Mega-Depressions on the Cocos Ridge: Links Between Volcanism, Faults, Hydrothermal Circulation, and Dissolution

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Abstract High-resolution bathymetry and three-dimensional seismic data along the Cocos Ridge reveal a 245 km² field of ~1–4 km in diameter seafloor depressions. The seafloor depressions are part of a two-tiered honeycomb pattern. The lower-tier depressions have steep faults that truncate strata with chaotic internal reflections consistent with sediment collapse into the depression. These extend into a lens shaped interval just above igneous basement. Overlying these depressions is a second broader set with rough seafloor morphology with gently dipping boundaries defined by pinch-out stratigraphic patterns. Drilling results indicate that the lens-shaped zones that host the deeper depressions represent anomalous regions of high porosity, low velocity, and low density within calcareous rich sediment. Analysis of nannofossils from IODP Site U1414 suggests the collapse structures formed during the late Miocene, whereas the younger shallower depressions likely formed between the early Pliocene and the Pliocene-Pleistocene boundary. Geochemical and petrological analysis at Site U1414 suggests that hydrothermal circulation during the late Miocene led to carbonate dissolution and collapse. Following collapse, focused fluid-flow and bottom current scouring resulted in formation of the upper overlying set of depressions and a honeycomb seafloor morphology. Similar sets of depressions along the Carnegie Ridge to the south support the hypothesis that two-tiered depressions formed in response to processes that occurred broadly across the Panama Basin between the late Miocene and the Pliocene-Pleistocene transition. Geochemical results at Site U1414, combined with geophysical data, suggest this two-tiered system of depressions currently guides ongoing fluid outflow.

Plain Language Summary We characterize a vast field of mega seafloor depressions along the Cocos Ridge using three-dimensional geophysical data tied to drilling results. The mega depressions display distinct two-tiered structures that form a honeycomb-like pattern on the seafloor. By imaging faulting and sediment layers within the depressions, we reveal that the older, steeper-walled depressions formed through collapse processes whereas the younger, broader depressions likely formed through a combination of fluid-flow and current scouring. Drilling results indicate that the older collapses formed during the late Miocene, and geochemical results suggest that hydrothermal circulation, likely along ridge-parallel faults, dissolved carbonate-rich sediments and led to collapse. In contrast, drilling results suggest the younger depressions formed sometime between the Pliocene and Pliocene-Pleistocene boundary. Similar depressions imaged within the Panama Basin and along the Carnegie Ridge to the south suggest widespread Galapagos Hotspot volcanism and hydrothermal circulation led to dissolution and collapse of carbonate-rich sediments across the eastern equatorial Pacific. Fluid-flow through the existing collapses and water current activity following the closing of the Central American Seaway likely led to the formation of the younger depressions. Drilling results, seismic reflection indicators of fluid pathways, and indicators of seafloor seepage suggest these depressions are actively guiding fluid outflow.

1. Introduction
Circular-to-elliptical enclosed seafloor depressions are reported from continental margins and other marine environments throughout the world’s oceans. These features are often referred to as pockmarks, implying formation by sediment erosion from fluid-flow processes (Judd & Hovland, 2007). They range from tens of meters to several kilometers across and a few to more than a hundred meters deep, with the larger ones (typically >1 km
diameter) often referred to as mega-depressions or mega-pockmarks (e.g., Pilcher & Argent, 2007), but their origin is enigmatic. Almost all suggested origins involve movement of fluids and/or gas through the sedimentary section and bottom currents leading to erosional processes, but in unknown ways. Possible explanations include submarine dissolution (Bertoni & Cartwright, 2005; Lonsdale & Fornari, 1980; Michaud et al., 2005; Villinger et al., 2017), silica diagenesis (Davies, 2005), slope instability (Pilcher & Argent, 2007), a combination of fluid flow and bottom currents (Betzler et al., 2011; Michaud et al., 2018; Sun et al., 2011), thermogenic degassing related to volcanic activity (Collins et al., 2011), or destabilization of methane hydrate (Davy et al., 2010; Hill et al., 2004). These different processes have different implications for physical, chemical, mechanical, and thermal properties of the upper crust, as well as hydrogeology and the biosphere (Tryon et al., 2001).

Large, enclosed seafloor depressions have been noted from several geologic settings around the world's oceans (Judd & Hovland, 2007), including within the Guatemala Basin (Villinger et al., 2017) and along the Carnegie Ridge to the south (Michaud et al., 2005, 2018). Most enclosed depressions along continental margins are considered to originate through fluid flow resulting in the erosion of sediments (termed pockmarks); however, other enclosed seafloor depressions have been linked to collapse due to evaporite or dissolution processes (e.g., Bertoni & Cartwright, 2005; Michaud et al., 2005). Most regions with widespread seafloor depressions or pockmarks coincide with areas of thick, rapidly deposited sediments, such as continental margins where dewatering and degassing of biogenic-rich sediments is to be expected. However, regions of thin sediment cover, such as along the Carnegie Ridge and conjugate Cocos Ridge flank, the focus of this study, generally lack the thick sediment piles to drive this process.

This paper focuses on large, enclosed seafloor depressions seaward of the Middle America Trench (Figure 1). The depressions are imaged by three-dimensional (3D) seismic reflection and multibeam bathymetry data collected

Figure 1. Base map showing shaded bathymetric data of the study area located along the intersection of western edge of the Cocos Ridge and the Middle America Trench. Inset shows the regional location of the base map (red rectangle) and relevant tectonic features. Bathymetric grid made from the Global Multi-Resolution Topography (GMRT) synthesis (Ryan et al., 2009). Black polygon represents location of 3D seismic volume. Dashed red line denotes the approximate location of the Middle America Trench axis. Green arrow denotes convergence direction. Edge of the mega-depression field is denoted by the dashed white line. CA = Central America, GI = Galapagos Islands, MR = Malpelo Ridge, PB = Panama Basin, PFZ = Panama Fracture Zone, SA = South America.
offshore southern Costa Rica in 2011 and are part of a larger (∼1700 km²) field of depressions, located along the northwestern flank of the subducting Cocos Ridge (Figure 1). High-resolution multibeam and backscatter data illustrate the surface morphology of these features particularly well, and the 3D seismic data reveal the complex 3D structure and formation history of these features. We correlate our results to drilling data located within the 3D seismic volume (IODP Leg 344 Site U1414) and provide formation age estimates using an age model derived from nannofossil identification. We use seismic attribute analysis to map fault networks and fluid-pathways through the sedimentary section and discuss their relationship to the observed depressions.

The depressions can be divided into an upper and lower tier based on different morphologies, leading us to propose a multi-stage development process. We explore various formation mechanisms, that incorporate the structural and stratigraphic observations, along with recent geochemical analyses derived from Site U1414. We discuss differences in formation timing between the two depression types and compare our results to other studies of seafloor depressions located elsewhere, including along the Carnegie Ridge to the south and within the broader Panama Basin. Lastly, we discuss the implications of these results have for understanding the volcanic and hydrothermal history of the Cocos Ridge, the closing of the Central American Seaway, and ongoing fluid-flow through the two-tiered depressions as they approach the Middle American Trench.

2. Geologic Background

The Cocos Ridge (Figure 1) is presently colliding with Central America beneath the Osa Peninsula (Gardner et al., 1992; LaFemina et al., 2009), but the initial age of collision is not clear. The collision appears to be associated with thrusting in both the forearc (Sak et al., 2009) and backarc (Silver et al., 1990; Suarez et al., 1995) regions, and the forearc thrusting (Fila Costena thrust belt) appears to have taken up a large portion of the convergence since the end of the Pliocene (e.g., Morell et al., 2019). Abratis and Wörner (2001) pointed out that the end of calc-alkaline magmatism in southern Costa Rica was about 8 Ma, and they suggested that the Cocos Ridge collision was responsible for this change. Gräfe et al. (2002) dated uplift of the Talamanca Range and (together with estimated plate kinematics) suggested that initial collision of the Cocos Ridge occurred between 5.5 and 3.5 Ma. Based on plate reconstructions, Lonsdale and Klitgord (1978) suggested that the collision occurred at approximately 1 Ma. Using 3D seismic stratigraphy and drilling results, Edwards et al. (2018) concluded that a large erosional event along the submerged outer forearc occurred between 2.5 and 2.3 Ma and was driven by the migration of the Panama Fracture Zone that bounds the Cocos Ridge to the east (Figure 1).

The Cocos Ridge is part of a double hot spot trace, that, along with the Carnegie Ridge, formed over the Galápagos Hotspot (Hey & Vogt, 1977). The age of the seafloor beneath the Cocos Ridge as it collides with the front of the Osa Peninsula is between 15 and 17 Ma, based on interpretation of the magnetic anomaly pattern by Barckhausen et al. (2001) and dredging results (Werner et al., 1999). Seismic tomography shows that the Cocos Ridge is about 200 km wide and nearly 20 km thick (Sallarès et al., 2003; Walther, 2003), with most of that thickness in the lower crustal layer and extending to meet the Galapagos spreading center. Along the northwest edge of the Cocos Ridge, the upper crustal layer is thickened somewhat (Walther, 2003), and displays a highly reflective sub-horizontal layering in seismic reflection data, likely due to interbedded volcaniclastic rocks, flows, and sills (von Huene et al., 2000; Werner et al., 1999).

Four sites have been drilled on the Cocos Ridge. Site 158 (DSDP Leg 16) is located on the northern flank of the ridge, about 200 km from the trench, in 1953 m of water. The drilled section consisted of 322 m of nannofossil foraminiferal ooze and chalk, with scattered ash (van Andel et al., 1973). The section was underlain by basaltic flows. ODP Site 1242 (Figure 1) is in 1364 m of water and ~50 km from the intersection of the Cocos Ridge crest with the Middle America Trench. A 287.74 m thick sediment sequence was collected, spanning the middle Miocene to the Holocene with a prominent hiatus from ~2.5 to 12.0 Ma that separates younger nannofossil clays and clayey oozes from older diatom-bearing nannofossil ooze (Mix et al., 2003). Site 1381 (IODP Expedition 334) is situated in 2067 m of water and located 5 km from the trench axis (Figure 1) and the sedimentary section is 100 m thick and overlies pillow basalt (Vannucchi et al., 2012). Heat flow measurements encountered values higher (149 mW/m²) than the half-space prediction for crust of this age. Site U1414 (IODP Expedition 344) is positioned in 2457 m of water, approximately 2 km from the trench within the 3D seismic volume and the mega-depression field (Figure 1). The sedimentary section is ~375 m thick and is composed of hemipelagic silty clay to nannofossil-rich clay, calcareous and siliceous oozes, and siliceous cemented silt- and sandstone (Harris...
et al., 2013). Below the sedimentary section, drilling encountered basaltic flows interbedded with sediments (Harris et al., 2013).

South of the Cocos Ridge and along the northern flank of Carnegie Ridge, enclosed depressions seen in seismic profiles (Lonsdale, 1976, 1977) were hypothesized to have formed due to current-driven enhanced dissolution (Lonsdale & Fornari, 1980). Mayer, (1981) described erosional troughs in the equatorial Pacific and Michaud et al. (2005) also described large seafloor depressions on the flanks of the Carnegie Ridge using modern bathymetry and considered several alternative hypotheses to explain the formation of these features, including sediment creep, differential compaction above basement topography, subbottom currents, and subaerial and submarine dissolution. Michaud et al. (2005) argued against all options and concluded submarine dissolution to be the most likely formation mechanism. In a follow-up study, Michaud et al. (2018) concluded that the seafloor depressions formed through a combination of fluid-flow, carbonate dissolution and current scouring. Villinger et al. (2017) also concluded that large pits observed within the Guatemala Basin formed from hydrothermal venting and sediment dissolution. Conventional deep-water multibeam data (gridded at 100 m cell size) collected along the edge of Cocos Ridge revealed a coarse image of an expansive field of large seafloor depressions extending over 150 km seaward from the Middle America Trench (Figure 1). Near the trench, these depressions were imaged with high-resolution multibeam bathymetry and 3D seismic in 2011, and this region is the focus of this study (Figures 2 and 3). Additional conventional multibeam coverage across the Cocos Ridge revealed numerous other clusters of honeycomb-like seafloor depressions (Figure 1).

### 3. Geophysical Data and Methods

During the spring of 2011 we collected a 11 × 55 km grid of 3D seismic data onboard the R/V Marcus G. Langseth offshore southern Costa Rica as part of the Costa Rica Seismogenesis Project (CRISP; Bangs et al., 2018). The survey extended from the middle shelf region onto the western edge of the Cocos Ridge (Figure 1). Multibeam...
bathymetry and seafloor backscatter data were collected simultaneously, and coverage extended seaward of the 3D seismic survey due to wide ship turns and seismic equipment down times (Figure 2).

Taking advantage of the 300 m line spacing needed for 3D seismic acquisition, we constrained the receiver swath width of the pod-mounted EM122 1° × 1° 12 kHz deep-water sonar system to 1.4 km, resulting in an increase in sounding density across-track and along-track. In addition, these acquisition settings resulted in 4–5 times swath overlap at depths greater than 255 m below sea level (mbsl) within the 3D seismic survey region. On the Cocos Ridge, bathymetry data were gridded at 10 m and backscatter data were mosaicked at 10 m (Figure 2). Details of multibeam acquisition and processing methods are described in Appendix S1 of Kluesner et al. (2013).

The processing of the 3D seismic field data set was conducted at Repsol-CGG/Veritas in Madrid, and included: gain recovery, designature, low-cut filter, cascade swell-noise attenuation, geometry, shallow water demultiple, predictive tau-p deconvolution, antialiasing F-K filter, trace drop, geometry (12.25 × 18.75 m), 2D and 3D surface-related multiple elimination, Radon demultiple, velocity analysis, 3D amplitude destriping, 2-pass denoise in shot domain, and 3D regularization and interpolation. The enhanced data set was then stacked and migrated using an F-K migration. This produced a time-migrated 3D volume that is used for structural and stratigraphic interpretations in this study. In addition, a 3D Kirchhoff prestack depth migration algorithm and a velocity model build during the iterative process were used for depth imaging (Bangs et al., 2014). In this study, we used the time-migrated volume for mapping and interpreting the sedimentary section without distortions in frequency from depth stretching, but we used the depth-migrated volume for correlating reflections to drilling information at Site U1414 (Figure 4).

Using the OpendTect software package and associated plug-ins, we calculated advanced meta-attributes to detect and visualize probable faults and fluid-migration pathways on the Cocos Ridge. The workflow starts with calculating a dip-steered volume from the standard 3D seismic data that contains the local dip and azimuth of the seismic events at every sample position (Tingdahl, 1999; Tingdahl and De Rooij, 2005; Tingdahl et al., 2001). A dip-steered median filter is used to reduce randomly distributed noise and enhance laterally continuous events.
while preserving edges (Brouwer & Huck, 2011). Dip steering also improves single and multi-trace attribute calculations, providing better imaging of discontinuity features such as faults and gas chimneys (Tingdahl and De Rooij, 2005). For the chimney neural-network attribute calculations, we use specific attributes, such as vertical similarity and frequency attenuation, that highlight geologic features such as gas chimneys. A 3D meta-attribute volume is then calculated for the region of interest and then visualized for analysis and interpretation of fluid-pathways. Additional details on the chimney calculation are provided in the supplementary section and are described in Kluesner and Brothers (2016). In addition, we calculated the spectral decomposition along a key horizon mapped within the study area and the results were color-blended and projected along the horizon to provide visualization of subtle 3D frequency variations along the mapped horizon. Furthermore, the Thinned Fault Likelihood (TFL) attribute calculation is used within the region of interest to provide unbiased 3D mapping of faulting patterns within the sedimentary sections. TFL uses a semblance-based approach that scans over multiple strikes and dips to maximize the accuracy of fault mapping (Hale, 2013).

4. Results

Here we investigate the geomorphology and subsurface structure of mega-depressions imaged along the western edge of the Cocos Ridge, but that extend across a larger region. Our primary focus is on depressions located directly adjacent to the Middle America Trench that are imaged by both the 3D seismic data and high-resolution multibeam and can be directly tied to IODP Site U1414 (Figures 3 and 4).

4.1. Seafloor Depression Geomorphology

Along the western flank of the Cocos Ridge, we imaged a large cluster (245 km²) of 38 enclosed mega-depressions on the seafloor using high-resolution bathymetry and backscatter data (Figure 2). This group is part of a much larger field of depressions clustered between approximately 1800 to 2300 mbsl, along a narrow corridor (~10–14 km wide) that extends over 150 km seaward (southwest) of the Middle America Trench mapped on the regional multibeam bathymetry maps (Figure 1), but that possibly extend along much of Cocos and Carnegie Ridges. In the area with high resolution data, the diameters of the depressions vary from approximately 1 to 4 km. Relief ranges from ~20 to 90 m, with relief decreasing near the Middle America Trench due to increasing sediment infill (Figure 3). The imaged depression field exhibits a honeycomb-like pattern, forming a complicated matrix of large depressions separated by ridges (Figure 2).

On the seafloor, depressions commonly exhibit a two-tiered, merged morphology (Figures 3 and 4). Sidewalls of the upper-tier depressions show an average slope of 15°, whereas the deep-seated depressions below exhibit steeper sloped walls. The two-tiered morphologies can be clearly observed seaward of the trench where the
depressions are not buried by sediment (Figures 2 and 4). Depression shapes range from circular to elongate, with multiple depressions exhibiting a crescent shape and gullied walls (Figure 3). Numerous depressions show local highs or mounds near their centers (Figures 2 and 3), with some mounds reaching ~50 m in relief. High-backscatter strength is frequently observed along the base of the upper depression walls (Figures 2 and 4). In addition, small high-backscatter mounds that range from approximately 50 to 200 m across and up to 15 m in relief are present within a few depressions, most of which are located near the base of the walls of the depressions (e.g., Figure 4). Based on average depth, base diameter, and rim diameter observed on the seafloor, we computed the approximate volume of depressions over an area of 1700 km$^2$, finding an average depression volume of 0.08 km$^3$ and a density of 25 depressions per 100 km$^2$.

Upslope of the depression field along the Cocos Ridge are additional mega depressions (Figure 1). These depressions range from approximately 1.5 to 3.5 km across and some show up to ~160 m in relief. They are circular to elongate in shape and commonly show greatest relief along the western side. The circular rings of a few of the depressions overlap, and some of these form linear chains where multiple rings overlap. No subsurface imagery or high-resolution bathymetry were collected across these features.

### 4.2. IODP Drilling Results

Located ~2 km from the trench axis at 2457 mbsl (Figure 3), IODP Site U1414 drilled through the sedimentary section atop the western edge of the Cocos Ridge, penetrating the top of the igneous basement (Harris et al., 2013). Figure 5 shows the location and drilling results of Site U1414 along a prestack depth migration seismic inline for depth-to-depth correlation.

Lithology at Site U1414 is broken into three main sedimentary units and associated sub-units. These units include Unit I (0–145.34 mbsf) composed of silty clay/clay, Unit II (145.34–309.4 mbsf) dominated by calcareous...
eous and siliceous oozes, and Unit III (309.4–375.3 mbsf) consisting of calcareous and siliceous-cemented silt and sandstone (Figure 5). Below the sedimentary section are three units composed of massive basalt and intercalated sediment (Harris et al., 2013). The top igneous unit comprises a ~65 m sequence of basalt overlying a ~1.5 m section of indurated sediment. Flooring the sediment section is another massive basalt unit at least 30 m thick (Harris et al., 2013). Shipboard scientists suggested that the presence of partially recrystal-
ized sediment below the top igneous unit meant that the basalt was intruded as a sill, similar to ODP results offshore Nicoya Peninsula to the North (Kimura et al., 1997). A mean thermal conductivity of 0.89 W/(m-K) was measured between 0 and 85 mbsf, yielding a heat flow of 149 mW/m². In addition, the abundance of pyrite and carbonate within the upper portion of the igneous section and carbonate-bearing veins and silicates in the sediments directly above imply a history of lateral fluid flow at this boundary (Harris et al., 2013). Geochemical analyses of pore fluids further supported this interpretation; an atypical secondary sulfate concentration minimum was observed at ~330 mbsf, suggesting lateral flow of sulfate-depleted fluids and ongoing sulfate reduction within this interval. Shipboard scientists attributed low Ca concentrations observed within this inter-
val to a second carbonate diagenetic reaction zone and ongoing laterally migrating sulfate-depleted fluids (Figure 5; Harris et al., 2013).

Between 253 and 257 mbsf at Site U1414, P-wave velocities sharply decrease to below 1600 m/s, with a local minimum at ~255 mbsf. In addition, bulk density values decrease from 1.71 gm/cm³ at ~252 mbsf to 1.46 gm/ cm³ at ~256 mbsf. Furthermore, downhole logging recorded a rapid drop in density, resistivity, compressional velocity, and shear velocity centered at ~255 mbsf (Harris et al., 2013). Correlating these drilling results to the depth-migrated 3D seismic data indicates that a high-amplitude reverse polarity reflection (RPR) coincides with the velocity and density inversion observed at approximately 255 mbsf (Figure 5). The depth of the RPR also coincides with a sharp spike in porosity (Figure 5). The rapid recovery of velocities and decrease in porosity below the RPR coincides with a positive polarity cross-cutting reflection (CCR) imaged directly below the RPR and where this reflector cross-cuts the RPR (Figure 5).

Located to the southeast of Site U1414 above a basement high, Site U1381 was drilled at 2067 m water depth (Figure 1). Lithology at Site U1381 is broken into two sedimentary units (Unit I and Unit II), and Unit III consisting mainly of pillow basalts (Expedition 334 Harris et al., 2013). Unit I consists of greenish-gray soft clay sediment with minor layers of silty clay and tephra layers. Unit II is composed of dark grayish to yellowish brown clay and siliceous and calcareous ooze. Within Unit II the abundance of clay and calcareous components increase with depth. Geochemical analyses indicate lateral flow of altered seawater in the basement rocks and diffusional communication with the sediment column (Vannucchi et al., 2012). Heat flow was measured at 178 mW/m², which is significantly higher than the half-space predicted cooling model (77 mW/m²) for 15 Ma crust, indicating significant fluid-flow within the crust (Vannucchi et al., 2012).

### 4.3. Subsurface 3D Structure

Two different types of buried and partially buried depressions are present within the sedimentary section imaged by the 3D seismic volume. We refer to these structures as type A and B that together form two-tier, merged morphologies (Figure 4). Within the lower half of the sedimentary section are pit-like depressions that clearly truncate surrounding strata (Figure 6; type A). Reflectors within the type A depressions display a chaotic pattern. Three-dimensional horizon mapping reveals faults with normal offsets along the steep walls (Figure 7), like “ring faults” observed within volcanic collapses (Branney, 1995), karst sinkhole structures (Cunningham et al., 2018), and evaporate dissolution structures (Bertoni & Cartwright, 2005). Offsets across concentric faults step down toward the center of the depressions, indicating subsidence (Figure 7). The walls of the type A depressions typically show a continuous reflector with reverse polarity, indicating a negative impedance contrast along the depression wall (Figure 6).

Located above the type A depressions are larger diameter depressions that exhibit gently dipping walls (type B). An example of this relationship is shown on backscatter-draped bathymetry on Figure 4; Figure 6 shows an example of a type B depression located directly above an older type A depression that clearly truncates strata. In contrast, reflectors below the walls of the type B structures exhibit gentle convergence, or pinching-out patterns toward the depression walls (Figures 6 and 8). In addition, sediment infill of the type B depressions differs from that of type A, with clear, parallel onlapping reflectors exhibiting patterns typical of basin-fill stratigraphy.
(Figure 6). In some instances, local mound-shaped highs are present within the type B depressions, and these also show convergence or pinching toward the walls of the depressions (Figure 8). Lastly, smaller type A depressions are also scattered along a distinct high-amplitude reverse polarity reflector (RPR, Figure 6).

Throughout the southeastern portion of the seismic volume the RPR can be traced within the sedimentary section at approximately 80–100 m above the reflection marking the top of the igneous basement (Figures 3 and 8). The RPR and the positive polarity reflector equivalent (i.e., where polarity flips back to positive along the same surface) was mapped throughout the 3D region and this effect is shown on Figure 9. Once mapped, we employed spectral frequency decomposition to highlight regions of anomalous frequencies along this geological contact. This process blends red, blue, and green colors assigned to specific frequency bands. The blended result reveals the 3D spatial extent of the high-amplitude RPR, which is marked by a distinct light blue zone (Figure 9c). The RPR extends from the seaward edge of the survey to below the trench axis and decollement (Figures 3, 9c and 10). The RPR terminates at the walls of the larger type A depressions (e.g., Figures 6 and 8), which appear to be spatially tied to the RPR (Figure 9c). In other regions where the RPR terminates, or flips polarity, it is commonly intersected by low angle cross cutting reflectors (CCRs), which are characterized by positive polarity and moderate to high amplitudes (Figures 8 and 11). On horizontal time slices within the 3D seismic volume the observed CCRs are extensive and mostly linear, extending across the middle and western part of the 3D volume. In addition, the CCRs can be traced below the RPR and frequently form lens-like structures between the two. Figure 11 shows one of these lens zones along the flank of a depression structure and the internal reflector character is of low amplitude with minimal polarity variation.
4.4. Faulting and Fluid-Pathways

In addition to horizon mapping and manual fault picking, we calculated advanced attributes to delineate and visualize faulting patterns and probable fluid pathways within the sedimentary section. Using the attribute calculation Thinned Fault Likelihood (TFL; Hale, 2013), we were able to visualize faulting patterns along the mapped RPR horizon (Figure 9b). The attribute results reveal a series of Cocos Ridge parallel faults, which may be part of the system created during the formation of the large rift cresting Cocos Ridge near the trench (Figure 1). The mapped collapse structures (type A depressions) commonly abut against or intersect the ridge parallel faults (Figure 9b). The ridge parallel faults can also be seen bounding and intersecting partially buried depressions on the high-resolution bathymetry (Figure 3). These faults can also be clearly seen on the more regional-scale bathymetry maps (Figures 1 and 2) and bound the upslope limit of the larger field. Imaged scarps are up to 30 km in length and show offsets ranging from approximately 50 to 200 m. The large scarps form a left stepping, en echelon pattern, stepping toward the trench axis (Figure 1). The high-resolution bathymetric survey revealed linear patches of high-backscatter strength along the fault scarps (Figure 2). In addition, Figures 8, 10 and 11 show apparent offsets in the igneous basement section associated with ridge-parallel faulting. Furthermore, indications of fluid-flow such as stacked bright spots (Figure 11) and zones of reflector discontinuity (Figure 5) are frequently present within the sedimentary section above faulted basement highs. The well-layered igneous stratigraphy can be traced below the trench axis where it becomes further offset and tilted from plate-bending related faulting (Figure 10). In addition to the laterally continuous ridge-parallel and plate-bending faulting, smaller length and offset faults are present throughout the sedimentary section, such as those within the type A depressions (Figures 7 and 10).

In order to detect and map probable zones of fluid migration within the sedimentary section, we employed a neural network based chimney meta-attribute approach to the 3D seismic volume. This approach has previously been used in other geologic settings to characterize near-vertical fluid-migration pathways in sediments imaged with 3D seismic data (e.g., Brouwer et al., 2011; Kluesner & Brothers, 2016; Ligtenberg, 2005). Using this technique, we can evaluate probable fluid migration pathways associated with the observed depressions and faults. The chimney attribute results indicate numerous probable fluid-pathways, most of which are located along faults and rooted into and below the RPR (Figures 9 and 12a). Zones with high chimney probability are also clustered within the oldest depressions (type A), and along the edges of the RPR where the CCRs intersect the horizon (Figures 9b and 12a). Within both the older (type A) and younger (type B) depressions the attribute analysis suggests fluid migration is focused along the walls (e.g., Figure 12a). High backscatter features indicative of seafloor seepage are also observed along the depression walls on the seafloor, supporting this observation at depth (Figure 4).

5. Discussion

5.1. Depression Development

Both the 3D seismic and high-resolution multibeam datasets reveal that the mega-depressions often overlap with one another to form linear chains, exhibit a two-tiered structure and have a honeycomb morphology (e.g., Figures 5 and 6). The tiered features are composed of two fundamentally different types of depressions (type A and B), identified and categorized based on their age (depth below seafloor) and structural differences. Here we discuss these differences and propose a model of tiered development within the sedimentary section.

The oldest depressions (type A) are located near the base of the sedimentary section and are steeply walled features that truncate surrounding strata (Figure 6). The observed truncation, concentric faults, and chaotic infill suggests erosion from gas blowout or collapse, in contrast to surface erosional processes. Type A depressions are
co-located with and terminate against the RPR throughout the area imaged by the 3D seismic volume (Figures 6, 8 and 9). Below the RPR are positive polarity CCRs that represent the base of multiple lens-shaped features (Figure 11). The base of the type A depressions root into the lens-like zones (e.g., Figures 6 and 8). These zones can be traced throughout the region and are adjacent to the type A structures (Figure 11). In some regions the CCR rapidly shoals toward the RPR (Figure 6). Drilling results correlated to the prestack depth migrated seismic data indicate that the RPR represents a significant drop in measured density, compressional velocity, shear velocity, and resistivity, within the calcareous Unit II sediments, likely representing a region of significant void space. Conversely, the positive polarity CCR correlates to a rebound, or increase in density and velocity within the Unit II sediments (Figure 4). Sediments imaged between the RPR and CCRs (lenses) typically show little-to-no impedance contrast (Figure 11), suggesting a relatively homogenous low density, low velocity zone with abundant void space between the two reflector types.

The combination of truncated strata, observed “ring” faulting patterns, and chaotic infill within the type A depressions suggests the features formed due to collapse within the calcareous and siliceous ooze Unit II sediments sampled at Site U1414. This structural pattern is similar to that observed in other seismic reflection studies of evaporite and dissolution collapse structures (e.g., Bertoni & Cartwright, 2005; Jenyon, 1983). The type A depressions are tied to the anomalous section of low density and high porosity (lens between RPR and CCRs), with a large potential for volume loss, and thus collapse (Figure 5). The correlation of the seismic observations

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**Figure 9.** Four panels of perspective views showing the mapped reverse polarity horizon (RPR) horizon and attribute analyses. Site U1414 location denoted with vertical red line. (a) Mapped horizon along which the RPR is located, including the positive polarity equivalent. 2D seismic profiles are located near the edges of the 3D volume. (b) RPR horizon with thinned fault likelihood (TFL) calculated in black along the horizon showing probable faults. Neural network chimney analysis is projected along the same horizon showing zones of probable fluid-migration. Dashed red lines show edges of type A depressions (collapse features). Note extensive linear zones of ridge-parallel faulting associated with the type A depressions (c) Spectral decomposition revealing the main region of reverse polarity (light blue) outlined by the dashed blue lines. (d) Spectral decomposition with an additional crossline through the mapped region showing profile view of a type A depression near site U1414.
to the drilling results suggests diagenetic-dissolution processes likely led to the development of the void space and subsequent collapse. This process is akin to karst development in calcareous-rich rocks or polygonal faulting where porosity loss due to compaction or diagenesis causes desiccation-type faulting in regions without tectonic activity (e.g., Davies & Ireland, 2011). The likely dissolution process leading to the generation of the high porosity/high void space zone and subsequent collapse is discussed in detail in the Possible Origins section (5.2) below.
Type B depressions are located above the steep walls of the type A collapse structures (Figures 5, 6 and 10), forming a two-tiered morphology. Type B structures are significantly larger and broader than the type A collapses, lack evidence of concentric faulting, and surrounding strata gradually pinch-out against the gently dipping walls (Figure 6), suggesting that they formed through different mechanisms. Seismic bright spots, reverse polarity reflectors, and calculated probable fluid-pathways (chimneys) are common along type B depressions, suggesting they likely act as focused fluid pathways toward the seafloor (Figure 12). Non-uniform fluid-flow through the depressions, as suggested from the chimney attribute results (Figure 12), could lead to asymmetrical depositional patterns within the depressions through time. This process may help explain the observed crescent-shaped type B depressions (Figure 3), as deposition would occur where fluid-flow was absent or not as persistent through time. In addition, high backscatter patches and mounds are observed along the walls of the type B structures located farther away from the trench (Figure 5), and such anomalous features are consistent with seafloor fluid seepage (e.g., Judd & Hovland, 2007; Kluesner et al., 2013).

Alternatively, the morphologies and sedimentation patterns of the type B may reflect depositional patterns formed from current-driven erosional and sediment transport processes. For example, Sun et al. (2011) observed kilometer-scale mega-pockmarks in the South China Sea and determined that the features formed due to initial fluid-flow related pockmark formation, modified then by unstable bottom-water currents. In a follow-up study in the same broader region, Sun et al. (2017) concluded that a seafloor honeycomb pattern surrounding a seamount was caused by cut and fill processes related to unstable bottom water currents. Offshore New Zealand, Klaucke et al. (2018) proposed that giant elliptical-shaped depressions imaged along the Chatham Rise occurred because of scouring by strong water bottom currents for which diagenetic-driven fluid-flow may have created nucleation points. Central mounding (Figure 8) and the asymmetrical elliptical or elongated morphologies (Figure 3) of the type B pockmarks within this study are like observed sediment drift morphologies formed from bottom current flow within various drift types (e.g., Sun et al., 2017). Furthermore, kilometer-scale depressions exhibiting honeycomb-like morphologies have been observed along the Carnegie Ridge to the south (Lonsdale, 1975; Malfait, 1974; Michaud et al., 2005), and it has been suggested that strong water bottom currents scoured previously damaged sediments, enlarging older depressions and were forming a similar honeycomb-like pattern (Michaud et al., 2005, 2018). In addition, moat-like drift morphologies can be seen on the seafloor along the base of the Quepos Ridge to the west (Figure 1), suggesting a history of strong bottom water current flow in the region.

Based on our results and comparison to other studies of depressions with similar morphologies, we propose a depression structural evolution in which: (a) type A depressions form within calcareous and siliceous ooze sediments of Unit II due to dissolution and subsequent collapse between the RPR and CCR reflectors. (b) Following collapse, a possible combination of continued fluid-flow and current-driven processes leads to development of the type B depressions and the asymmetrical honeycomb-like morphologies observed on the seafloor. (c) The tiered depressions are rapidly buried as they near the Middle American Trench axis.

5.2. Possible Origins

Here we expand the discussion of the possible drivers responsible for the apparent dissolution and collapse and formation process of the two-tiered honeycomb pattern along the Cocos Ridge.

Several origins for mega-pockmarks and mega-depressions have been previously proposed on continental margins and sediment covered oceanic crust. Davies (2005) showed internal structure beneath mega-pockmarks/depressions formed by silica diagenesis using 3D seismic data collected on the northeastern Atlantic Margin. In contrast to sediment erosion leading to pockmark formation, Davies (2005) showed these pockmarks likely formed due to differential compaction and subsidence along the silica diagenesis front, resulting in large overlying circular...
depressions. This reaction was also tied to the initiation and propagation of polygonal fault arrays, which in turn control the observed pattern of subsidence (Davies & Ireland, 2011). The diagenetic front, which transitions from lower velocity/density Opal-A to higher velocity/density Opal-CT, was easily identified as a positive polarity BSR at depth, advancing up-section beneath pockmarks above (Davies, 2005). Although silica diagenesis is known to occur on the Cocos Ridge (e.g., van Andel et al., 1973), no clear Opal A-CT transition was recorded within Unit II at Site U1414 and 3D seismic data reveal no clear indications of an Opal transition, which typically produces a high-amplitude, positive polarity reflector that is laterally continuous and simulates the seafloor relief (Berndt et al., 2004). However, within Unit III, located directly above the igneous section (~310–375 mbsf, Figure 4), calcareous and siliceous cemented silt and sandstone was sampled that lacked biogenic material and contained calcite veins, indicating diagenetically modified sediments (Harris et al., 2013). A recent study of fluid inclusion petrology and microthermometry at Site U1414 suggested that advective heat transport effectuated lithification of Unit III and veins reveal that fluid flow occurred over several episodes, possibly up to recent times (Brandstätter et al., 2016). Although silica diagenesis is present within the lower part of Unit III, this is below the anomalous region of void space within Unit II and does not appear be directly tied to the observed pattern of type A collapses.

Another possible origin for collapse or pockmark formation on the Cocos Ridge is rapid gas expulsion, either as water vapor caused by volcanic intrusion, or as hydrocarbon gas, principally methane. If water vapor were the cause we would expect the base of the depressions to be at the top of the igneous crust or a sill, neither of which appears to be the case here. Hydrocarbon gas blowouts require significant accumulations of gas below a seal that breaches, or accumulation of gas hydrate that is destabilized by sea-level change and/or warming bottom water (Davy et al., 2010). The lack of a BSR within imaged sediments on the Cocos Ridge and absence of methane hydrate sampled at Site U1414 seems to preclude the hydrate hypothesis as well as the possibility of migration of significant methane-rich fluids from strata adjacent to the ridge (i.e., Stakes et al., 2002) as a gas source. Additionally, Collins et al. (2011) pointed out that the hydrate suggestion of Davy et al. (2010) was unlikely to be significant in water depths of 2 km or more, as the stability field of gas hydrate increases with pressure (depth). Although depressions are observed in shallower waters on the Cocos Ridge (Figure 1), the depression field that is the focus of this study occurs between 1800 and 2300 mbsl.

Offshore Florida, Land et al. (1995) and Land and Paull (2000) showed that onshore aquifers likely contributed to or were wholly responsible for the formation of dissolution sinkholes/karst, although these were only found in shallow waters. In the eastern Mediterranean Sea, Bertoni and Cartwright (2005) imaged large (1–4 km) circular depressions with “ring” faults similar to those observed in this study (Figure 7) and concluded evaporite dissolution driven by focused fluid-flow as the driving mechanism. Along the Carnegie Ridge south of the Cocos-Nazca spreading center, Michaud et al. (2005) documented 1–4 km wide and typically 100–400 m deep depressions between ~1500 and 2600 mbsl and evaluated five possible mechanisms to explain the large fields of depressions that are geomorphologically very similar and within approximately the same depth range as those identified in this study. These options were (a) sediment creep, 2) paleotopography of the volcanic basement, (c) bottom currents, (d) subaerial karst formation, and (e) marine carbonate dissolution. Michaud et al. (2005) proposed underwater dissolution as the most probable process to have formed the mega-depressions. A follow-up study by Michaud et al. (2018) suggested that the seafloor depressions initially formed through dissolution of carbonate sediments by movement of hydrothermal fluids, whereas strong water-bottom currents enlarged the initial depressions, producing a honeycomb seafloor pattern.
Moore et al. (2007), Bekins et al. (2007), Villinger et al. (2017), and Michaud et al. (2018) all suggested that within the equatorial Pacific Ocean the likely driver for sub-seafloor fluid-flow and sediment erosion is tied to hydrothermal circulation. The location and linear distribution of the two-tiered mega-depressions form a corridor along the western edge of the Cocos Ridge where there is extensive evidence of ridge-parallel faulting, with linear zones of high-backscatter associated with fault scarp observed on seafloor bathymetry (Figures 1 and 2). Such faulting might tap into deep crustal or upper mantle materials exposing them to seawater intrusion; seawater access to the crust could occur either through the faults or through nearby high-backscatter basement exposures on the Cocos Ridge (Figure 2). At Site U1414, Brandstätter et al. (2018) concluded the main source of fluids within sampled carbonate veins is from invaded seawater, modified into a hydrothermal fluid by subsequent heating, indicating hydrothermal circulation. Fluid inclusion analyses and isotope data indicate communication with deeply sourced, high-temperature hydrothermal fluids within the magmatic basement (Brandstätter et al., 2017). A lack of high-temperature alteration observed in the igneous section could be attributed to high fluid-flow rate, supported by the evidence of hydrofracturing in Unit III. Isotope analysis at Site U1414 indicates CO₂ rich fluid could have triggered hydrofracturing and vein formation (Brandstätter et al., 2018).

Bekins et al. (2007) concluded that observed seafloor depressions located above basement highs within the equatorial Pacific Ocean could have resulted from discharge of hydrothermal basement fluids that cooled to bottom water temperatures and became undersaturated with carbonate, thus leading to dissolution. Similarly, Villinger et al. (2017) observed high heat flow (up to 300 mW/m²) over pits observed in the Guatemala Basin and concluded a hydrothermal origin of the relic pits, where seamounts within the region provided cold seawater recharge. Hydrothermal circulation of CO₂ rich fluid within the sedimentary cover could provide the corrosive fluid-flow needed to lead to carbonate dissolution. Hydrothermal circulation with a permeable basement aquifer also provides a better fit of thermal models to the anomalous high heat flow values observed at drill Sites U1414 and U1381. However, as heat-flow values decrease away from the trench axis, it is possible that hot fluids released in the subduction zone migrate up-dip along the well stratified volcanic layering of the Cocos Ridge igneous crust (Harris et al., 2010; Hass & Harris, 2016). This process could be responsible for the geochemical indications of ongoing fluid-flow through the sedimentary section at Site U1414 (Harris et al., 2013), as well as the geophysical indicators observed within the 3D seismic (Figure 12a) and bathymetric/backscatter data (Figure 4).

Results from this study align best with the hypothesis of hydrothermal-driven subsurface fluid-flow leading to dissolution and collapse of carbonate sediments and formation of the type A depressions. We discount surface (seafloor), current-driven dissolution as the formation mechanism, as the 3D seismic data and results from Site U1414 support the hypothesis of lateral subsurface fluid-flow leading to carbonate dissolution, creation of void space, and subsequent collapse. Geochemical studies at Site U1414 indicate the main source of fluid as infiltrated seawater, modified into hydrothermal fluid by heating (Brandstätter et al., 2018). Ridge-parallel faulting along the Cocos Ridge supported by the large-scale faults revealed in the bathymetry, exposing basement at the seafloor across their up to 1 km tall walls (Figures 1 and 2). Faulting imaged within the igneous section, as seen in the 3D seismic volume (Figures 5, 9b, 11), suggests hydrothermal circulation occurred via crustal ridge faulting. This process appears to have led to hydrofracturing and diageneis at the base of the sedimentary cover (Unit III) and dissolution, creation of void space, and subsequent collapse of the overlying carbonate sediments (Unit II). Michaud et al. (2018) suggested that on the Carnegie Ridge, hydrothermal-driven hydrofracturing and diageneis of sediments above the basement led to the development of a polygonal network of faults and pits that underpin the observed honeycomb morphology. Most of the collapses are located along the long ridge-parallel faults (Figure 9b), which are likely acting as conduits for hydrothermal fluid-flow. Small offset polygonal faults could be present within the diagenetically altered Unit III sediments; however, this is not resolvable within the 3D seismic data (e.g., Figure 5).

The origin of the younger type B depressions is less clear. Still, seismic data and geochemical analysis from Site U1414 indicate fluid-flow occurs through the sedimentary unit. Fluid flow is also supported by high-backscatter features within depressions not buried from sediment coming off the subduction margin (Figure 4), which is consistent with seafloor seepage. These likely seepage indicators, in combination with subsurface chimney meta-attribute results (Figure 12), support focused fluid-flow through the depression structures. The increase in seafloor backscatter indicates the possible presence of carbonates and/or chemosynthetic communities, both of which commonly produce anomalous high-backscatter strength patterns on sonar images (Orange et al., 2010). This interpretation is also consistent with recent seafloor studies on the Costa Rican margin (Klaucke et al., 2008;
Klüsner et al., 2013; Sahling et al., 2008) and other numerous geoacoustic studies conducted around the world (Judd & Hovland, 2007). However, as observed along the Carnegie Ridge to the south (e.g., Michaud et al., 2018), drift-like patterns within and along the walls of the type B-equivalent depressions also suggest formation or modification from bottom-water current activity. This hypothesis is further supported by previous studies in the Panama Basin using current meters (Lonsdale, 1975), geophysical data (Lyle et al., 2000), submersible dive observations (Lonsdale & Fornari, 1980), and is discussed in more detail below.

5.3. Timing

Three-dimensional seismic data correlated to IODP site U1414 reveal that type A collapse structures formed sometime between the deposition of sedimentary Unit IIB and Unit IIA (Figure 5). There is a distinct change in the seismic character between these two sedimentary units, with Unit IIB exhibiting a stacked sequence of moderate impedance contrasts, consistent in magnitude and depth with the variations in density and porosity seen in drilling data through this interval (Figure 4). In contrast, Unit IIA shows gradual changes in density and porosity and exhibits low-impedance contrasts within the seismic data. The walls of the type A collapse structures extend up to the Unit IIB/IIA boundary, suggesting that the collapse structures formed during this period. Using the radiolarian nannofossil data from U1414 and other IODP drilling locations offshore Costa Rica, Sandoval et al. (2017) developed a radiolarian age model for Site U1414 and tied this model to existing calcareous nannofossil biozones for the region. The contact between Unit IIB and Unit IIA falls within the early portion calcareous nannofossil zone NN11 (Figure 5), which has been attributed to the late Miocene in the equatorial Pacific Ocean, approximately 8.5 to 5.5 My (Farida et al., 2012; Sandoval et al., 2017).

Fluid inclusion petrology and microstructural data from hydrothermal veins recovered from Site U1414 provide a tectono-magmatic history of the western Cocos Ridge, with initial formation occurring due to Galapagos Hotspot activity during the middle Miocene (Brandstätter et al., 2016, 2017). Brandstätter et al. (2017) proposed that a subsequent advective heating event occurred during the middle-to-late Miocene, likely from Galapagos Hotspot activity, and this isobaric heating event led to hydrofracturing and vein formation within the sedimentary cover. In addition, isotopic and elemental analysis of carbonate veins revealed hydrothermal circulation of hot, corrosive CO$_2$-rich fluid, which implies that after diagenesis and lithification of Unit III sediments, high temperatures derived from a shallow magma chamber or intrusive event further affected the Cocos Ridge basalts and sedimentary cover during the late Miocene (Brandstätter et al., 2018).

Silver et al. (2004) suggested that sill intrusion during the late Miocene (8–10 Ma) offshore northwestern Costa Rica was likely associated with widespread Galapagos Hotspot activity. This hotspot activity affects the Cocos-Nazca (Galapagos) spreading center in a 150–200 km long segment where Cocos and Carnegie Ridges are formed, and the intensity of the activity during crustal accretion (exemplified by thick crust) depends partially from the distance between spreading axis and the hotspot, which varies through time as the spreading center gradually migrates and approaches the trench, and eventually realigns closer to the hotspot by ridge jumps (Barckhausen et al., 2001, 2008). These ridge jumps likely created major disturbances in the volcanic evolution of the segment of formation of the Cocos and Nazca Ridges. It is well documented that hotspot-related intrusive magmatism and submarine volcanism spans a larger region than the spreading center producing thick crust (i.e., Cocos and Carnegie Ridges), and includes more distant areas of the flanks of the spreading center that were originally little affected during crustal accretion. Many of the intraplate volcanos to the northwest of Cocos Ridge have similar ages to the Cocos Ridge at the trench (12–14 Ma; Werner et al., 1999) even though the plate where they formed is older (14–23 Ma; Barckhausen et al., 2001, 2008). These results suggest magma-related hydrothermal activity occurred in a wider region and a longer time span than at normal spreading centers. Based on this history of widespread Galapagos Hotspot activity and the results from this study tied to Site U1414, we propose that hydrothermal circulation, driven by intraplate volcanism along the Cocos Ridge during the late Miocene (~8–6 Ma), resulted in sediment hydrofracturing, diagenesis, and movement of corrosive CO$_2$-rich fluid-flow through Units III and IIB, and this process led to sub-seafloor carbonate dissolution and formation of collapse structures (type A).

The formation timing of the secondary type B depressions is difficult to discern, as the drift-like pinching patterns observed along the walls of the depressions suggest these features potentially formed or were modified over an extended period. Site U1414 penetrated through the side wall of one of the type B depressions, and this contact aligns with the transition between the base of Units IB and the top of Unit IIA within the drilling results.
(Figure 4). Using the Site U1414 age model from Sandoval et al. (2017), this period aligns with the late Pliocene to the Pliocene-Pleistocene boundary. Although Site U1414 shows a well-preserved sedimentary sequence, a ∼8 m.y. hiatus was observed at nearby Site U1381 and Sandoval et al. (2017) suggested that this hiatus could indicate the closing of the Central American Seaway (CAS), dated to approximately 2.8 Ma (O’Dea et al., 2016), which led to a reorganization of circulation patterns in the area. A similar hiatus was observed at ODP Site 1242 located to the east along the intersection between the central portion of the Cocos Ridge and the Middle American Trench (Figure 1; Mix et al., 2003). Bathymetry collected across Site 1242 shows numerous enclosed depressions nearby, and a 2D seismic profile reveals erosional patterns within the depressions consistent with type B depressions observed in this study (Lyle et al., 2000). Mix et al. (2003) observed that the ∼9.5 m.y. hiatus (∼2.5–12 Ma) observed at Site 1242 was plausibly connected to the closing of the CAS. The 2.5 Ma upper limit of the hiatus at Site 1242 aligns approximately with the Pliocene-Pleistocene transition age of the base of Unit IA at Site U1414, which overlies the side of the type C depression (Figure 4). Similarly, Michaud et al. (2018) concluded that strong bottom currents occurring at the Pliocene-Pleistocene boundary, perhaps driven by the closing of the CAS, were responsible for carving the honeycomb morphology observed above pit-like depressions along the Carnegie Ridge to the south.

Three-dimensional chimney analysis (Figure 12a), bright spots, and high-backscatter features on the seafloor (Figure 5) indicate the type A and type B structures are acting as fluid pathways toward the seafloor. Geochemical porewater studies at Site U1414 also suggest ongoing lateral fluid-flow within Unit III (Harris et al., 2013), and this flow could be driven by ongoing hydrothermal circulation or up-dip migration of hot fluids along the subducting permeable crustal aquifer (Harris et al., 2010). In addition, analysis of hydrothermal veins at Site U1414 show that additional heat advection occurred in multiple stages since the middle Miocene (Brandstätter et al., 2016), and Ca and Li isotope data from porewaters indicate communication with high-temperature hydrothermal fluids ranging from ∼300 to 350°C. Although it is difficult to discern the impact fluid-flow had on the formation timing of the type B depressions, geophysical and geochemical data suggest this process is ongoing in the study region and utilizing the two-tiered depressions as fluid conduits toward the seafloor.

6. Conclusions

1. High-resolution multibeam bathymetry and 3D seismic data collected along the western edge of the Cocos Ridge imaged in unprecedented detail part of a large (∼10 × 150 km) field of mega-depression that extends to the Middle American Trench. The mega-depressions range from ∼1 to 4 km in diameter with 20–90 m in relief and form a honeycomb morphologic pattern. Two types of depressions are identified based on structural and temporal differences (a) circular, deep-seated, steep-walled depressions (type A) that truncate surrounding strata and (b) large diameter (typically >1 km) depressions (type B) that range from circular to elliptical and are located above the walls of the type A depressions. The depressions form a distinct two-tiered geomorphology and become increasingly buried as they approach the Middle American Trench.

2. Within the 3D volume, type A depressions are associated with lens-like zones bounded by a reverse polarity reflector (RPR) above, and positive polarity cross-cutting reflectors below (CCRs). Correlation of the RPR with IODP Site U1414 indicates the lens-like zones on the seismic imagery represent a zone of low velocity, low density, and high porosity within the calcareous-rich sediments of Unit II. Type A depressions show concentric normal faulting that resemble “ring faults” commonly attributed to roof subsidence in collapse structures. Chaotic infill patterns are observed within the type A depressions, and these are consistent with collapse infill. The walls of the larger diameter and younger type B depressions exhibit a pinching-out pattern, like that observed in sediment drift deposits. Neural-network chimney analysis and observed bright spots suggests the type A and type B depressions are acting as fluid conduits toward the seafloor. On the seafloor, high-backscatter features are observed near and along the walls of the type B depressions, and these are likely indicators of seafloor seepage.

3. We propose an evolution in the depression formation where: (a) type A depressions form from collapse within the low velocity/low density observed zone within calcareous and siliceous ooze sediment of Unit II. (b) Following collapse, focused fluid flow and bottom-current scouring results in the development of the type B depressions and outward growth through time, resulting in pinching-out patterns of surrounding strata, formation of middle highs or mounds, and ultimately the observed asymmetrical honeycomb-like seafloor morphologies. (c) The tiered depressions are rapidly buried as they near the Middle American Trench axis.
4. For type A depressions we prefer the formation mechanism of hydrothermal-driven, corrosive fluid-flow leading to dissolution and collapse of carbonate sediments within Unit II. Geochemical studies at Site U1414 indicate the main source of fluid as infiltrated seawater, modified into hydrothermal fluid by heating. Faulting imaged on bathymetry and within the 3D seismic volume, along with heat flow data at Site U1414, suggests hydrothermal circulation occurred via faulting approximately parallel to the Cocos Ridge. This process appears to have led to the delivery of warm, CO₂-rich hydrothermal fluids to the base of the sedimentary cover, resulting in hydrofracturing, diagenetic alteration, and dissolution and collapse of carbonate sediments. Correlation to a nannofossil age model at Site U1414 suggests the collapse structures formed sometime during the late Miocene, and geochemical studies suggest widespread intraplate volcanism related to the Galapagos Hotspot occurred along the Cocos Ridge during the late Miocene, leading to hydrothermal circulation.

5. Based on results from this study we propose the secondary type B depressions formed from a combination of ongoing fluid-flow through the collapse structures and bottom-water current scouring. Initial formation timing is less clear; however, it is likely that current scouring was initiated or strengthened by the closing of the Central American Seaway (CAS) during the Pliocene-Pleistocene transition, resulting in the reorganization of bottom-water currents. Site U1414 drilled through the side of a type B depression, and this site approximately aligns with the late Pliocene to the Pliocene-Pleistocene boundary. This timing is also consistent with the 2.5 Ma upper limit of the erosional hiatus observed at ODP Site 1242, located along the intersection between the central portion of the Cocos Ridge and the Middle American Trench.

6. Comparison to other studies along the Carnegie Ridge (Michaud et al., 2005, 2018) and the broader Panama Basin (Lonsdale, 1975; Lonsdale & Fornari, 1980; Lyle et al., 2000) indicates the formation of the two-tiered depressions is widespread across the eastern equatorial Pacific Ocean. This further supports the interpretation of widespread hydrothermal fluid-flow related to far-reaching Galapagos Hotspot volcanism, along with strong bottom-water current activity likely related to the closing of the CAS, as suggested by Michaud et al., 2018.

7. Geochemical results from Site U1414 indicate that lateral fluid-flow is ongoing through the base of the sedimentary section, and geophysical data indicate the two-tiered depressions are acting as conduits toward the seafloor. This process is likely due to ongoing hydrothermal circulation or up-dip migration of hot fluids along the subducting, permeable igneous aquifer of the Cocos Ridge.

Data Availability Statement
The 3D seismic volume used for this study is hosted in the data repository at http://www.marine-geo.org/collections, with identifier https://doi.org/10.1594/IEDA/500204. The bathymetric data are available at https://doi.org/10.1594/IEDA/321022 and the backscatter data are available at https://doi.org/10.1594/IEDA/321024.

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