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Demasking Multiple Artifact in Crustal Seismic Images from Marine Reflection Data in the Southern California Borderland

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ABSTRACT: Marine seismic reflection surveys are often masked by strong water-bottom multiples that limit the use of data beyond the first multiple waves. In this study, we have successfully suppressed much of the multiple artifacts in the depth images of two of the marine seismic reflection profiles from the Los Angeles regional seismic experiment (LARSE) by applying reverse time migration (RTM). In contrast to most seismic reflection methods that use only primary reflections and diffractions, the two-way RTM migrates both primaries and multiple reflections to their places of origination: seabed multiples to the sea bottom and primaries to the reflecting interfaces. Based on the RTM depth sections of LARSE lines 1 and 2, we recognize five stratigraphic units from the sea bottom to a depth of 6 km. These units are Pliocene and younger strata, probably Miocene syntectonic strata, two deeper sequences of unknown age and lithology as well as Miocene volcanic layers on Catalina ridge. Several inferred igneous intrusions in the upper crust comprise a sixth unit. The existence of a thick sedimentary section in the Catalina Basin, which might include Paleogene and Cretaceous fore-arc strata, has important geologic significance. If borne out by further studies, significant revisions of current structural and stratigraphic interpretations of the California borderland would be warranted.
KEY WORDS: demasking multiple artifact, reverse time migration, LARSE, Catalina schist, hydrocarbon basin.

0 INTRODUCTION

The southern California continental borderland has a complex tectonic history. During Cretaceous and Paleogene time, the borderland was the forearc region of the Pacific-North American Plate subduction zone. In the Late Paleogene–Early Miocene, collision of the Pacific Plate spreading center with North American Plate began the formation of the San Andreas Plate boundary and transtensional deformation. In this transition period, southern California experienced plate capture, translation, rotation of crustal blocks, extension and volcanic eruptions. In the Late Miocene, the present transpressional phase of deformation began with the breakaway of Baja California from the North American Plate and the formation of the present San Andreas fault. Structures formed during this period include folds, faults and inverted grabens (Atwater, 1998; Nicholson et al., 1994).

The principal lithotectonic belts that comprise the California continental borderland are the northwest-trending Franciscan accretionary wedge, outer continental borderland (OCB), inner continental borderland (ICB) and peninsular ranges. The western transverse ranges, a major clockwise-rotated structural block, adjoin the borderland area on the north (Fig. 1) (ten Brink et al., 2000; Bohannon and Geist, 1998; Crouch and Suppe, 1993).

The California inner continental borderland is an extensional region with a dominant SE-NW structural trend of alternating basins and ridges and basin-bounding faults, similar to the extensional basin and range province of the western U.S.. Crouch and Suppe (1993) proposed that the Mesozoic Catalina schist is the basement rock in the ICB and that the Catalina schist was uplifted to shallow depths during the Miocene crustal extension of the region. The extent and depth of the Catalina schist in the ICB are not well-established. In most places, Miocene and younger rocks are present on the sea bottom. Outboard from the ICB and onshore in the Los Angeles Basin, Cretaceous to Oligocene fore-arc strata underlie Miocene and younger rocks. The presence of Miocene plutons in the upper crust can be inferred from gravity and magnetic data and outcrops on Santa Catalina Island (Ridgway and Zumberge, 2002; Rowland, 1984; Forman, 1970). Volcanic rocks are interbedded with Miocene strata throughout the ICB. The only occurrences of incontrovertible in-place Catalina schist are the outcrops on Catalina Island.

The Los Angeles regional seismic experiment (LARSE) was initiated in 1994 to acquire data to better understand the structure and composition of the transition zone from continental to oceanic crust across the Los Angeles Basin area

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and the California borderland. Part of this project included the acquisition of LARSE lines 1 and 2 (Brocher et al., 1995) (Fig. 2). Because of a powerful source and highly reflective sea bottom, strong multiples were generated that masked all primaries beyond the first occurrence of multiples, as illustrated in Fig. 3, a constant velocity stack of LARSE Line 1 using water velocity. This stack section shows a number of strong sea-bottom multiples as well as additional background noise. The maximum depth that is unaffected by multiple reflections is about 2.5 km, which precludes meaningful interpretations of deeper crustal structures in the presence of multiples.

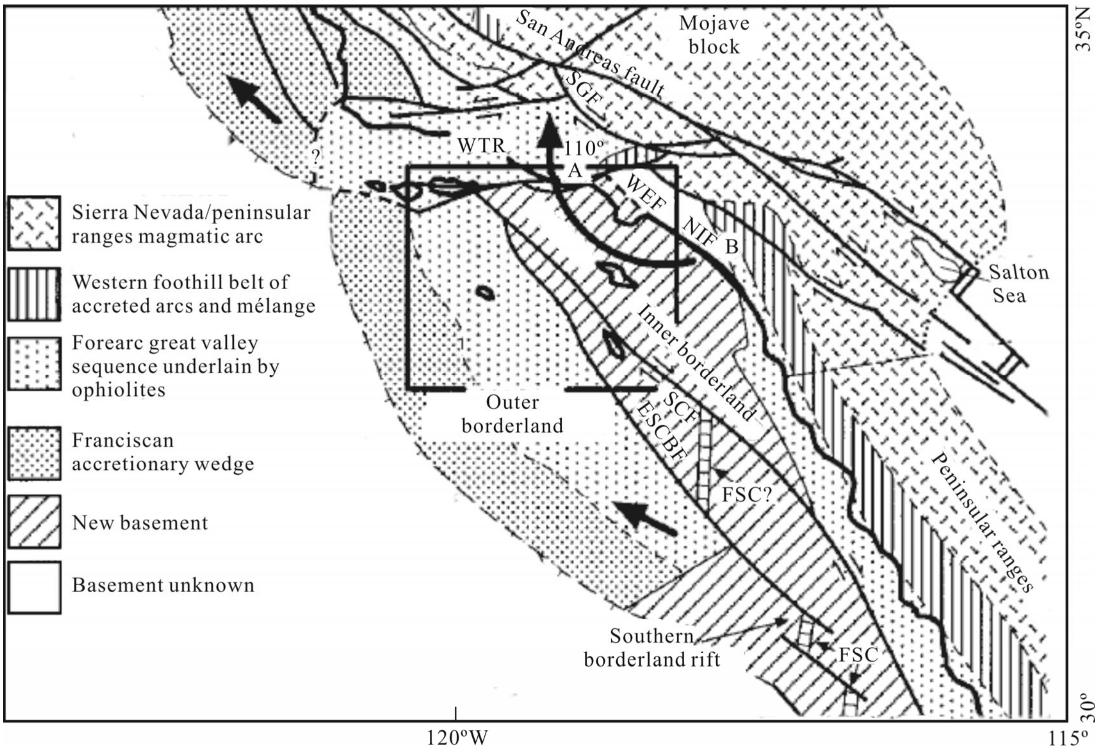

Figure 1. Principal lithotectonic belts in southern California. Rectangle shows location of Fig. 2 (modified from ten Brink et al., 2000). ESCBF. Eastern Santa Cruz Basin fault; FSC. fossil spreading center; SCF. San Clemente fault; SGF. San Gabriel fault; WEF. Whittier-Elsinore fault; WTR. western transverse ranges; NIF. Newport-Inglewood fault; A and B. locations of Santa Monica Mountains-simi hills and of San Joaqin Hills.

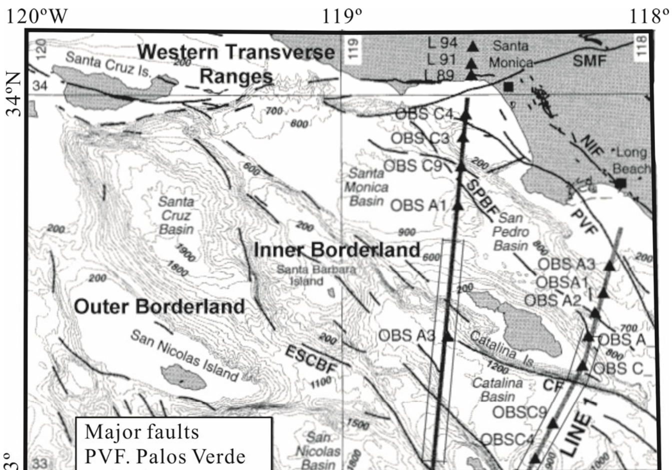

Figure 2. LARSE lines 1 and 2, California borderland. Two rectangles mark the segments processed via RTM (after ten Brink et al., 2000).

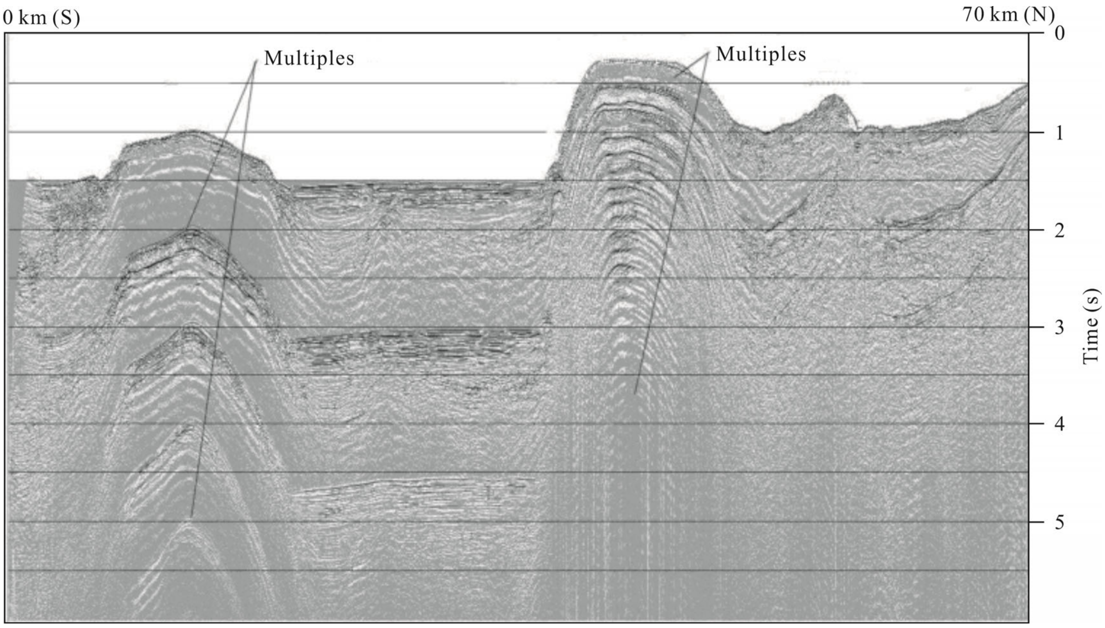

Figure 3. LARSE Line 1 constant velocities stack using water velocity.

We have previously investigated the application of a prestack reverse time migration (RTM) method that uses multiples as signal rather than noise to process real seismic data and model data (Youn and Zhou, 2001). Our results accurately imaged primaries and multiples showing overall significant improvements when compared to conventional processing. We have successfully applied this method to improve images of onshore segments LARSE lines 1 and 2 (Thornton and Zhou, 2008). The present study applies RTM to demask the multiple artifact in offshore segments of LARSE lines 1 and 2 (Fig. 2)

Our results indicate that much of the artifact due to water-column multiples can be demasked by prestack RTM based on a two-way acoustic wave-equation. The high quality depth images from the RTM in this study show stratigraphic and structural features that are not evident in published seismic sections.

1 MARINE SEISMIC REFLECTION DATA

In this study, we used RTM to process marine seismic reflection data from LARSE dip-line profiles 1 and 2. These profiles lie mostly within the inner continental borderland between the East Santa Cruz Basin fault and the coastline of southern California (Fig. 2).

Seismic reflection data were recorded using a 4 200 m 160 channel digital streamer with a receiver group interval of 25 m. A tuned array of 20 air guns with a total volume of 137.7 liters (8 470 cu. in.) was fired every 50 m, resulting in a subsurface coverage of 40 fold and a common midpoint interval of 12.5 m. The data were recorded to a length of 16 s with a sampling interval of 2 ms.

2 REVERSE TIME MIGRATION

Most ray-based or one-way wave-equation migration methods use only primaries and diffractions as signals to image subsurface reflectors. Multiple reflections are regarded as noise and are eliminated prior to the imaging process. It is very difficult to remove multiples in areas where the sea bottom is hard and the bathymetry is highly variable like the California borderland. Since multiples contain information of the target zone along their travel paths, using multiples as signal can improve illumination coverage and thereby enhance the image.

RTM is a pre-stack depth imaging technique. When based on a two-way wave-equation, RTM uses both primaries and multiples to map reflection boundaries. RTM requires a known source wavelet, a migration velocity model and preconditioned seismic data. The general processing workflow is the following.

1. The forward propagation wavefield is excited at source location from time zero to maximum recording time using a waveform modeling engine. The modeling engine may be based on one-way or two-way wave-equations.

2. The preconditioned data traces are time reversed as pseudo source wavelets and excited at receiver locations to produce a reversely propagated wavefield using the modeling engine and the velocity model.

3. The forward and reversely propagated wavefields at each image grid and each time step are multiplied and summed over time to obtain a raw shot image.

4. The final stack is produced by stacking all raw shot images and then enhanced by post processing, including amplitude balancing, filtering and muting.

In this study, a finite difference modeling approach with up to eighth order accuracy in space and second order accuracy in time was used as the modeling engine to produce primary and multiple reflections. A free surface boundary condition was used at the sea surface to generate multiples, and absorbing boundary conditions were used to eliminate reflections from three artificial boundaries of the migration velocity model.

Factors that influence the quality of RTM images are: the source wavelet, velocity model, background noise, data acquisition geometry and preprocessing workflow. The sharp velocity interface near sea-bottom is preserved in order to generate multiples in the forward and backward propagation steps. Strong amplitude and low frequency marine background noise are removed before the migration process.

Velocity models for Line 1 and Line 2 were computed on a grid with a 12.5 m interval to maximum depths of 8 and 15 km, respectively. The velocity grid for Line 1 was based on a structure velocity model developed by Baher et al. (2005). The velocity grid for Line 2 was derived from results of deformable layer tomography analysis (Zhou, 2003) that used first arrival time picks from LARSE ocean bottom seismometer data.

Artifacts observed on the shallow portion of the raw migration results are generated by the RTM process. They are produced where high velocity contrast exists at the sea bottom interface. They are also produced when diving waves, head waves or backscattered waves cross-correlate (Guitton et al., 2007).

3 RESULTS AND DISCUSSION

Figure 4 shows a comparison of conventional seismic depth profiles of LARSE lines 1 and 2 (Figs. 4a and 4c) overlain by a velocity model (ten Brink et al., 2000) with RTM depth profiles produced in this study (Figs. 4b and 4d). Some of the most prominent events on the conventional profiles are probably artifacts produced by multiples. In the RTM depth profiles, due to the process of demasking of multiples, the primary reflections have been significantly enhanced, which results in higher resolution of structural and stratigraphic features in both shallow and deep parts of the profile. In addition to mapping multiples to their origination locations, the cross correlation step of the RTM also filters out other noises such as side-scattering in the 2-D data that are uncorrelated with the forward wavefield from the model (Thornton and Zhou, 2008).

We recognize five stratigraphic units on the RTM depth images of the Catalina Basin and ridge area (Figs. 4b and 4d). Unit 1 includes the near-horizontal reflectors from the sea bottom to the green horizon. Unit 2 underlies Unit 1 and consists of discontinuous and in places deformed strata. The base of Unit 2 is the yellow horizon, which truncates some of the strata in Unit 1. Unit 3 is the interval between the yellow and pink horizons with discontinuous and deformed strata in the upper part. Unit 4 includes the pink reflector and underlying reflectors that range to depths of 3.5 to 5 km. These strata are near-horizontal when the vertical scale is not exaggerated and contrast sharply with the shape of the base of Unit 2. Since near-horizontal reflectors underlie and overlie Unit 2, the base of Unit 2 is probably an erosional surface and not cut by faults. The top part of Catalina ridge with strong, northeast-dipping irregular reflectors is Unit 5.

Sparse data are available to definitively determine the identification and age of the five stratigraphic units defined above. Miocene volcanic rocks crop out on San Clemente Island. Miocene volcanic rocks, a Miocene quartz diorite pluton and the Mesozoic Catalina schist facies crop out on Santa Catalina Island. Sea bottom samples are probably detritus from all of these outcrops, which are separated from the Catalina Basin section by major basin-bounding faults and not necessarily reliable indicators of the lithologies of the subsurface strata.

Unit 1 and Unit 2 are generally equivalent to the Pliocene and younger strata and probably Miocene syntectonic fill strata respectively, mapped on USGS Line 120 (Bohannon and Geist, 1998), about 30 km east of LARSE Line 1, but are higher resolution images on the RTM profiles. The age correlations are loosely based on reflectivity similarities to coastal seismic lines that are tied to well data. The interval below the yellow horizon is probably what most workers would consider to be “basement,” that is, the Mesozoic Catalina schist, but the depth of “basement” in the Catalina Basin has not been clearly defined in published papers (Bohannon and Geist, 1998; Crouch and Suppe, 1993; Vedder, 1987).

Definitive lithological and age data on units 3, 4 and 5 are lacking in the Catalina Basin and ridge area. Deep reflectors like the top of Unit 4 are masked by the reflection artifact on published seismic profiles (e.g., ten Brink et al., 2000; Bohannon and Geist, 1998). Several interpretations of these stratigraphic units are possible, including the following.

1. The seismic characteristics of Unit 3 are similar to those of the Paleogene to Cretaceous fore-arc section of the outer continental belt, which Bohannon and Geist (1998) described as a section of “pronounced reflectivity”. Fore-arc strata would indicate the presence of a heretofore unknown, narrow, deep Miocene basin. Such a basin could have potential for hydrocarbon accumulations.

2. The continuous reflector at the top of Unit 4 may be a segment of the regional detachment fault proposed by Crouch and Suppe (1993) to be the upper surface of the Catalina schist in this area, suggesting an apparent 3 to 4 km downward displacement of the Catalina schist.

3. The Unit 5 reflectors may be Miocene intrusive rocks such as diorite sills in a section of unknown lithology or age.

The shallow, strong, northeast-dipping reflectors of Unit 5 on Santa Catalina ridge are possibly Miocene volcanic rocks like those that crop out on Santa Catalina Island and San Clemente Island. Volcanic rocks would tend to resist erosion and cap bathymetric and topographic high areas. Some of these reflectors are interbed multiples, possibly from volcanic flows, that were not demasked by the limited RTM process of this study. A second iteration would remove these multiples.

Unit 6 consists of possible plutons that may underlie San Clemente Island, Santa Catalina Island and Emery Knoll based on the absence of reflectors on RTM profiles (Fig. 4b) The presence of Miocene plutons in the upper crust has been inferred from gravity and magnetic data and outcrops on Santa Catalina Island (Ridgway and Zumberge, 2002; Rowland, 1984). Tomographic results and the distribution of overlying volcanic rocks suggest the presence of a diorite pluton in the subsurface of the southeastern Los Angeles Basin (Bjorklund et al., 2002). Volcanic rocks are interbedded with Miocene strata that are present throughout the ICB. The source of these igneous bodies could be an underplated fossil oceanic layer at the base of the continental crust in the transition zone of a stalled segment of the Pacific subducting plate (Brocher et al., 1999; Miller et al., 1992; Crandall et al., 1983).

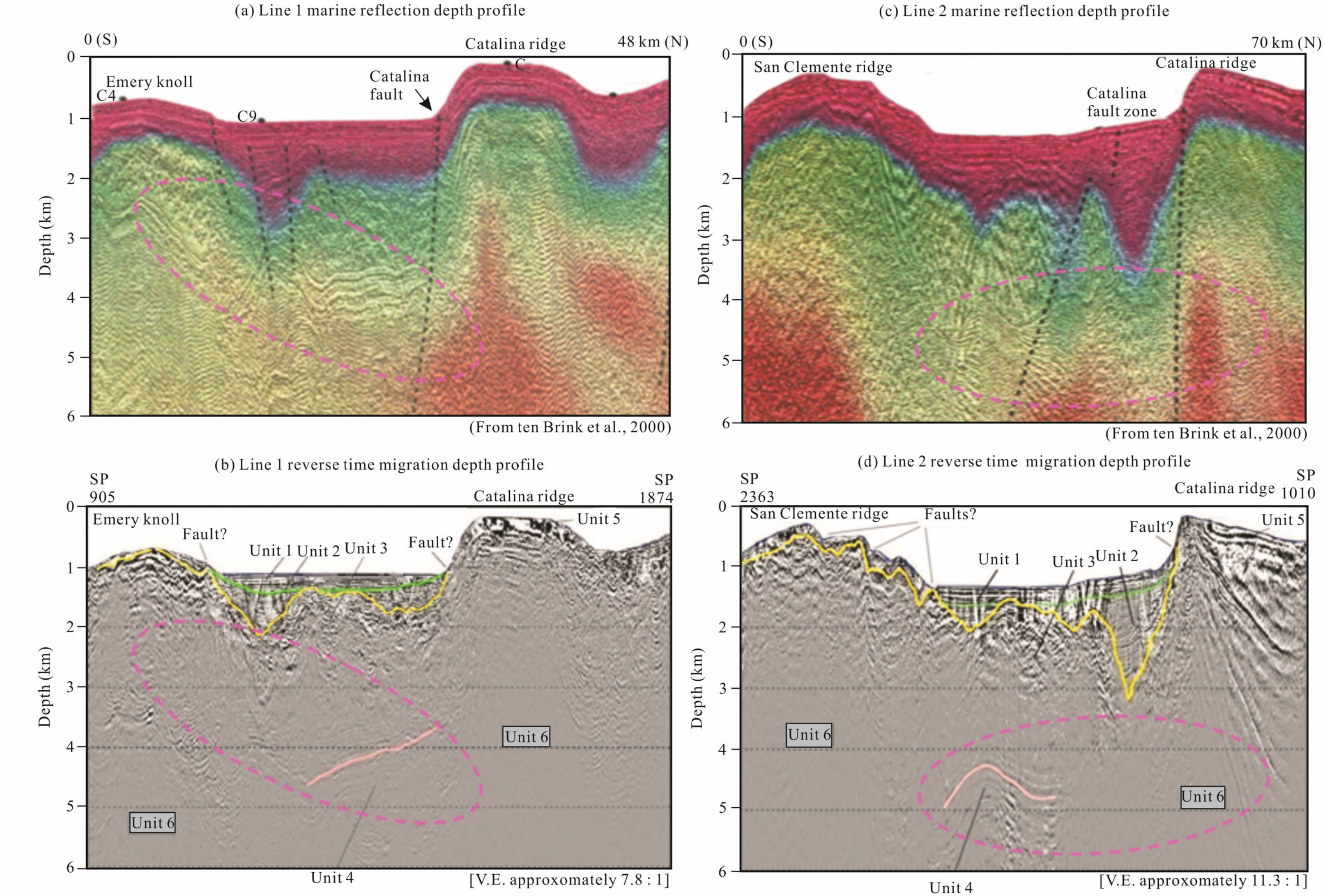

Figure 4. (a) and (c) LARSE lines 1 and 2 reflection depth profiles with color overlays of velocity model (Plates 1a and 1b, ten Brink et al., 2000). (b) and (d) LARSE lines 1 and 2 RTM depth sections. The dashed ellipses in color highlight places where many events in (a) and (c) are likely multiple artifacts. Labeled in (b) and (d): Unit 1. Pliocene and younger strata; Unit 2. probably Miocene syntectonic strata after Bohannon and Geist (1998). The base of Unit 1 is the green line. The base of Unit 2 is the yellow line. Unit 3. Strata between the yellow and pink lines. Unit 4. pronounced reflectors at 4–5 km. The top of Unit 4 is the pink line. The age and lithology of strata below probably the Miocene Unit 2 are unknown. Unit 5. strong, near surface reflectors on Catalina ridge. The strong events may represent Miocene volcanic strata. Unit 6 is an area characterized by the absence of reflectors that may indicate the general location of a shallow, Miocene, igneous intrusion (pluton) underlying a bathymetric high area.

4 CONCLUSION

The misinterpretation of sea bottom multiple artifacts as primary reflections is a common pitfall in the analysis of marine seismic profiles. On Los Angeles regional seismic experiment (LARSE) lines 1 and 2 in the California borderland, this study describes how to effectively demask the sea bottom multiple artifact using RTM. The processing of the LARSE lines using RTM has enabled us to define five stratigraphic units and to infer the presence of a sixth unit, an igneous intrusion, in the Catalina Basin and ridge area. These results allow us to speculate that the Catalina Basin may be much deeper than previously thought and may have potential for commercial hydrocarbons.

Since extensive seismic survey data are available over the California borderland, reprocessing additional seismic profiles using RTM could significantly improve our understanding of the structure and stratigraphy of the borderland and better constrain interpretations of the three-dimensional evolution of the region.

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