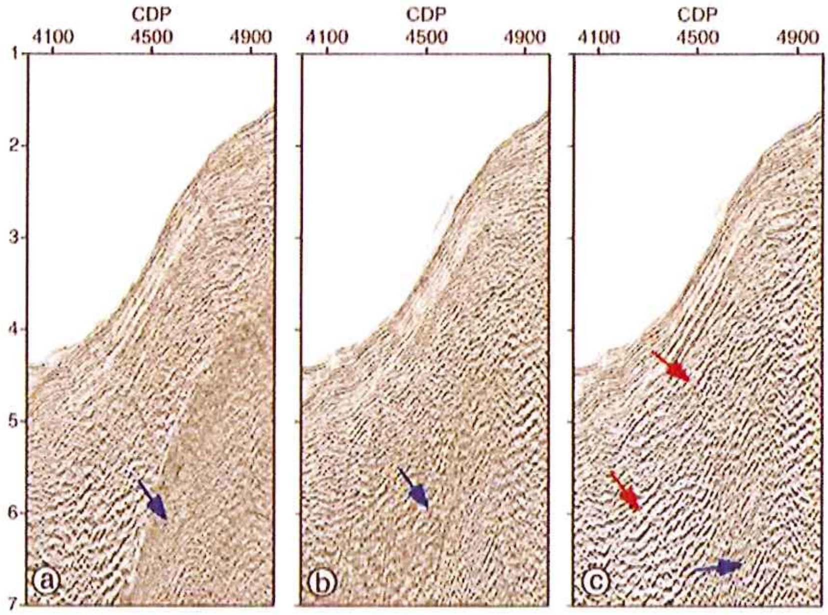

Figure 8. Section crossing the northern tip of the volcanic island arc southeast of Taiwan. (a) Partial prestack migration (DMO) and stacked; (b) Radon-filtered and time-variant frequency filtered; and (c) migration after addition poststack *f-k* and time-variant frequency filtering. Previously mapped multiple energy in the upper parts of the section is now suppressed. Blue arrows indicate the sea-floor multiple. Red arrows show previously hidden reflections which we assign to volcanic flow units.

Luzon Island Arc with the Eurasian continent and the involved subduction zones.

Outcropping igneous rocks. On the northern end of the Luzon Island Arc southeast of Taiwan (Figure 8), we suppressed the sea-floor multiple to a large extent by consecutively applying six methods: inside mute, *f-k* filter in the CMP domain, Radon filter, weighted stacking and time-variant frequency filter, and another *f-k* filter after stack. The rapid velocity increase with depth in areas with outcropping volcanic rocks results in sufficient partial moveout to apply moveout-dependent demultiple techniques.

Due to the rough geometry of the reflectors, migrating the data is mandatory. The steep dip, however, causes remaining multiple energies to be mapped into the area which was unaffected by multiples before migration (Figure 8a). Therefore, we apply a second *f-k* filter after stack to suppress this residual multiple energy. Because the multiple reflections have twice the dip as the primaries, it is possible to find suitable *f-k* filters. This method has to be used with care, since the choice of the *f-k* filter already includes an interpretation of the data, and it is easy to suppress real events that are dipping steeply (Figure 8b). It is possible to identify dipping events at dip angles similar to the sea floor. Based on their frequency content and shape we interpret these as flow units generated by the arc volcanism. Unfortunately, the rough hummocky topography generates considerable out-of-plane backscattering which cannot be accounted for in a 2-D survey. Hence the problematic signal-to-noise ratio in these areas is not primarily due to multiples but rather to the inherent limitations in the use of 2-D data.

Conclusions. The choice of a multiple-attenuation method, when working with marine data, depends to a large extent on the geologic environment. In general, geology plays a much stronger role in areas of shallow water. These data sets often require more sophisticated methods or even combinations of methods. Figure 9 shows the relevant processing steps for the various environments discussed in this article. E

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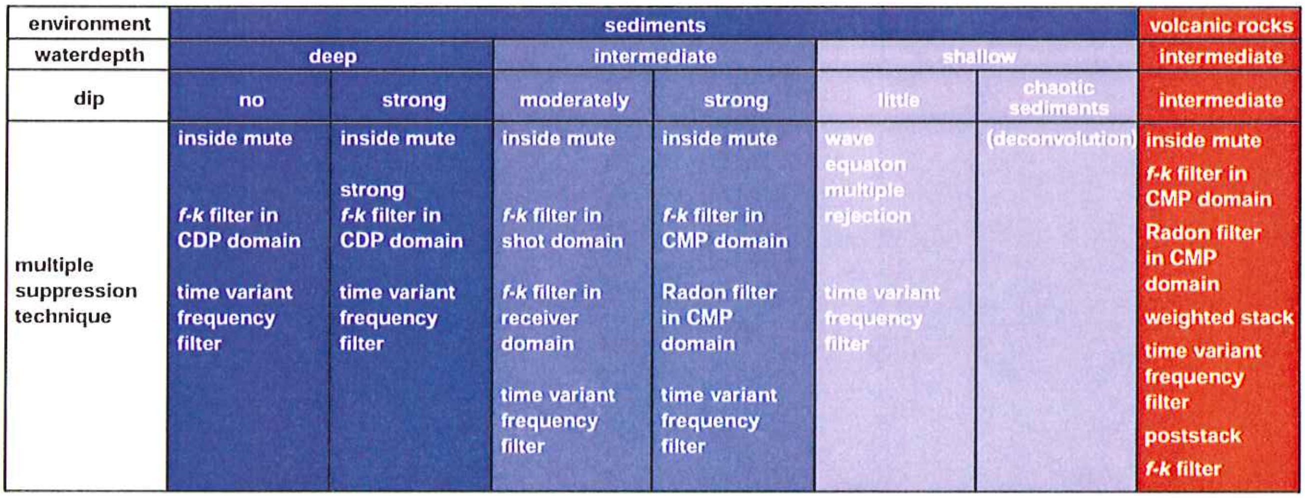

environment	sediments						volcanic rocks
waterdepth	deep		intermediate		shallow		intermediate
dip	no	strong	moderately	strong	little	chaotic sediments	intermediate
multiple suppression technique	inside mute *f-k* filter in CDP domain time variant frequency filter	inside mute strong *f-k* filter in CDP domain time variant frequency filter	inside mute *f-k* filter in shot domain *f-k* filter in receiver domain time variant frequency filter	inside mute *f-k* filter in CMP domain Radon filter in CMP domain time variant frequency filter	wave equaton multiple rejection time variant frequency filter	(deconvolution)	inside mute *f-k* filter in CMP domain Radon filter in CMP domain weighted stack time variant frequency filter poststack *f-k* filter

Figure 9. Relevant processing steps for various geologic environments. Blue is for sedimentary areas and red for a volcanic environment. Processing not related to multiple suppression is omitted.