Integrated Ocean Drilling Program
Expedition 340 Scientific Prospectus

Lesser Antilles Volcanism and Landslides

Drilling volcanic landslides deposits and volcanoclastic sediments in the Lesser Antilles arc: implications for hazard assessment and long-term magmatic evolution of the arc

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Abstract

Integrated Ocean Drilling Program Expedition 340, the "Lesser Antilles Volcanism and Landslides" project, is designed to give us a better understanding of the constructive and destructive processes related to volcanism along island arcs. Processes occurring along these arcs are among the most fundamental occurring on Earth, as roughly 50% of volcanism along the circum-Pacific ring of fire is associated with island arcs. Nonetheless, several aspects of this type of volcanism, such as the processes controlling the changes and diversity in magmatism and eruptive activity on individual islands as well as along an arc or the emplacement processes of large debris avalanches, need to be better constrained. Identification of the controlling mechanisms of these processes is essential because of their potential association with large geohazards (explosive eruptions and tsunamis).

Our knowledge of island arc volcanism is mainly derived from on-land studies. It has been shown that the on-land geological record is far from complete and that only a combined record of marine and on-land deposits can give us a complete picture of volcanic activity. The Lesser Antilles arc is especially suited for a project like this, as it is very well studied, and thus the necessary information exists for making such a drilling project a success. In addition, magmatism and eruptive activity along the arc are quite diverse in space and time, the frequency of flank collapse resulting in deposition of debris avalanches is high, and the style of flank collapse varies along the arc. Thus, we will be able to sample deposits related to a large diversity of processes in a short time span.

In general, core and logging data retrieved during this expedition will be used to investigate the magmatic evolution and the eruptive activity in space and time along the Lesser Antilles arc and to identify the mechanisms controlling triggering, transport, and deposition of volcanic debris avalanches, including an assessment of volcanic hazards potentially coupled with eruptive processes and debris avalanche emplacement.

Schedule for Expedition 340

Expedition 340 is based on part of Integrated Ocean Drilling Program (IODP) drilling proposal number 681-Full2 (available at **iodp.tamu.edu/scienceops/expeditions/antilles_volcanism_landslides.html**). Following ranking by the IODP Scientific

Advisory Structure, the expedition was scheduled for the R/V *JOIDES Resolution*, operating under contract with the US Implementing Organization (USIO). At the time of publication of this *Scientific Prospectus*, the expedition is scheduled to start in St. John's, Antigua (Lesser Antilles), on 6 February 2012 and to end in Curacao, Netherlands, on 18 March 2012. A total of ~38 days will be available for the drilling, coring, and downhole measurements described in this report (for the current detailed schedule, see **iodp.tamu.edu/scienceops/**). Further details about the facilities aboard the *JOIDES Resolution* and the USIO can be found at **www.iodp-usio.org/.**

Introduction

The Lesser Antilles volcanic arc constitutes a unique setting where volcanic activity since the mid-Oligocene has resulted in construction of numerous volcanic edifices (Fig. **F1**). More than 12 of these edifices have been active in the last 10,000 y. Generally, volcanism along-strike the arc is characterized by an exceptional diversity of magma composition, production rate, and eruptive style, as well as of the frequency and style of flank collapses. These north–south variations are not fully understood but are probably related to the morphology and structure of the arc (Boudon et al., 2007). Furthermore, recent studies have shown that at least 52 flank-collapse events have occurred on volcanoes of the Lesser Antilles, 15 of which occurred within the last 12,000 y (Boudon et al., 2007; Lebas et al., 2011). Thus, the frequency of flank collapses in this area is at least an order of magnitude larger than at other regions (e.g., Hawaii: 1/350 k.y.; Moore et al., 1989). Two-dimensional seismic surveys around the Lesser Antilles have provided excellent images (Figs. AF01–AF18) of the debris avalanche deposits, including their basal surfaces (e.g., Deplus et al., 2001; Le Friant et al., 2003a), contrary to seismic lines in other geodynamic contexts. For the Lesser Antilles, Le Friant et al. (2009, 2010) have shown that as much as 70 vol% of the erupted products along the arc are finally deposited in the surrounding marine environment, emphasizing the need for submarine studies in this tectonic environment to retrieve a complete picture of the constructive and destructive processes associated with arc volcanism. Furthermore, the constructive as well as the destructive processes along island arcs are often associated with large geohazards. For example, (1) arc volcanoes could erupt explosively, producing large eruption clouds, and (2) flank collapses in these areas can be accompanied by large tsunamis.

Nonetheless, the majority of marine volcanic studies targeting volcaniclastic sediments and/or debris avalanche deposits (1) were not associated with entire volcanic island arcs but with oceanic intraplate volcanism (Ocean Drilling Program [ODP] Leg 136: e.g., Garcia, 1993; Garcia and Meyerhoff Hull, 1994; ODP Leg 200: e.g., Garcia et al., 2006; ODP Leg 157: e.g., Schneider et al., 1997; Goldstrand, 1998; Schmincke and Sumita, 1998), (2) were drilled into distal turbidites away from the proximal parts of the debris avalanche deposits, or (3) used sampling techniques with only shallow ground penetration, thus retrieving only relatively recent samples. For instance, tephrochronological studies on several volcanoes of the Lesser Antilles arc using piston cores (length = ~7 m) have extended our knowledge about the eruptive history in this area to only the last 250,000 y (Duchoiselle, 2003; Vennat, 2004; Le Friant et al., 2008; fig. 5 in Machault, 2008). Therefore, this project will not only provide the first cores penetrating through volcanic debris avalanche deposits (DADs) but also cores covering more than the last 1 m.y. of magmatic activity along the Lesser Antilles arc.

This expedition will focus on constraining the processes responsible for the diversity of magmatism and eruptive activity in space and time and their environmental effects by documenting the evolution of three volcanic centers of the Lesser Antilles arc, representing the full range of observed magmatism and eruptive styles (Fig. **F1**):

1. Montserrat in the north, where the Soufrière Hills volcano has been erupting and resulting in serious hazards and social disruption since 1995 (proposed Sites CARI-01C, CARI-02C, CARI-03C, and CARI-04D);
2. Martinique (with the sadly famous Montagne Pelée volcano; proposed Sites CARI-07C, CARI-08B, CARI-09B, and CARI-10B); and
3. Dominica, where several large silicic eruptive centers are considered active and pose serious potential regional hazards because of the occurrence of large-magnitude ignimbrite-forming eruptions (proposed Site CARI-05D).

Background

Geodynamic setting

The Lesser Antilles arc results from the subduction of the Atlantic plate beneath the Caribbean plate (Fig. **F1**). Current convergence rates of the plates are relatively slow (2–4 cm/y; Feuillet et al., 2002), and magma productivity has been low relative to other arcs; estimations of magma productivity vary between 3 and 5 km^3/m.y./km (Sigurdsson et al., 1980; Wadge, 1984; MacDonald et al., 2000). Volcanism along the arc started ~40 m.y. ago (Martin-Kaye, 1969; Bouysse et al., 1990). North of Dominica, the arc is divided into two island chains, sitting on top of a Cretaceous ocean island arc (Bouysse and Guennoc, 1983; Wadge, 1986). The eastern chain corresponds to an older extinct arc, and its basement is largely covered by thick carbonate platforms (Fig. **F1**). The western chain is the site of active volcanism since 20 Ma (Briden et al., 1979). South of Dominica, the older and recent arcs are superimposed, forming one chain of islands bordered to the west by the 2900 m deep backarc Grenada Basin. The Grenada Basin (Fig. **F1**) serves as a major depocenter for large debris avalanches, volcanic turbidites, large pyroclastic flows, and hemipelagic sediment (Sigurdsson et al., 1980; Deplus et al., 2001; Picard et al., 2006; Boudon et al., 2007). Generally, background hemipelagic sedimentation rates vary from 1–2 cm/1000 y west of the northern islands of the arc to 10–20 cm/1000 y in the Grenada Basin (Reid et al., 1996; Duchoiselle, 2003).

Eruptive history and long-term magmatic evolution of the volcanic arc

Volcanism varies markedly along the Lesser Antilles arc (MacDonald et al., 2000; Lindsay et al., 2005a). For example, magmas become enriched in incompatible elements, notably K, and radiogenic isotopes southward. This enrichment has been interpreted to reflect the increasing influence of subducted Orinoco sediment supplied from the South American continent into the forearc, as well as variations in subduction rate and geometry normal to the arc. The southern part of the arc (St. Vincent, Grenada, and the Grenadine Islands) is dominated by basaltic to basaltic andesitic magmas. The central part of the arc (St. Lucia, Dominica, and Martinique) is dominated by silicic magmas and characterized by relatively high eruption rates (e.g., 2.6 eruptions/1000 y for Montagne Pelée, Martinique; Duchoiselle, 2003), as inferred from marine tephra layers around these islands (Sigurdsson et al., 1980) and large volcanic centers. Volcanism in this area has also produced several large Plinian-style explosive eruptions with associated ignimbrites in the recent geological past. The northern part of the arc is characterized by andesitic and basaltic volcanism. The volcanoes of Soufrière Hills on Montserrat and Soufrière on Guadeloupe have produced dominantly andesitic magmas, whereas Nevis, St. Kitts, St. Eustatius, and Saba have erupted substantial volumes of basaltic as well as andesitic magmas. Magma production rates and eruption frequency are comparatively low in this area (e.g., 0.5 eruptions/1000 y, Soufrière on Guadeloupe; Komorowski et al., 2005). In addition, volcanoes in this area are also characterized by magmatism alternating on a timescale of ~1 m.y. from long production periods of almost constant magmatic composition to short periods of large compositional variations (from basalts to dacites; see, e.g., Mt. Pelée and adjacent centers; Boudon et al., 2005; Annen et al., 2006, 2008).

Much of the compositional variability in arc volcanoes can be related to the processes in the crust where magmas are generated and transported. Annen et al. (2006, 2008) provide a conceptual framework for understanding the dynamics of magma generation, magma differentiation, and transport, including the formation of differentiated magmas in deep hot zones, partial melting of the preexisting crust, transport, and formation of shallow magma chambers in which phenomena such as degassing, crystallization, and magma mixing can take place to control the characteristics of the erupted magmas and, ultimately, styles of volcanic activity. Magma flux rates are considered to be the major control on the formation of shallow magma chambers containing eruptible magma and on their compositions. Understanding the igneous processes of volcanic arcs and the subduction zone engine is fundamental because they provide a viable mechanism to generate continental crust and are a key component of global-scale geochemical cycling.

On an individual island scale, the islands of the Lesser Antilles arc are characterized by the development of a number of discrete volcanic centers, many of them overlapping in space and time (Lindsay et al., 2005a). The *Volcanic Hazards Atlas of the Lesser Antilles* by Lindsay et al. (2005a) presents a good synthesis of the knowledge and available references on these volcanoes. Volcanic activity along these centers is interpreted to be episodic, migrating either from north to south (Montserrat, Harford et al., 2002) or vice versa (Martinique, Boudon et al., 2005), or clustered in several contemporaneous centers (Dominica, Lindsay et al., 2005b). In each case, these centers appear to remain active for 5×10^5 to 5×10^6 y, although these inferred timescales are not well constrained. However, deciphering a complete eruption record from onshore geology is commonly problematic because of burial by deposits from younger events, dense vegetation, erosion, and catastrophic removal of deposit by flank-collapse events. Marine sediments preserve a much more complete record of volcanism (Sigurdsson et al., 1980; Le Friant et al., 2008). Recent marine tephrochronological studies have been undertaken for several volcanoes of the Lesser Antilles arc from piston cores (Duchoiselle, 2003; Vennat, 2004; Le Friant et al., 2008; fig. 5 in Machault, 2008). Correlations have been made between tephra sampled in a core off one island and onshore deposits from different volcanoes of different islands. In the case of the Montagne Pelée volcano in Martinique, 25 eruptive events have been identified in marine deposits between 5,000 and 15,000 y before present versus only 10 magmatic events previously recognized onshore. For Montserrat (SHV), the marine core records several Plinian explosive eruptions, which have yet to be identified on land (Le Friant et al., 2008). Integration of marine tephrochronology and onshore geologic studies are thus the principal way to investigate the complete history of volcanoes. However, conventional coring only samples the recent activity (tens to hundreds of thousands of years), which is not sufficient to characterize the complete evolution of volcanic systems that can extend to a few million years.

Flank-collapse events (with large debris avalanche emplacement) and sedimentation processes along the arc

Volcano flank collapses are increasingly recognized as a normal process in the construction and destruction of volcanic edifices (Ida and Voight, 1995; McGuire, 1996; Voight, 2000). Thus, they play a significant role in the evolution of volcanic edifices and on the dynamics of subsequent eruptions and are a significant potential geohazard. The recognition of flank-collapse events is based on mapping debris avalanche deposits that can be traced to a generally horseshoe-shaped collapse depression (Voight, 1981). The most voluminous events (volumes from tens to hundreds or even thousands of cubic kilometers) have been recognized on oceanic islands: Hawaii (Lipman et al., 1988; Moore et al., 1989), La Réunion (Labazuy, 1996; Oehler et al., 2004, 2008), and in the Canary archipelago (Holcomb and Searle, 1991; Watts and Masson, 1995; Urgeles et al., 1997; Krastel et al., 2001).

On volcanoes of the Lesser Antilles arc, at least 52 flank-collapse events have been identified (Deplus et al., 2001; Le Friant, 2001; Le Friant et al., 2002, 2003a, 2003b, 2004; Lebas et al., 2011; Boudon et al., 2007). In the northern part of the arc, flank collapses are repetitive, do not exceed 1 km^3 in volume, can occur in all directions, and are promoted by intense hydrothermal alteration and well-developed fracturing of the summit part of the edifices. For example, several prehistoric flank collapses have been recognized on the Soufrière Hills volcano, Montserrat (Fig. **F2**) (Le Friant et al., 2004; Lebas et al., 2011). The English's crater event occurred ~2000 y ago, producing debris avalanche Deposit 1 (volume = ~1.5 km^3). Debris avalanche Deposit 2 probably resulted from a combined submarine and subaerial flank collapse of the eastern flank of the volcano dated between 130 and 112 ka (Le Friant et al., 2004). In the southern part of the arc, flank collapses are larger (with volumes up to tens of km^3), always directed to the west, and related to the higher overall slopes of the leeward side of the islands. For example, the evolution of the active Montagne Pelée volcano, Martinique, has been marked by three major flank collapses (~0.1 Ma, ~25,000 y ago, and ~9000 y ago) that systematically destroyed the western flank of the volcano (Le Friant et al., 2003a, 2003b; Boudon et al., 2005, 2007). Collapse volumes varied from 2 to 25 km^3, and debris avalanches flowed down to the Grenada Basin (Fig. **F3**). In addition, marine and terrestrial evidence indicate a succession of at least three flank collapses on Dominica (Fig. **F4**) (Le Friant et al., 2002). Dominica was also the site of the generation of the most voluminous debris avalanches in this area, with submarine deposits that cover 3500 km^2. The proximal debris avalanche deposit consists of megablocks (as long as 2.8 km and as high as 240 m) that reflect the predominance of lava flows and lava domes as observed in the source Plat Pays volcanic complex and in terrestrial relict debris avalanche material.

Despite the importance of flank collapses and associated debris avalanches in the lifetime of arc volcanoes, mainly areas of intraplate volcanism associated with large submarine volcanic landslides, such as Hawaii (ODP Leg 136: e.g., Garcia, 1993, Garcia and Meyerhoff Hull, 1994; ODP Leg 200: e.g., Garcia et al., 2006) and the Canary Islands (ODP Leg 157: e.g., Schneider et al., 1997; Goldstrand, 1998) have been drilled. However, all these drill sites were located in distal turbidites, far away from proximal debris avalanche deposits. Flank-collapse deposits in those locations (e.g., Canary or Hawaiian Islands and Izu Bonin arc) extend to deeper (>4000 m) water depths and are relatively thick, which limits the resolution and penetration of seismic surveys. Despite considerable efforts, avalanche deposits around the Canary and Hawaiian Islands or the Izu Bonin arc have not been successfully penetrated and seismically imaged in much detail. In contrast, previous two-dimensional seismic surveys show that debris avalanche deposits and their basal contacts can be imaged successfully in the Lesser Antilles (Deplus et al., 2001; Le Friant et al., 2004). This can be largely explained by the fact that collapse deposits around Montserrat occur in shallower water (<1200 m) and that offshore Dominica and Martinique, the debris avalanche flew into the Grenada Basin and was emplaced on top of sedimentary units that provide good seismic reflectors. Seismic images in the Lesser Antilles thus provide the essential background information to facilitate effective drilling into debris avalanche deposits.

Different morphologies and deposit geometries of debris avalanche deposits have been observed along the Lesser Antilles. Large hummocks (as large as 2 km) characterize the debris avalanches off Dominica, whereas the morphology of the debris avalanches off Martinique is smooth. These differences are probably related to contrasted lithologies of the volcanic products (dominantly pyroclastic deposits versus massive lavas) (Boudon et al., 2007). Northern island volcanoes collapsed repeatedly and contrast with southern island volcanoes where collapses are infrequent. Such size and frequency variations along a volcanic arc have not been documented previously for any other arc.

The majority of detrital material resulting from the erosion of the islands of the arc is transported into the surrounding ocean (e.g., Sigurdsson et al., 1980; Le Friant et al., 2004; Picard et al., 2006). Studies of offshore deposits from the 1902 eruption of St. Vincent (Carey and Sigurdsson, 1982), from the recent eruption of SHV (Le Friant et al., 2004; Hart et al., 2004; Trofimovs et al., 2006, 2008) and from prehistoric eruptions on Dominica (Sigurdsson et al., 1980; Whitham, 1989) demonstrate that most of the erupted material reaches the ocean. Volcanogenic sediments are channeled by debris flows, turbidity currents, and persistent ocean currents through deep submarine canyons located west of the volcanoes and which, for Guadeloupe and Dominica, lead into the northern part of the Grenada Basin (Fig. **F1**).

Around Montserrat there are examples of single or multiple stacked carbonate turbidites that contain reworked shallow-water sediment and fauna. These are likely sourced from large carbonate platforms associated with islands such as Antigua and Redonda. Understanding the origin of these bioclastic turbidites is important because, for example, the volume exceeds that of volcaniclastic deposits associated with the more recent (<100 ka) eruptions of the Soufrière Hills volcano. Shallow vibrocores have only recorded bioclastic turbidites associated with the late glacial period. One possibility is that they are caused by instability of carbonate platforms during rapid sea level rise at the end of major glaciations. Alternatively, major regional earthquakes may trigger them, in which case the occurrence of such events may be unrelated to climatic cycles.

Site survey data

Previous work has involved on-land geological, geochemical, petrological, geochronological, and geophysical studies and offshore marine studies:

1. The *Endeavour* cruise of 1979 gathered a regional collection of piston cores allowing assessments of rates of volcanism and sedimentation, dating of major explosive eruptions, recognition of submarine pyroclastic flow deposits, and establishment of a biostratigraphic framework for the eastern Caribbean (Sigurdsson et al., 1980; Sparks et al., 1980a, 1980b; Reid et al., 1996). Westbrook and McCann (1986) analyzed large-scale seismic experimental data on the overall arc crust and showed that the subduction history has been episodic (e.g., shift of the axis of volcanism in the Lesser Antilles at the beginning of the Pliocene).
2. Site 30 of Deep Sea Drilling Project (DSDP) Leg 4 in 1969 was drilled to investigate the geologic history of the Aves Ridge (west of the Grenada Basin). Site 48

of DSDP Leg 15 was located north of Site 30, also investigating the Aves Ridge. However, no DSDP, ODP, or IODP sites have been studied in the Grenada Basin or close to the Lesser Antilles islands up to now.

3. During the Aguadomar (December 1998–January 1999) and Caraval (March 2002) cruises of the RV *L'Atalante* (principal investigators (PIs): C. Deplus and G. Boudon), Simrad EM12D swath bathymetry and backscatter data, 3.5 kHz echosounder, gravity, magnetic, and six-channel seismic reflection data were collected from Montserrat to St. Vincent (Deplus et al., 2001). During Caraval, seismic profiles using a 24-channel streamer (Deplus et al., 2002), sediment piston cores, and dredge samples were also collected (see overview Table **T1**).
4. During the JCR123 cruise of the RRS *James Clark Ross* in May 2005 (PI: R.S.J. Sparks), sediment cores were collected from around Montserrat to study the submarine pyroclastic deposits from the recent eruption (Trofimovs et al., 2006).
5. Two Natural Environment Research Council (NERC)-funded cruises took place in December 2007. The first cruise (PI: M. Palmer) collected box cores and shallow gravity cores at ~34 sites around Montserrat to constrain how diagenesis of tephra from the recent eruptions has influenced seawater geochemistry. The second cruise, a component of the SEA-CALIPSO seismic experiment sponsored by the US National Science Foundation (NSF), NERC, and collaborating agencies (PIs: Profs. S. Sparks and B. Voight), aimed at imaging the interior of Montserrat and the Soufrière Hills volcano, using source seismic techniques in combination with ~240 onshore seismometers and offshore ocean borehole seismometers (OBS) (Voight et al., 2008; Sparks et al., 2008).
6. During the Gwadaseis cruise of the RV *Suroit* (February–March 2009), high-resolution seismic data were collected as well as piston cores (see overview Table **T1**).
7. During the JC45/46 cruise of the RRS *James Cook* in April–May 2010 (PI: P. Talling), high resolution 2D and 3D seismic data were collected around Montserrat (see overview Table **T1**).

The swath bathymetry data were processed using the Caraïbes software developed by the Institut francais de recherche pour l'exploitation de la mer (IFREMER). The multichannel seismic reflection data were filtered, stacked, and migrated using the Seismic Unix software for the 1999, 2002, and 2009 data, with Landmark's ProMAX software for the 2010 data. The Aguadomar and Caraval cruise data were migrated at a seawater velocity of 1450 m/s, a normal move-out (NMO) correction was applied for the Gwadaseis cruise data, and the JC45/46 data were migrated at a linearly increasing velocity of 1450–2500 m/s.

To estimate the average thickness of debris avalanche deposits, we selected a seismic velocity of 2150 m/s, derived from JC45/46 seismic data analysis (common-reflection point NMO velocity picking). This value is slightly higher than some assumed velocity values used previously in similar deposits (e.g., 1800 m/s: Urgeles et al., 1997; Collot et al., 2001; Le Friant et al., 2004; 2000 m/s: Bull et al., 2009) and in the proposal 681-Full2. Consequently, to account for uncertainties related to the seismic velocity used, drilling depths have been recalculated using a maximum seismic velocity of 2200 m/s.

The supporting site survey data for Expedition 340 are archived at the **IODP Site Survey Data Bank.**

Scientific objectives

Generally, the "Lesser Antilles Volcanism and Landslide" project is designed to understand the constructive and destructive processes occurring along island arcs using the Lesser Antilles arc as a prime example. This project involves drilling, coring, and logging along one transect with three sites southeast of Montserrat, one site southwest of Montserrat, one site southwest of Dominica, one site northwest Martinique, as well as one transect with three sites southwest of Martinique (Fig. **F1**). The record of eruptive activity and volcanoclastic sedimentation obtained during coring and logging will be used to accomplish the following primary goals (three main topics [1–3] and two additional ones [4 and 5]).

1. *Identify the mechanisms controlling processes and timing of potentially tsunamigenic, large volcanic debris avalanches emplacement.*

Volcano flank collapses are an integral part in the lifetime of a volcano (Ida and Voight, 1995; McGuire, 1996; Voight, 2000) and are a large geohazard since they produce large debris avalanches and, in oceanic settings, tsunamis. However, up to now it is generally unclear what factors control the timing of large flank failures, how such failures evolve, and what are the emplacement mechanisms of the debris avalanches associated with these collapses (Voight, 2000; Voight and Elsworth, 1997). For example, understanding whether significant substrate erosion occurs during such processes is crucial for determining the mobility of debris avalanche and for including realistic parameters in numerical simulations of flow processes (Heinrich et al., 2001; Le Friant 2003b; Kelfoun and Druitt, 2005). Deplus et al. (2001) proposed that submarine debris avalanches in the Lesser Antilles erode significantly into underlying sedimentary layers, incorporating large amounts of marine sediment as well as disturbing the underlying stratigraphy. Such erosion and sediment deformation is apparent in some seismic profiles. In addition, the volume of deposits deduced from seismic data (several hundreds of cubic kilometers) is typically one order of magnitude larger than the estimated collapsed volume on land (Le Friant et al., 2003a). Cores will document the internal facies architecture and stratigraphy of debris avalanche deposits and reveal the degree to which given debris avalanche deposit volumes result from erosion and entrainment during emplacement. Identification of subunits within debris avalanche deposits will indicate multiple episodes of emplacement. In addition, deposits of longer run-out turbidity currents generated during debris avalanche emplacement may provide some of the best records of emplacement dynamics (Wynn and Masson, 2003). For instance, large-scale flank-collapse events on the Canary Islands and Hawaiian Islands have generated distinctive turbidites that comprise multiple fining-upward subunits (Wynn and Masson, 2003; Garcia and Meyerhoff Hull, 1994), which suggest that flank collapse occurred in a number of stages separated by days to weeks. Thus, with the cores recovered during this expedition we will investigate whether specific flank collapse events are random in time or if they are linked to some external or internal forcing as well as the controlling mechanisms of debris avalanche emplacement being triggered by such collapses. We will specifically try to answer the following questions:

1. Are flank-collapses associated with magmatic intrusions, or major volcanic eruptions?
2. Are failures triggered by factors such as more rapid volcano edifice construction, strength reduction by hydrothermal processes, or by rapid sea level change (Quidelleur et al., 2008)?
3. Do flank collapses lead to changes in magmatic evolution by depressurizing the magma system (Voight, 1981; Pinel and Jaupart, 2000)?
4. What is the frequency of occurring flank collapses?
5. Are bulking, erosion, and sediment incorporation the same for subaerial and submarine landslides (Glicken, 1991; Komorowski et al., 1991; Voight, 1978; Voight and Sousa, 1994; Schneider et al., 2004)?
6. What is the dynamic role of the undrained loading of overridden compressible marine sediments (Voight and Elsworth, 1997)?
7. Is the sedimentary substratum deformed with the emplacement of the debris avalanche (Schneider et al., 2004)?
8. Is the matrix facies of a debris avalanche more abundant at the bottom part of the deposit (Takarada et al., 1999) or do the submarine debris avalanche deposits contain thin basal layers of thoroughly homogenized sediment, indicating that

the avalanche was emplaced above a thin horizon of localized shear (Gee et al., 1999; Clavero et al., 2002; Shea et al., 2008)?

9. Do the mixed facies (debris avalanche + incorporated substratum) outcrop essentially at the base of the unit (Reubi et al., 2000), or is the shearing more pervasive due to the postulated high proportion of wet marine sediments in the debris avalanche?
10. How large is the volume of reworked sediment (erosion and entrainment during emplacement) in a given debris avalanche deposit?
11. Is a large flank collapse a singular failure involving a rapid virtually instantaneous movement of the entire slide mass into the ocean (Ward and Day, 2001), or do collapses occur retrogressively as several closely spaced failures leading to multiple debris avalanches (Wynn and Masson, 2003; Mattioli et al., 2007) and proportionately less severe consequences for tsunami generation?

2. Characterize the eruptive history to assess major volcanic hazards and volcano evolution.

It has to be emphasized that our knowledge of volcano history is mainly founded on the shore-based geological record. However, deciphering a complete eruption record from onshore geology is commonly problematic, due to burial by deposits from younger events, erosion, or removal of deposits by catastrophic events such as flank collapses. Marine sediment cores typically preserve a much more complete record of volcanism. However, this improvement from regular piston cores is still not sufficient to characterize the evolution of volcanic systems that can extend to a few million years and is also insufficient to diagnose the return periods of very large magnitude, infrequent but very high consequence volcanic events, such as explosive eruptions and major flank collapses. Drilling will allow us to get a complete eruptive history of a volcano and thus to address several important but yet unanswered questions:

1. Are the volcanoes as discrete as onshore studies suggest?
2. Are interpretations of the onshore record correct, or will the much more complete marine record show that, in contrast to the ideas of episodic activity, volcanism is continuous with onshore geology reflecting an artifact of deposit preservation?
3. What are the characteristics of products erupted at the onset of activity from a specific center, particularly if they initially develop below sea level?
4. What processes control the migration from one volcanic center to another?
5. Are the end of activity of one center and the onset of another center synchronous, or are there eruptive hiatuses?

6. What is the nature of volcanism during the construction of a volcanic complex (magma evolution, production rate, eruptive styles, spatio-temporal distribution of eruptive vents and products, and importance of constructional versus destructional processes)?
7. Are there systematic patterns in the time series of volcanic eruptions in terms of eruptive style, eruption magnitude, and repose periods? If so, can these systematic patterns be linked to major processes of volcano construction and destruction (e.g., flank collapse), external factors (e.g., climate and sea level), or to deeper magmatic processes?
8. Can the information from such studies be used for a present-day hazards assessment of the active arc volcanoes?

As each of the volcanic islands along the arc has erupted magmas with a distinctive mineralogy and geochemistry (Sigurdsson et al., 1980; Lindsay et al., 2005a), we are sure that the questions raised above can be answered from the material we core since the distinguishing of the sources of the tephra layers in the cores is straightforward.

3. Characterize the magmatic cycles and long-term magmatic evolution of the arc.

This third objective shares some common objectives with those aimed at elucidating volcanic history and behavior. Volcanism along the Lesser Antilles arc is characterized by large variability in magmatic activity, magma composition, and eruptive activity in space and time as summarized above. Even though we have acquired an enormous amount of information on this system and also have a great deal of knowledge on magma generation and evolution processes in general, this knowledge has given rise to reams of questions on the different controlling mechanisms of magmatism and eruptive activity in settings like this. Thus, we will use the time-series and spatial records of variations in magma composition (mineralogy, major and trace element composition, and isotopic signatures) and volume to be encountered at the different sites to characterize the processes governing magma composition (composition of the primary material, ascent rates, production rates, and differentiation processes), associated eruption mechanisms, and eruption frequencies. In particular, we will try to answer the following questions.

1. Why do some magma systems remain steady state for long periods of time, generating very similar magmas (e.g., Montserrat and Mount Pelée), whereas others erupt compositionally diverse magmas?
2. Why do others show much more variability in composition?

3. Why are there marked excursions from mafic to silicic magmatism or vice versa?
4. Are switches in composition sudden or gradual?
5. Can changes in composition be linked to major explosive eruptions or flank collapses that perturb the crystal magma systems, or do these changes reflect internal dynamics of crustal magma systems, such as buoyancy instabilities related to accumulation of regions of partial melt?

4. Characterize nondebris avalanche-related sedimentation processes in the deep ocean around the arc.

The majority of detrital material resulting from the erosion of the islands of the arc is transported into the surrounding ocean (e.g., Sigurdsson et al., 1980; Le Friant et al., 2004; Picard et al., 2006). Volcanogenic sediments are channeled by debris flows, turbidity currents, and persistent ocean currents through deep submarine canyons located west of the volcanoes and which, for Guadeloupe and Dominica, lead into the northern part of the Grenada Basin (Fig. **F1**). In addition, around Montserrat there are examples of single, or multiple stacked, carbonate turbidites that contain reworked shallow-water sediment and fauna, the volume of which exceeds that of, for example, volcaniclastic deposits associated with the more recent (<100 ka) eruptions of the Soufrière Hills volcano. The source of these carbonates is most likely the large carbonate platforms associated with islands such as Antigua or Redonda (Fig. **F1**). Apparently, these turbidites have not been triggered by volcanic eruptions but either by platform instabilities during rapid sea level rises at the end of major glaciations or by major regional earthquakes. This points out that the sedimentation processes occurring along the Lesser Antilles arc might be more complex than previously thought. Thus, with the cores obtained during this expedition we will contribute to the understanding of the sedimentary facies on the submarine flanks and in the basins that surround arc volcanoes, characterize the sedimentation processes, and estimate local sedimentation rates in the northern and southern parts of the arc as well as the relative fraction of volcanogenic material in the sediment. Furthermore we will answer the following questions:

1. What are the differences between the north and the south parts of the arc in terms of sedimentation processes?
2. What is the proportion of volcanogenic sediments versus hemipelagic and carbonate sediments?
3. Do debris avalanches have the potential to generate turbidity currents?

4. Are most turbidite units linked to volcanic eruptions or can they also be linked to nonvolcanic processes such as submarine slope failures triggered by regional earthquakes or gravitational instabilities?

5. Determine the processes and element fluxes associated with submarine alteration of volcanic material.

The processes associated with submarine alteration of magmatic matter are of fundamental importance on a global as well as on a regional scale. For example, (1) the composition of ocean water is largely buffered by alteration of magmatic material in the ocean basins, (2) the composition of the Earth's mantle is influenced by the subduction of altered oceanic crust and seamounts, and (3) major elements, trace elements, or isotopes are used to model the magmatic history of volcanic settings, requiring knowledge about which of the geochemical patterns encountered are of primary magmatic origin and which are not (Palmer and Edmond, 1989; Palmer et al., submitted). Nonetheless, systematic studies of natural alteration processes reflecting the diversity of magmatic systems on our Earth are generally rare (e.g., Gardner et al., 1986; Gérard and Person, 1994; Martin, 1994; Stroncik and Schmincke, 2001; Utzmann et al., 2002). Generally, submarine alteration processes (including, e.g., element fluxes and alteration rates) are controlled by the following parameters: (a) the structure, composition (e.g., glassy versus crystalline, microfracture density, and basaltic versus silicic), and grain size of the parent material, (b) the physical emplacement mechanism and resulting internal structure of the deposit (e.g., thin air fall deposits versus thick debris flows), and (c) temperature. Continued coring and logging at the proposed sites will allow us to systematically study alteration processes as a function of those different parameters in a magmatically relatively diverse system and will allow us to answer the following questions:

1. How does the process of submarine alteration change (e.g., congruent versus incongruent dissolution) as a function of parent material composition (basalt, basaltic andesite, andesite, or dacite) for a given environment?
2. How does the rate of alteration change as a function of grain size and structure of the parent material for a given environment?
3. How does the process of alteration and the alteration rate change as a function of the structure of the deposit (e.g., air fall versus debris flow)?
4. Do the temperature changes encountered in the studied environment have an effect on the alteration process and name?

Drilling and coring strategy

Drilling strategy

The overall operations plan and time estimates are summarized in Table T2. Alternate sites have been selected and are presented in Table AT1. Time estimates are based on anticipated formation lithologies and depths inferred from seismic and regional geological interpretations. After departing from Antigua we will transit for 4 h to the first site and prepare for drilling operations.

The proposed drilling strategy is to begin by drilling at proposed Site CARI-02C and end drilling at proposed Site CARI-09B following the sequence laid out in the operations plan (Table T2). With the exception of Site CARI-01C, two holes are planned to be cored at the each site. At all sites, the holes will be cored with the advanced piston coring (APC) system to refusal. The coring system will then be changed over to the extended core barrel (XCB) system and will be cored to total depth as determined by the scientific objectives. An estimate of the required depths can be found in Table T2. The exception (Site CARI-01C) will be a single hole piston cored to a depth of ~132 meters below seafloor (mbsf).

All holes will be plugged and abandoned with heavy mud.

Coring strategy

The first hole at each site (Hole A) will be cored with APC/XCB to planned depths (Table T2). The second hole (Hole B) at each site will also be cored with APC/XCB to planned depth. After reaching the planned depth the "B" holes will be conditioned, displaced with logging mud, and logged as per the logging plan (see **"Downhole tools and logging strategy"**). Should all objectives be fulfilled coring the "A" hole, a second hole will not be drilled and the "A" hole will be logged. While coring, a number of advanced piston coring temperature tool (APCT-3) measurements will be made, as formation conditions permit. Core orientation with the FlexIt tool will also be measured during the APC-cored sections at each site. If depth objectives cannot be achieved with APC/XCB coring system, an option will be to deploy the rotary core barrel (RCB) system.

Downhole tools and logging strategy

Downhole logging will complement coring operations during Expedition 340 and assist in achieving scientific objectives by providing in situ geophysical characterization of drilled volcanic debris avalanche deposits and sedimentary sequences. Logging data will provide a continuous record to aid in identification of boundaries between multiple avalanche deposits and to evaluate the structures and textures of volcanogenic sediments, avalanche deposits, and breccia. Logging data will be used in conjunction with core images and other data to reorient structures and deposit boundaries, which is valuable for characterizing variations in debris avalanche deposits through time. In addition, logs allow direct correlation of wireline measurements with discrete core measurements and offer data coverage where core recovery is poor.

Wireline logging is planned for eight of the nine primary sites of Expedition 340. Logging is not currently planned for proposed Site CARI-01C because of the shallow target depth (132 mbsf). Two standard tool strings will be deployed in each logged hole. The first run will be the triple combination (triple combo) tool string, which will record resistivity, neutron porosity, bulk density, and natural and spectral gamma radiation. The caliper log provided by the density tool will allow assessment of hole diameter, log quality, and the potential for success of the following runs. The second run, with the Formation MicroScanner (FMS)-sonic tool string, will record gamma radiation, sonic velocity (for compressional and shear waves), and oriented high-resolution electrical resistivity images. A third logging run is planned at three sites (CARI-03C, CARI-07C, and CARI-10B) using the Versatile Seismic Imager (VSI) to acquire a zero-offset vertical seismic profile (VSP) for calibrating the integration of borehole and seismic data. The survey is planned with ~25 m spacing of stations over the open hole interval below 80 mbsf. Spacing may be adjusted based on hole condition. The seismic source for the VSP will be a parallel cluster of two 250 in^3 Sercel G guns (Table **T3**), positioned 2–7 m below sea level and offset by ~50 m from the side of the ship. VSP operations will be subject to the IODP marine mammal policy and may be postponed or cancelled if policy conditions are not met. Operational time estimates for each site can be found in Table **T2.** For more information on specific logging tools, please refer to **iodp.ldeo.columbia.edu/TOOLS_LABS/.**

At three of the sites (CARI-02C, CARI-03C, and CARI-04C) we would like to deploy the Magnetic Susceptibility Sonde (MSS) currently being built by the Lamont-Doherty Earth Observatory Borehole Research Group. The MSS, which measures magnetic susceptibility, would be used identify flank collapse deposits from the island of Montserrat, where the volcanic material has a high magnetite content compared to background sediment. Although the MSS is still being developed, the current production and testing timeline for the MSS indicates that it will be available for deployment during Expedition 340. At these sites, the triple combo will be modified to replace the resistivity tool with the Magnetic Susceptibility Sonde.

APC cores at all Expedition 340 sites will be oriented with the FlexIt tool for paleomagnetic studies. Temperature measurements are planned for four sites (CARI-02C, CARI-03C, CARI-04C, and CARI-10B). We plan to deploy the APCT-3 in the interval where cores will be taken by APC to collect sufficient temperature measurements to calculate a thermal gradient at each location.

Risk and contingency

Three principal factors could affect the implementation of the drilling plan:

1. Adverse hole conditions at the principal sites (e.g., encountering thick intervals of loose sediment/rock that can collapse into the hole).
2. Weather conditions that can limit the ability to drill.
3. Time delays (arising from equipment breakdowns, or measures taken to respond to hole conditions).

Hole conditions

Poor hole conditions at all sites will be dealt with in the first instance by using frequent high-viscosity mud sweeps and or heavy mud to condition the holes. The only possible remedial action if hole conditions prove to be insurmountable is to plug and abandon the hole and move to an alternate site.

Weather conditions

Hurricane season at the operation area is between ~1 July and ~30 November; thus, Expedition 340 is scheduled (February–March) outside this window and weather-related risks are negligible and essentially avoided.

Timing

If significant time is spent responding to poor hole conditions, slower than expected penetration rates, and/or weather-related delays, a primary site may be shortened or dropped from the schedule. Such a decision will only be made following consultation with the science party.

Alternate sites

The alternate sites may be cored and logged if poor hole conditions or other operational difficulties are encountered at the respective primary sites and it is judged that better conditions may be meet at these sites. Seismic profiles of all proposed alternate sites (as well as of all primary sites discussed above) are included in the **"Site summaries."** The operations plan for the alternate sites can be found in Table **AT1.**

Sampling and data sharing strategy

Shipboard and shore-based researchers should refer to the IODP Sample, Data, and Obligations policy posted on the web at **www.iodp.org/program-policies/.** This document outlines the policy for distributing IODP samples and data to research scientists, curators, and educators. The document also defines the obligations that sample and data recipients incur. The Sample Allocation Committee (SAC; composed of co-chief scientists, staff scientist, and IODP curator on shore and curatorial representative on board ship) will work with the entire scientific party to formulate a formal expedition-specific sampling plan for shipboard and postcruise sampling.

Shipboard scientists are expected to submit sample requests (at **smcs.iodp.org/**) 3 months before the beginning of the expedition. Based on sample requests (shore based and shipboard) submitted by this deadline, the SAC will prepare a tentative sampling plan, which will be revised on the ship as dictated by recovery and cruise objectives. The sampling plan will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. The co-chief scientists, staff scientist, and curatorial representative on board ship must approve modification of the strategy during the expedition.

The minimum permanent archive will be the standard archive half of each core. All sample frequencies and sizes must be justified on a scientific basis and will depend on core recovery, the full spectrum of other requests, and the cruise objectives. Some redundancy of measurement is unavoidable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests.

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Table T1. Marine geophysical data used for this proposal.

	Aguadomar 1999	Caraval 2002	Gwadaseis 2009	JC45/46 2010
Research vessel	R/V *L'Atalante*	R/V *L'Atalante*	R/V *Le Suroit*	R/V *James Cook*
Swath bathymetry				
Multibeam echosounder	Simrad EM12D	Simrad EM12D	Simrad EM 300	Simrad EM120
Predicted depth accuracy	0.1–0.3% of depth (1–3m in water depth of 1000m)	0.1–0.3% of depth	0.1–0.3% of depth	0.1–0.3% of depth
Cell size (m)	50	50	50	50
GPS	Starfix differential GPS	GPS	GPS	GPS
Ship positioning accuracy	Few meters	Few meters	Few meters	Few meters
Seismic reflection				
Sources (Cu/in)	GI 45/45 and 105/105	GI 45/45	GI 35/35 and 45/45	GI 105/45
Number of guns	2	2	4	2
Gun depth (m)	7	1.5	3	3
Number of recording channels	6	24	72	60
Channel spacing (m)	50	12.5	6.25	1
Streamer depth (m)	5	3	3	1
Streamer length (m)	530	~500	358	100
Vertical resolution (m)	~20	~10	3	4

Notes: The swath bathymetry was processed using the Caraïbes software developed by IFREMER. The multichannel seismic reflection data were filtered, stacked and migrated using the Seismic Unix software for the 1999, 2002 and 2009 data, with Landmark's ProMAX software for the 2010 data. The AGUADOMAR and CARAVAL data were migrated at a seawater velocity of 1450 m/s, a NMO correction was applied for the GWADASEIS data, and the JC45/46 data were migrated at a linearly increasing velocity of 1450–2500 m/s. Recently, to estimate the average thickness of debris avalanche deposits, we selected as our best value the seismic velocity of 2150 m/s, derived from JC45/46 seismic data analysis (common-reflection point NMO velocity picking). This value is slightly higher than some assumed velocity values used previously in similar deposits [e.g., 1800 m/s; Urgeles et al., 1997; Collot et al., 2001; Le Friant et al., 2004, 2000 m/s Bull et al., 2009] and in the proposal 681-Full2. Consequently, to consider uncertainties related to seismic velocity used, the depth of drilling have been recalculated using a maximum seismic velocity of 2200 m/s.

Table T2. Operations plan summary.

Site No.	Location (Latitude Longitude)	Sea Floor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	Logging (days)
Antigua			**Begin Expedition** 0.5	port call days		
			Transit ~28 nmi to CARI-02C @ 10.5 knots	0.11		
CARI-02C	16° 43.13' N	951	Hole A - APC/XCB to 250 mbsf with orientation and APCT3 measurements		1.4	
EPSP Depth	62° 5.05' W		Hole B - APC/XCB to 250 mbsf - Logging with Triple Combo and FMS Sonic		1.0	0.7
Approved						
275m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 3.1			
			Transit ~5 nmi to CARI-03C @ 10.5 knots	0.02		
CARI-03C	16° 38.43' N	1133	Hole A - APC/XCB to 244 mbsf with orientation and APCT3 measurements		1.2	
EPSP Depth	62° 2.29' W		Hole B - APC/XCB to 244 mbsf - Logging with Triple Combo, FMS Sonic and VSI		1.1	0.8
Approved						
270m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 3.2			
			Transit ~10 nmi to CARI-04C @ 10.5 knots	0.04		
CARI-04D	16° 29.60' N	1211	Hole A - APC/XCB to 244 mbsf with orientation and APCT3 measurements		1.2	
EPSP Depth	61° 57.09' W		Hole B - APC/XCB to 244 mbsf - Logging with Triple Combo and FMS Sonic		1.1	0.7
Approved						
270m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 3.0			
			Transit ~29 nmi to CARI-01C @ 10.5 knots	0.12		
CARI-01C	16° 30.49' N	801	Hole A - APC to 132 mbsf with orientation		0.8	
EPSP Depth	62° 27.10' W					
Approved						
145m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 0.8			
			Transit ~101 nmi to CARI-05C @ 10.5 knots	0.40		
CARI-05D	15° 0.52' N	2654	Hole A - APC to 357 mbsf with orientation		2.3	
EPSP Depth	61° 38.00' W		Hole B - APC to 357 mbsf - Logging with Triple Combo and FMS Sonic		2.2	0.8
Approved						
395m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 5.4			
			Transit ~14 nmi to CARI-10B @ 10.5 knots	0.06		
CARI-10B	14° 54.41' N	2501	Hole A - APC/XCB to 314 mbsf with orientation and APCT3 measurements		2.1	
EPSP Depth	61° 25.35' W		Hole B - APC/XCB to 314 mbsf - Logging with Triple Combo, FMS Sonic and VSI		1.9	1.1
Approved						
345m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 5.1			
			Transit ~22 nmi to CARI-07C @ 10.5 knots	0.09		
CARI-07C	14° 32.58' N	2756	Hole A - APC/XCB to 510 mbsf with orientation		3.5	
EPSP Depth	61° 27.55' W		Hole B - APC/XCB to 510 mbsf - Logging with Triple Combo, FMS Sonic and VSI		3.4	1.2
Approved						
560m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 8.1			
			Transit ~17 nmi to CARI-08B @ 10.5 knots	0.07		
CARI-08B	14° 23.24' N	2911	Hole A - APC/XCB to 290 mbsf with orientation		2.0	
EPSP Depth	61° 42.69' W		Hole B - APC/XCB to 290 mbsf - Logging with Triple Combo and FMS Sonic		2.1	0.8
Approved						
320m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 4.9			
			Transit ~12 nmi to CARI-09B @ 10.5 knots	0.05		
CARI-09B	14° 16.70' N	2946	Hole A - APC/XCB to 264 mbsf with orientation		1.9	
EPSP Depth	61° 53.34' W		Hole B - APC/XCB to 264 mbsf - Logging with Triple Combo and FMS Sonic		1.8	0.8
Approved						
290m			Non-magnetic core barrels used on all holes.			
			Sub-Total Days On-Site: 4.4			
			Transit ~432 nmi to Curaco @ 11.0 knots	1.64		
Curaco			**End Expedition**	**2.6**	**31.0**	**6.9**

Port Call:	**0.5**	**Total Operating Days:**	**40.5**
Sub-Total On-Site:	**37.9**	**Total Expedition:**	**41.0**

Table T3. Airgun source levels.

Source	Specification
Energy source	One or two 250 in^3 G airguns
Source output (downward) (1 × 250 in^3)	0-pk* is 3.1 bar-m (229.8 dB re 1 µPa·m_p)† pk-pk‡ is 6.4 bar-m (236.2 dB re 1 µPa·$\text{m}_\text{p-p}$)
Source output (downward) (2 × 250 in^3)	0-pk is 5.2 bar-m (234.3 dB re 1 µPa·m_p) pk-pk is 10.8 bar-m (240.7 dB re 1 µPa·$\text{m}_\text{p-p}$)
Deployment depth of energy source (m)	2–7 1 µPa·m_p
Air discharge volume (in^3)	250 or 500
Dominant frequency components (Hz)	0–256

Notes: * = 0-pk = peak energy. † = the source level is a measure of the effective sound pressure at a given distance from the source array, relative to a reference value. It is commonly expressed in decibels at 1 m from the source relative to µPascal-m, or dB re 1 µPa·m. ‡ = pk-pk = peak to peak energy.

Figure F1. Left, the Lesser Antilles arc (bathymetry from Smith and Sandwell, 1997). Right, extent of debris avalanche deposits superimposed on swath bathymetry and proposed drill sites.

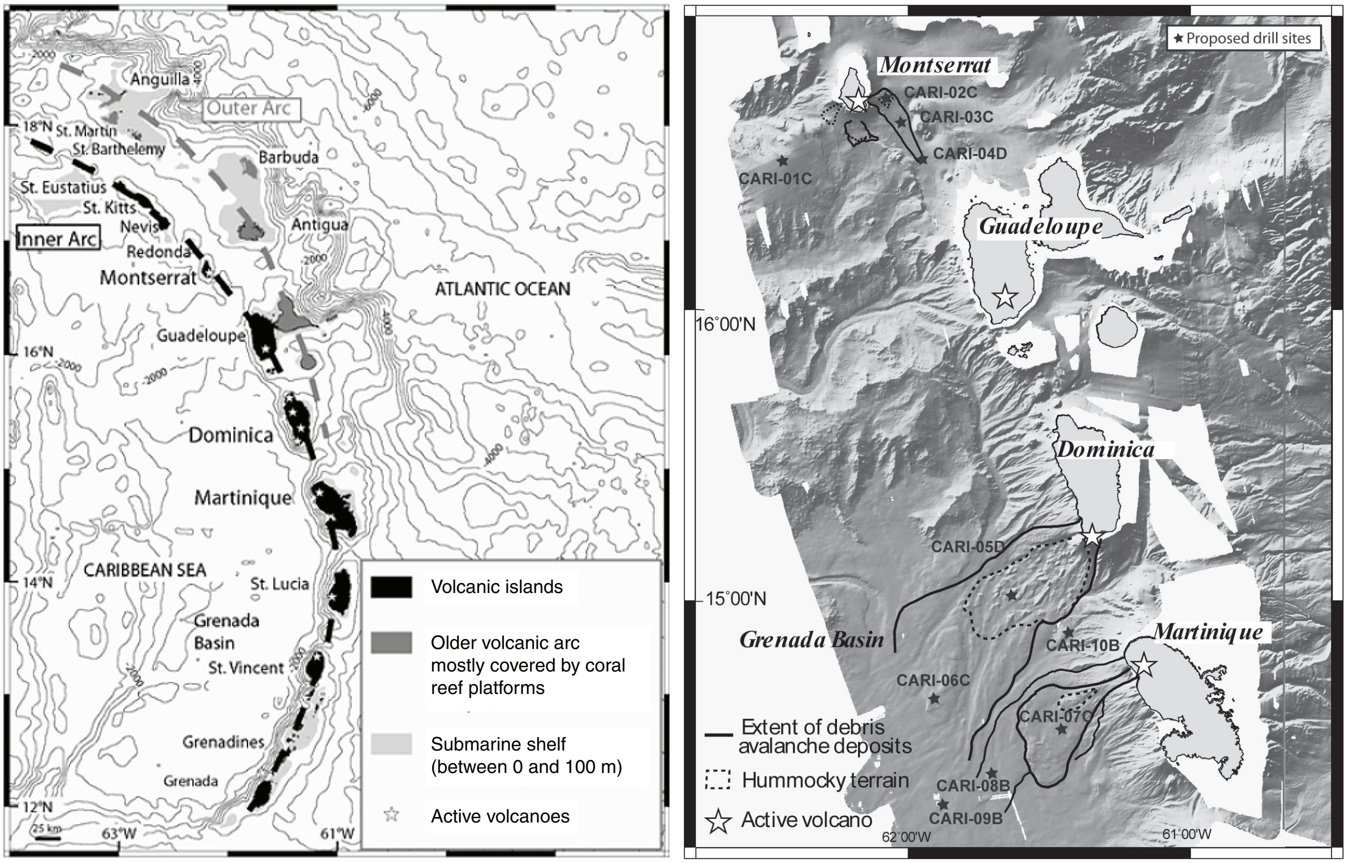


Figure F2. Shaded image of Montserrat's topography-bathymetry, debris avalanche deposits (DAD) and proposed drill sites.

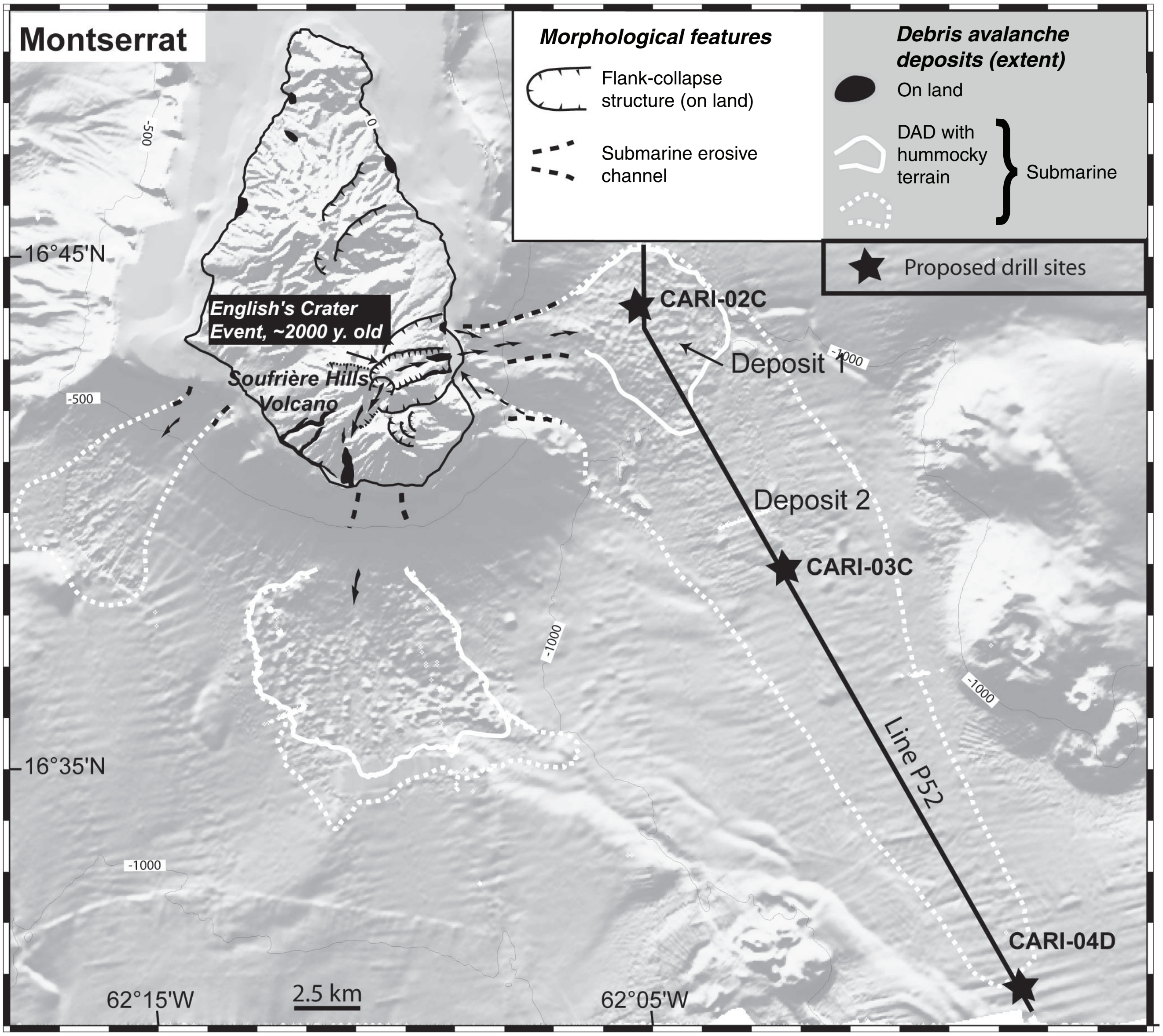


Figure F3. Shaded image of Martinique's topography-bathymetry, debris avalanche deposits (DAD) and proposed drill sites.

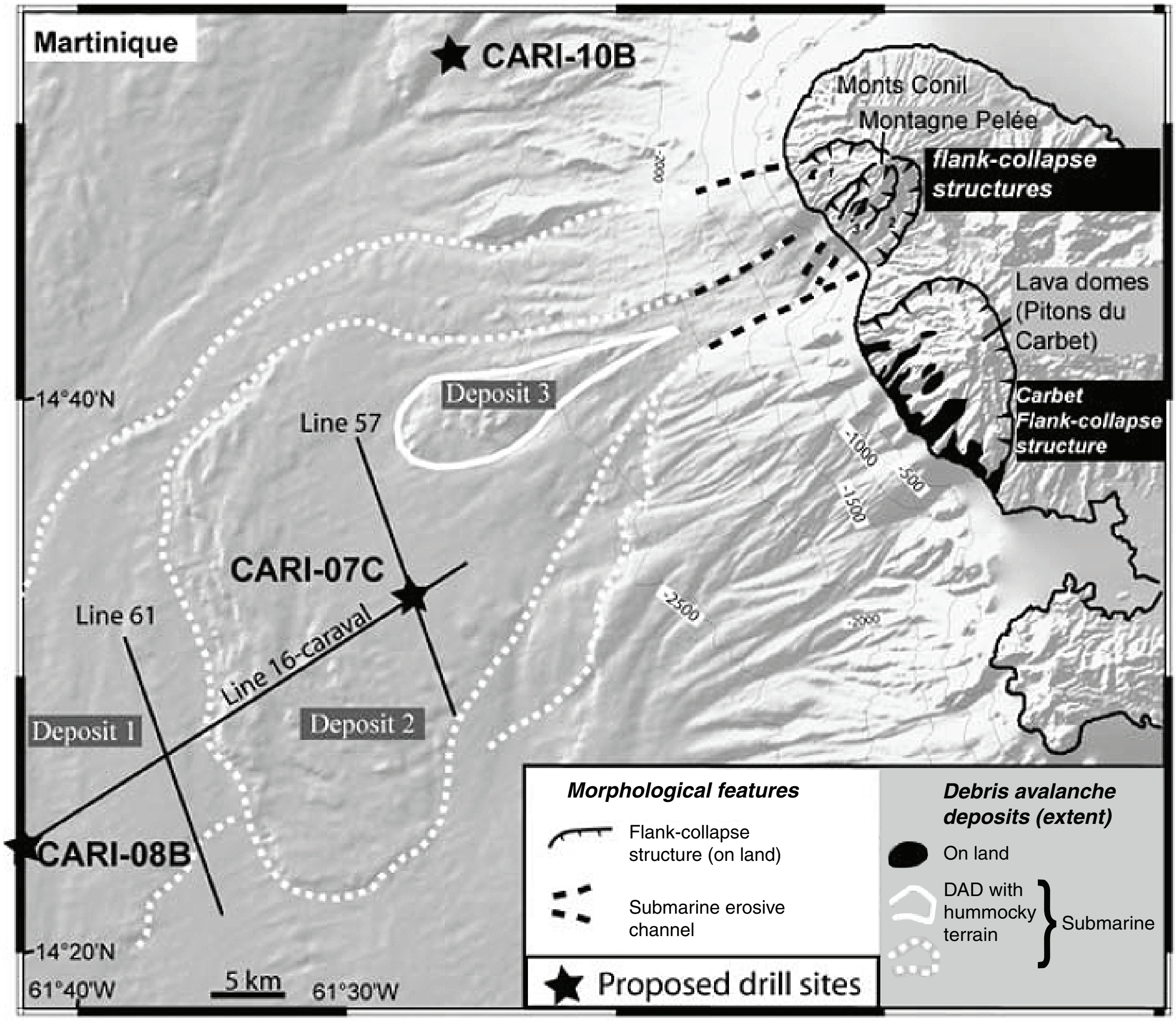
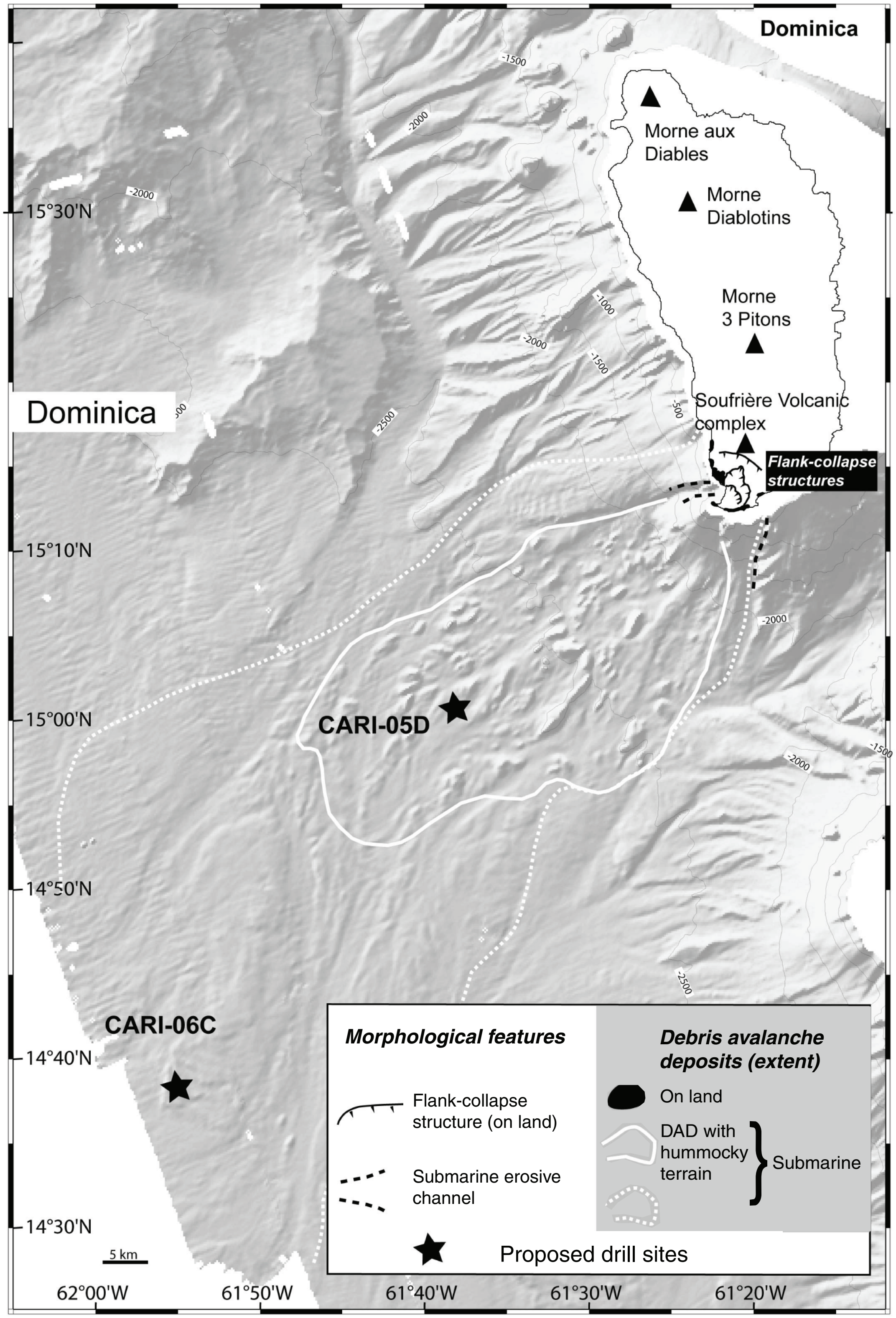


Figure F4. Shaded image of Dominca's bathymetry, debris avalanche deposits (DAD) and proposed drill sites.



Site summaries

Site CARI-01C (off Montserrat)

Priority:	Primary
Position:	16°30.49′N 62°27.10′W
Water depth (m below sea level):	790
Target drilling depth (m below seafloor):	132
Approved maximum penetration (mbsf):	145
Survey coverage (track map; seismic profile):	Line 47 (cdp 1118) Caraval Cruise 03.2002 and Line 214 (cdp 15670) Aguadomar Cruise 12.98 to 01.99 • Track map (Fig. AF1) • Seismic profile (Fig. AF1) • Location map (Fig. F1)
Objective(s):	Characterization of magmatic evolution and eruptive history
Drilling program:	Hole A: APC/XCB to TD with orientation
Logging program:	
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers
Estimated operation time (days):	0.8

Site summaries (continued)

Site CARI-02C (off Montserrat)

Priority:	Primary
Position:	16°43.13′N 62°5.05′W
Water depth (m below sea level):	940
Target drilling depth (m below seafloor):	250
Approved maximum penetration (mbsf):	275
Survey coverage (track map; seismic profile):	Line 52 (cdp 2994) Caraval Cruise 2002 and Line 41 (cdp 1430) Gwadaseis Cruise 2009 • Track map (Fig. AF2) • Seismic profile (Fig. AF2) • Location map (Fig. F1)
Objective(s):	Characterization of debris avalanche emplacement, of associated erosional processes and of tephra diagenisis
Drilling program:	• Hole A: APC/XCB to TD with orientation and APCT3 • Hole B: APC/XCB to TD
Logging program:	Triple Combo and FMS Sonic
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	3.1

Site summaries (continued)

Site CARI-03C (off Montserrat)

Priority:	Primary
Position:	16°38.43′N 62°2.29′W
Water depth (m below sea level):	1122
Target drilling depth (m below seafloor):	244
Approved maximum penetration (mbsf):	270
Survey coverage (track map; seismic profile):	Line 47 (cdp 4856) Caraval Cruise 2002 and Line 52 (cdp 2172) Caraval Cruise 2002 • Track map (Fig. AF3) • Seismic profile (Fig. AF3) • Location map (Fig. F1)
Objective(s):	Characterization of debris avalanche emplacement and associated erosional processes
Drilling program:	• Hole A: APC/XCB to TD with orientation and APCT3 • Hole B: APC/XCB to TD
Logging program:	Triple Combo, FMS Sonic and VSI
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	3.1

Site summaries (continued)

Site CARI-04D (off Montserrat)

Priority:	Primary
Position:	16°29.60′N 61°57.09′W
Water depth (m below sea level):	1200
Target drilling depth (m below seafloor):	244
Approved maximum penetration (mbsf):	270
Survey coverage (track map; seismic profile):	Line 52 (cdp 740) Caraval Cruise 2002 and Line 45 (cdp 385) JC 45/46 Cruise 2010 • Track map (Fig. **AF4**) • Seismic profile (Fig. **AF4**) • Location map (Fig. **F1**)
Objective(s):	Characterization of sedimentation processes (e.g. determining the association with debris avalanche emplacement)
Drilling program:	• Hole A: APC/XCB to TD with orientation and APCT3 • Hole B: APC/XCB to TD
Logging program:	Triple Combo and FMS Sonic
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias), maybe turbidites
Estimated operation time (days):	3

Site summaries (continued)

Site CARI-05D (off Dominica)

Priority:	Primary
Position:	15°0.52′N 61°38′W
Water depth (m below sea level):	2643
Target drilling depth (m below seafloor):	357
Approved maximum penetration (mbsf):	395
Survey coverage (track map; seismic profile):	Line 18 (cdp 16222) Caraval Cruise 2002 and Line 47 (cdp 10532) Aguadomar Cruise 2002 • Track map (Fig. AF5) • Seismic profile (Fig. AF5) • Location map (Fig. F1)
Objective(s):	Characterization of debris avalanche emplacement and associated erosional processes
Drilling program:	• Hole A: APC/XCB to TD with orientation • Hole B: APC/XCB to TD
Logging program:	Triple Combo and FMS Sonic
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	5.4

Site summaries (continued)

Site CARI-07C (off Martinique)

Priority:	Primary
Position:	14°32.58′N 61°27.55′W
Water depth (m below sea level):	2745
Target drilling depth (m below seafloor):	510
Approved maximum penetration (mbsf):	560
Survey coverage (track map; seismic profile):	Line 16 (cdp 5780) Caraval Cruise 2002 and Line 57 (cdp 15052) Aguadomar Cruise 2002 • Track map (Fig. **AF7**) • Seismic profile (Fig. **AF7**) • Location map (Fig. **F1**)
Objective(s):	Characterization of debris avalanche emplacement and associated erosional processes
Drilling program:	• Hole A: APC/XCB to TD with orientation and APCT3 • Hole B: APC/XCB to TD
Logging program:	Triple Combo, FMS Sonic, VSI
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	8.1

Site summaries (continued)

Site CARI-08B (off Martinique)

Priority:	Primary
Position:	14°23.24′N 61°42.69′W
Water depth (m below sea level):	2900
Target drilling depth (m below seafloor):	290
Approved maximum penetration (mbsf):	320
Survey coverage (track map; seismic profile):	Line 16 (cdp 3312) Caraval Cruise 2002 and Line 62 (cdp 17158) Aguadomar Cruise 2002 • Track map (Fig. AF8) • Seismic profile (Fig. AF8) • Location map (Fig. F1)
Objective(s):	Characterization of debris avalanche emplacement and associated erosional processes
Drilling program:	• Hole A: APC/XCB to TD with orientation • Hole B: APC/XCB to TD
Logging program:	Triple Combo and FMS Sonic
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	4.9

Site summaries (continued)

Site CARI-09B (off Martinique)

Priority:	Primary
Position:	14°16.70′N 61°53.34′W
Water depth (m below sea level):	2935
Target drilling depth (m below seafloor):	264
Approved maximum penetration (mbsf):	290
Survey coverage (track map; seismic profile):	Line 5 (cdp 8955) Caraval Cruise 2002 and Line 16 (cdp 1590) Caraval Cruise 2002 • Track map (Fig. **AF9**) • Seismic profile (Fig. **AF9**) • Location map (Fig. **F1**)
Objective(s):	Characterization of eruptive history and debris avalanche emplacement with an assement of tsunami hazards
Drilling program:	• Hole A: APC/XCB to TD with orientation • Hole B: APC/XCB to TD
Logging program:	Triple Combo and FMS Sonic
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias), turbidites
Estimated operation time (days):	4.4

Site summaries (continued)

Site CARI-10B (off Martinique)

Priority:	Primary
Position:	14°54.41′N 61°25.35′W
Water depth (m below sea level):	2490
Target drilling depth (m below seafloor):	314
Approved maximum penetration (mbsf):	345
Survey coverage (track map; seismic profile):	Line 135 (cdp 3078) Gwadaseis Cruise 2009 and Line 137 (cdp 2266) Gwadaseis Cruise 2009 • Track map (Fig. **AF10**) • Seismic profile (Fig. **AF10**) • Location map (Fig. **F1**)
Objective(s):	Characterization of magmatic evolution and eruptive history
Drilling program:	• Hole A: APC/XCB to TD with orientation and APCT3 • Hole B: APC/XCB to TD
Logging program:	Triple Combo, FMS Sonic, VSI
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers
Estimated operation time (days):	5.1

Site summaries (continued)

Site CARI-06C (off Dominica)

Priority:	Alternate
Position:	14°38.87′N 62°55.08′W
Water depth (m below sea level):	2821
Target drilling depth (m below seafloor):	488
Approved maximum penetration (mbsf):	535
Survey coverage (track map; seismic profile):	Line 18 (cdp 12260) Caraval Cruise 2002 and Line 63 (cdp 186) Aguadomar Cruise 2002 • Track map (Fig. **AF6**) • Seismic profile (Fig. **AF6**) • Location map (Fig. **F1**)
Objective(s):	Characterization of debris avalanche emplacement and associated erosional processes
Drilling program:	• Hole A: APC/XCB to TD with orientation and APCT3 • Hole B: APC/XCB to 250 mbsf
Logging program:	Triple Combo and FMS Sonic
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	7.6

Site summaries (continued)

Site CARI-11A (off Martinique)

Priority:	Alternate
Position:	14°54.06′N 61°25.70′W
Water depth (m below sea level):	2490
Target drilling depth (m below seafloor):	314
Approved maximum penetration (mbsf):	345
Survey coverage (track map; seismic profile):	Line 135 (cdp 2646) Gwadaseis Cruise 2009 and Line 45 (cdp 1608) Aguadomar Cruise 2002 • Track map (Fig. **AF11**) • Seismic profile (Fig. **AF11**) • Location map (Fig. **F1**)
Objective(s):	Tephrochronology northern Martinique volcanoes
Drilling program:	• Hole A: APC/XCB to TD with orientation • Hole B: APC/XCB to TD
Logging program:	Triple Combo, FMS Sonic, VSI
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers
Estimated operation time (days):	5.1

Site summaries (continued)

Site CARI-12A (off Martinique)

Priority:	Alternate
Position:	14°39.102′N 61°25.08′W
Water depth (m below sea level):	2590
Target drilling depth (m below seafloor):	500
Approved maximum penetration (mbsf):	550
Survey coverage (track map; seismic profile):	Line 17 (cdp 1778) Caraval Cruise 2002 and Line 56 (cdp 12728) Aguadomar Cruise 2002 • Track map (Fig. **AF12**) • Seismic profile (Fig. **AF12**) • Location map (Fig. **F1**)
Objective(s):	Characterization of debris avalanche emplacement and associated erosional processes
Drilling program:	• Hole A: APC/XCB to TD with orientation • Hole B: APC/XCB to TD
Logging program:	Triple Combo, FMS Sonic, VSI
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	5.1

Site summaries (continued)

Site CARI-13A (off Montserrat)

Priority:	Alternate
Position:	16°44.323′N 62°2.575′W
Water depth (m below sea level):	940
Target drilling depth (m below seafloor):	88
Approved maximum penetration (mbsf):	100
Survey coverage (track map; seismic profile):	Line 135 (cdp 3078) Gwadaseis Cruise 2009 and Line 137 (cdp 2266) Gwadaseis Cruise 2009 • Track map (Fig. **AF13**) • Seismic profile (Fig. **AF13**) • Location map (Fig. **F1**)
Objective(s):	Characterization of debris avalanche emplacement and associated erosional processes
Drilling program:	Hole A APC/XCB to TD with orientation
Logging program:	
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	0.7

Site summaries (continued)

Site CARI-14A (off Montserrat)

Priority:	Alternate
Position:	16°43.687′N 62°2.23′W
Water depth (m below sea level):	980
Target drilling depth (m below seafloor):	94
Approved maximum penetration (mbsf):	105
Survey coverage (track map; seismic profile):	Line 135 (cdp 3078) Gwadaseis Cruise 2009 and Line 137 (cdp 2266) Gwadaseis Cruise 2009 • Track map (Fig. **AF14**) • Seismic profile (Fig. **AF14**) • Location map (Fig. **F1**)
Objective(s):	Characterization of debris avalanche emplacement and associated erosional processes
Drilling program:	Hole A APC/XCB to TD with orientation
Logging program:	
Anticipated material:	Volcanic and biogenic sediments with intercalated tephra layers and chaotic debris avalanche deposists (breccias)
Estimated operation time (days):	0.7

Table AT1. Alternate sites.

Site No.	Location (Latitude Longitude)	Seafloor Depth (mbrf)	Operations Description	Drilling Coring (days)	Logging (days)
CARI-06C	14° 38.87' N	2832	Hole A - APC/XCB to 488 mbsf	3.4	
EPSP	61° 55.08' W		Hole B - APC/XCB to 488 mbsf - Logging with Triple Combo and FMS Sonic	3.2	1.0
Requested					
488 mbsf					
			Sub-Total Days On-Site: 7.6		
CARI-11A	14° 54.06' N	2501	Hole A - APC/XCB to 314 mbsf	2.1	
EPSP	61° 25.70' W		Hole B - APC/XCB to 314 mbsf - Logging with Triple Combo, FMS Sonic and VSI	1.9	1.1
Requested					
314 mbsf					
			Sub-Total Days On-Site: 5.1		
CARI-12A	14° 39.10' N	2601	Hole A - APC/XCB to 500 mbsf	3.3	
EPSP	61° 25.08' W		Hole B - APC/XCB to 500 mbsf - Logging with Triple Combo, FMS Sonic and VSI	3.2	1.2
Requested					
500 mbsf					
			Sub-Total Days On-Site: 5.1		
CARI-13A	16° 44.32' N	951	Hole A - APC to 88 mbsf	0.7	
EPSP	62° 2.58' W				
Requested					
88 mbsf					
			Sub-Total Days On-Site: 0.7		
CARI-14A	16° 43.69' N	991	Hole A - APC to 94 mbsf	0.7	
EPSP	62° 2.23' W				
Requested					
88 mbsf					
			Sub-Total Days On-Site: 0.7		

Figure AF1. A. Track map (50 m resolution, 10 m contour interval) for proposed primary Site CARI-01C. CDP = common depth point. (**Continued on next two pages.**)

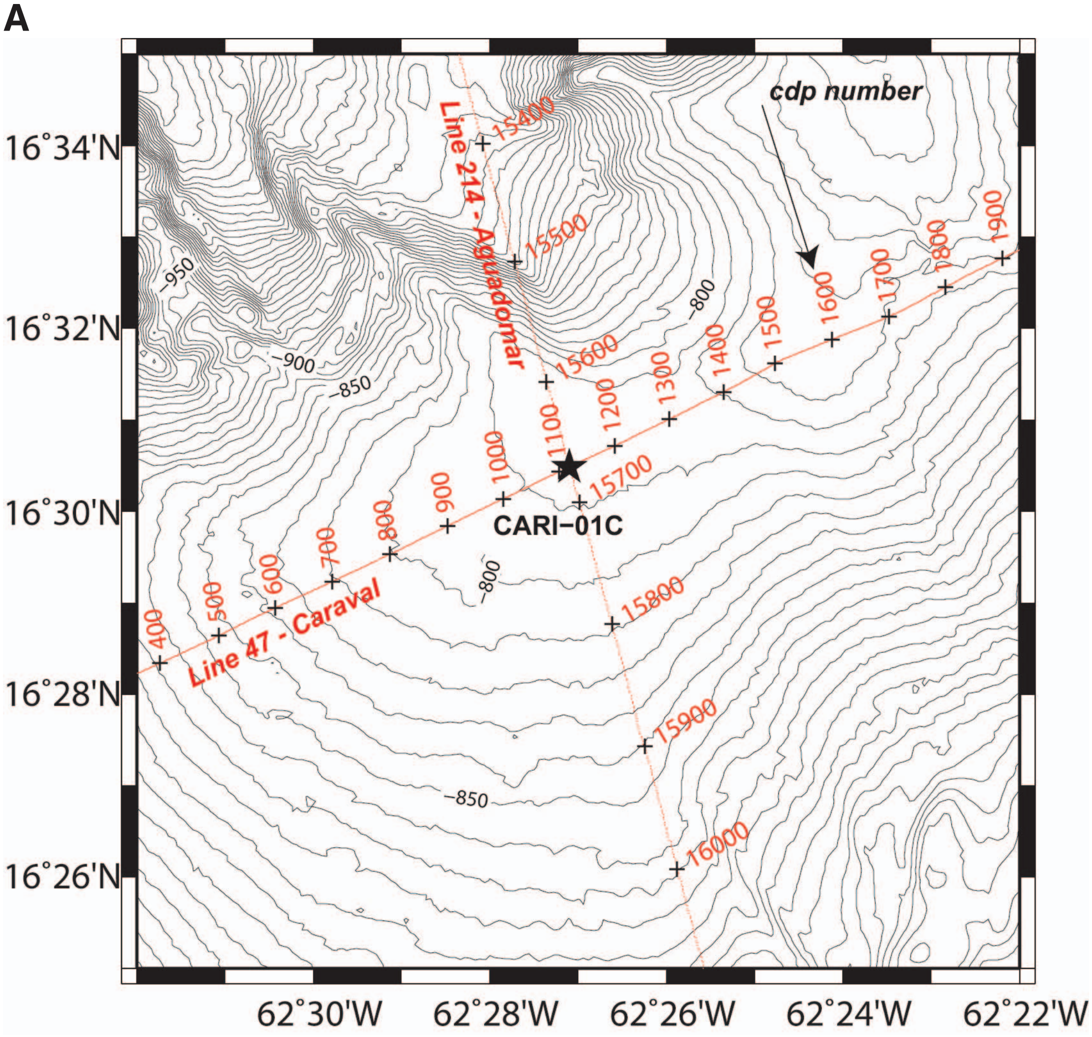


Figure AF1 (continued). B. Seismic line for Site CARI-01C from the Aguadomar cruise in December 1998 to January 1999. (**Continued on next page.**)

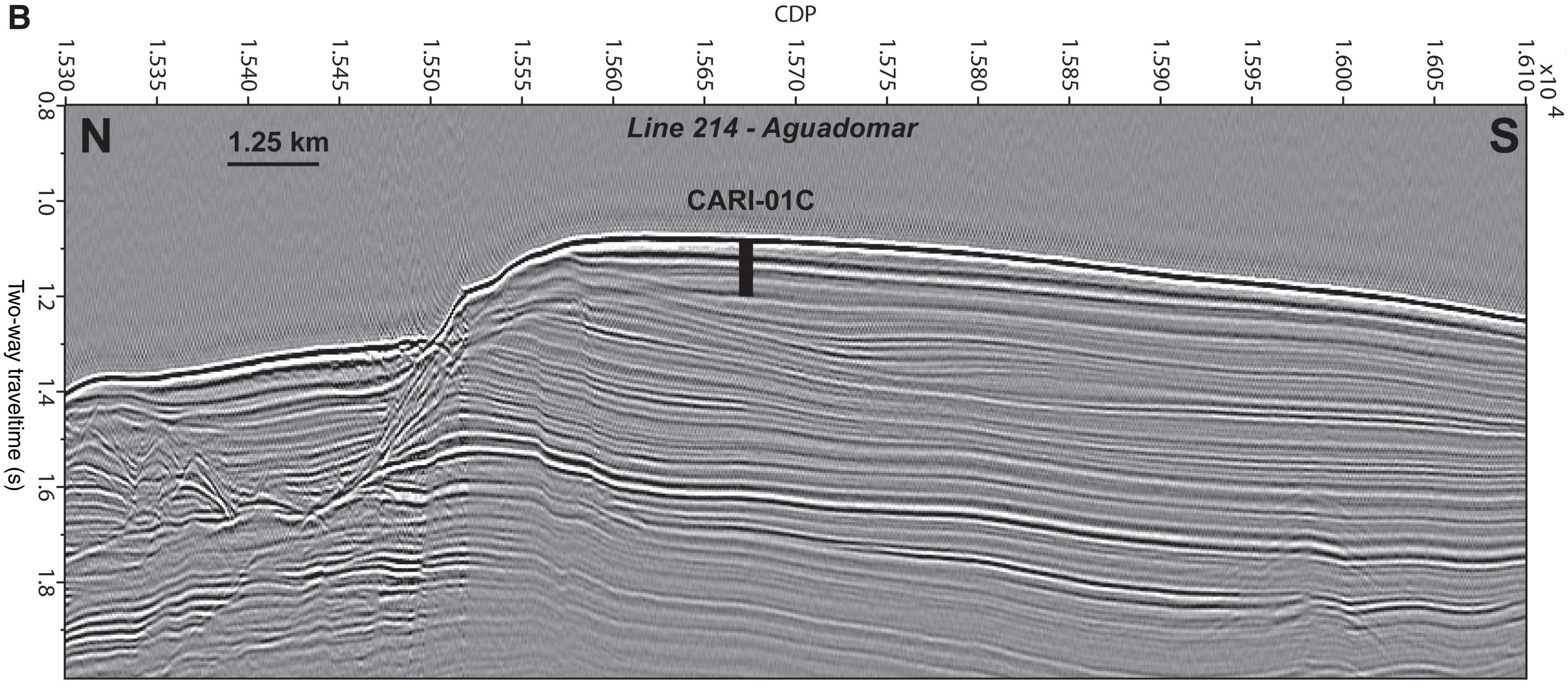


Figure AF1 (continued). C. Seismic line (penetration 132 m) for Site CARI-01C from the Caraval cruise in March 2002.

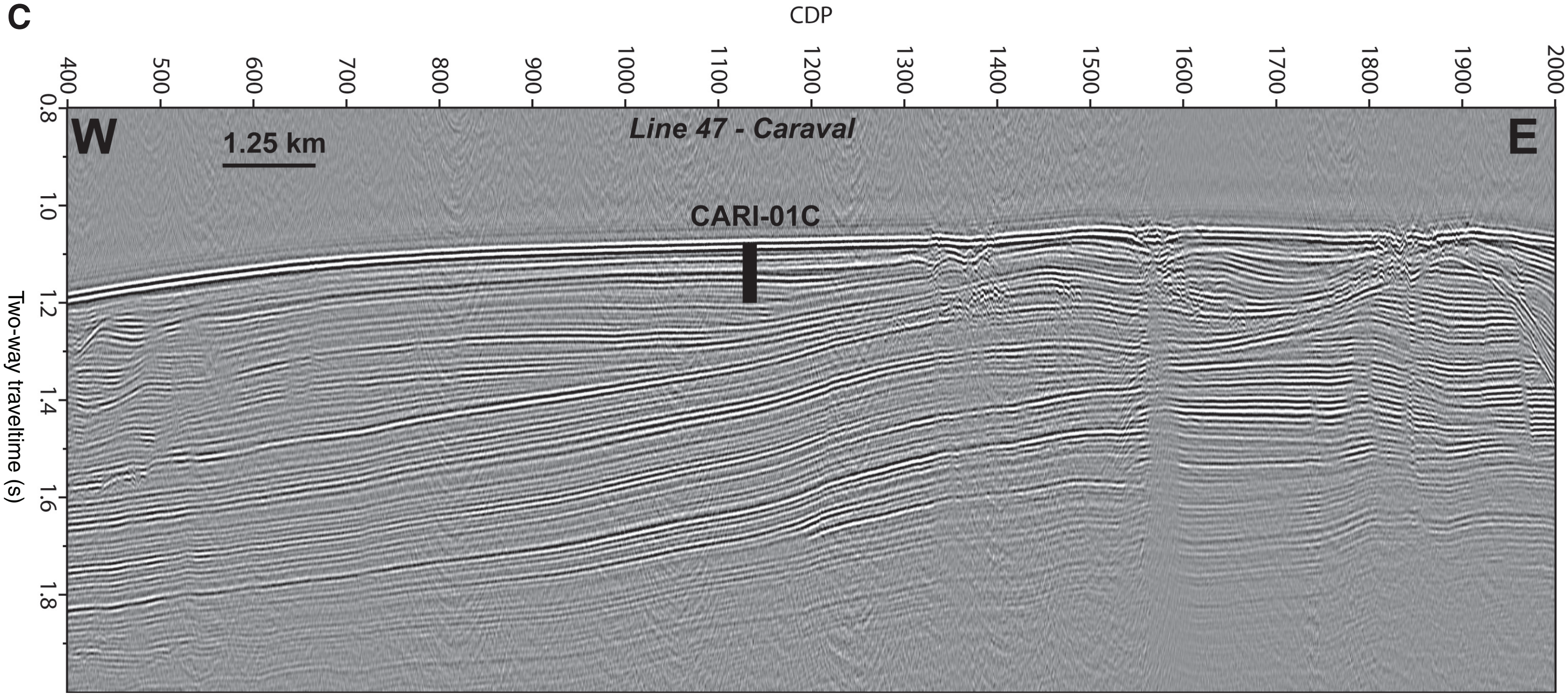


Figure AF2. **A.** Track map (50 m resolution, 10 m contour interval) for proposed primary Site CARI-02C. CDP = common depth point. (**Continued on next two pages.**)

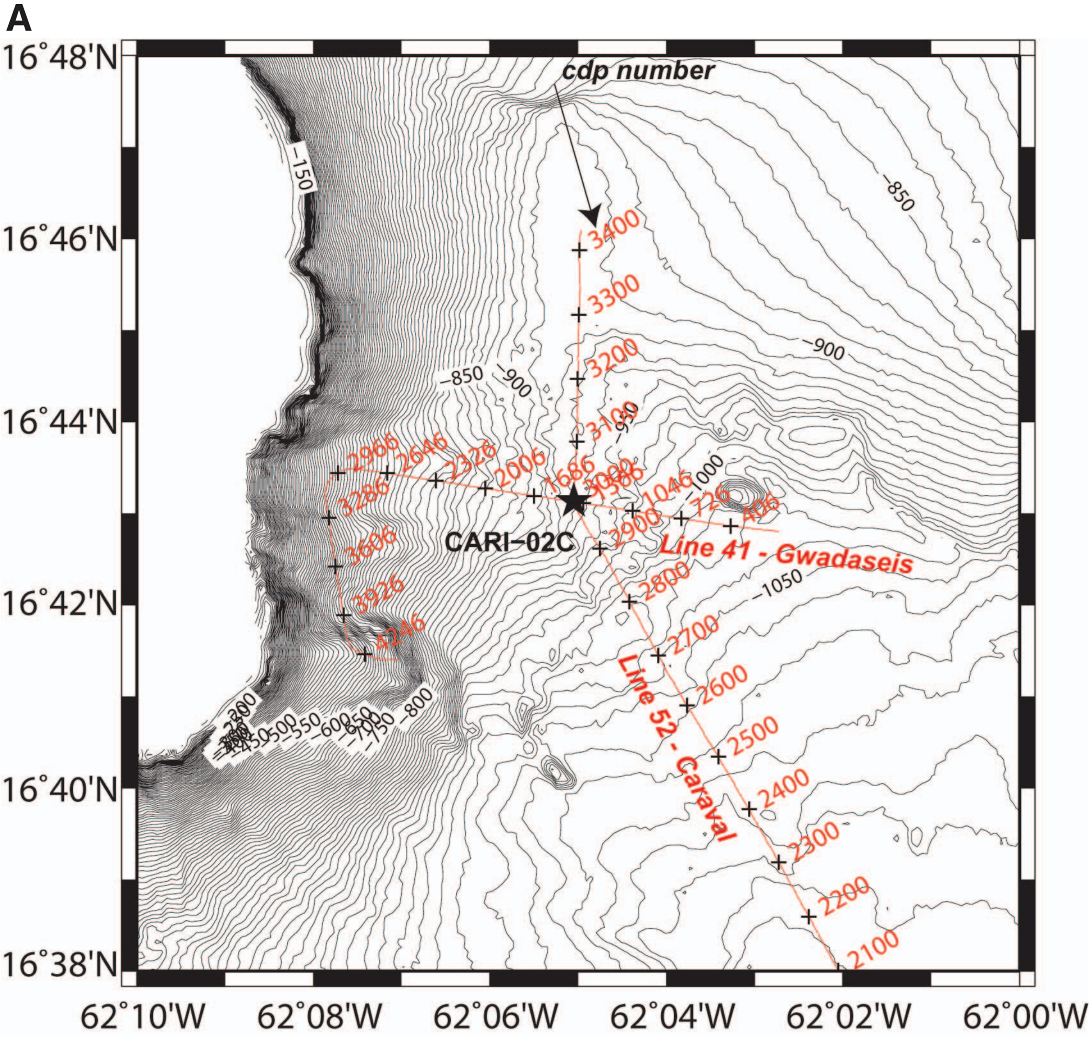


Figure AF2 (continued). B. Seismic line (penetration 250 m) for Site CARI-02C from the Caraval cruise in March 2002. DAD = debris avalanche deposit. (**Continued on next page.**)

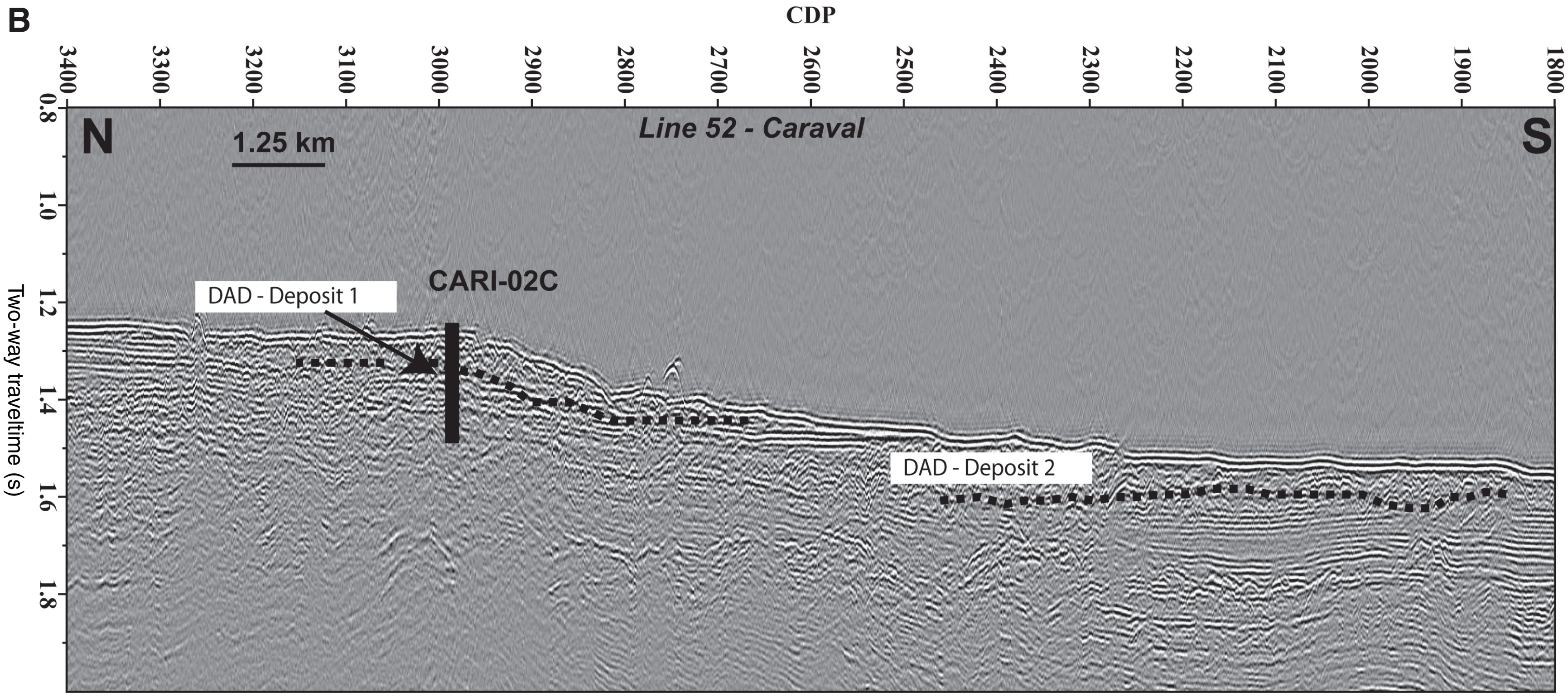


Figure AF2 (continued). C. Seismic line for Site CARI-02C from the Gwadaseis cruise in March 2009.

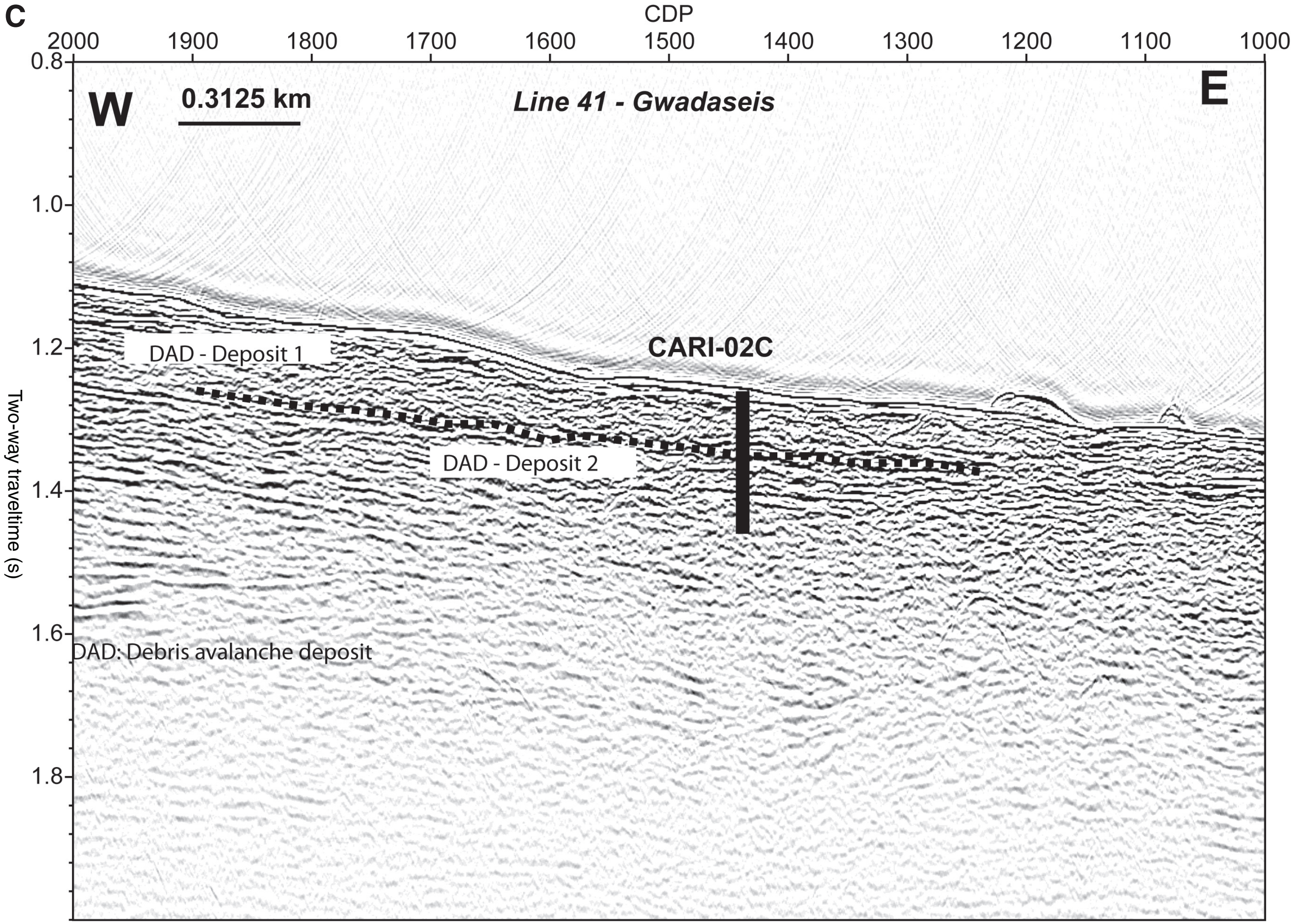


Figure AF3. A. Track map (50 m resolution, 10 m contour interval) for proposed primary Site CARI-03C. CDP = common depth point. (Continued on next two pages.)

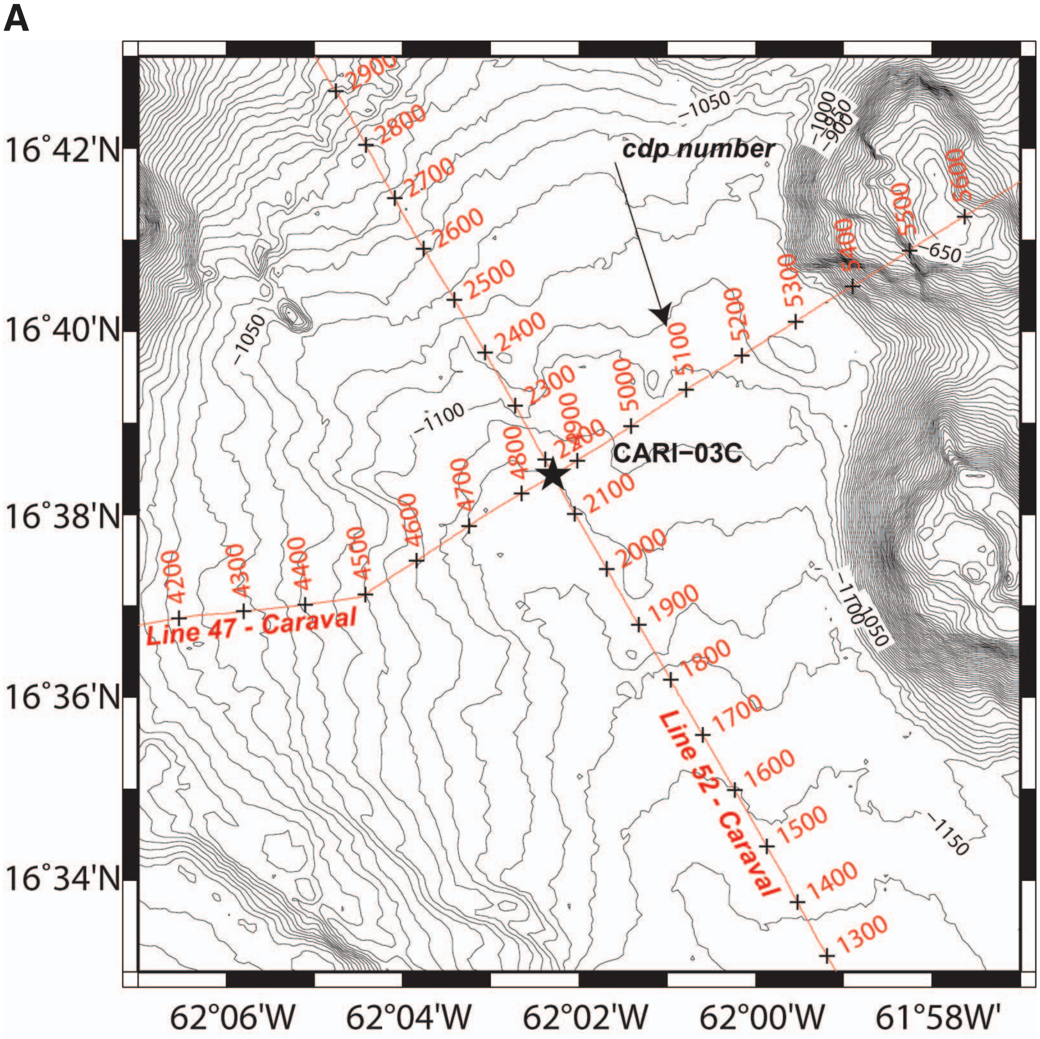


Figure AF3 (continued). B. Seismic Line 52 (penetration 244 m) for Site CARI-03C from the Caraval cruise in March 2002. (**Continued on next page.**)

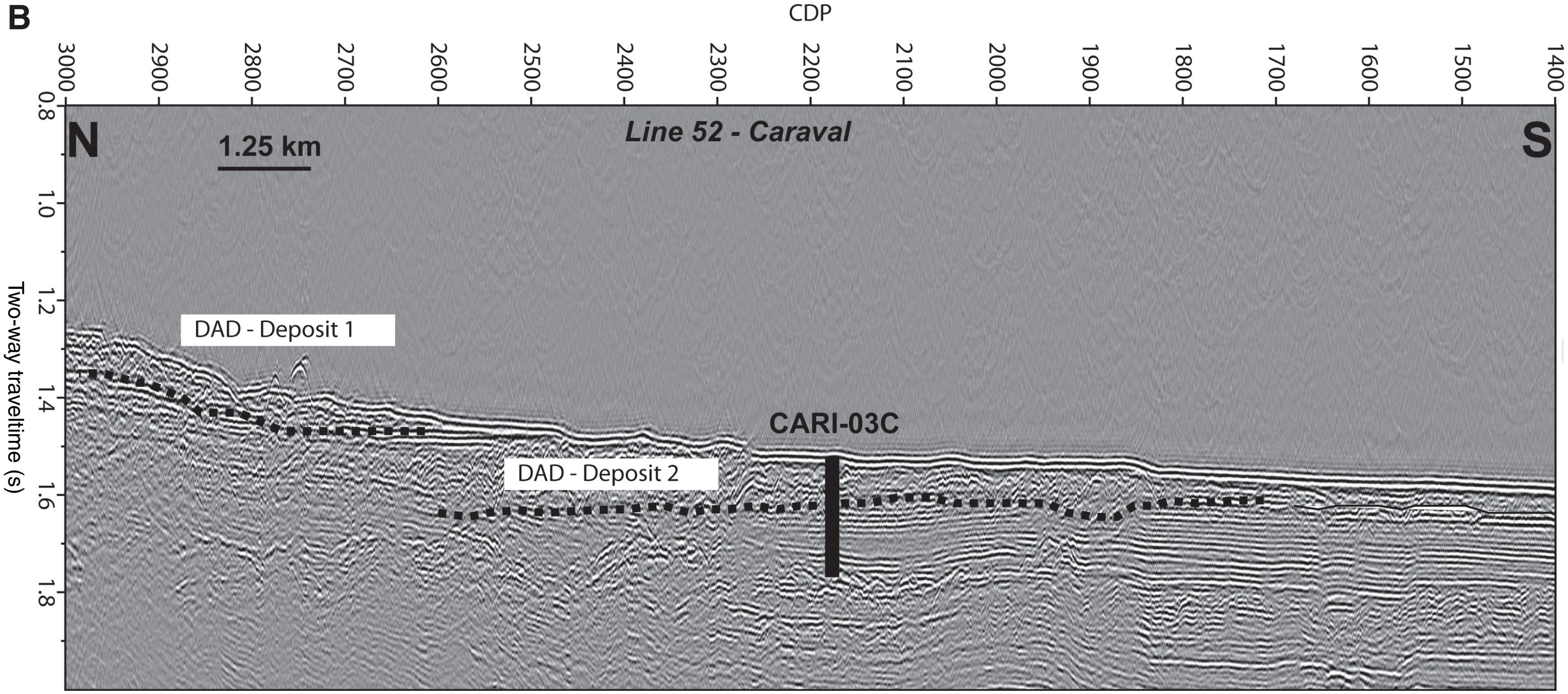


Figure AF3 (continued). C. Seismic Line 47 for Site CARI-03C from the *Caraval* cruise in March 2002.

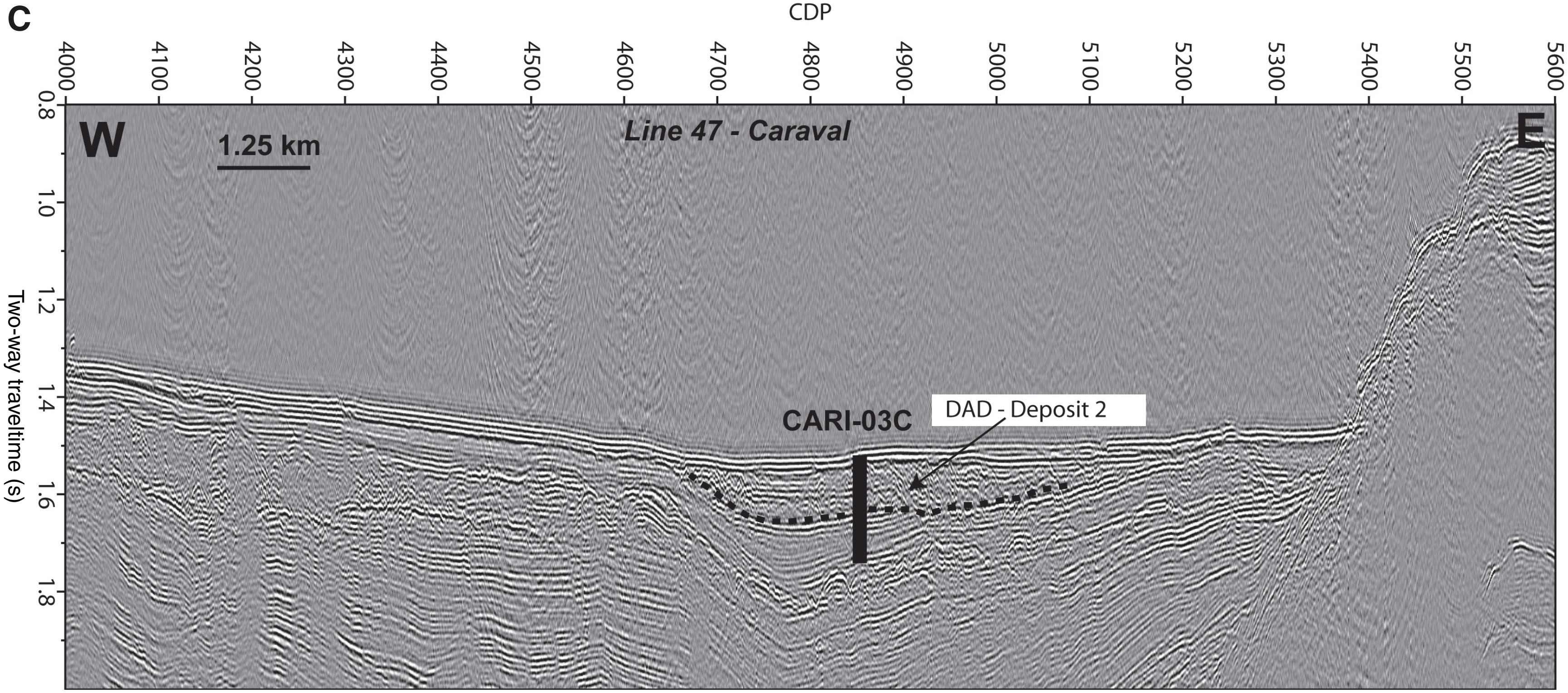


Figure AF4. (**A**) Track map (50 m resolution, 10 m contour interval) and (**B**) seismic line (penetration 244 m) for proposed primary Site CARI-04D. Data obtained from the Caraval cruise in March 2002. CDP = common depth point.

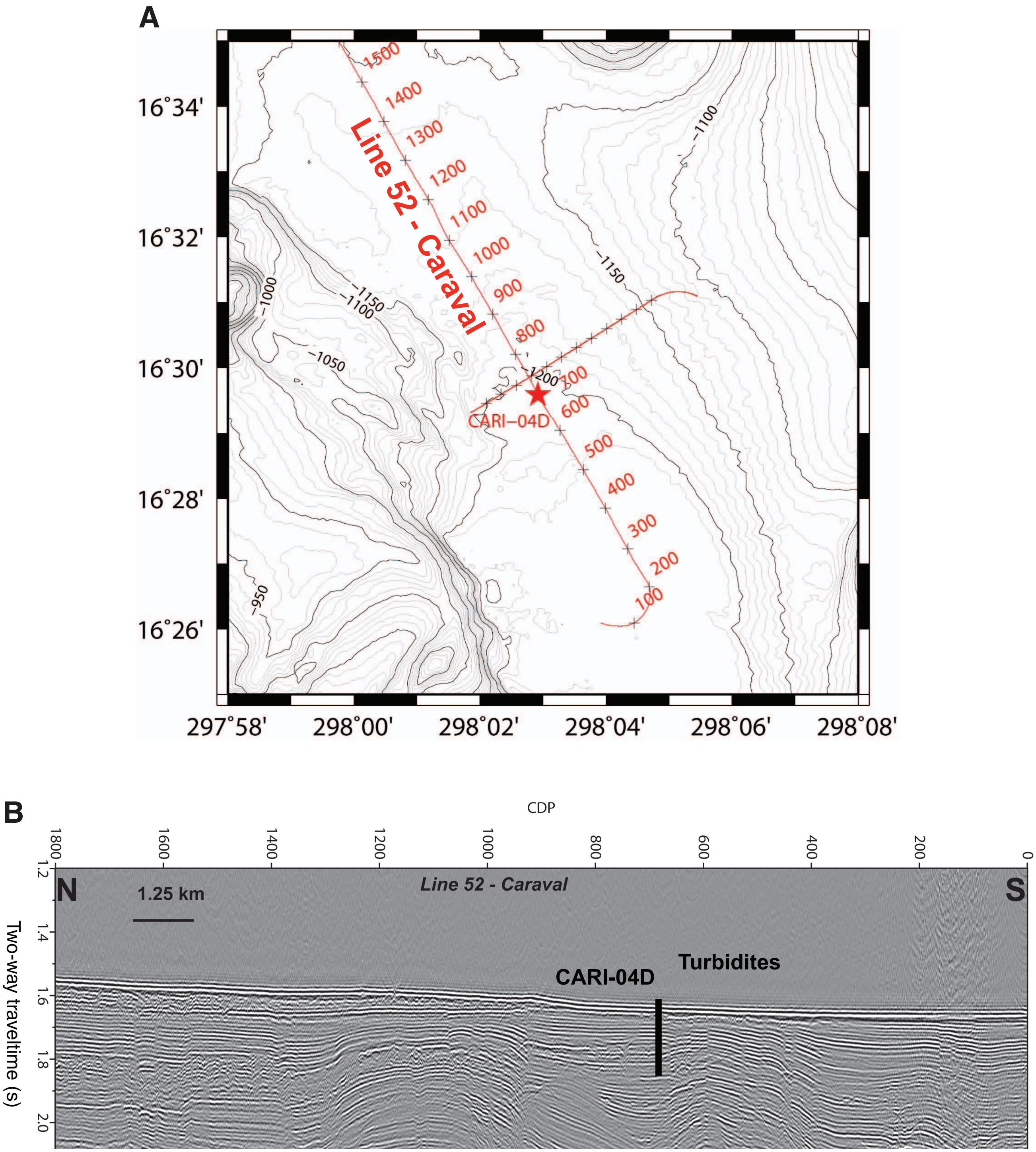


Figure AF5. (**A**) Track map (50 m resolution, 10 m contour interval) and (**B**) seismic line (penetration 357 m) for proposed primary Site CARI-05D. Data obtained from the Aguadomar cruise in 1999. CDP = common depth point, DAD = debris avalanche deposit.

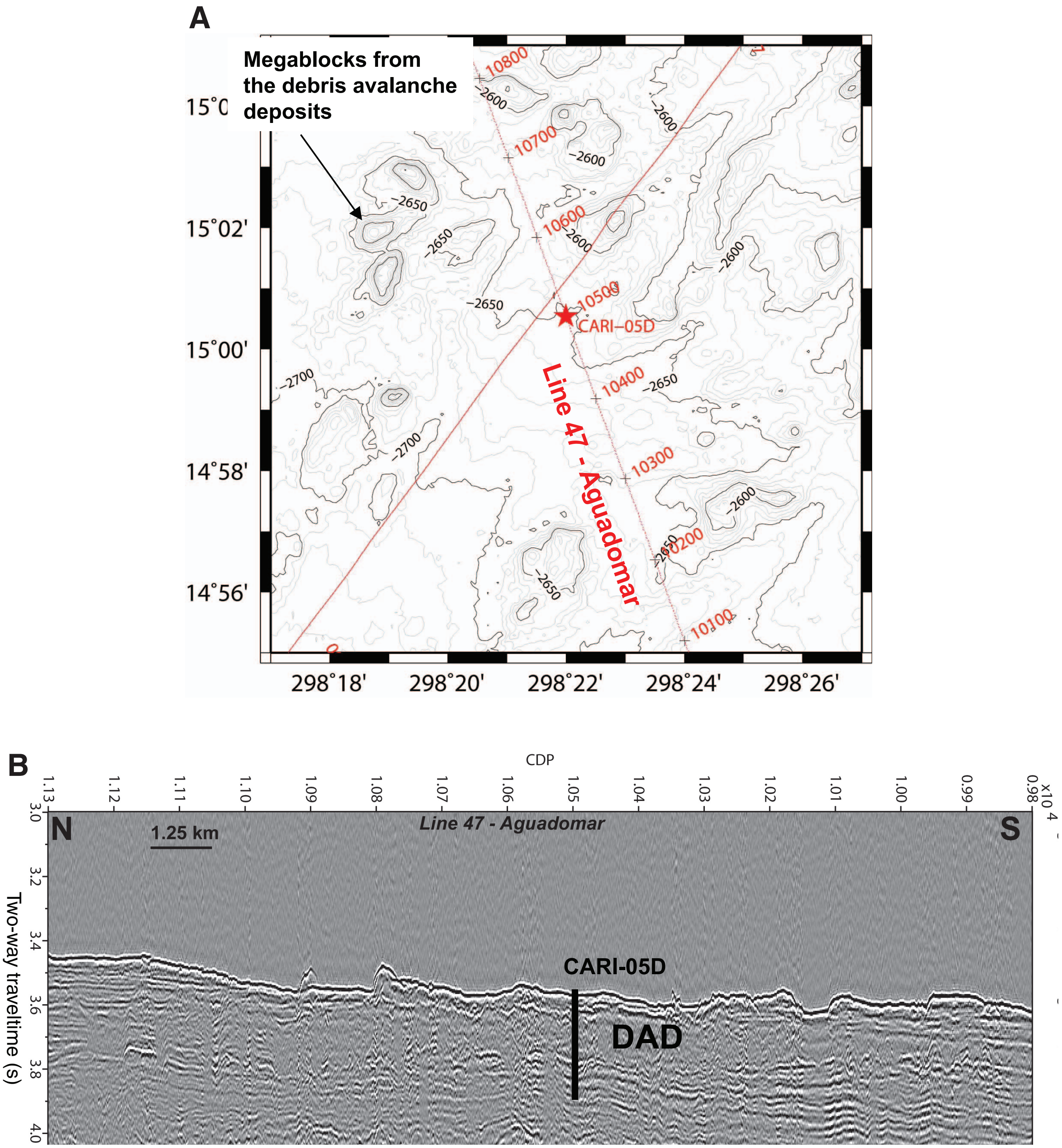


Figure AF6. A. Track map (50 m resolution, 10 m contour interval) for proposed alternate Site CARI-06C. CDP = common depth point. (**Continued on next two pages.**)

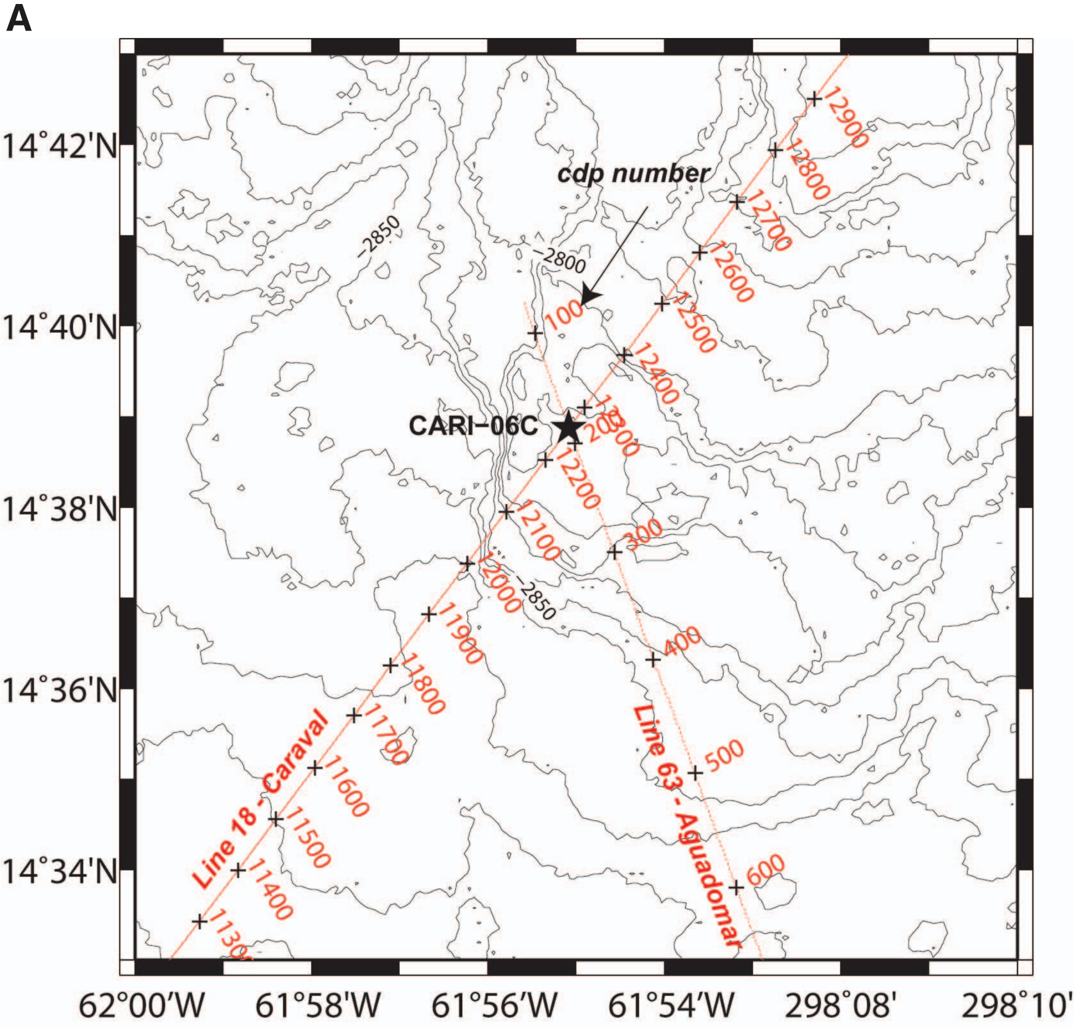


Figure AF6 (continued). B. Seismic line (penetration 488 m) for Site CARI-06C from the Aguadomar cruise in 1999. DAD = debris avalanche deposit. (**Continued on next page.**)

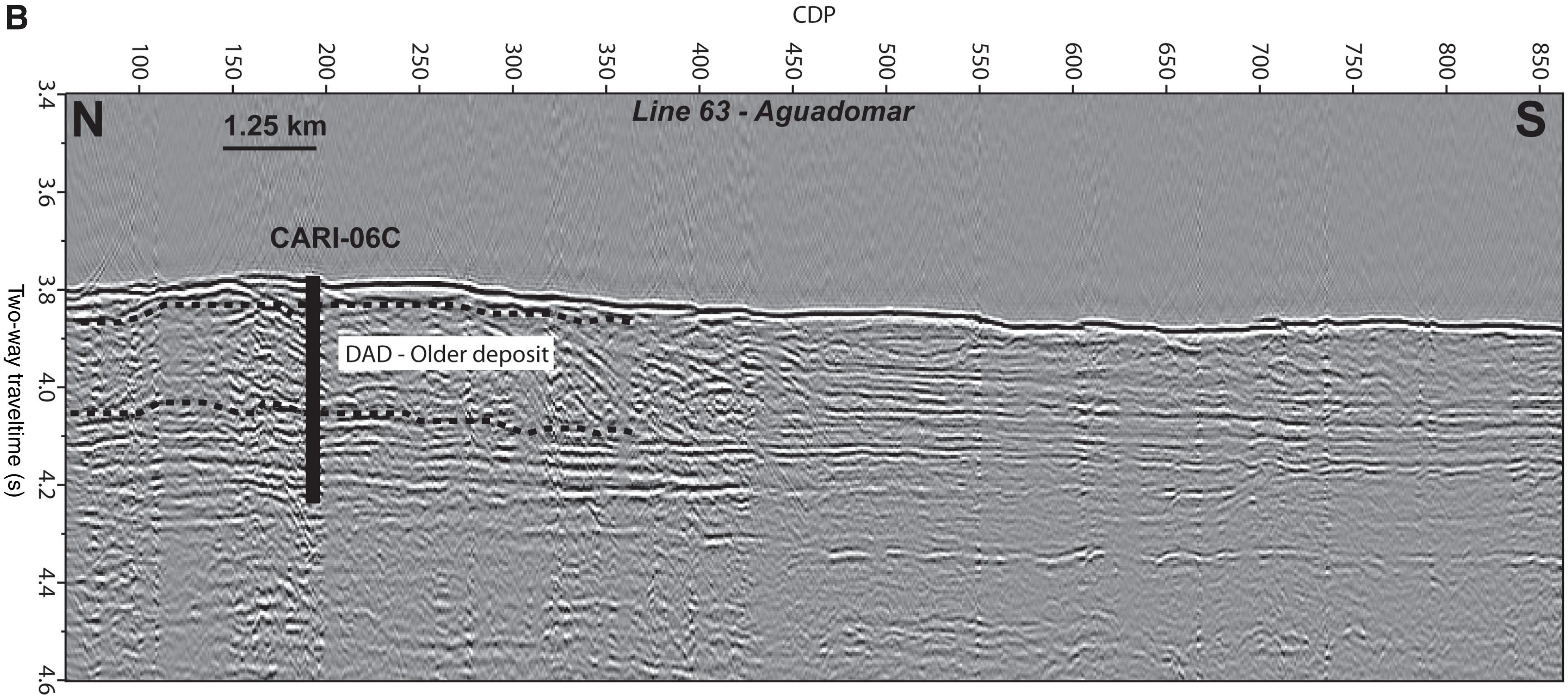


Figure AF6 (continued). C. Seismic line for Site CARI-06C from the Caraval cruise in March 2002.

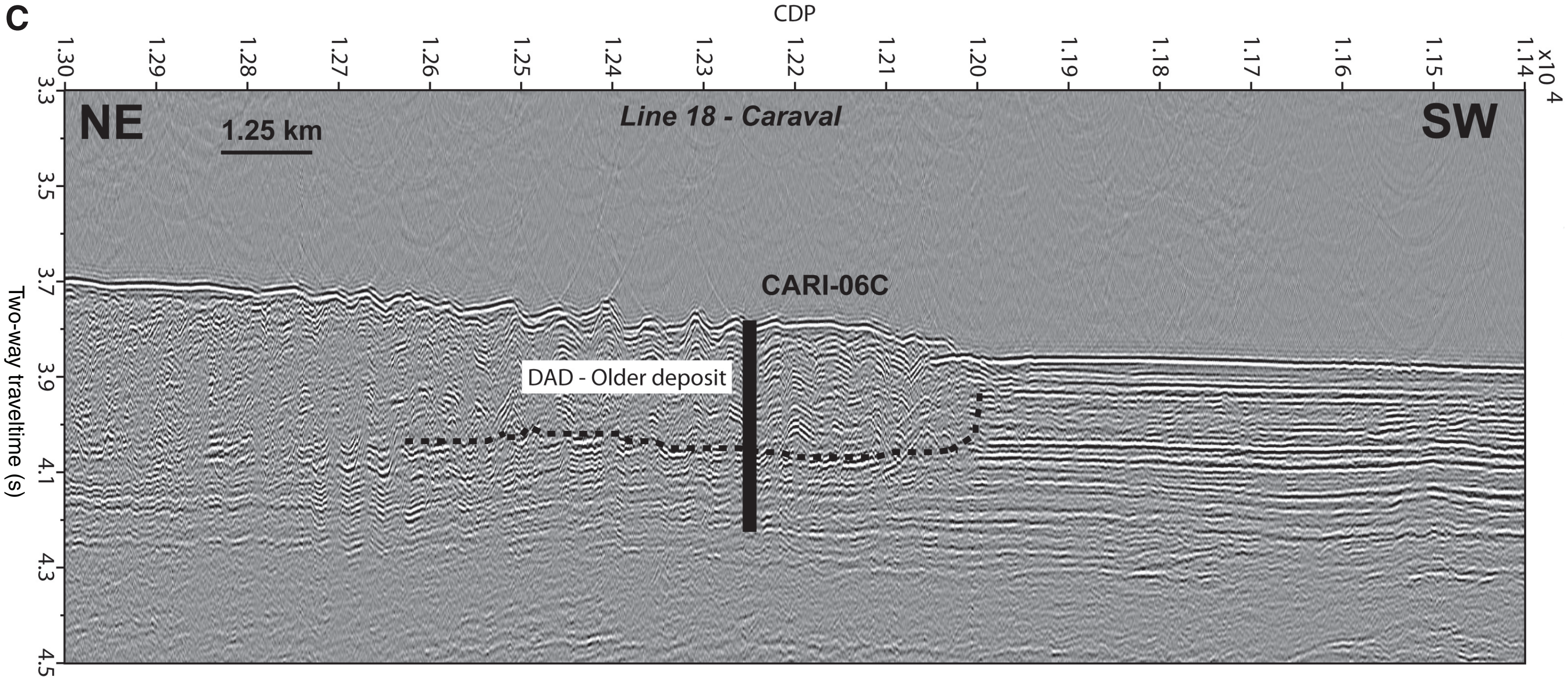


Figure AF7. A. Track map (50 m resolution, 10 m contour interval) for proposed primary Site CARI-07C. CDP = common depth point. (**Continued on next two pages.**)

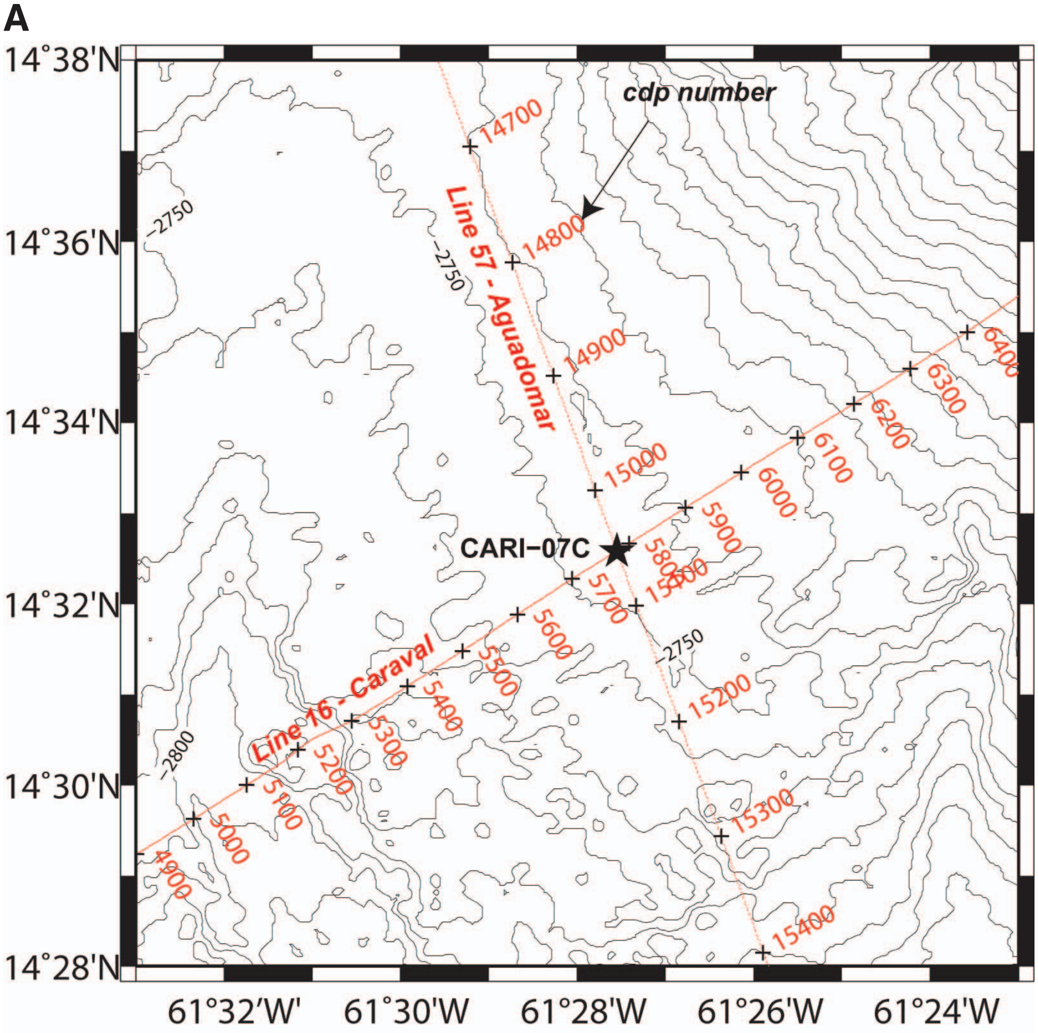


Figure AF7 (continued). B. Seismic line (penetration 510 m) for Site CARI-07C from the Aguadomar cruise in 1999. DAD = debris avalanche deposit. (**Continued on next page.**)

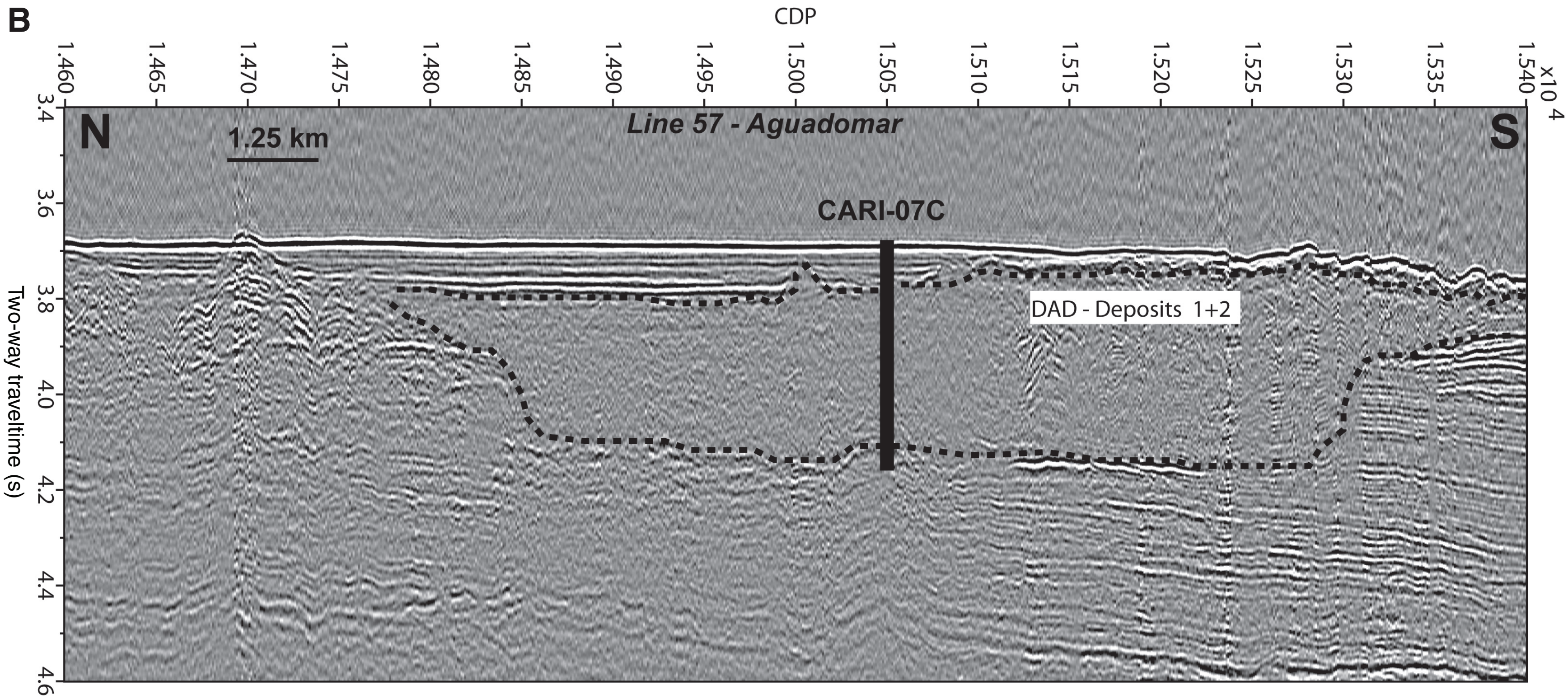


Figure AF7 (continued). C. Seismic line for Site CARI-07C from the Caraval cruise in March 2002.

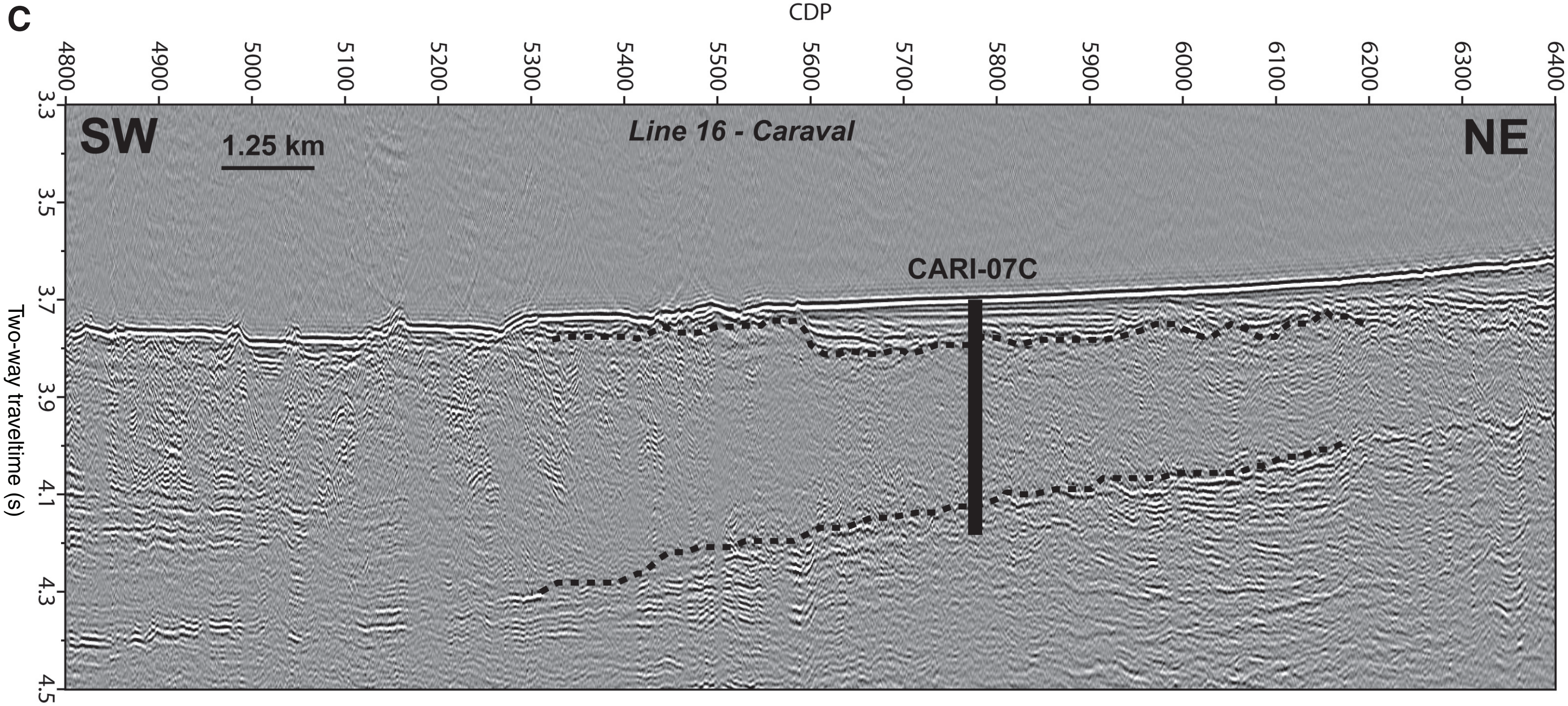


Figure AF8. A. Track map (50 m resolution, 10 m contour interval) for proposed primary Site CARI-08B. CDP = common depth point. (**Continued on next two pages.**)

A

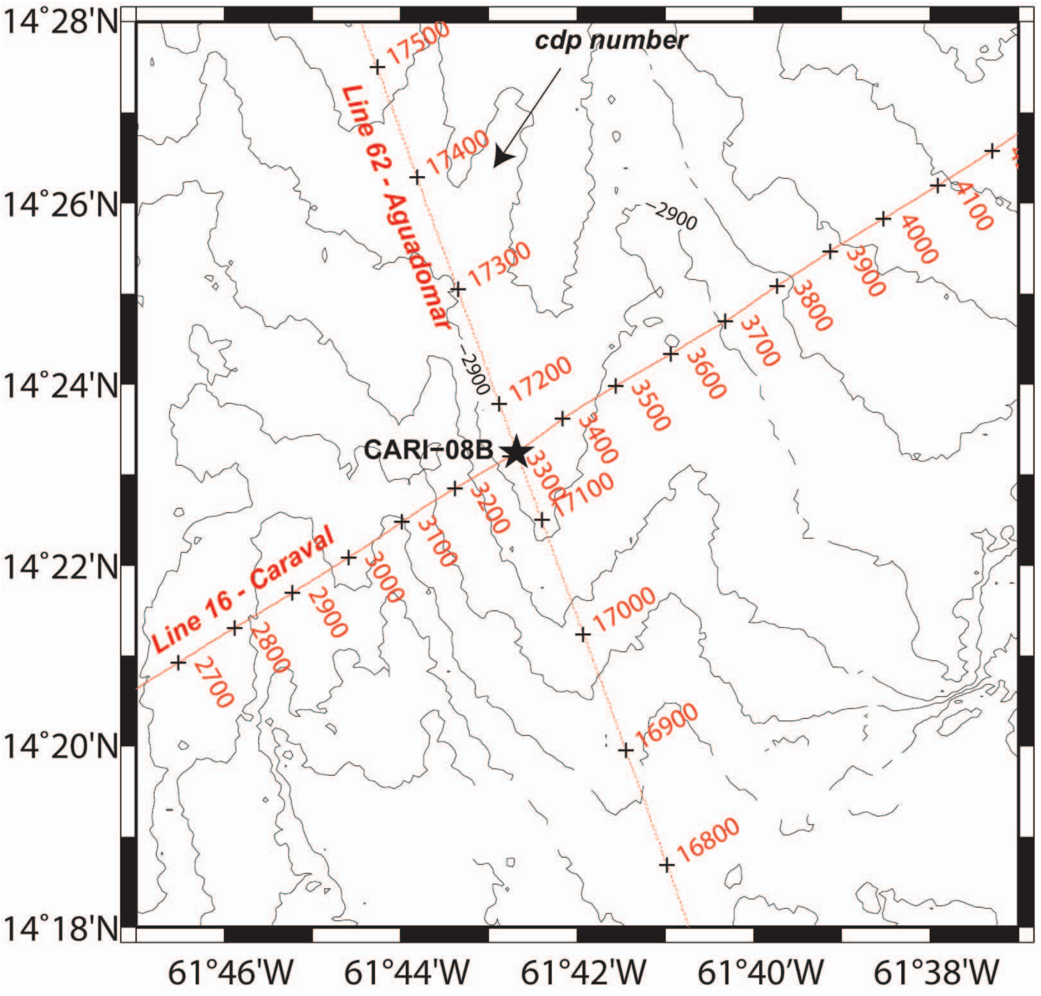


Figure AF8 (continued). B. Seismic line (penetration 290 m) for Site CARI-08B from the Aguadomar cruise in 1999. DAD = debris avalanche deposit. (**Continued on next page.**)

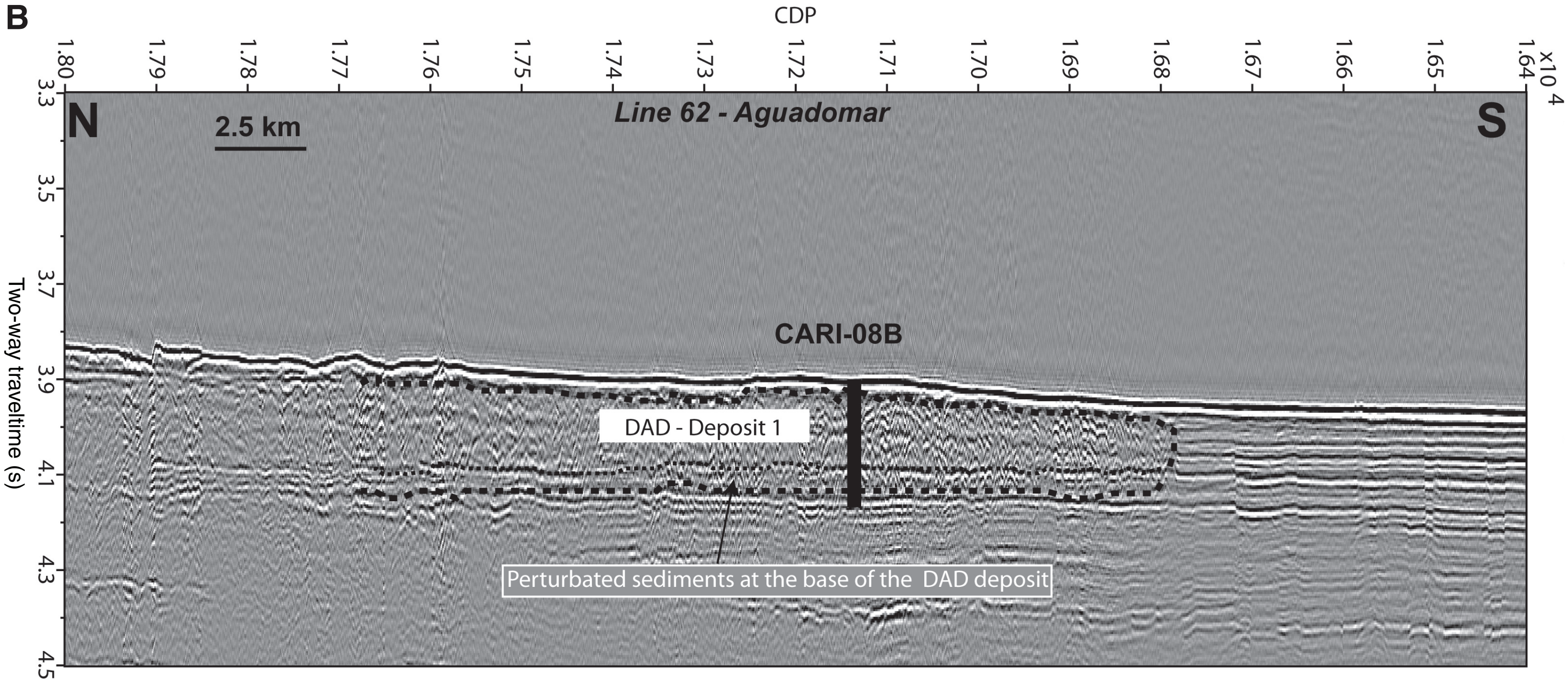


Figure AF8 (continued). C. Seismic line for Site CARI-08B from the Caraval cruise in March 2002.

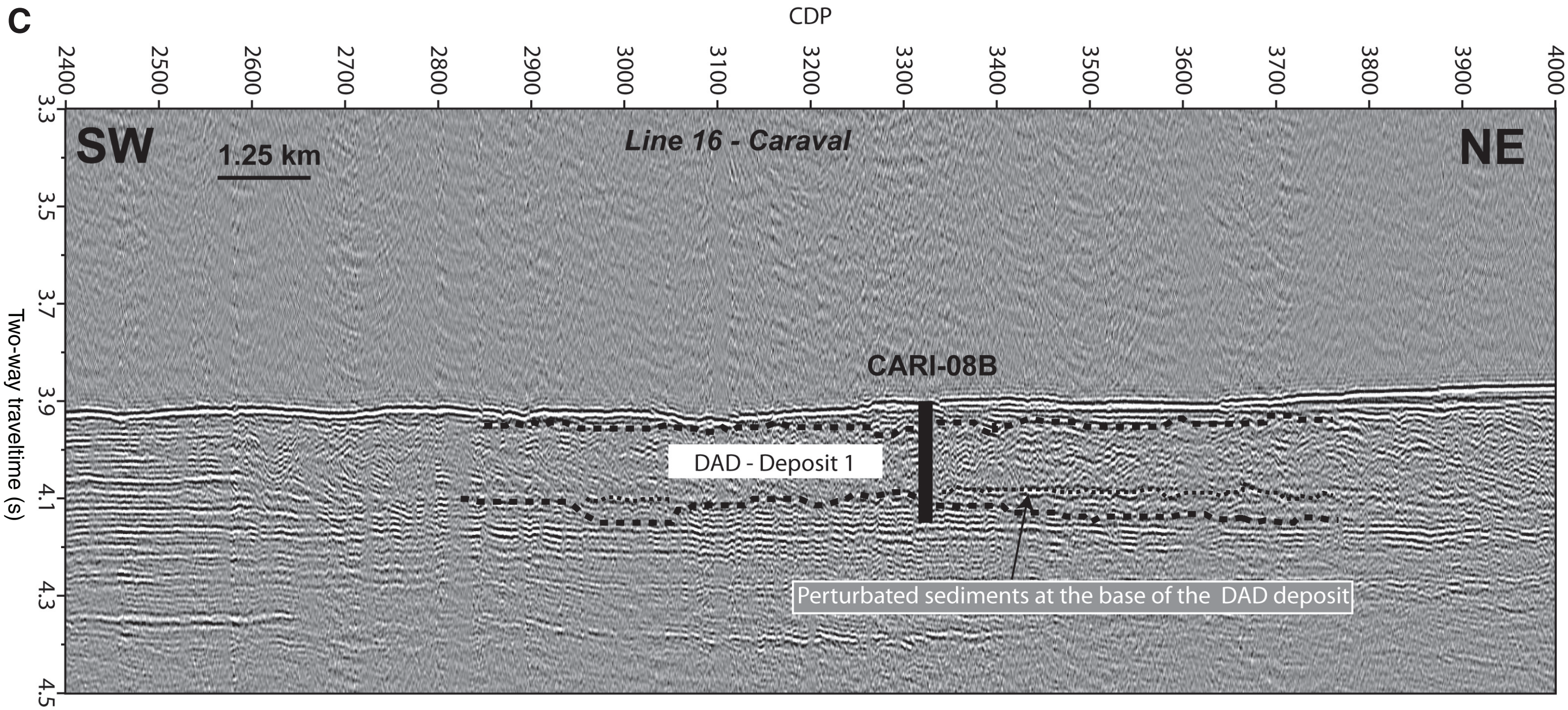


Figure AF9. A. Track map (50 m resolution, 10 m contour interval) for proposed primary Site CARI-09B. CDP = common depth point. (**Continued on next two pages.**)

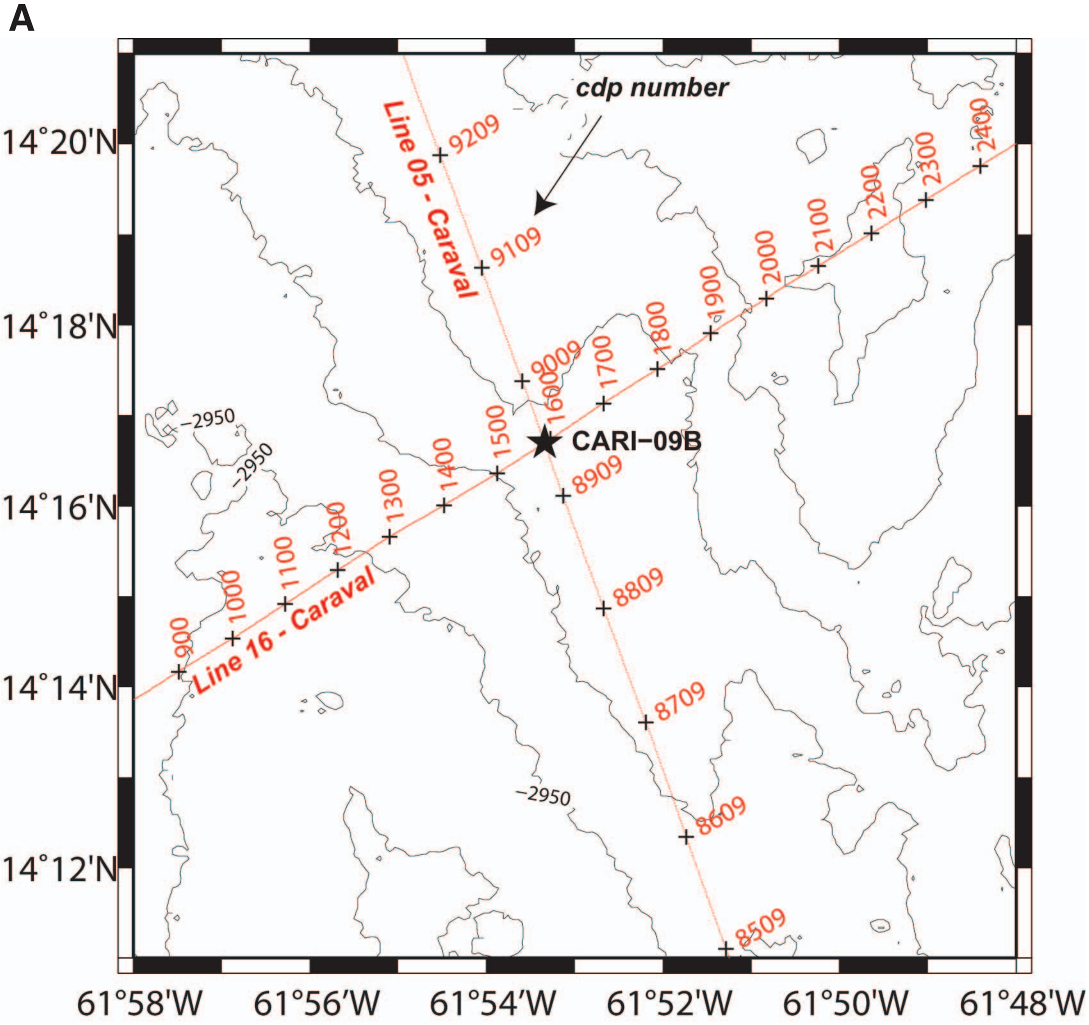


Figure AF9 (continued). B. Seismic Line 5 (penetration 264 m) for Site CARI-09B from the Caraval cruise in March 2002. (Continued on next page.)

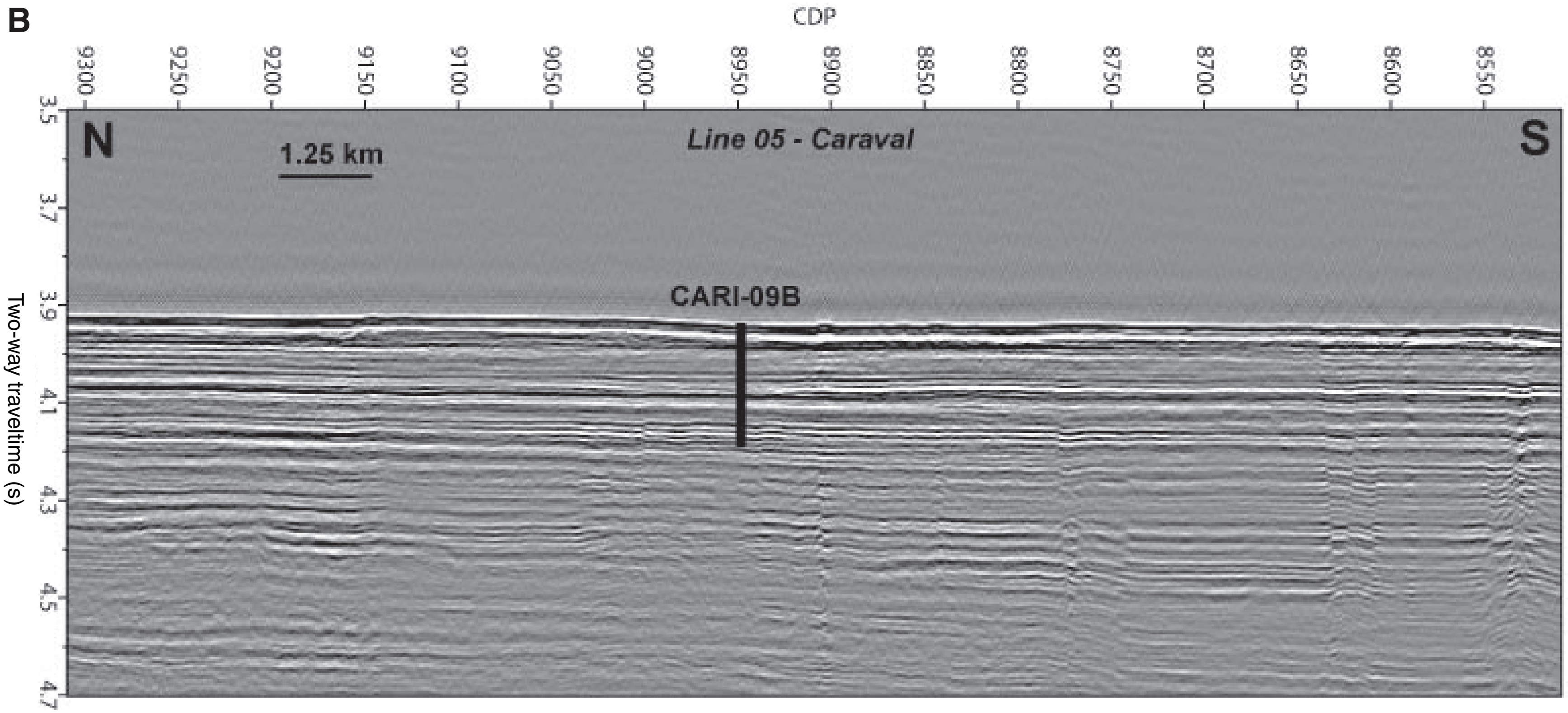


Figure AF9 (continued). C. Seismic Line 16 from the Caraval cruise in March 2002.

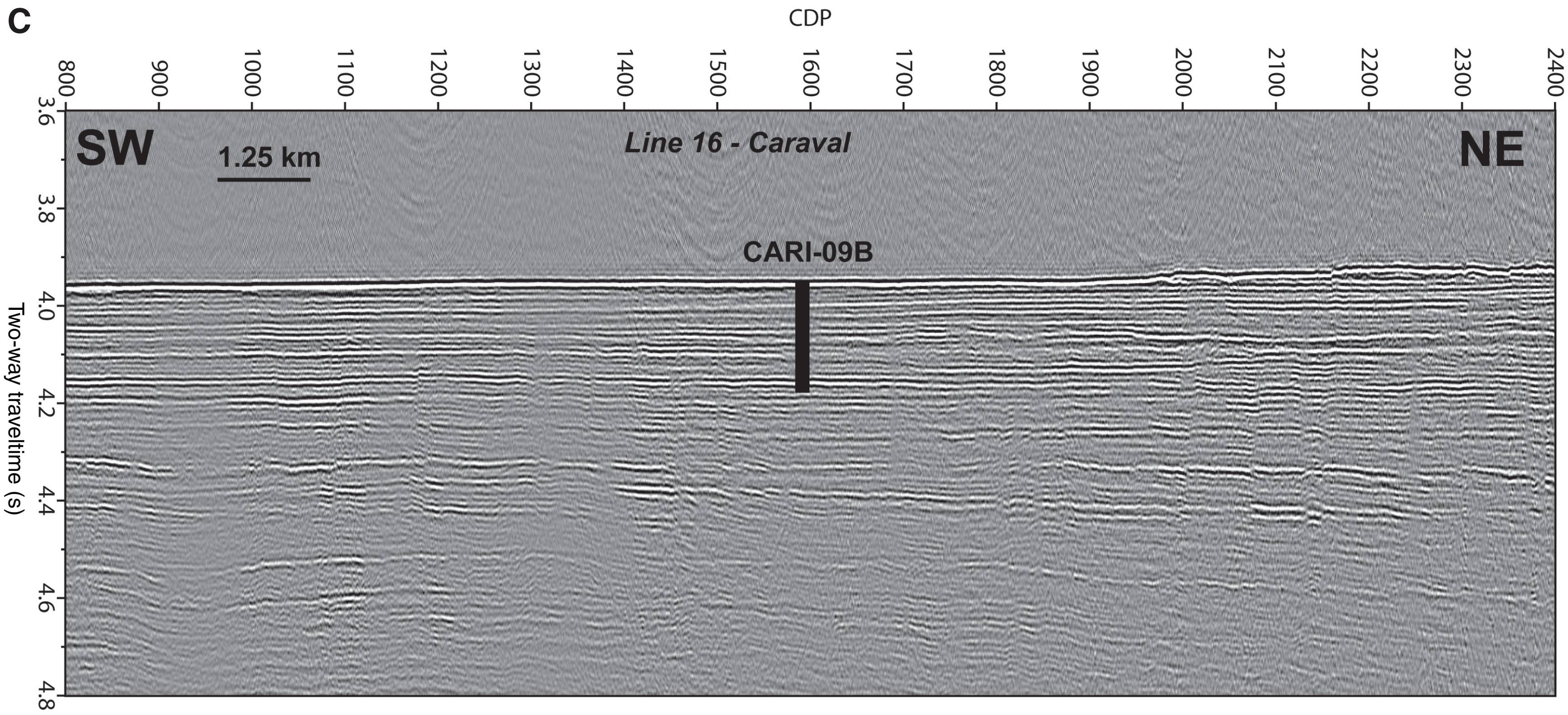


Figure AF10. A. Track map (50 m resolution, 10 m contour interval) for proposed primary Site CARI-10B. CDP = common depth point. (**Continued on next two pages.**)

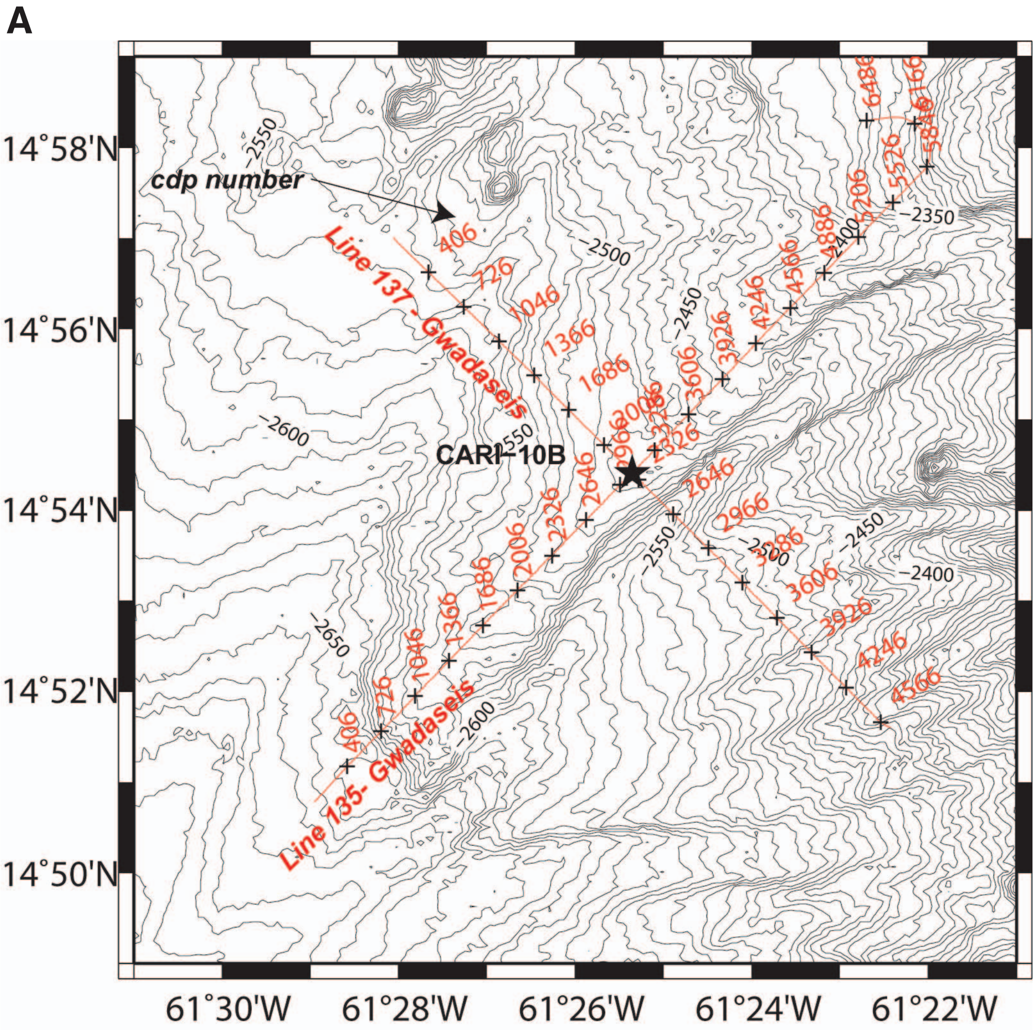


Figure AF10 (continued). B. Seismic Line 137 (penetration 314 m) for Site CARI-10B from the Gwadaseis cruise in March 2009. (**Continued on next page.**)

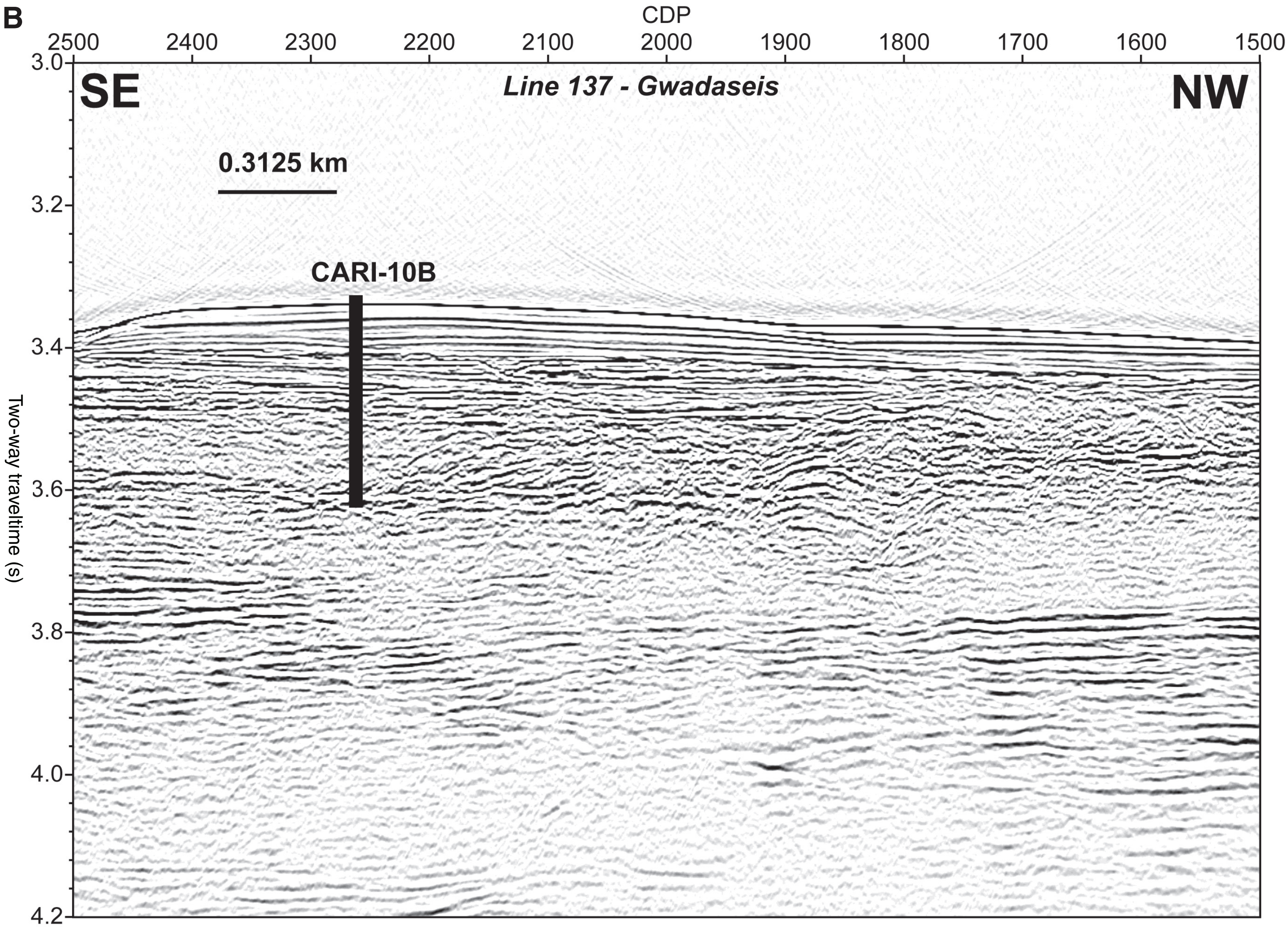


Figure AF10 (continued). C. Seismic Line 135 for Site CARI-10B from the Gwadaseis cruise in March 2009.

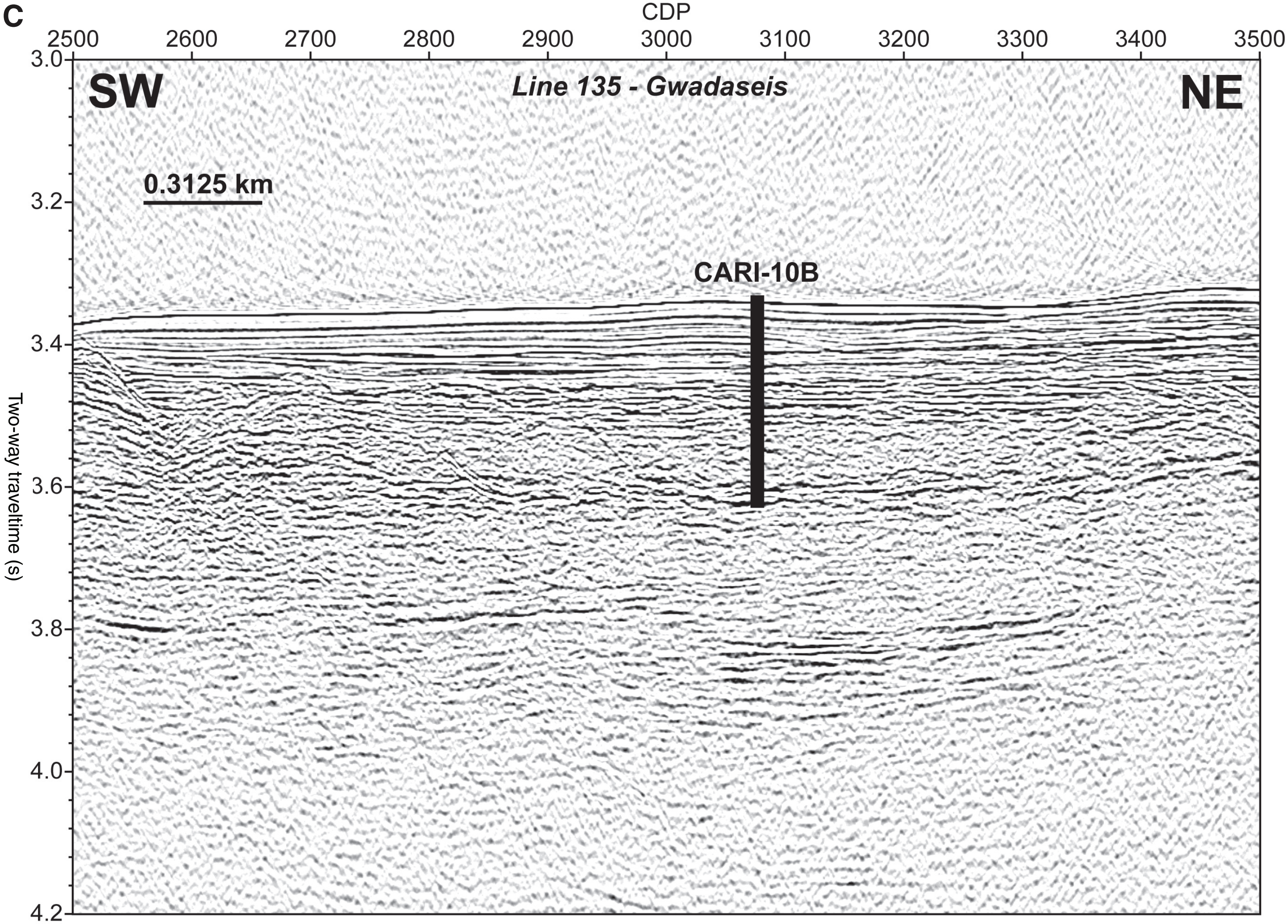


Figure AF11. A. Track map (50 m resolution, 10 m contour interval) for proposed alternate Site CARI-11A. CDP = common depth point. (**Continued on next two pages.**)

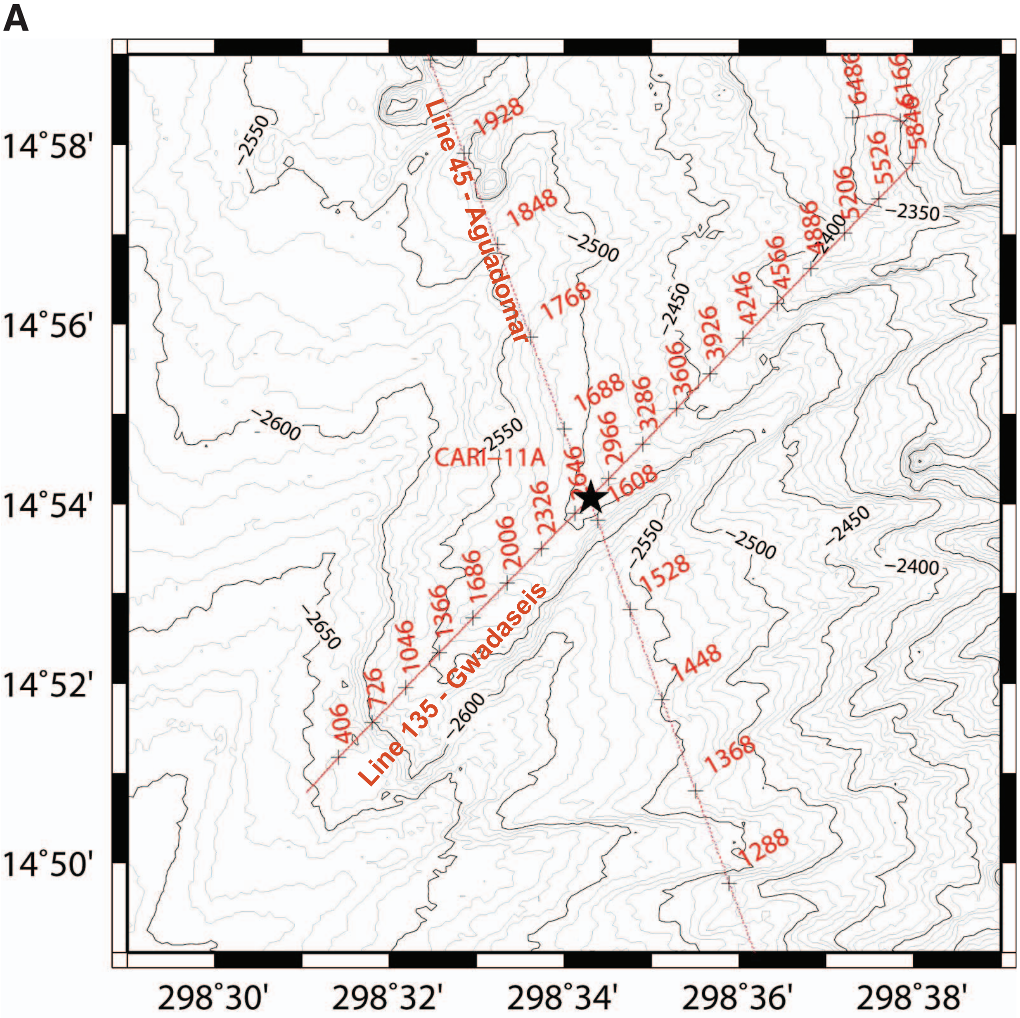


Figure AF11 (continued). B. Seismic line (penetration 314 m) for Site CARI-11A from the Aguadomar cruise in 1999. (**Continued on next page.**)

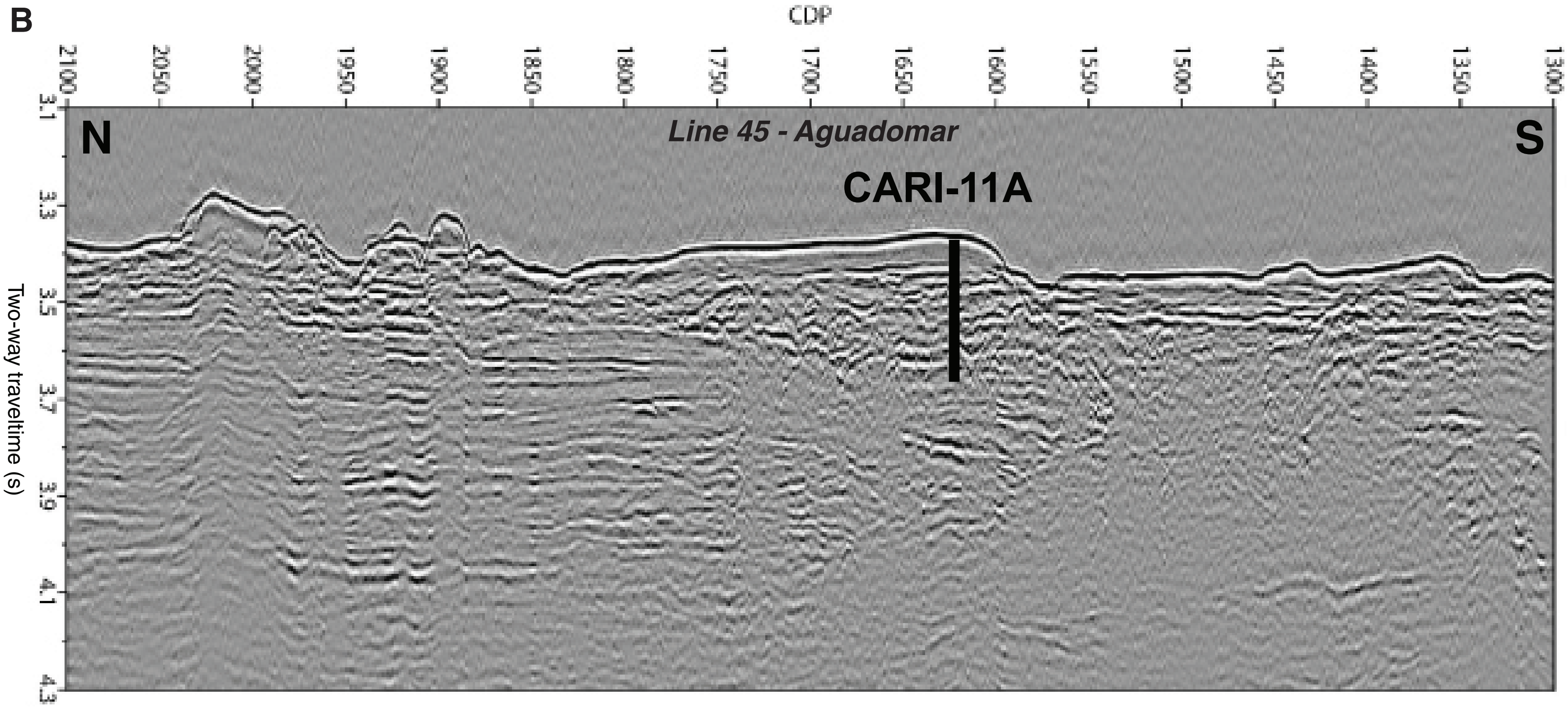


Figure AF11 (continued). C. Seismic line for Site CARI-11A from the Gwadaseis Cruise in March 2009.

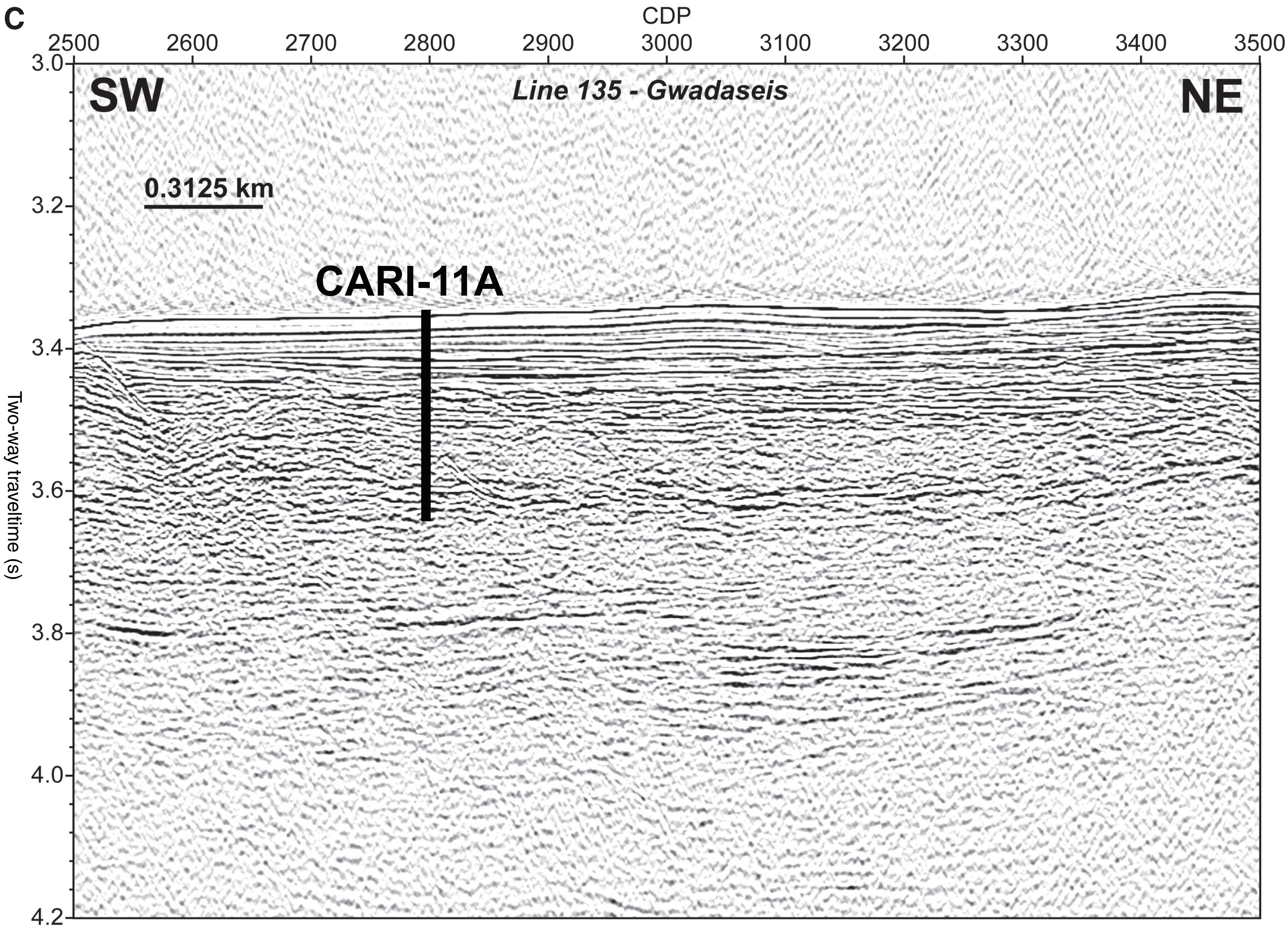


Figure AF12. A. Track map (50 m resolution, 10 m contour interval) for proposed alternate Site CARI-12A. CDP = common depth point. (**Continued on next two pages.**)

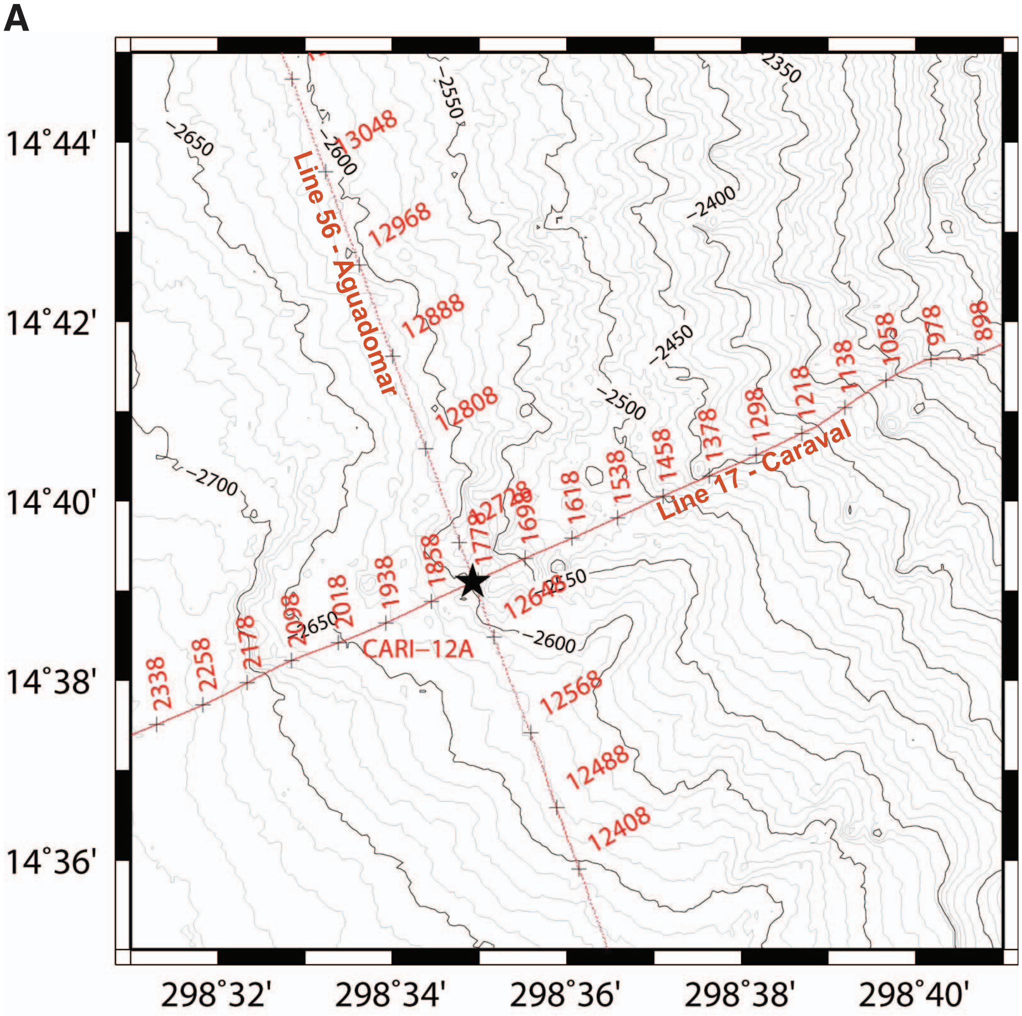


Figure AF12 (continued). B. Seismic line (penetration 500 m) for Site CARI-12A from the Aguadomar cruise in 1999. (**Continued on next page.**)

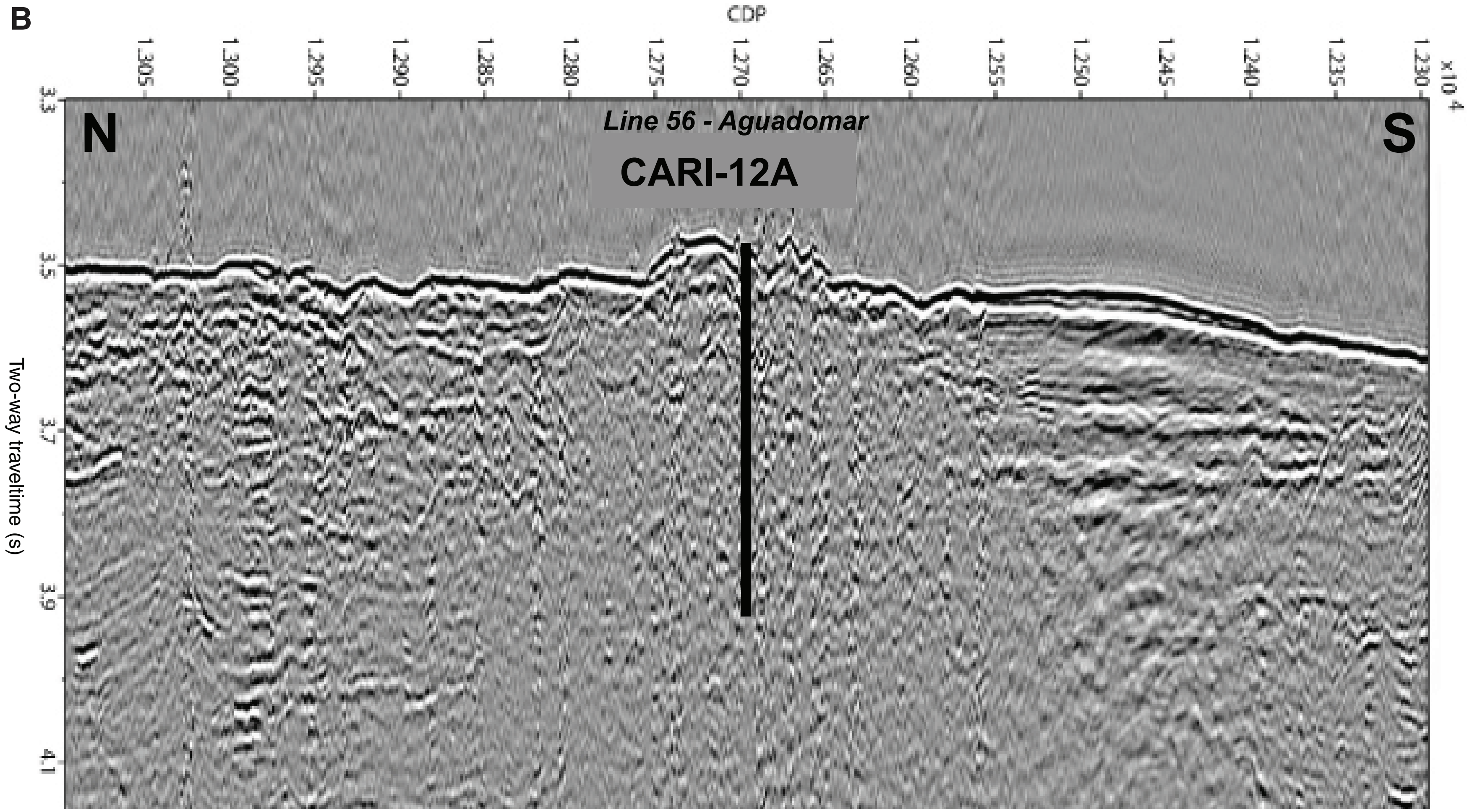


Figure AF12 (continued). **C.** Seismic line for Site CARI-12A from the Caraval cruise in March 2002.

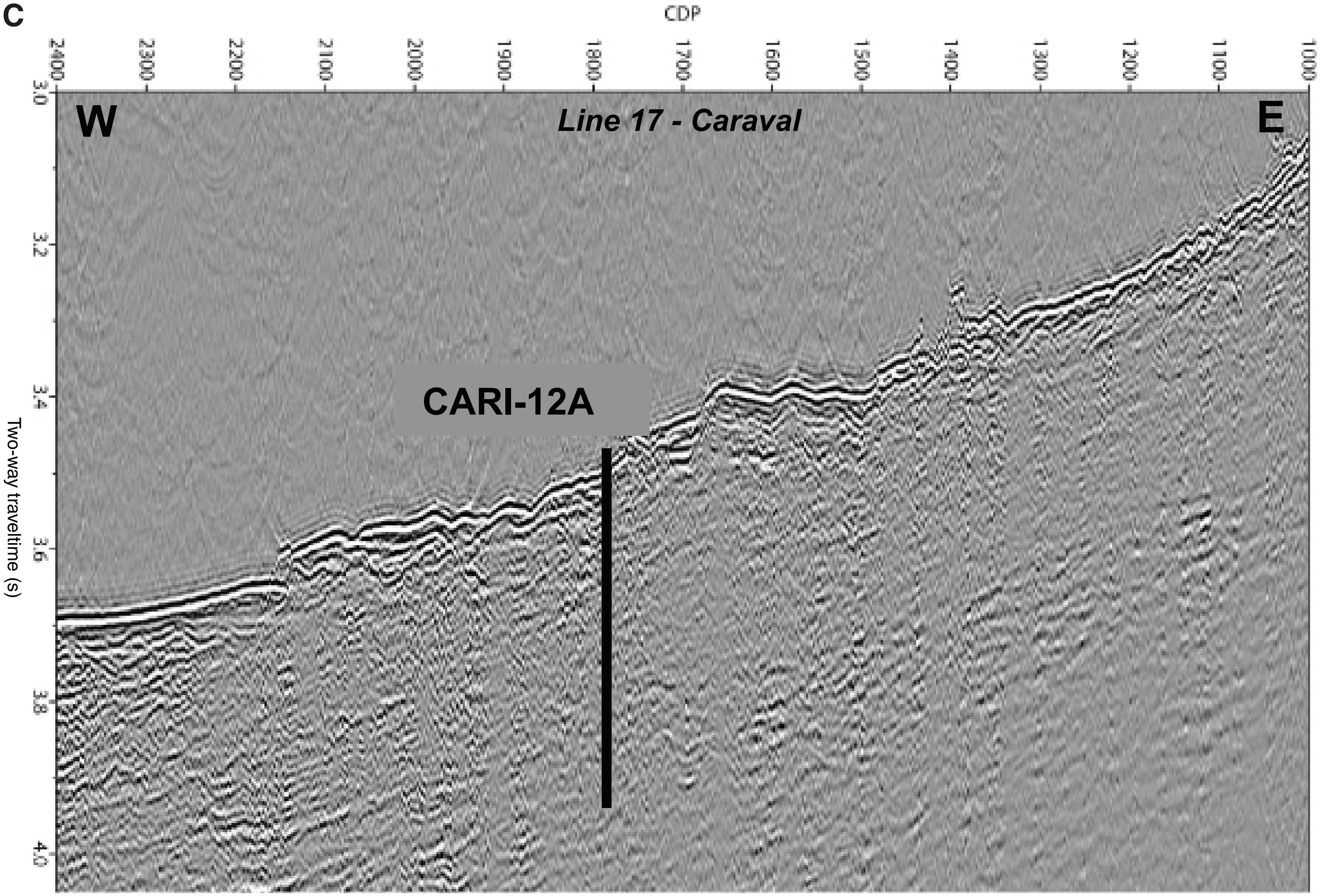


Figure AF13. A. Track map (50 m resolution, 10 m contour interval) for proposed alternate Site CARI-13A. (**Continued on next page.**)

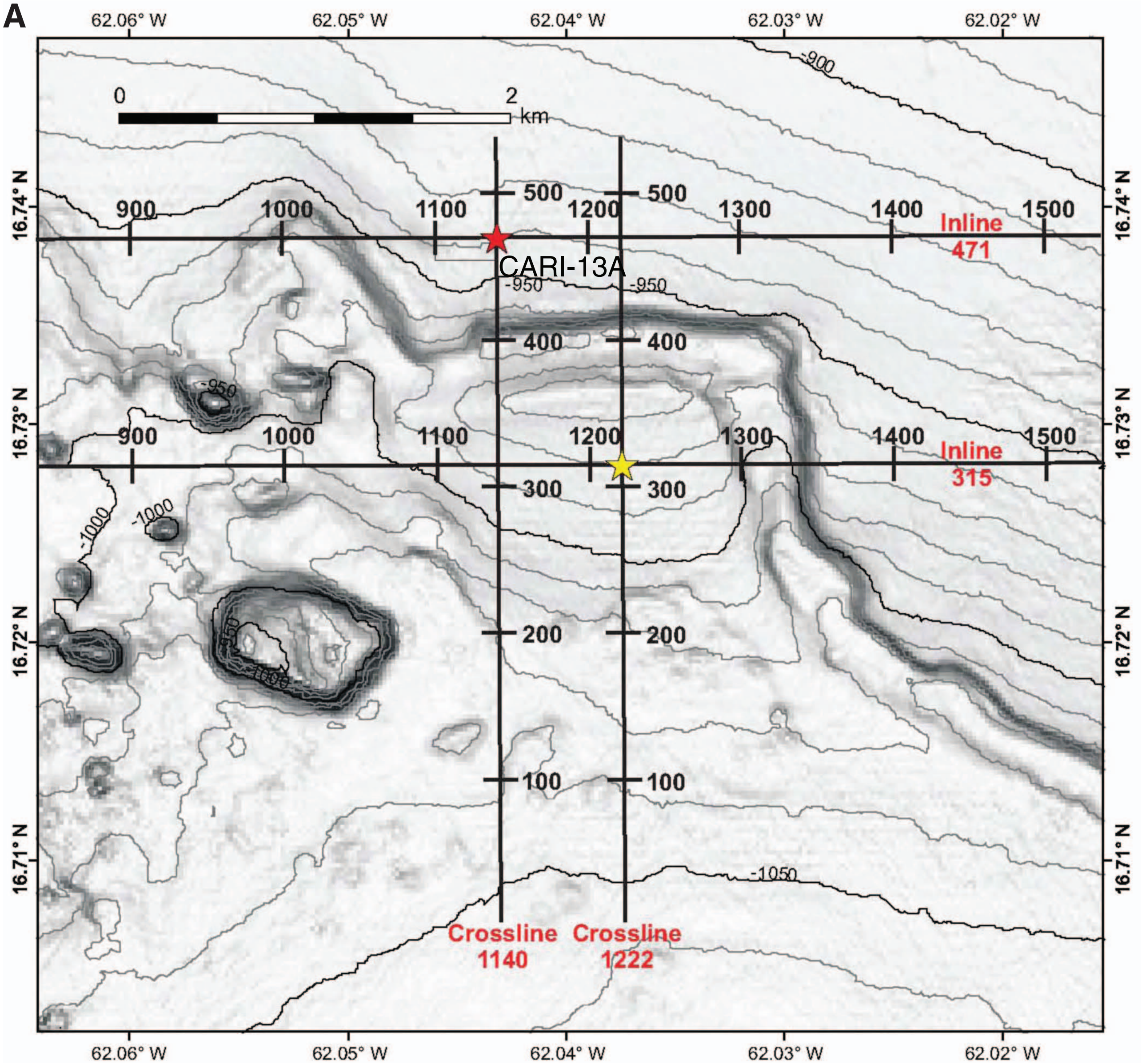


Figure AF13 (continued). B. Seismic Inline 471 (penetration 88 m) for Site CARI-13A from the JC 45/46 cruise. **C.** Seismic Crossline 1140 for Site CARI-13A.

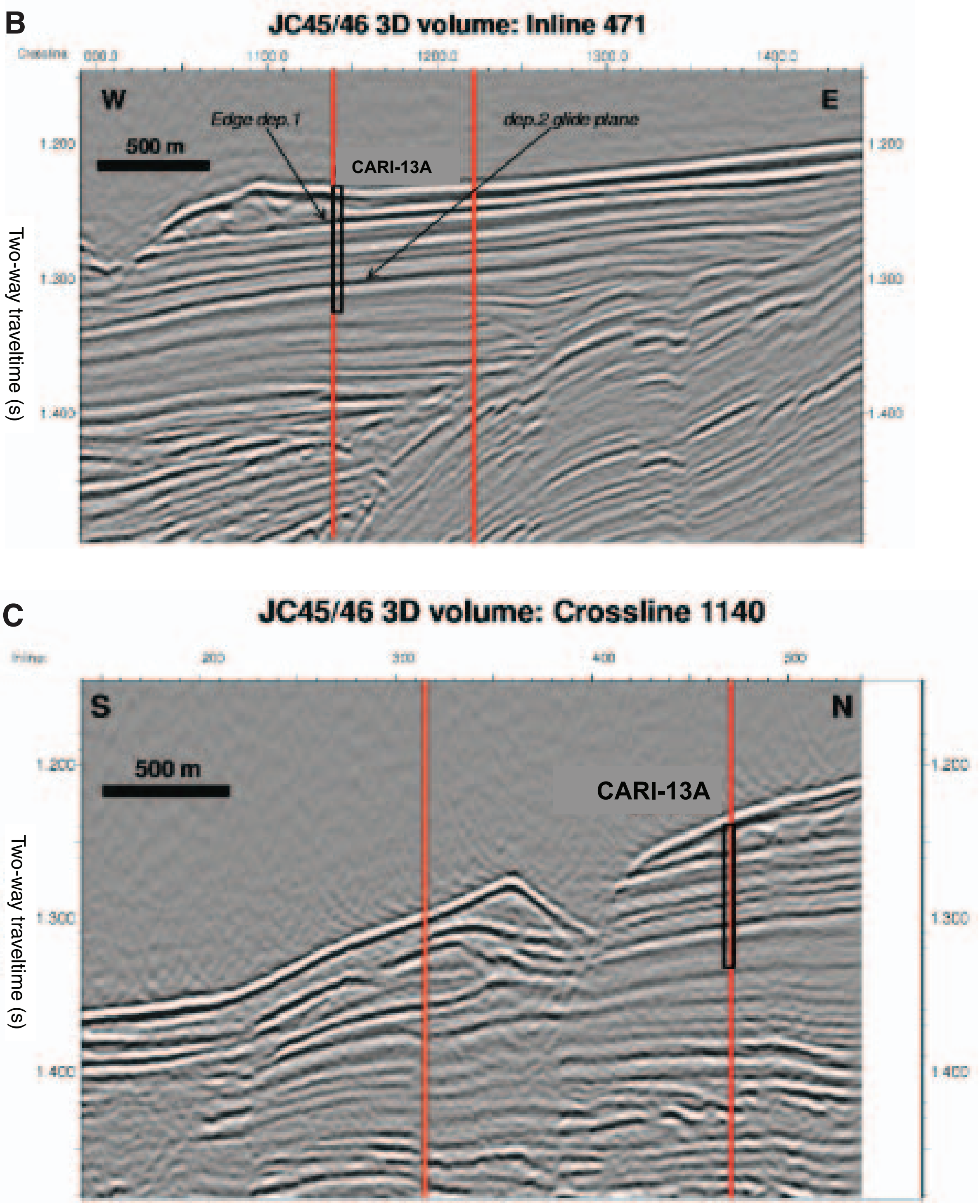


Figure AF14. **A.** Track map (50 m resolution, 10 m contour interval) for proposed alternate Site CARI-14A. (**Continued on next page.**)

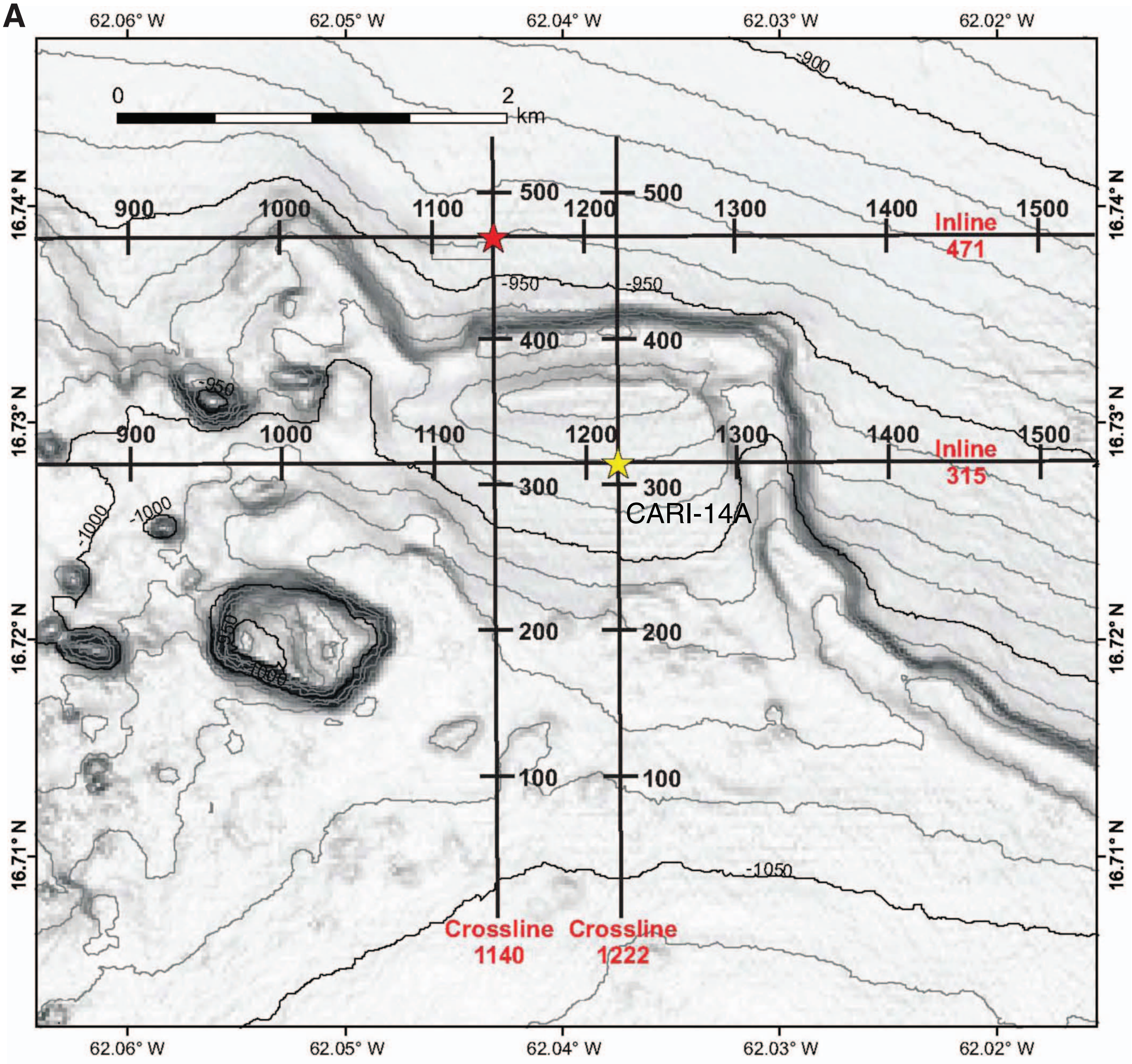
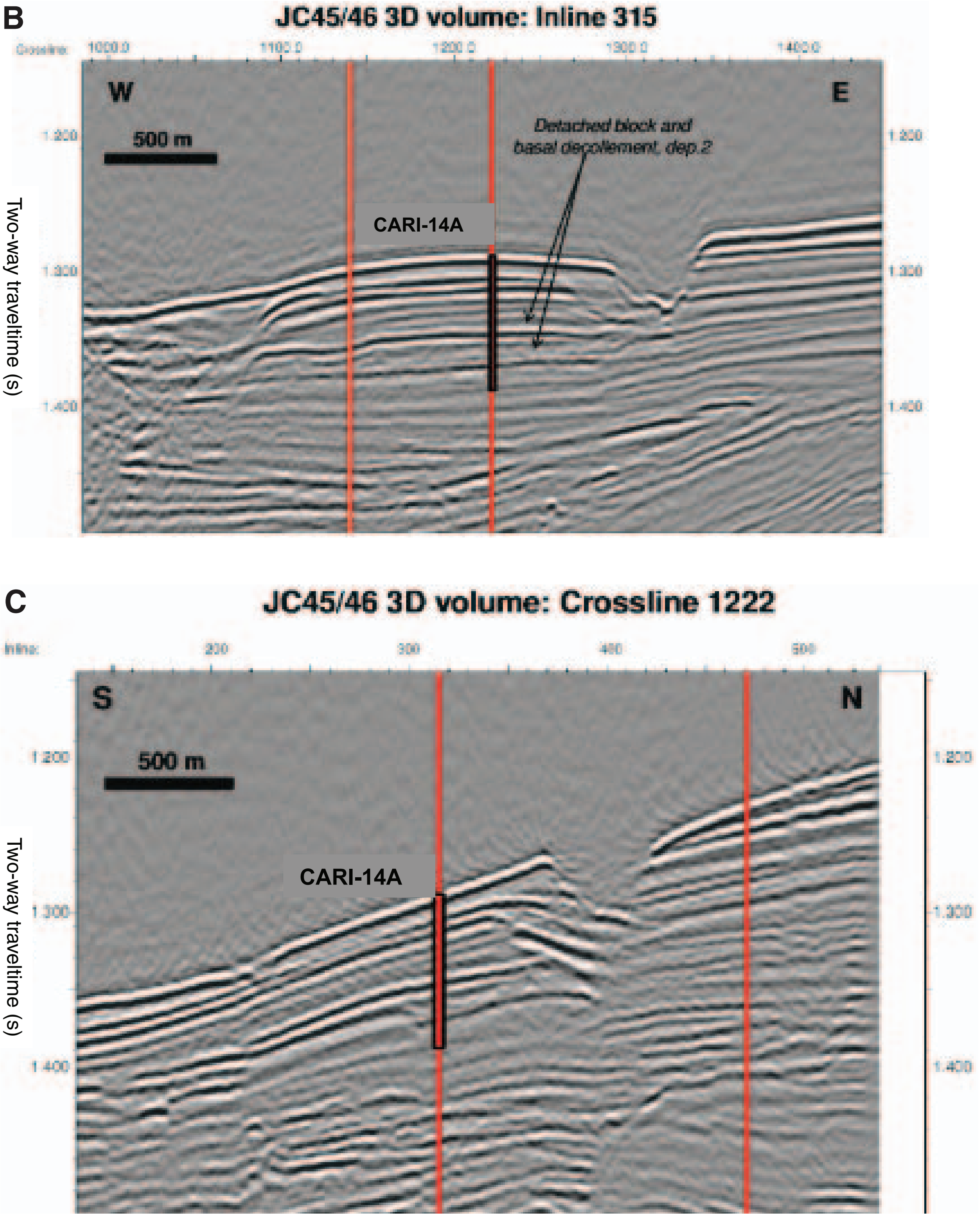


Figure AF14 (continued). B. Seismic Inline 315 (penetration 94 m) for Site CARI-14A from the JC 45/46 cruise. **C.** Seismic Crossline 1222 for Site CARI-14A.



Expedition scientists and scientific participants

The current list of participants for Expedition 340 can be found at **iodp.tamu.edu/scienceops/expeditions/antilles_volcanism_landslides.html.**