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Large enigmatic crater structures offshore southern California

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SUMMARY

Digital mosaics of swath and conventional bathymetry data reveal large, distinct near-circular crater structures in the Inner Continental Borderland offshore southern California. Two have maximum crater diameters that exceed 30 km and a third has a crater diameter of approximately 12 km. All three features exhibit the morphology of large complex craters (raised outer rim, ring moat and central uplift) yet their exact origin remains a mystery. Preliminary analyses of available seismic, gravity and magnetic data over these structures reveal both similarities and distinct differences in geometry, structure and geophysical signature to known impact sites. All three crater structures, however, occur within the Catalina terrane, a highly extended volcanic and metamorphic province floored by Catalina schist basement. A likely alternative origin may thus involve explosive volcanism, caldera collapse and resurgent magmatism, and/or possibly plutonism and schist remobilization associated with the Catalina terrane. No single model for crater formation, whether impact, caldera or pluton, fully accounts for all of the present observations regarding the morphology, internal structure and known geology of these near-circular features. Timing of crater formation post-dates the initial rifting and rotation of the western Transverse Ranges, and appears to predate major right slip along the San Clemente and San Diego Trough fault systems—or approximately 18 to 16 Ma. Regardless of their origin, these complex craters represent some of the largest structures of their kind in western North America and provide a unique opportunity to better understand the development of unusual crater structures in a submarine environment.

Key words: caldera, California margin geology, crater, diapirism, impact, volcanic structure.

1 INTRODUCTION

On the Earth, few geological processes are capable of forming large, near-circular complex crater structures that exhibit a raised central peak, annular depression and distinct outer rim (e.g. French 1998; Grieve 1998; Stewart 2003). Salt, shale and sand diapirs with associated withdrawal ring synclines can produce geomorphic features that resemble complex crater structures, but these are typically small in size (<5 km). Resurgent calderas associated with explosive volcanism can produce complex crater structures, but those with diameters larger than 10 km are rare, especially in a submarine environment, and typically exhibit significant asymmetry at sizes larger than approximately 20 km in diameter. Eroded plutons can be quite large and near-circular, however, pluton geomorphology is not normally associated with annular depressions and raised outer rims. The most common crater formation process, especially for very large (>30 km) near-circular complex crater structures is bolide impact (Melosh 1989; Pilkington & Grieve 1992; French 1998; Stewart 2003), although to date most confirmed large impact sites are on land, where crater morphology is often poorly preserved as a result of subsequent tectonism, erosion, or burial.

In the Inner Continental Borderland offshore southern California (Fig. 1), new bathymetric maps, compiled from dense grids of conventional echo-sounding (NOS 1999) and multibeam bathymetry data (Goldfinger *et al.* 2000), reveal at least three large, distinct near-circular features (Fig. 2). Two have maximum diameters that exceed 30 km and a third has a diameter of approximately 12 km. These features exhibit the classic morphology of large complex crater structures, including a domal central uplift, a raised outer rim and an intervening annular depression or ring moat (e.g. Fig. 3). All three structures occur within the Catalina terrane (Fig. 1), a highly extended volcanic and metamorphic province floored by Catalina schist basement. The schist basement was uplifted and exposed during early Miocene oblique extension of the continental margin associated with the rifting and rotation of the western Transverse Ranges province (Crouch & Suppe 1993; Nicholson *et al.* 1994).

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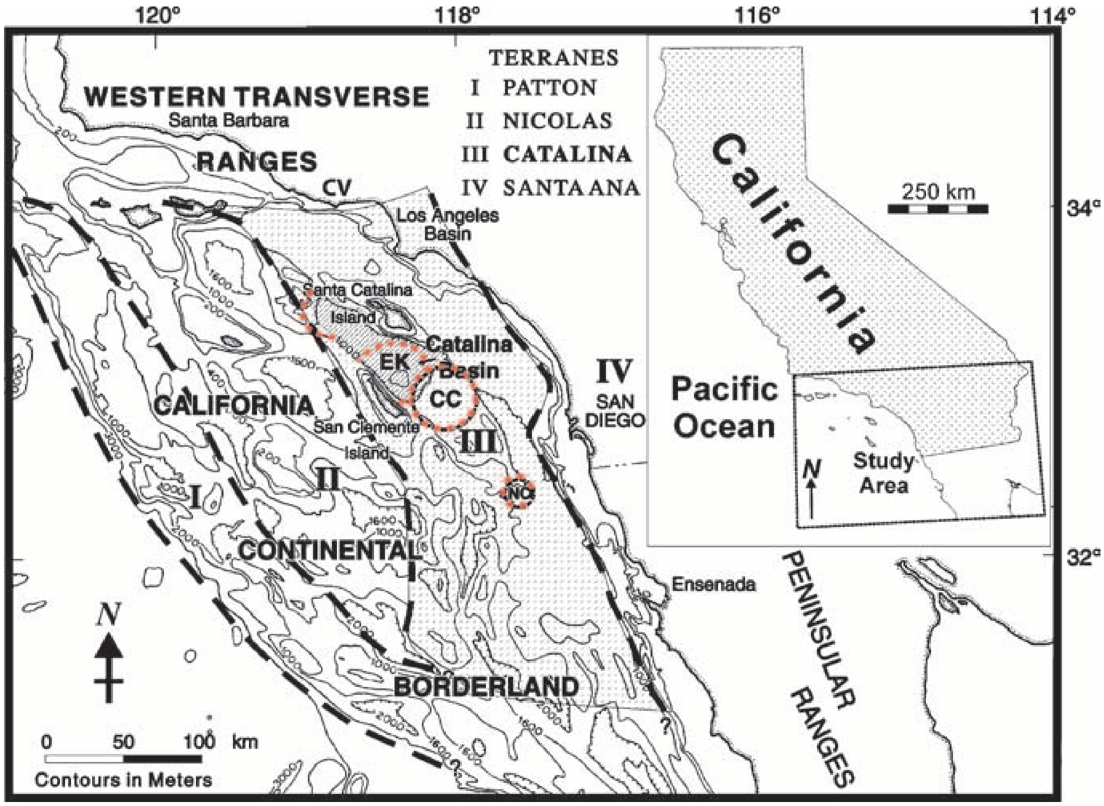

Figure 1. Regional tectonostratigraphic terranes of the California Borderland (after Howell & Vedder 1981). Catalina Crater (CC); Emery Knoll Crater (EK); Navy Crater (NC); Conejo Volcanics (CV) associated with mid-Miocene caldera formation (Weigand *et al.* 2002). The Catalina terrace is lightly shaded; Catalina Basin has darker shading.

Here we present some of the geological, geomorphic and geophysical characteristics of these submarine structures. More importantly, we present how each of the currently accepted models for large complex crater formation (impact, resurgent caldera, diapir, pluton, etc.) appears to be inconsistent with certain key observations, or the absence of certain diagnostic features, that would be expected if these structures are of impact, volcanic or diapiric origin.

2 CATALINA, EMERY KNOLL AND NAVY CRATERS

The most prominent and well defined of these offshore structures is located just east of San Clemente island at the southeast end of Catalina Basin (Fig. 2a). Because this feature exhibits the morphology of a large complex crater structure (Fig. 3), we call this feature Catalina Crater. The maximum diameter of the Catalina Crater rim is approximately 32 km. Bathymetric relief between the 7 to 8 km wide central uplift and the adjacent moat seafloor is approximately 400 m. In places, the outer rim rises ∼110 m above the moat and ∼400 m above the adjacent Catalina Basin seafloor. There also appears to be a small, 15-km-wide, circular depression that disrupts the southern rim.

Seismic profiles show that Catalina Crater deforms the regional Catalina schist basement (Fig. 4) (Moore & Beyer 1975; Bohannon & Geist 1998). The crater structure lies entirely between the San Clemente fault (Vedder *et al.* 1986) and the Thirtymile Bank detachment fault (Legg *et al.* 1992) on what appears to be a raised regional plateau whose elevation decreases towards Catalina Basin (Fig. 2a). The structural relief of the crater exceeds its bathymetric expression, as in places the annular depression contains more than 800 m of stratified fill (inferred middle Miocene and younger strata, Fig. 4). A possible breccia or other deposit may also fill the deeper moat areas. Seafloor samples from the area include Pliocene and Quaternary sediments, middle Miocene volcanic and sedimentary rocks, and metamorphic rock fragments of the Catalina schist basement (Fig. 5) (Junger & Vedder 1980; Vedder 1990). The annular basin is asymmetric and deeper on the east side, whereas the western rim is broader and shallower (Fig. 4). The maximum fill depth would be approximately 1.6–1.8 km assuming an average velocity of 2.2 km s^{-1}. Normal and reverse separation faults of moderate dips and some high-angle inferred strike-slip faults disrupt the moat fill and truncate the central uplift. Subsequent shortening of moat strata is responsible for at least some of the observed structural relief and continues to deform the seafloor. The relative flat top of the central uplift and outer rim suggests subsequent bevelling by wave action, implying that the overall structure has likely subsided, as it is presently hundreds of metres deeper than known eustatic sea level lowstands.

A second structure, Emery Knoll, consists of a subcircular uplift, approximately 13 km wide and 500 m high, located northwest of Catalina Crater (Fig. 2a). Emery Knoll is ringed by a set of mapped faults (Fig. 2a) (Junger & Vedder 1980; Vedder *et al.* 1986) within a well-defined circular moat filled with middle Miocene and younger deposits (Fig. 5) (Junger & Sylvester 1979) and what looks like a mostly buried outer rim truncated by the San Clemente fault. Seismic reflection and refraction data across this crater structure image in cross-section the buried symmetric annular depression and outer rim (Fig. 6) (ten Brink *et al.* 2000). The missing southwest

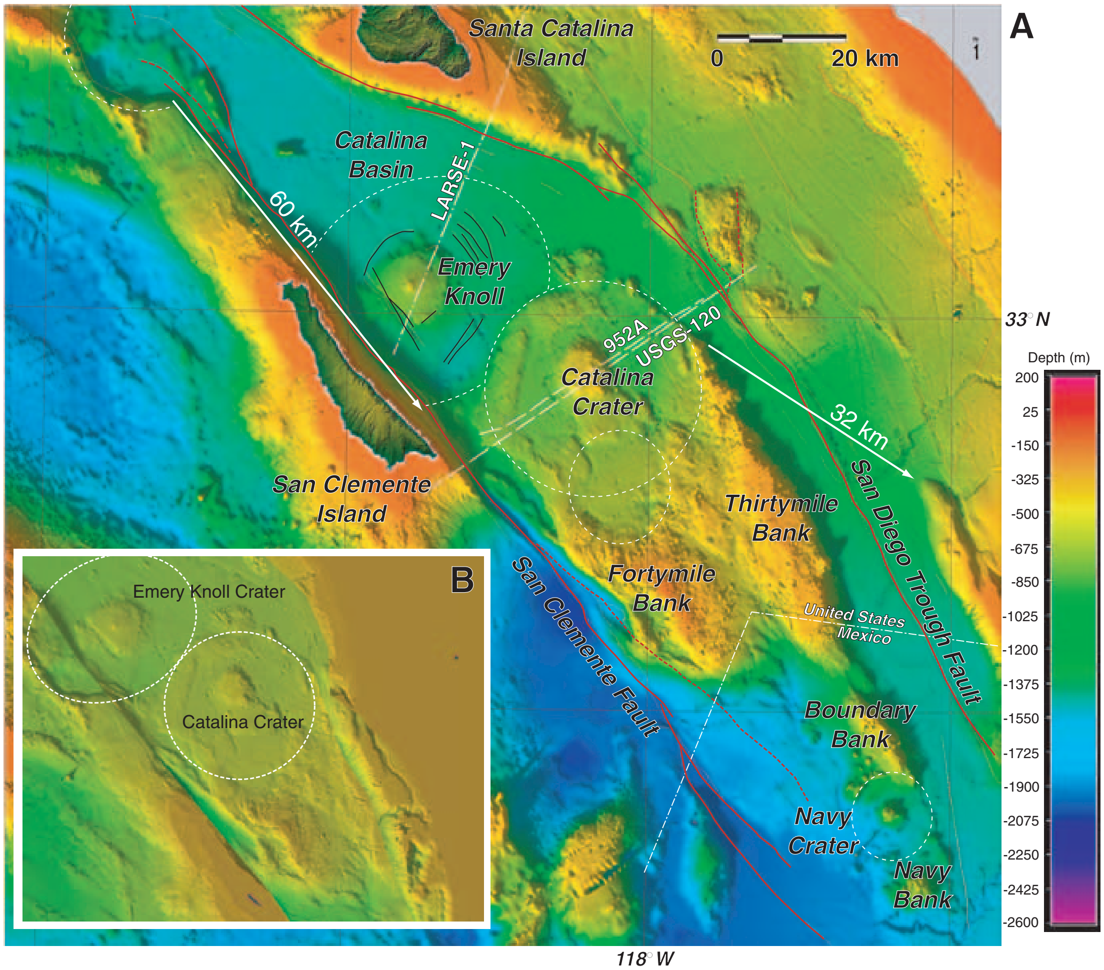

Figure 2. (a) Shaded relief bathymetry of Inner California Borderland showing location of inferred crater structures (white), active faults (red), older faults (black) and white displacement vectors used to create palinspastic map shown in (b) (Legg *et al.* 2002). Dashed circles outline inferred crater outer rims and a possible secondary feature that overlaps Catalina Crater to the south. Note ring fault segments around Emery Knoll mapped by Junger & Vedder (1980) and Vedder *et al.* (1986). (b) Palinspastic reconstruction after 60 km of right slip along San Clemente fault and 32 km of right oblique extension across San Diego Trough have been removed. After reconstruction, the inferred western outer rim of Emery Knoll Crater is restored.

segment of the crater outer rim is still visible, offset approximately 60 km to the northwest (Fig. 2a), as expected for right slip along the San Clemente fault (Legg *et al.* 1989). Palinspastic reconstruction of regional bathymetry restores the complete near-circular crater structure once this offset along the fault is removed (Fig. 2b). This reconstruction reinforces the interpretation that Emery Knoll itself is the central uplift of a much larger near-circular crater structure and that crater formation pre-dates major right slip on the San Clemente fault. Maximum diameter of the reconstructed Emery Knoll Crater is approximately 37 km.

A third subcircular structure, Navy Crater, is centred approximately 60 km southeast of Catalina Crater near Navy Bank (Fig. 2a). Navy Crater has an ∼4-km-wide central uplift, approximately 400 m high, and an annular moat with a partial outer rim forming a maximum crater diameter of ∼12 km (Fig. 7). The eastern and western segments of the outer rim appear to be breached and eroded, whereas a well-defined arcuate scarp remains as part of the north to northwestern rim. Navy Crater, like Catalina Crater, forms a subcircular depression in the otherwise elevated regional basement uplift, represented here to the south by Boundary Bank and Navy Bank (Fig. 7). All three near-circular structures (Catalina, Emery Knoll and Navy craters) thus resemble volcanic or impact craters observed on Earth (Melosh 1989; Grieve & Pilkington 1996; French 1998; Thouret 1999) or other planetary bodies (e.g. Shoemaker 1962; Pike 1980; Herrick & Forsberg 1998; Bottke *et al.* 2000).

3 REGIONAL GEOLOGY, TECTONICS AND EVENT TIMING

All three crater structures are located along the northwest-trending axis of the Inner Borderland Rift, an inferred regionally extensive metamorphic core complex of the Catalina terrane (Fig. 1) (e.g. Howell & Vedder 1981; Crouch & Suppe 1993). Catalina Schist basement was exhumed during early to middle Miocene oblique extension, as the Pacific—North America transform plate boundary evolved, and the western Transverse Ranges rifted and rotated away from the mainland coast (Kamerling & Luyendyk 1985; Nicholson *et al.* 1994). Because the craters lie entirely within the Inner Borderland Rift, their age must post-date the initial rifting and at least 40 km of subsequent extension. Major rifting in this area likely initiated just after chron C6, or approximately 19 Ma (Lonsdale 1991; Nicholson *et al.* 1994; Atwater & Stock 1998). Rift timing is

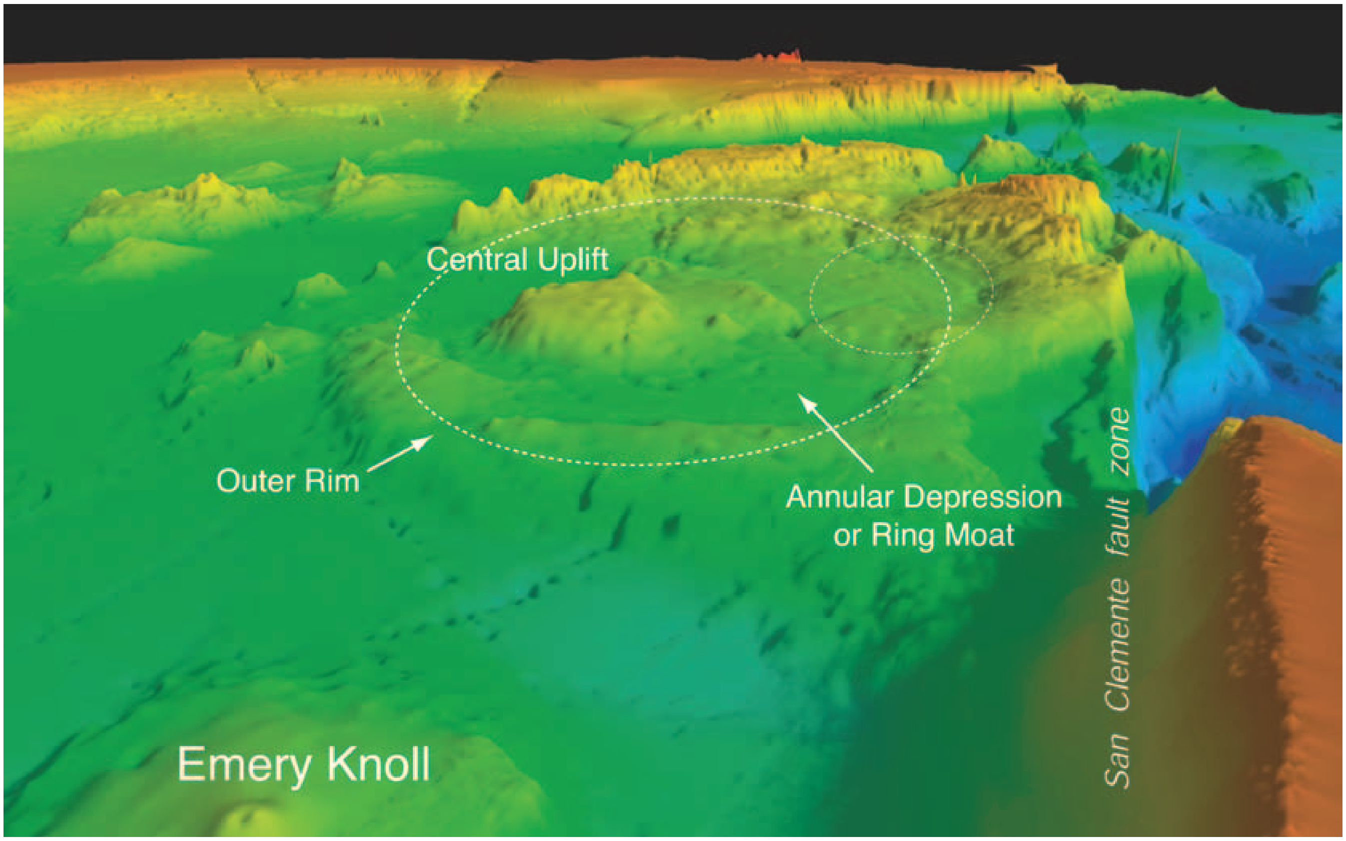

Figure 3. Oblique 3-D view of shaded bathymetry looking southeast across Catalina Crater. Crater morphology, including central uplift, ring moat and raised outer rim (large dashed circle), resembles that of a resurgent caldera or complex oblique impact structure. Possible secondary crater structure overlaps the south rim (small dashed circle).

controlled stratigraphically by the presence of the regionally distributed San Onofre breccia containing Catalina schist detritus (Stuart 1979) and the onset of widespread rift volcanism (Vedder *et al.* 1974; Weigand 1994; Weigand *et al.* 2002). $^{40}Ar/^{39}Ar$ ages of earliest rift-related volcanic rocks in the Inner Borderland are approximately 18–19 Ma (Luyendyk *et al.* 1998). Formation of these crater structures must thus post-date approximately 18 Ma.

Truncation of the crater margins by right slip on high-angle faults provides estimates of both cumulative fault offsets and a minimum age of crater formation. As mentioned, removal of ~60 km of dextral slip on the San Clemente fault restores the inferred western moat and outer rim of Emery Knoll Crater (Fig. 2b) (Legg *et al.* 2002). Independent estimates of cumulative offset of the San Clemente fault made prior to the discovery of the possible crater structures also total approximately 60 km (Goldfinger *et al.* 2000). Removal of an additional 32 km of oblique extension across San Diego Trough juxtaposes Thirtymile Bank against Coronado Bank (Fig. 2b), and positions Catalina and Navy craters as possible sources for volcanic and volcaniclastic rocks in the middle Miocene Rosarito Beach basin (Legg 1991). Radiometric ages of basalt flows on San Clemente island offset by the San Clemente fault are 14.5–16 Ma and on the adjacent Baja California coast are 15.5–16.2 Ma (Luyendyk *et al.* 1998). Thus, crater formation most likely occurred between approximately 16 to 18 Ma. Coincidentally, sample ages that bracket the Santa Cruz Island volcanics are approximately 16.3–17.0 Ma and intrusive rocks on Santa Rosa Island are approximately 18.1 Ma (Luyendyk *et al.* 1998).

4 POSSIBLE ORIGINS OF CATALINA, EMERY KNOLL AND NAVY CRATERS

Large-scale features associated with intense deformation in a circular pattern can arise from endogenetic processes, in which some igneous, metamorphic, or tectonic activity may be involved; or exogenetic processes, involving asteroidal or cometary impacts (French 1990; Stewart 2003). While the origins of Catalina, Emery Knoll and Navy craters remain uncertain, their morphology, size and structure are consistent, at least to some extent, with: (i) resurgent calderas associated with explosive volcanism; (ii) schist remobilization associated with possible plutonic activity; or (iii) impact structures from hypervelocity impacts into the exhumed Catalina schist basement. While distinct, these three hypotheses are not mutually exclusive. Impacts can occur within volcanic provinces (e.g. Barringer Crater), and impacts can be associated with subsequent volcanic activity (e.g. Sudbury Crater). Therefore, different processes or elements of more than one process may have formed each crater structure.

4.1 Caldera from siliceous volcanism

If the craters represent large resurgent caldera systems (Smith & Bailey 1968), then they most resemble the Valles type described by Williams & McBirney (1979). Resurgent domes of large calderas can rise several hundred metres from the crater floor, like the central uplifts of Catalina Crater, Navy Crater and Emery Knoll. Siliceous magmatism and caldera formation is broadly related to large magnitude crustal extension in other areas of the Cordillera (Armstrong &

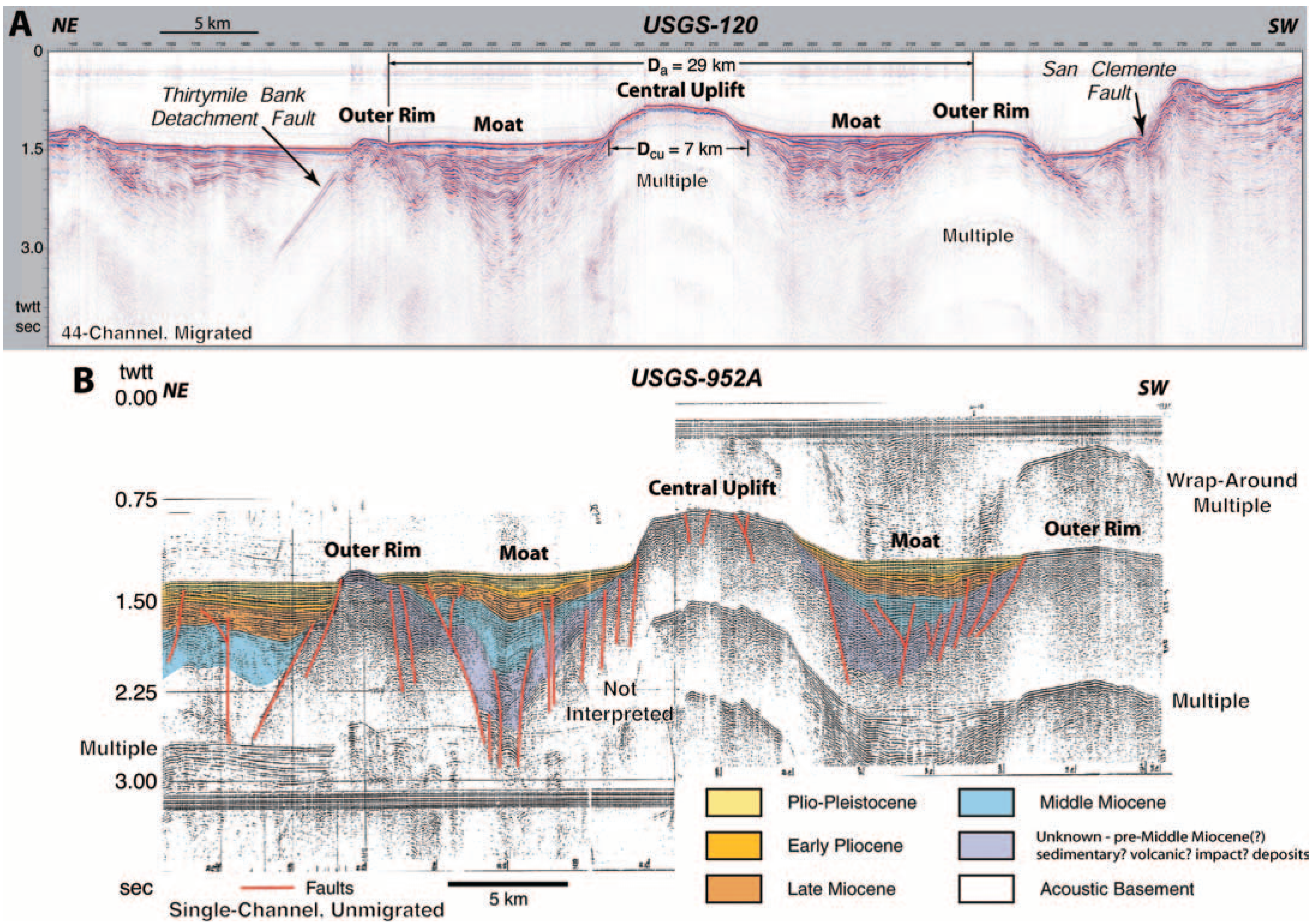

Figure 4. (a) Uninterpreted multichannel seismic time section USGS-120 and (b) interpreted single-channel seismic time section USGS-952A across Catalina Crater. Data in (a) reprocessed from Bohannon & Geist (1998). Data in (b) from Moore & Beyer (1975); stratigraphic interpretation after Junger & Vedder (1980). Line locations shown in Fig. 2(a). Note general asymmetry, and deposits of unknown age and origin (light purple) imaged as part of the deeper moat fill (b). Moat strata are folded, suggesting some structural relief may be related to later compressive overprint. Depth of moat fill is inferred assuming an average sediment velocity of 2200 m s^{-1}.

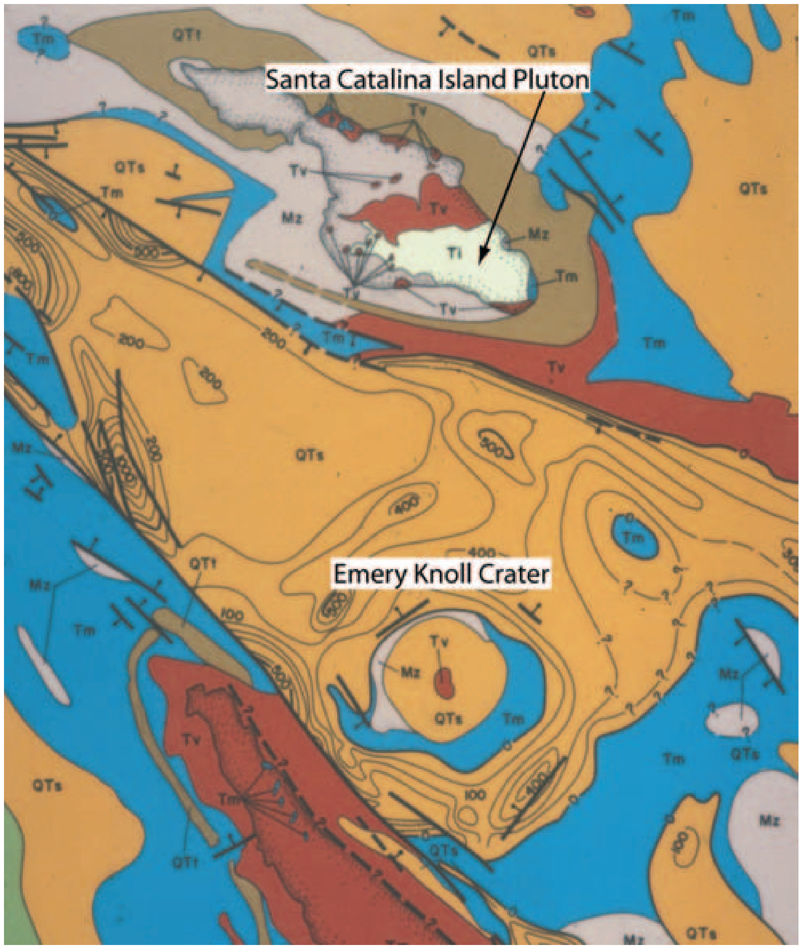

Figure 5. Seafloor geological map of Emery Knoll and surrounding Catalina Basin area (after Junger & Sylvester 1979) showing uplifted Catalina Schist basement (grey—Mz), Miocene volcanics (red—Tv), Miocene sediments (blue—Tm) and younger sequences (yellow and brown—QT). Igneous intrusion (white—Ti) on Santa Catalina Island represents a large Miocene pluton deformed by subsequent tectonic activity.

Ward 1991) and therefore might be expected in the Inner Borderland Rift. The Conejo volcanics, located approximately 110 km farther north of Emery Knoll in the western Santa Monica mountains and situated on the rotated and displaced western Transverse Ranges block (Fig. 1), are part of a large caldera complex that formed from approximately 17 to 14 Ma (Weigand *et al.* 2002). The inferred position of the caldera when it formed in middle Miocene time would have been close to Emery Knoll Crater, but likely farther north along the axis of the Inner Borderland Rift (Nicholson *et al.* 1994; Weigand *et al.* 2002).

Lithology of samples from seafloor outcrops located in the Inner Borderland Rift include andesitic basalt and basalt, siliceous tuff, perlitic glass and pumice, hyaloclastite, rhyolite, hornblende andesite and vitric tuff (Vedder *et al.* 1974; Vedder 1990), as well as Catalina schist detritus. Petrologic studies around the Borderland have identified bimodal volcanism with samples ranging from siliceous rhyolite and dacite to andesite and basalt (Hawkins & Divis 1975; Vedder 1990; Weigand 1994; Weigand *et al.* 2002). The Blanca formation on Santa Cruz Island and the Beecher's Bay member on Santa Rosa Island represent large siliceous volcanic deposits up to 1.4 km in thickness (Fisher & Charlton 1976). The volcanic sources of these deposits are unknown, but palaeocurrent directions suggest a source region in the Inner Borderland (Kamerling & Luyendyk 1985). These volcanic deposits are often interbedded with San Onofre breccia, derived from Catalina schist basement rocks exhumed during Inner Borderland rifting. In most places, the San Onofre Breccia has a tuffaceous matrix, suggesting that rifting and basement exhumation was contemporaneous with possible explosive volcanism.

Widespread eruption of basalt and andesitic basalt, often inferred to post-date a caldera collapse, occurred around the perimeter of the crater structures: at San Clemente Island (Vedder *et al.* 1974), along the mainland coast (Minch 1967; Hawkins 1970; Kennedy 1975), and around Thirtymile and Fortymile banks (Vedder *et al.* 1974; Vedder 1990). Early to middle Miocene igneous rocks on Santa Catalina Island include a quartz diorite stock and dyke-swarm complex, dacite dome and andesite flows (Vedder *et al.* 1986; Vedder 1987). Emery Knoll has long been considered of volcanic origin based on its conical shape and rocks dredged from its crest (Gaal 1966), although this does not preclude a possible impact localizing this volcanic activity. Geological samples from the Inner Borderland Rift and surrounding area thus support the presence of silicic volcanism in the region capable of producing caldera-related crater forms.

The difficulty with a volcanic or caldera model for crater formation is that given the large size of these Inner Borderland structures, huge deposits of ignimbrite, siliceous tuff and other volcanic debris should be evident. To produce just Catalina Crater alone as a caldera

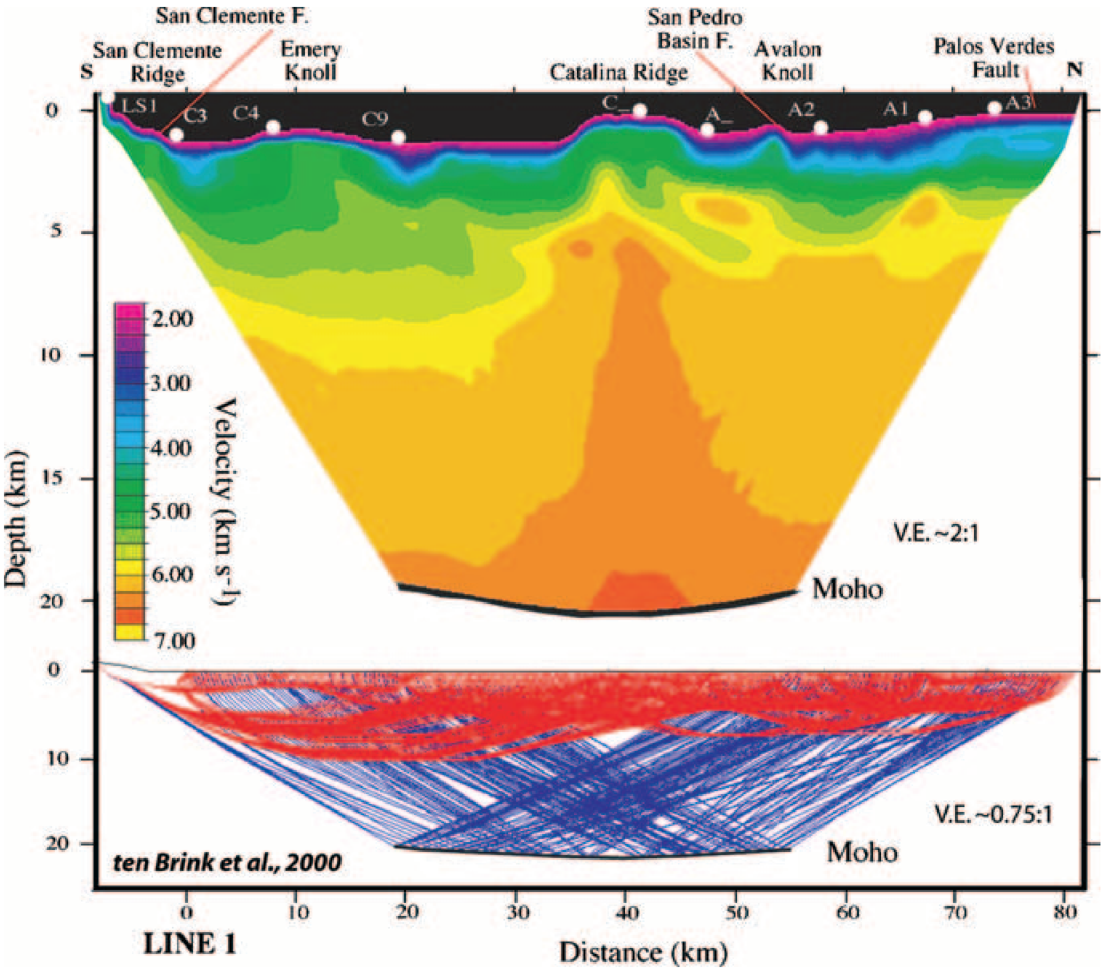

Figure 6. 2-D tomographic velocity model along LARSE-1 derived from OBS (white dots) refraction data (ten Brink *et al.* 2000) across Emery Knoll Crater (left) and Catalina Ridge (middle) at the south end of Santa Catalina Island. Line location shown in Fig. 2(a).

collapse structure, over 700 km^3 of volcanic material must be explosively ejected during caldera forming eruptions. To date, such large volumes of volcaniclastic material have yet to be discovered, although some silicic deposits, like the Blanca formation, do exist and lightweight volcanic products (such as fine ash and pumice) could have been carried away from the eruptive centres by winds and ocean currents. Indeed, as much as one-third of the eruptive volume may be widely dispersed as airfall deposits (Lipman 1992). Furthermore, much of the volcanic material recovered from the Inner Borderland is andesitic or basaltic in composition and, although presumed-Miocene normal-separation faults have been interpreted within the crater moat from seismic reflection data (Fig. 4), much of the later faulting around the outer rim of Catalina Crater appears to be reverse separation, suggesting uplift rather than caldera collapse. This subsequent deformation, however, could be post-crater formation. Caldera models alone thus fail to account for the apparent absence of the expected large volumes of pyroclastic and ignimbrite deposits in the area around these offshore structures; nor do such models necessarily explain the inferred metamorphic basement composition of the crater central uplifts.

4.2 Plutonism and possible schist mobilization

The central peak of Catalina Crater and to a large extent Emery Knoll have been interpreted as domal uplifts of the regional Catalina schist basement (Junger & Sylvester 1979; Bohannon & Geist 1998; Ridgway & Zumberge 2002). Most Inner Borderland Rift models exhume schist basement along regional low-angle normal (detachment) faults during oblique extension (Crouch & Suppe 1993; Nicholson *et al.* 1993; Bohannon & Geist 1998). Isostasy provides a major driving force for the uplift of the ductile schist basement during rifting. Ductility of the schist basement would be increased further by magma injection as a result of crustal thinning and possible decompression melting. Such metamorphic core complexes, however, often develop shapes elongated parallel to detachment fault strike (e.g. Davis 1980), not the near-circular morphology exhibited by Catalina Crater (Fig. 3).

Evidence for subsequent or partly contemporaneous siliceous volcanism in the region could indicate the emplacement and intrusion of silicic magmas at depth, causing the uplift and doming of the near-surface schist basement. Folding and reverse faulting of moat strata within Catalina Crater (Fig. 4) may reflect emplacement of such a silicic magma diapir or batholith at depth (e.g. Clemens 1998) pushing the schist basement up into the more brittle shallow crust. The development of Santa Catalina Island, located north of Emery Knoll, may have been related to an earlier episode of plutonic emplacement in Miocene time (Fig. 5) (e.g. Vedder 1987), a feature reflected in the high-velocity anomaly observed beneath the island and Catalina Ridge (Fig. 6) (ten Brink *et al.* 2000). Such plutonic activity can produce large circular shaped structures. A good

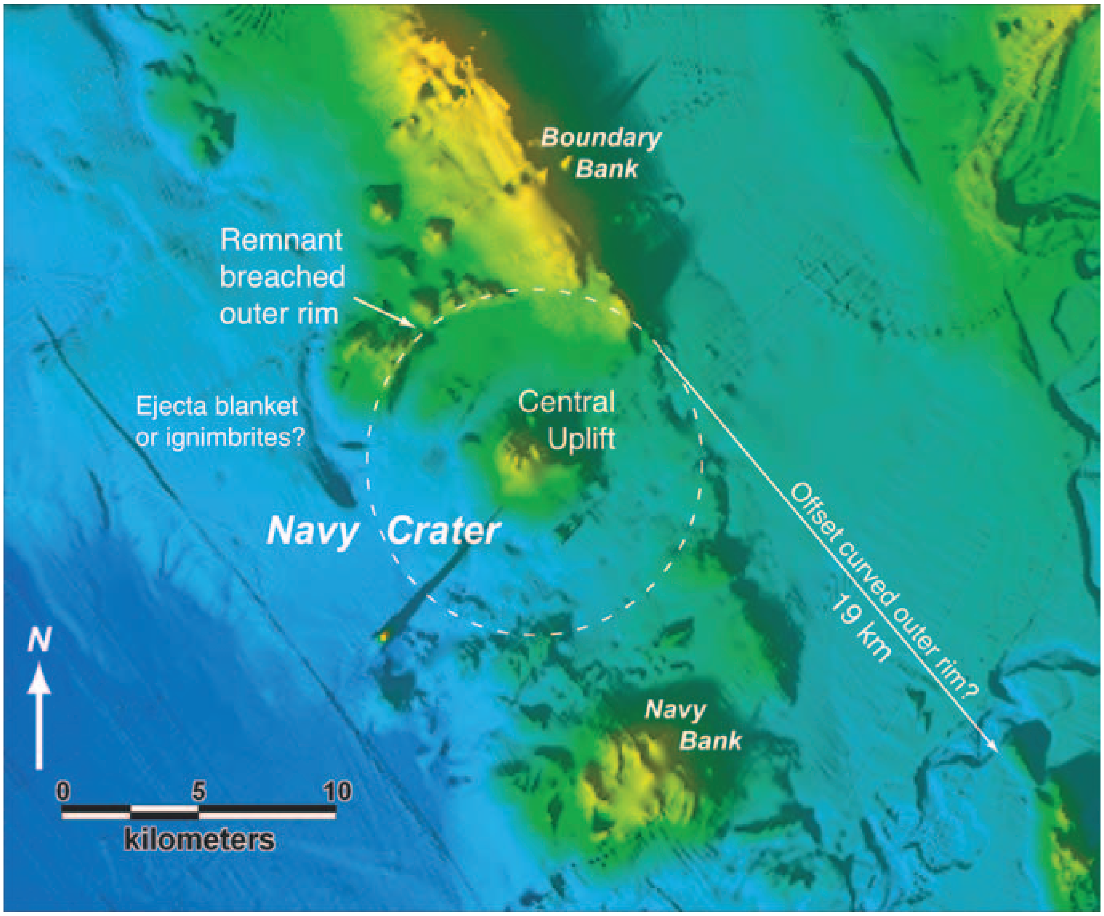

Figure 7. Colour shaded bathymetry of Navy Crater and vicinity offshore northern Baja California, Mexico. Smooth elevated seafloor located to northwest of crater may be a possible ignimbrite or ejecta blanket resulting from crater formation. Erosion and tectonic activity have breached and disrupted crater rim.

example is the >40-km-diameter San Quintin pluton in northern Baja California, Mexico, adjacent to the Inner Borderland Rift (Fig. 8a) (Gastil *et al.* 1971). Its enormous size and near-circular shape were not fully appreciated until space shuttle images that reflected the lithologic variation in outcrop pattern were made available (Fig. 8b).

Based on seafloor sampling, magnetic, seismic and deep-towed gravity data, Emery Knoll has been modelled as a metamorphic basement uplift associated with a dense plutonic intrusion at depth (Junger & Sylvester 1979; Ridgway & Zumberge 2002). These models, however, only focused on the 13-km-wide uplift of the knoll itself. The models do not consider that this feature may be part of a much larger crater structure that includes both a large annular depression and an outer rim 35–37 km in diameter (Fig. 2b), nor do such models necessarily explain the more well-preserved crater morphology of Catalina Crater (Fig. 3). Furthermore, emplacement of a dense (mafic?) pluton at depth might be expected to produce a similar high-velocity anomaly as is observed beneath Catalina Ridge (Fig. 6), but such a high-velocity anomaly does not appear to be present beneath Emery Knoll, although deeper velocities are not well resolved.

Metamorphic core complex formation within the Inner Borderland Rift may have involved vertical emplacement of schist basement that appears diapiric in form. Salt, shale and sand diapirs typically produce a withdrawal depression or ring moat around the central uplift as the ductile, more buoyant material migrates upward. The emplacement of such a large volume of ductile schist, as would be required to produce the central uplift of Catalina Crater (>60 km^3), could have formed a similar near-circular withdrawal feature. Yet the size of the annular depression within Catalina Crater is an order of magnitude larger, and explanations of how and why the relatively dense Catalina schist would form a diapir are difficult. Furthermore, models for crater origin that involve upward schist remobilization, whether as metamorphic core complex, diapir, or the result of an intrusion at depth, do not fully explain how and why such near-circular crater morphology, which includes an annular depression and outer rim, can form and remain relatively undisturbed in an area dominated by distributed oblique dextral shear during middle Miocene time.

4.3 Impact structure

Identification of impact structures in the submarine environment is still relatively rare. Of the recognized impact structures on earth, less than 10 have been identified in marine environments (e.g. Montanari & Koeberl 2000). Impact structures are recognized by their crater morphology and by the physical and chemical effects of impact. On silicate planets like Earth, there appears to be a regular progression of impact crater morphology from small simple craters, through complex central peak and peak-ring craters, to large multiring crater basins (Grieve *et al.* 1981; Pike 1985; Melosh 1989), although final crater morphology also appears to be a function of the mechanical strength of the target rocks with depth. Simple craters

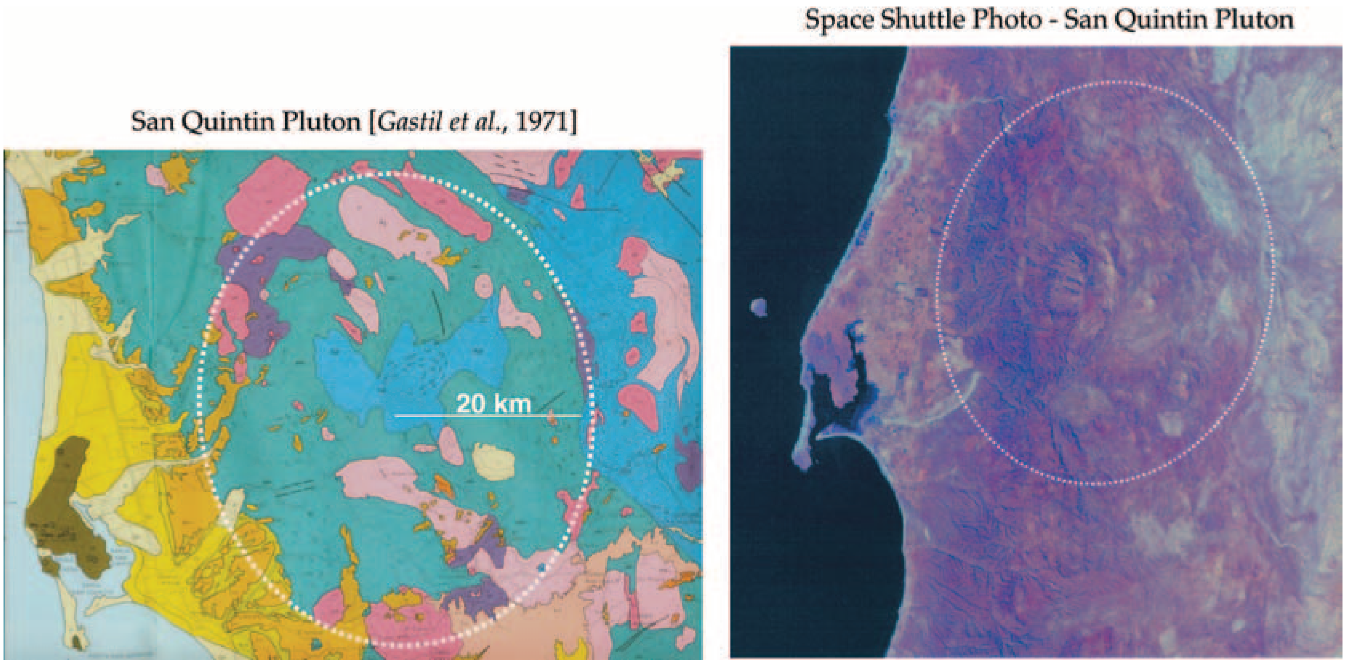

Figure 8. (Left) Geological map (Gastil *et al.* 1971) and (right) space shuttle image of San Quintin pluton, northern Baja California, Mexico. Maximum diameter of San Quintin pluton exceeds 40 km.

lack the uplifted central core of larger, more complex crater structures. Complex craters are usually relatively shallow, circular features over 4 km in diameter (for crystalline rocks), with a central core of uplifted, shocked rocks surrounded by one or more concentric, peripheral depressions. Thrust faults are present on the flanks of the central uplift, and radially distributed normal faults associated with post-impact slumping and collapse occur along the interior rim zone. Impact craters are usually breccia filled and exhibit intense deformation that wanes with depth and distance from the central uplift.

For complex impact craters, empirical relationships exist between the observable diameter, depth and the size and extent of the central structural uplift (Grieve *et al.* 1981; Pike 1985; Grieve & Pilkington 1996; Grieve 1998) of the crater. These relationships are a direct result of impact mechanics and post-impact processes. Emery Knoll, Catalina and Navy craters exhibit many of these morphometric relationships (Figs 2–6), although each has been clearly modified by erosion, faulting and perhaps other processes. For example, the ratio of minor to major axes of the crater diameter, the diameter of the central uplift to crater diameter, and the structural uplift (inferred from seismic data) to crater diameter (Table 1) are all within observed parameters for known terrestrial impacts (Grieve & Pilkington 1996; French 1998; Grieve 1998). Although the observed heights of the central uplifts tend to exceed the elevations of the surrounding outer rims (a rare condition for impact craters of this size), this is not entirely atypical for some large known impact craters. The 19-km-wide Yuty impact crater on Mars (French 1998), the 40-km-wide Mjølnir impact crater in the Barents sea off Norway (Tsikalas *et al.* 1999), the 45-km-wide Montagnais crater off Nova Scotia (Jansa & Piper 1987) and the recently identified Bedout impact structure on the northwest shelf of Australia (Becker *et al.* 2004) all exhibit central uplifts higher than their outer rims. For submarine impacts, Ormo & Lindstrom (2000) offer a link between target water depth and crater morphology, suggesting that while craters in relatively shallow target water depths may resemble land target craters, complex craters in deep water often exhibit stronger collapse of their outer rims, resulting in lower apparent elevations with respect to their central uplifts.

The central uplift of Catalina Crater is off-centre (Fig. 3), but this is also not unusual for impacts (Shoemaker 1962; Bottke *et al.* 2000; Ekholm & Melosh 2001). The outer rim of Catalina Crater is suggestive of a possible multiple impact, or other multiple crater forming process, as a smaller, secondary near-circular feature appears to overlap the southern rim (Figs 2a and 3).

Table 1. Morphometric parameters of Emery Knoll, Catalina and Navy craters as compared with typical values for complex impact craters and calderas.

Crater Structure	Da (km)	Do (km)	Dcu (km)	d (km)	SU (km)	Ratios AR	Dcu/Da	d/Da	SU/Da
Catalina Crater	26–29	28–32	7–8	∼1.0	>2.2	0.9	0.25	0.03–0.04	0.09+
Emery Knoll Crater	30–36	33–37	11–14	0.9–1.0	>2.6	0.85	0.3	0.025–0.03	0.07+
Navy Crater	11–12	13–14	3–4	0.7–1.1	>1.1	0.9	0.3	0.06–0.09	0.09+
Impact craters†	4–100+	4–100+	1–40+	0.5–4	1–10	0.85–1.0	0.2–0.3	0.01–0.07	0.05–0.1
Calderas	2–50	2–75	na	0.5–4	1–40	0.5–1.0	na	0.2–0.5	0.5–1.0

Da = diameter, inside rim; Do = diameter, outside rim; Dcu = diameter, central uplift; d = crater depth; SU = structural uplift; AR = aspect ratio (diameter minor_axis/diameter major_axis); † = complex impact craters with central uplifts. Typical values for large impact craters and calderas modified after Stewart (2003) and using empirical equations including: $SU = 0.1\ Da$ (French 1998); $SU = 0.086\ Da^{1.03}$ (Grieve 1998); $Dcu = 0.22\ Da$ (Pike 1985); $Dcu = 0.31\ D^{1.02}$ (Therriault *et al.* 1997); $d = 0.15\ D^{0.43}$ (Grieve & Pesonen 1992).

The major difficulty with an impact model for Catalina Crater (or any of the other offshore structures) is the absence so far of shocked minerals, shatter cones, exotic metals or other geochemical and petrologic signatures indicative of an impact—although until now, no one has had a reason to look. The structure also appears to lack extensive ejecta deposits that would be associated with an impact of this size (Croft 1981, 1985), although some stratified moat fill deposits of unknown origin are imaged by the seismic data (Fig. 4b). The structure lacks the peak-ring morphology usually present for a terrestrial impact of this size (Grieve *et al.* 1981; Melosh 1989), but this may be a function of the mechanical strength of what was once recently uplifted and exposed, ductile schist basement target rocks. The general asymmetry of the annular depression and outer rim (Fig. 4) contrasts with typical well-defined impact craters, although much of this asymmetry may be related to post-crater deformation. Given this asymmetry, the structure also appears to lack other internal concentric features expected of impacts. Junger & Vedder (1980), on the other hand, did map a series of ring faults surrounding Emery Knoll (Fig. 2a). Another basic problem of the impact model arises if all three offshore structures (Navy Crater, Catalina Crater and Emery Knoll Crater) are assumed to be impact related. In this case, their obvious alignment along the regional tectonic trend of the Inner Borderland Rift would be highly fortuitous.

5 POTENTIAL FIELD SIGNATURES: IMPACT VERSUS CALDERA

5.1 Gravity

The most notable geophysical signature associated with terrestrial impact structures is a negative gravity anomaly (Pilkington & Grieve 1992; Grieve 1998). These gravity lows are generally circular and typically extend to, or slightly beyond, the outer rim of the structure. For large, complex impact craters, the low surrounds a central high that occurs within the area of the central uplift. Magnetic and gravity anomalies associated with calderas, on the other hand, vary widely with the geological setting, the properties and shallow structural features of the volcanic rocks, and the nature and depth of intrusive bodies (Eaton *et al.* 1975). In general, most calderas associated with voluminous eruptions of pumice show negative gravity anomalies (Yokoyama 1963); calderas associated with eruptions and intrusions of basaltic lavas show positive gravity anomalies. The centres of the gravity highs on both active and extinct volcanoes is eccentric with respect to the calderas and may lie outside the bounding faults (Williams & McBirney 1979).

The gravity field in the Inner Borderland is complex (e.g. Roberts *et al.* 1990), and results from the extensive rifting, faulting and volcanism associated with the tectonic breakup of the California margin. Bouguer and free air anomalies show a gravity *high* associated with Emery Knoll and a prominent subcircular *low* over Catalina Crater, with minor highs on the central uplift and outer rim (Fig. 9a) (Beyer & Pisciotto 1986; Beyer 1987; SEG 1982). The isostatic residual gravity field (Fig. 9b) shows a subcircular high associated with Emery Knoll, surrounded by lows that likely reflect the density contrast between the basement rocks of the central uplift and the sediments in the surrounding annular depression. The signature over Catalina Crater is also somewhat circular with an off-centre peak (Fig. 9b). A high-resolution, near-bottom, gravity survey of Emery Knoll suggests uniform high-density basement material with a local higher density body at shallow depth (Ridgway & Zumberge 2002). Unfortunately, this survey did not extend much beyond the bathymetric expression of Emery Knoll and no similar high-resolution gravity data exist over Catalina Crater. Although of low resolution, the observed differences in regional gravity signatures between Emery Knoll and Catalina Crater, may indicate a similar difference in structure, origin, or subsequent tectonic evolution.

5.2 Geomagnetics

Magnetic anomalies associated with terrestrial impacts are generally more complex than associated gravity anomalies and reflect the greater variation possible in the magnetic properties of target rocks. The dominant effect for impact structures is typically a magnetic low or subdued zone, which is smaller and more centralized than the gravity anomaly, and commonly manifested as a truncation of the regional magnetic signature (e.g. Coles & Clark 1978; Grieve 1998; Pilkington & Hildebrand 2003). The magnetic signature at calderas, where shallow volcanic rocks are present, generally results in strong local highs and lows depending on the field polarity at time of eruption.

Aeromagnetic data (Langenheim *et al.* 1993) delineate Catalina Crater, with an annular low corresponding to the annular depression, and subdued highs corresponding to the rim and central uplift (Fig. 9c). Nearby Emery Knoll has a similar subdued magnetic signature, although this signal tends to be overwhelmed by the strong magnetic anomalies associated with the San Clemente fault and buried magnetic source rocks west of San Clemente Island. In contrast, the central uplift of Navy Crater appears to be associated with a magnetic low (Beyer 1987).

The net result is that although the gravity data over Catalina Crater and to some extent Emery Knoll are consistent with low-density fill within subcircular annular depressions separating higher-density central uplifts and raised outer rims, the magnetic data do not strongly support either the impact or volcanic caldera hypotheses.

6 SUMMARY AND IMPLICATIONS

Stewart (2003) recently proposed a set of simple criteria to classify the origin of buried circular structures in terrestrial sedimentary basins where direct geological sampling or evaluation is not yet available. Using these criteria, and given the size, circular shape, crater form, central uplift and depth-to-diameter ratio of these offshore structures, Catalina Crater, Emery Knoll Crater and Navy Crater would each qualify as either large igneous resurgent caldera or impact craters. Owing to the known regional volcanism of similar age (Luyendyk *et al.* 1998; Weigand *et al.* 2002) and obvious alignment within the Inner Borderland Rift, we prefer a volcanic origin for these structures, although this line of reasoning has been known to be previously misleading (*cf.* Hoyt 1987; French 1990). The present lack of recognized extensive pyroclastic or ejecta deposits associated with these structures we attribute to their unusual marine setting, their significant age (>15 Ma), and the subsequent erosion and rafting away of lighter volcanic materials.

If these offshore structures are volcanic in origin, they represent the largest previously undiscovered caldera complex in western North America. These may be the elusive source of early to middle Miocene silicic volcanic and breccia deposits found on adjacent islands and onshore regions, although the amounts of silicic deposits identified to date are orders of magnitude less than expected. If any of these structures represents an impact site, it would be the first of its kind to be discovered in the eastern Pacific and the first to be recognized to occur in what was once recently exhumed, ductile schist basement. If these structures result from mid-crustal exhumation, plutonic intrusion and/or schist remobilization, then they represent

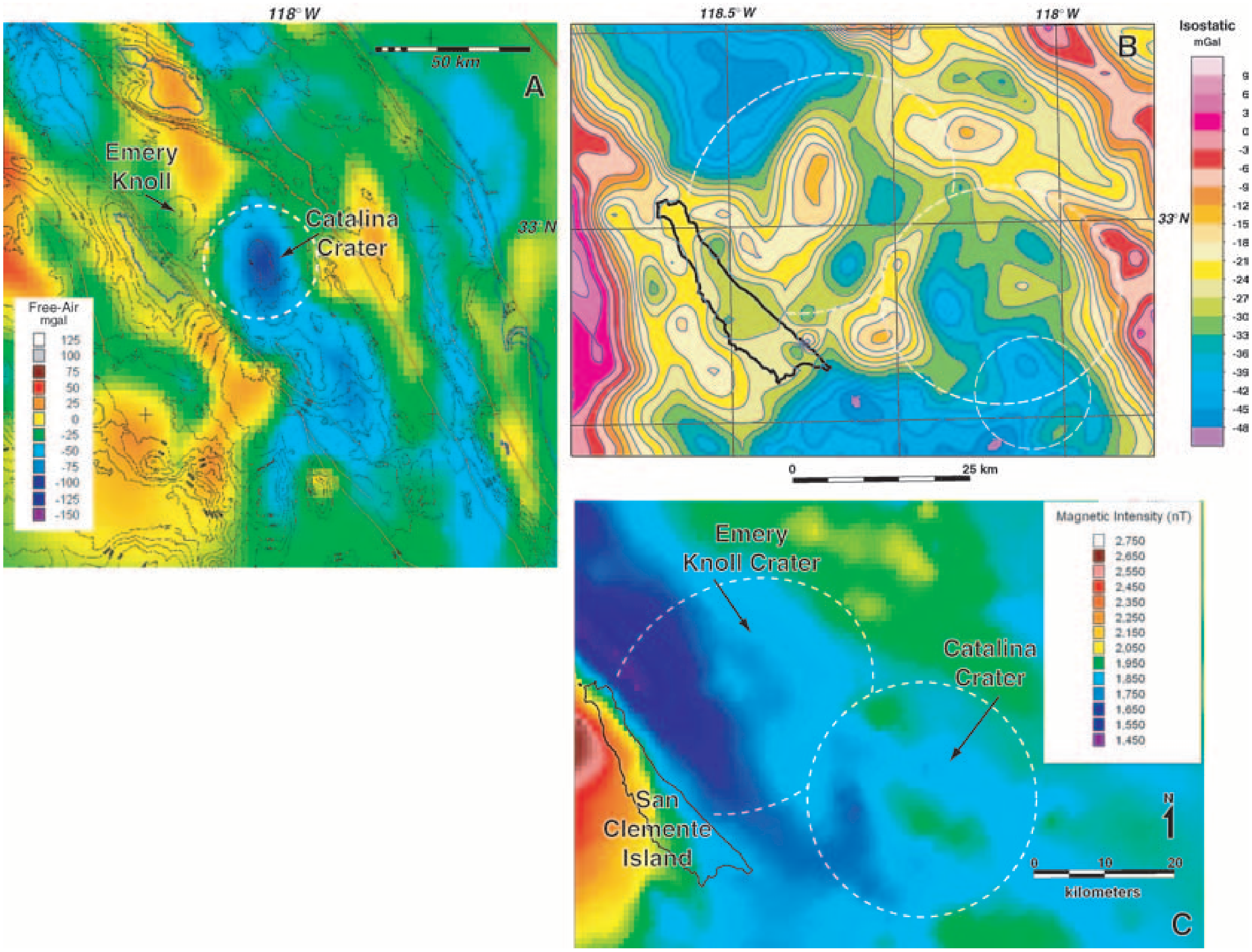

Figure 9. (a) Shaded free air gravity (4-km grid, SEG 1982); (b) isostatic residual gravity (Roberts *et al.* 1990); and (c) aeromagnetic (Langenheim *et al.* 1993) data over Catalina and Emery Knoll craters. Free air gravity shows a prominent low centred over Catalina Crater (dashed circle), while the isostatic residual and areomagnetic data show subtle ring anomalies over both Emery Knoll and Catalina craters. Large magnetic anomalies associated with San Clemente fault and buried source rocks west of San Clemente Island obscure more subtle anomaly patterns near Emery Knoll.

some of the largest structures of their kind and would illuminate how such large, circular features develop in an oblique shear environment and evolve on such a large regional scale.

With the available data, we cannot conclusively exclude any of the three hypotheses for the formation of these large, offshore structures. More importantly, no single model for how such large, near-circular complex craters form on the Earth can adequately explain all the current observations we have, or, in this case, the conspicuous lack so far of diagnostic signatures, such as shocked minerals or large ignimbrite deposits, which would be expected if these structures were of impact or volcanic origin. In any case, the existence of such large offshore structures implies that care must be taken in inferring origin based solely on crater morphology (e.g. Underhill 2004) and that models for creation of such large, circular features may need to be modified. Regardless of their origin, the presence of such unusual features offshore of southern California suggests that the regionally extensive San Onofre breccia, previously interpreted to represent a near-fault breccia associated with Inner Borderland rifting, may be, at least in part, an explosion breccia associated with caldera formation or impact.

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