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Field exercises in the Pinacate volcanic field, Mexico: An analog for planetary volcanism

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ABSTRACT

The Pinacate volcanic field is ~330 km SSW of Phoenix, and it is a popular destination for volcanology and planetary geology field trips. The volcanic field, located on the Pinacate Biosphere Reserve in Sonora, Mexico, is a 1500 km^2 basaltic field including a shield volcano, lava tubes, maars, a tuff cone, cinder cones, pāhoehoe and ‘a‘ā lava flows as young as 12 ka, and phreatomagmatic constructs as young as 32 ka. We developed an image-based set of exercises for a 2 day field trip focusing on (1) Crater Elegante, a maar crater, (2) pāhoehoe and ‘a‘ā flows near Tecolote Cone campground, (3) the complex eruptive history of Mayo (cinder) Cone, and (4) Cerro Colorado tuff cone. This paper discusses exercises to teach concepts in visible and radar image interpretation and planetary volcanology, and provides an overview of the field trip.

INTRODUCTION

Volcanology and planetary geology are major foci for research and teaching at Arizona State University. Much planetary geology research is based on remote sensing of the terrestrial planets and outer planet satellites from robotic spacecraft, including orbital and surface visible, near-infrared, thermal-infrared, or radar images; visible, near-infrared, or thermal-infrared spectroscopy; and orbital gravity and altimetry data analyses. Thus, to correctly interpret these spacecraft data, students require experience in terrestrial field geology, including participation in field courses and visits to terrestrial analogs. Students gain a much better understanding of the types of processes that form planetary features, as well as recognition of their complexity, through studying field analogs. An understanding of geology and experience with field analogs will be required for future astronauts exploring the surfaces of the Moon, Mars, and beyond.

The purpose of this paper is to describe a set of image-based field exercises that we developed as part of a field trip to the Pinacate volcanic field, within the Pinacate Biosphere Reserve in Sonora, Mexico. After providing some brief background information, we describe our exercises in the Pinacate volcanic field. It is our hope that these exercises will be useful for future geology classes and/or astronaut training. For an up-to-date review of current geologic knowledge of the Pinacate volcanic field, see Gutmann (2007).

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BACKGROUND

The exercises build upon the Pinacate volcanic field road log and field trip guide by Gutmann and Sheridan (1978). The goal of the trip is to familiarize participants with basaltic volcanism, including maars and tuff cones. The Pinacate volcanic field has been well studied (e.g., Arvidson and Mutch, 1974; Gutmann, 1974, 1976, 1977, 1979, 1986, 2002, 2007; Wood, 1974; Gutmann and Sheridan, 1978; Lynch and Gutmann, 1987; Lutz and Gutmann, 1995), including by two of us (Greeley and McHone), who conducted photogeology and field work in the Pinacate volcanic field and the neighboring Gran Desierto dune field related to Shuttle Imaging Radar (SIR) missions (Greeley et al., 1985, 1987; McHone et al., 2002). The Pinacate volcanic field was incorporated in the Pinacate Biosphere Reserve when it was created in 1993 by decree of the president of Mexico. With this status, visitors are no longer allowed to descend into craters without special permission, collect rock samples, or climb cinder cones where trails do not already exist. In the following sections, we describe the image-based exercises.

FIELD EXERCISES

Exercise 1: Drive to the Pinacate Volcanic Field

We recommend that, prior to departure on the field trip, visitors to the Pinacate volcanic field read one or more articles listed in the bibliography (e.g., Gutmann, 2007), and/or that trip leaders have an in-class or group discussion to introduce the primary features to be visited. We assume that field trip participants have some background in terrestrial or planetary remote sensing and radar image interpretation (e.g., Sabins, 2007; Campbell, 2002) and basic knowledge of terrestrial volcanology (e.g., Schmincke, 2004). On the day of departure, we give each participant a copy of the exercise (Appendix, also included as a PDF on the CD-ROM accompanying this volume and in the GSA Data Repository[1]); field trip leaders should have the answer key (also in Appendix, and included as a separate PDF on the CD-ROM [see footnote 1]). Some individuals may want to start their road logs at the U.S.–Mexico border station at Lukeville, Arizona (stop 4, mile 163).

From the Phoenix or Tucson areas, drive on I-10 and I-8 to stop 1 (a rest stop) at Gila Bend, Arizona. This stop is an ideal location to discuss an overview of the geology of southern Arizona (see e.g., Chronic, 1983). Proceeding south on Arizona Highway 85 from Gila Bend, stop 2 is suggested at an open-pit mine in Ajo, Arizona. This stop is an ideal location to discuss mineral deposits and mining in Arizona (see e.g., Nations and Stump, 1981, their Chapter 15). Proceeding south, there is an optional stop 3 at Organ Pipe Cactus National Monument visitor's center, which has facilities (bathrooms and picnic areas) and books, maps, etc. Three miles (~4.8 km) south of the visitor's center, one comes to the Mexican border and the hamlet of Lukeville, Arizona (stop 4). Note that U.S. law requires all visitors to Mexico to show identification for re-entry to the U.S.; thus, *field trip participants must bring their passports*. Across the border is the Mexican town of Sonoyta, which is the last place to pick up supplies before continuing into the Pinacate volcanic field. Note that water is not available in campgrounds within Pinacate Biosphere Reserve, nor are there restrooms. From Sonoyta, the trip proceeds south on Mexican Route 8 toward Puerto Peñasco. The oldest volcanic center (the shield volcano known as Volcan Santa Clara) of the Pinacate volcanic field is visible to the west.

The drive to the Pinacate volcanic field affords an opportunity for participants to examine the color SIR-C/X-SAR (X-band Synthetic Aperature Radar) radar images of the Pinacate volcanic field (Fig. 1; Appendix). Radar and microwave radiation interact with surface materials, such that the degrees of absorption

Figure 1. The Pinacate volcanic field as imaged by the Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar (SIR-C/X-SAR) carried onboard the space shuttle *Endeavor* on 18 April 1994. Image is centered at 31.84°N, 113.47°W. The colors are assigned to different radar frequencies and polarizations of the radar as follows: red is L band (23.5 cm), horizontally transmitted and received; green is L band, horizontally transmitted, vertically received; and blue is C band (4–8 cm), horizontally transmitted, vertically received. Numbers refer to major feature locations: 1—Pinacate Biosphere Reserve visitor's center, 2—Crater Elegante maar, 3—Mayo cinder cone, 4—lava flows, 5—Cerro Colorado tuff cone, 6—La Laja cinder cone. National Aeronautics and Space Administration (NASA) photojournal image PIA 01852.

[1]GSA Data Repository Item 2011323, Planetary volcanology field trip: Pinacate Volcanic Field, Sonora, Mexico, exercise and answer key, is available at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

and scattering depend upon radiation wavelength relative to the length scale of surface roughness elements. In general, bright features in radar images are rough at the scale of the radar (L band: 23.5 cm; C band: 4–8 cm), and smooth features are dark. Thus, ‘a‘ā lava flows, river channels with cobbles, and vegetation are bright, and sand dunes, pyroclastic rocks, and playa deposits are dark. Steeply sloped features (in the direction of the incident radar) or features with sharp corners also appear bright because of their strong radar returns. Assuming some practice studying radar images prior to departure, participants can correlate surface features observed during the drive with the radar images (e.g., washes and drainages with vegetation and cobbles, sand dunes), and they can describe variations in radar brightness and their causes relative to different volcanic features (e.g., cinder cones vs. lava flows). Participants can compare the radar and the false-color Landsat Thematic Mapper images of the Pinacate volcanic field (Fig. 2), and they can compare Figure 2 with a plot containing the spectra of common rocks and minerals (Fig. 3).

Figure 2. Landsat Thematic Mapper false color image of the Pinacate volcanic field. Band 7 (2.08–2.35 mm) is displayed in the red channel, band 4 (0.76–0.90 mm) in the green channel, and band 2 (0.52–0.60 mm) in the blue channel. Figure is modified from an image by John Dohrenwend reproduced in Bezy et al. (2000).

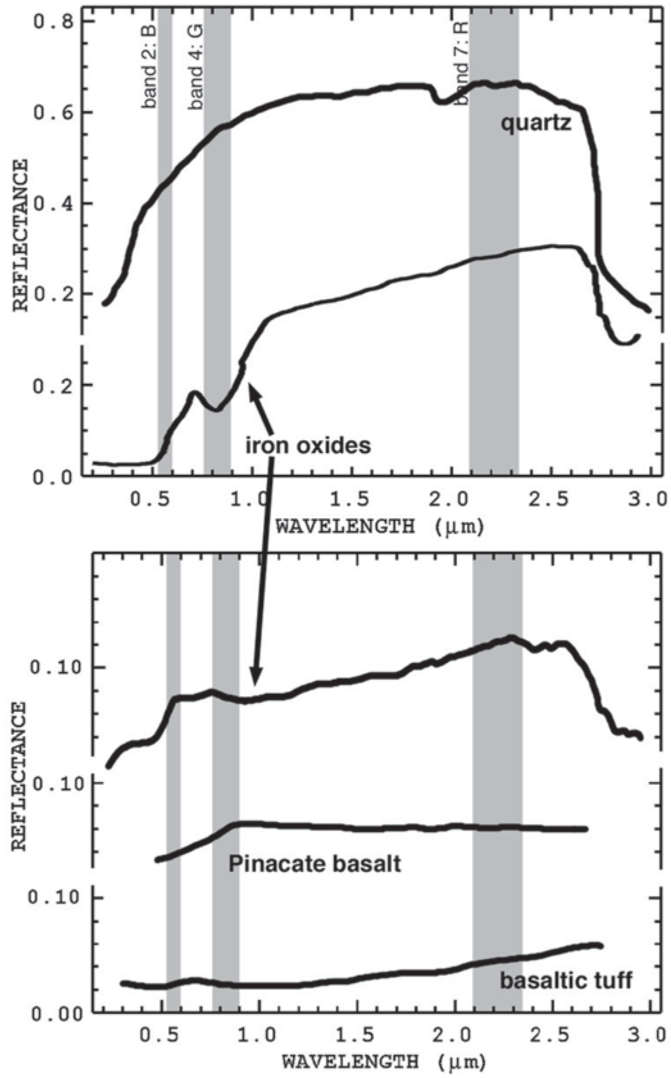

Figure 3. Visible reflectance spectra for rocks and minerals relevant to the Pinacate study area. Vertical bars indicate wavebands of Landsat Thematic Mapper data used to create false color image (Fig. 2).

These resources are helpful to answer questions in the exercises regarding features such as oxidized scoria on the cinder cones, the spectral response of basalt (dark in visible light, compared to variability in radar depending upon morphology of the deposits), and quartz-rich sand dunes.

Stop 5 is at the Pinacate Biosphere Reserve visitor’s center (number 1 in Fig. 1) for registration and to obtain camping permits.[2] The visitor’s center contains displays of volcanic bombs and other rocks, and images of the Pinacate volcanic field. Continue north on the dirt road for ~16 km and then bear left at a fork in the road, following signs to Crater Elegante. This is stop 6 (number 2 in Fig. 1), which can also serve as a convenient lunch stop.

[2]Note: A new Pinacate Biosphere Reserve visitor’s center has reportedly been built further south near Puerto Peñasco (J.T. Gutmann, 2010, personal commun.), but it has yet to be visited by any of the authors.

Exercise 2: Crater Elegante Maar

Crater Elegante is ~1600 m in diameter, 244 m deep, and formed some 32,000 ± 6000 yr ago (Gutmann and Turrin, 2006). The rim affords a great perspective of the surrounding geology: Volcan Santa Clara dominates the southwestern horizon. To the northeast, there are the cinder cones of Tecolote and Mayo. The low-lying area to the south hosts abundant small cinder cones. Lava flows are clearly visible to the west and northeast. Participants may hike up to the rim and scramble down a few meters to examine outcrops on the inside rim. Participants should describe these deposits in terms of their components, bedding structures, dip, etc., and recognize the thinly bedded, outward-dipping layers of tuff breccia. These beds contain dune forms, swell structures, bomb sags (indicating sticky and cohesive material), and poorly sorted, reverse-graded, poorly indurated, and partly palagonitized material. Juvenile tan basaltic ash is also present. The lithics present are mostly angular basaltic blocks, ~50% derived from precursor flows and ~50% from deeper volcanic materials. These observations enable a discussion of the eruption mechanism for this material, i.e., pyroclastic surge deposits produced in explosive phreatomagmatic activity, involving relatively little water (only partial palagonitization-induration), with no accretionary lapilli and little construction around the crater (for additional details, see Gutmann, 1976; Gutmann and Sheridan, 1978).

Participants can walk west along the crater rim for 500–1000 m and look across to the highest point along the rim on the opposite side. They may notice changes in the dip of the bedding, reddish scoria, and a pitchfork-shaped dike in the far wall (Gutmann, 1976). Next, if participants backtrack and walk east around the crater toward the highest point (covered in 32 ka tuff breccia), they will notice along the way the changes in relief of the crater rim in relation to the surrounding area, the dip of the beds, and the depth to crater floor. There is a variety of ejecta types, and participants may recognize the presence of a truncated scoria cone in the rim (Gutmann, 2002; Gutmann and Turrin, 2006), representing an initial magmatic volatile-driven stage prior to onset of phreatomagmatic activity and formation of the crater at Elegante (Gutmann, 1976; Gutmann and Sheridan, 1978). After study of the deposits and features at Crater Elegante, participants have the opportunity to discuss and classify the features (maar, tuff ring, caldera, or impact crater). The provided images (Figs. 1 and 4) can be used to compare radar image brightness variations with the visual appearance from the rim of deposits on the crater floor.

From Crater Elegante, travel northeast around the Tecolote cinder cone. Stop 7 is an ‘a‘ā lava flow front, where participants examine the lava textures and discuss emplacement processes of ‘a‘ā flows. Participants discuss the ways in which textures of these ‘a‘ā flows and their surroundings relate to radar brightness in the figures, and they can locate their position on Figure 4. Returning to the vehicles, continue along the road, and turn left into the Tecolote campground.

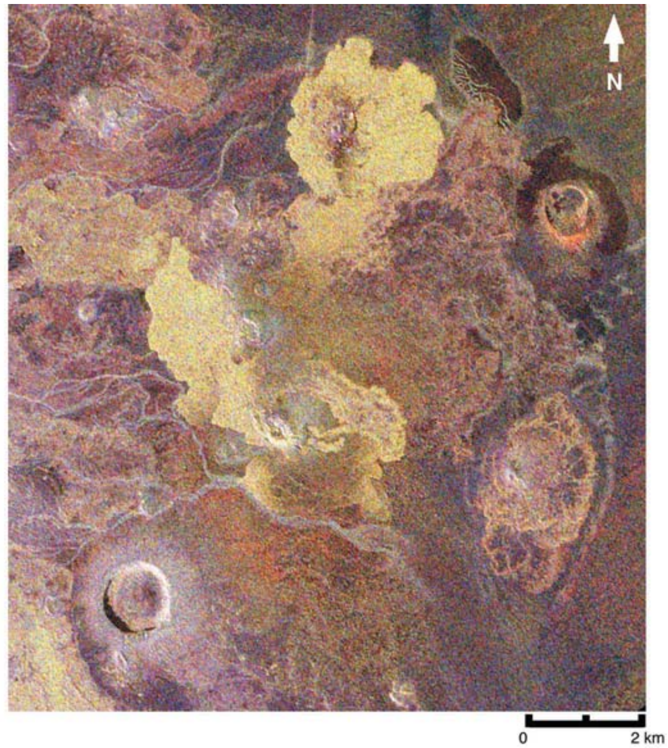

Figure 4. Enlargement of Figure 1, focused on the primary volcanic features of the Pinacate volcanic field visited during field excursion. Compare with Figure A1. National Aeronautics and Space Administration (NASA) photojournal image PIA 01852.

Exercise 3: Mayo Cone Lava Flows

After parking in the Tecolote campground, participants can walk west along the short road through the campground for ~500 m until they enter a broad basin surrounded by thick lava flows. One flow emanates from Mayo Cone, immediately to the north of the campground; another comes from the Tecolote Cone complex to the south. Participants can walk clockwise around the margins of the basin to examine the three different lava flows (there are two ‘a‘ā flows present, one from Tecolote and one from Mayo). Participants can locate the pāhoehoe flow, note the surface textures, and determine its underlying stratigraphic relationship and older age relative to the adjacent ‘a‘ā flows. Then, based on study of the radar images, participants can discuss the abundance of pāhoehoe flows relative to ‘a‘ā in the Pinacate volcanic field. These activities conclude day 1.

Exercise 4: Mayo Cinder Cone (Cone 10 of Gutmann, 1979)

Day 2 activities begin when participants skirt westward along the base of Mayo Cone and hike over the saddle into the interior of the breached cone complex (stop 8). Participants can describe characteristics of pyroclastic materials comprising the cone’s outer flanks and identify the way in which this material differs from that observed at Crater Elegante. Cone flanks are composed of vesicular, scoriaceous, juvenile lapilli that are larger than the ash-sized juvenile material at Crater Elegante (Gutmann, 1979). Participants can then hike into the interior of the breached cone, where they describe the deposits, noting the large bombs up to ~0.5 m and larger, some of which are breadcrusted and deformed. Based on their observations of the cone complex and its pyroclastic material, participants can describe possible eruption mechanisms responsible for the deposits and, from interpretation given in Gutmann (1979), the ways in which the eruption might have evolved through time. This discussion should include (1) initial lava effusion (magma contained too few volatiles to exsolve sufficiently to fragment magma), or alternatively, that the initial lava effusion was essentially degassed during storage or ascent, and it was only as the eruption progressed that more volatile-rich magma was tapped for stage 2 (note that results of these processes are more clearly visible at La Laja Cone; J.T. Gutmann, 2010, personal commun.); (2) transition to Strombolian activity (ascent of a more volatile-rich magma, including exsolution, bubble growth, and fragmentation); (3) transition back to effusion as more volatile-poor magma erupted, lava piled up inside the cone, the cone was breached, and the lava flowed downslope to the west; (4) lava cooling and crystallization in the vent/conduit, inducing further exsolution in the melt phase; and (5) final late-stage ejection of large, dense bombs, producing spatter collars on cone tops and around interior vents (Gutmann, 1979). Participants may note that the Tecolote ash (27 ± 6 ka) is resting on Mayo Cone (J.T. Gutmann, 2010, personal commun.).

Returning to the vehicles, participants leave the campground and proceed east to Cerro Colorado. Stop 9 is a view of Cerro Colorado to the north. Participants can note relief of the structure and dip of the bedding. Participants then drive 3 mi (~4.8 km) to stop 10, the north rim of Cerro Colorado.

Exercise 5: Cerro Colorado Tuff Cone

Although Cerro Colorado was originally thought to be between 1000 and 10,000 yr old based on Indian artifacts found in the vicinity (Shakel and Harris, 1972), it is superposed by the 27 ka Tecolote ash (Gutmann et al., 2000). The crater is ~1000 m in diameter, with the crater floor lying >100 m below the highest point on the south rim. The crater's scalloped morphology records multiple centers of activity. Participants can note the presence of Diaz Playa to the north of Cerro Colorado.

Participants can walk down a few meters inside the crater onto the benches to examine rim deposits and to describe characteristics of the deposits (clast types, bedding, dip, etc.) as they did at Crater Elegante. These deposits consist of a well-indurated, palagonitized tuff, which contains diverse lithics (including quartzofeldspathic gravels), and which is laterally extensive along the crater rim. These tuff deposits contain normally graded beds with steep outward dips and accretionary lapilli. Participants should recognize that these are pyroclastic falls, resulting from phreatomagmatic explosions (Gutmann and Sheridan, 1978). They can note the rounded nature of lithic clasts, indicative of derivation from a fluvial environment. Participants can compare/contrast these deposits with those at Crater Elegante, and they can note that these deposits are more indurated/palagonitized, contain accretionary lapilli, and that more water was involved in the explosions that formed these deposits. These beds are planar and laterally extensive, with an absence of cross-bedding, pinch and swell forms, dunes, etc., indicating that they are pyroclastic fall, not surge, deposits (Gutmann and Sheridan, 1978).

Participants can walk toward and down the west rim of the crater until they see the pinkish tan deposits exposed at the base of the crater's north wall. These are mudstones deposits that probably represent preexisting playa deposits. Participants can comment on the morphology of the crater interior (scalloped margins and inward-dipping beds) and suggest ideas regarding the multiple foci of eruptive activity (Gutmann and Sheridan, 1978).

Returning to the crater rim, participants can walk counterclockwise around to the northwest part of the rim. They can note the presence of long-wavelength dunes on the outer flanks, oriented radial to the crater rim. Participants can examine the deposits on the outer slopes of the tuff cone and comment on potential eruption mechanisms. They should recognize the dune forms as evidence for turbulent emplacement that produced differential deposit thicknesses (dunes), i.e., these units are pyroclastic surge deposits (Gutmann and Sheridan, 1978). Instructors can note that this is one of a few known localities for longitudinal dunes formed from pyroclastic surge deposits (cf. Mount St. Helens—Rowley et al., 1985; Moyer and Swanson, 1987). Alternatively, these beds have been interpreted to be fall deposits that accumulated in gullied terrain. Participants should consider their observations of cone relief, deposit characteristics, and bedding dip, and the relevant information the observations provide about eruption style and the role of meteoric water, to identify the type of feature that Cerro Colorado represents. The participants can recognize that the larger accumulation of material at the rim suggests sticky, cohesive material. More water was involved in the eruption here than at Crater Elegante, as indicated by accretionary lapilli and palagonitization/induration. Here, surface water (rather than groundwater) could have been involved in the eruption, as suggested by the presence of pinkish-tan mudstones. Cerro Colorado is thus defined as a tuff cone (Gutmann and Sheridan, 1978). Participants then return to the crater rim and head back to the vehicles.

At the vehicles, participants can locate Cerro Colorado on Figure 1 and discuss the cause of the radar-dark apron (it is a smooth, flat-lying apron of fine pyroclastics from Cerro Colorado). Participants can then study the radar image to determine the locations of major craters. Given what the participants now know about the formation of volcanic craters at Pinacate, they can infer the paleohydrology of this region. One idea is that water from the ancient Sonoyta River was displaced by the growing volcanic field and concentrated around the north and east margins of the Pinacate volcanic field, where the maars and tuff rings/cones are now located. Alternatively, as originally proposed by Jahns (1959), abundant groundwater in permeable river gravels, perhaps in a buried, abandoned channel of the

Sonoyta River, would have promoted maar formation along an arc within the volcanic field.

Finally, participants can discuss the ways in which one might distinguish impact craters from volcanic craters such as Cerro Colorado and Crater Elegante in remotely sensed data (see e.g., McHone et al., 2002). Many points can be made here, but participants should note that Cerro Colorado has significant accumulation of material as a cone, and it would be easier to distinguish it from an impact crater than Crater Elegante. Cerro Colorado's floor is only 10 m below surrounding terrain, in contrast to pristine impact craters. Multispectral imaging data could also yield clues as to composition and hence point to a volcanic versus impact origin. The lack of overturned bedding such as that observed at Meteor Crater (Greeley et al., 2011, this volume, Chapter 23) is also an important point for participants to recognize.

Ideally, vehicles can leave Cerro Colorado and head north out of the reserve by driving through Playa Diaz, heading north on a cinder road (but check at the visitor's center to determine if this road is still accessible). Upon exiting the Pinacate Biosphere Reserve, vehicles will be on Mexican Route 2. Turn right, heading east. Next, turn left at the junction with Route 8 and head north through Sonoyta to the border. After crossing the border, reverse the outbound route to return home.

CONCLUSION

These field exercises were conducted during two class field trips to the Pinacate volcanic field in the spring 2002 and spring 2007 semesters. In the class evaluations submitted upon completion of the course, students commented how much they enjoyed the field trip, how useful it was to see phreatomagmatic constructs and their deposits in the field (for many students, this was the first time seeing maars and tuff cones), and how good it was to "get calibrated" with radar data and to understand how different geologic features (i.e., 'a'ā vs. pāhoehoe lava flows, volcanic craters, cinder cones, dunes, playa deposits, etc.) appear in radar images.

This field trip is designed to be done over a 2 d weekend, although some participants commented that they would have preferred a 3 d trip. If a third day were added, additional features in the Pinacate Biosphere Reserve could be covered. The hike to the top of Volcan Santa Clara takes ~12 h (round trip). At least one lava tube in the Pinacate volcanic field is large enough to stand in upright and study without crawling on all fours. Furthermore, sand dune morphology can be studied in the neighboring Gran Desierto dune field, which contains unique "star" dunes, which have also been observed in images of Mars (e.g., Breed et al., 1982; Edgett and Blumberg, 1994). Regardless of the vast potential of these additional features, it is our hope that these exercises and field trip to the Pinacate volcanic field will be useful to future geology classes, and that they may prove useful for future astronaut training initiatives.

APPENDIX *(see footnote 1)*

PINACATE FIELD TRIP STUDENT EXERCISE QUESTION SHEETS

Name ____________________________________

GLG 490/598 Field Trip to the Pinacate Volcanic Field

Sarah A. Fagents, David A. Williams, Ronald Greeley, and John F. McHone

INTRODUCTION

This is a 2 d field trip to the Pinacate Biosphere Reserve in Sonora, Mexico. The Pinacate volcanic field has been active for the past 2–3 m.y. Lavas are derived from melting of deep, garnet-bearing asthenosphere, possibly as a miniplume that welled up near, but distinct from, a spreading center in the adjacent Gulf of California (Sea of Cortez) to the south (Goss et al., 2008). The Pinacate field contain diverse volcanic landforms, including a shield volcano, a tuff cone, maars, cinder cones, and lava flows. Two different alkalic rock series are represented: One constitutes the >400 monogenetic cones and craters formed over the last 1.2 m.y. or more; the other forms the extinct Santa Clara shield volcano. The former consists of basalts and hawaiites, whereas the latter constitutes an entire alkaline differentiation series: basalt, hawaiite, mugearite, benmoreite, and trachyte.

This trip will focus on the deposits and morphologic expressions of explosion craters, volcanic cones, and lava flows.

Guidebook Cover Image: The Pinacate volcanic field as imaged by the Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar (SIR-C/X-SAR) carried onboard the space shuttle *Endeavor* on 18 April 1994. Image is centered at 31.84°N, 113.47°W. The colors are assigned to different radar frequencies and polarizations of the radar as follows: red is L band (23.5 cm), horizontally transmitted and received; green is L band, horizontally transmitted, vertically received; and blue is C band (4–8 cm), horizontally transmitted, vertically received. National Aeronautics and Space Administration (NASA) photojournal image PIA 01852.

<u>**DAY 1**</u>

Mile 0	**Depart Tempe:** Head south on Rural Road to Broadway Road.
Mile 1	Turn right on Broadway.
Mile 3.5	At the junction with I-10, head south toward Tucson for ~8.5 miles.
Mile 12	Take the Maricopa road exit and head south for 29 miles.
Mile 43	At the junction with Hwy 84, turn west.
Mile 49	Take I-8 west.
	Stop 1. Rest area (or Gila Bend). Overview of geology of the area.
Mile 83	Take exit 116 at Gila Bend, turn south on Hwy 85.
Mile 126?	**Stop 2.** Mining pit in Ajo. Discussion of mineral deposits and mining operations. **Mile 160?**
Stop 3	(optional) Organ Pipe National Monument visitor center.
Mile 163	**Stop 4.** Mexican border at Lukeville. After crossing, proceed to Sonoyta.
Mile 165	Turning right onto Route 8, heading southwest towards Puerto Peñasco. The oldest volcanic center (Volcan Santa Clara) of the Pinacate volcanic field will become visible to the west.

EXERCISE 1. Remote sensing of the Pinacate region.

En route to the Pinacate volcanic field, examine the color SIR-C/X-SAR radar image of the volcanic field (the front cover of your field guide). Based on your understanding of how microwave radiation interacts with surface materials, together with what you see from the van, suggest answers to the following questions:

1.1 What are the anastamosing channels in the southeast portion of the image? What causes the bright radar return?

____

1.2 What might compose the broad, dark patterned surface in the far southwest of the image?

____

1.3 What causes the reddish hues in the image?

____

1.4 Within the main volcanic area, how many prominent (>500 m diameter) craters can you identify? Comment on the variations in morphology and crater floor brightness/color.

1.5 What are the lobate, bright yellowish features prominent in the eastern part of the field? What is the cause of their radar brightness?

Now examine the false-color Landsat image of the Pinacate volcanic field (Fig. 1). This was constructed with band 7 (2.08–2.35 μm), band 4 (0.76–0.90 μm), and band 2 (0.52–0.60 μm) in the red, green, and blue channels, respectively. By referring to Figure 2, which shows spectra of common rocks and minerals, answer the following questions.

1.6 What are the abundant circular red features? Why are they red?

1.7 Note that many of the craters and other features that are prominent in the radar image are less distinct in visible to near infrared wavelengths. Why is much of the volcanic field dark?

1.8 What is the material making up the yellowish surface to the southwest?

Mile 200 At the sign for the Pinacate Biosphere Reserve, turn right off Route 8 onto dirt road, stop at visitor's center to register and obtain a camping permit. Continue north on the dirt road for ~10 mi (~16.1 km).
Mile 210 Bear left at fork in road, following the sign to Crater Elegante.
Mile 217 **Stop 6.** Crater Elegante. Lunch.

Crater Elegante is ~1600 m in diameter and 244 m deep, and it formed some 32,000 yr ago. The rim affords a great perspective of the surrounding geology: Volcan Santa Clara dominates the southwestern horizon. To the northeast, there are the cones of Tecolote, Mayo, and Cerro Colorado. The low-lying area to the south hosts abundant small cones. Lava flows are clearly visible to the west and northeast.

EXERCISE 2. Crater Elegante.

Walk up to the crater rim and (with caution) scramble a few meters down the slope toward the crater floor to examine the outcrops.

2.1 Describe the deposits in terms of their components, bedding structures, dip, etc.

2.2 What eruption mechanism do these deposits represent?

Walk west along the crater rim for 500–1000 m. Look across to the highest point along the rim on the opposite side.

2.3 What do you notice about the structure in the opposite wall?

Now backtrack and walk east around the crater toward the highest point. Along the way, note the relief of the crater rim in relation to the surrounding area, the dip of the beds, and the depth to crater floor. Also note the variety of large ejecta types.

2.4 Describe the material comprising the highest point of the rim. How does it differ from that found elsewhere? What is the relationship of this structure to the crater?

2.5 Based on everything you've observed, what type of feature is Elegante? How did it form?

2.6 Examine the enlargement of the radar image covering Elegante (Fig. 3). Explain the variation in radar brightness in the crater floor.

2.7 What features does Elegante have or lack compared to impact craters?

Returning to the vans, leave Elegante and travel north around Tecolote Cone.

Mile 221 **Stop 7.** ‘A‘ā lava flow front. We will examine the lava textures and discuss the emplacement processes of ‘a‘ā flows. Walk up and examine the textures of the lava surface and flow front. How do these characteristics relate to the radar brightness? Noting the characteristics of the surrounding surfaces, examine the enlarged radar image (Figs. 4, A1, A2) to locate our position.

Mile 224 **Stop 8.** Continuing along the road, we will turn left into the Tecolote campground.

EXERCISE 3. Lava flows.

Walk west along the short road through the campground for ~500 m until you enter a broad basin surrounded by thick lava flows. One flow emanates from Mayo Cone, immediately to the north of the campground; another comes from the Tecolote Cone complex to the south. Walk clockwise around the margins of the basin to examine the different lava flows.

3.1 Locate the pāhoehoe flow. Note the surface textures. What is its stratigraphic relationship and age relative to the ‘a‘ā flow?

3.2 From the radar image, what can you say about the abundance of pāhoehoe flows relative to ‘a‘ā in the Pinacate volcanic field?

DAY 2

EXERCISE 4. Mayo Cone.

Starting from the campground, skirt westward along the base of the Mayo Cone and head up over the saddle into the interior of the breached cone complex.

4.1 Describe the characteristics of the pyroclastic material comprising the cone's outer flanks. How does this differ from the material you saw at Elegante?

4.2 Describe the characteristics of the pyroclasts and deposits within the interior of the breached cone.

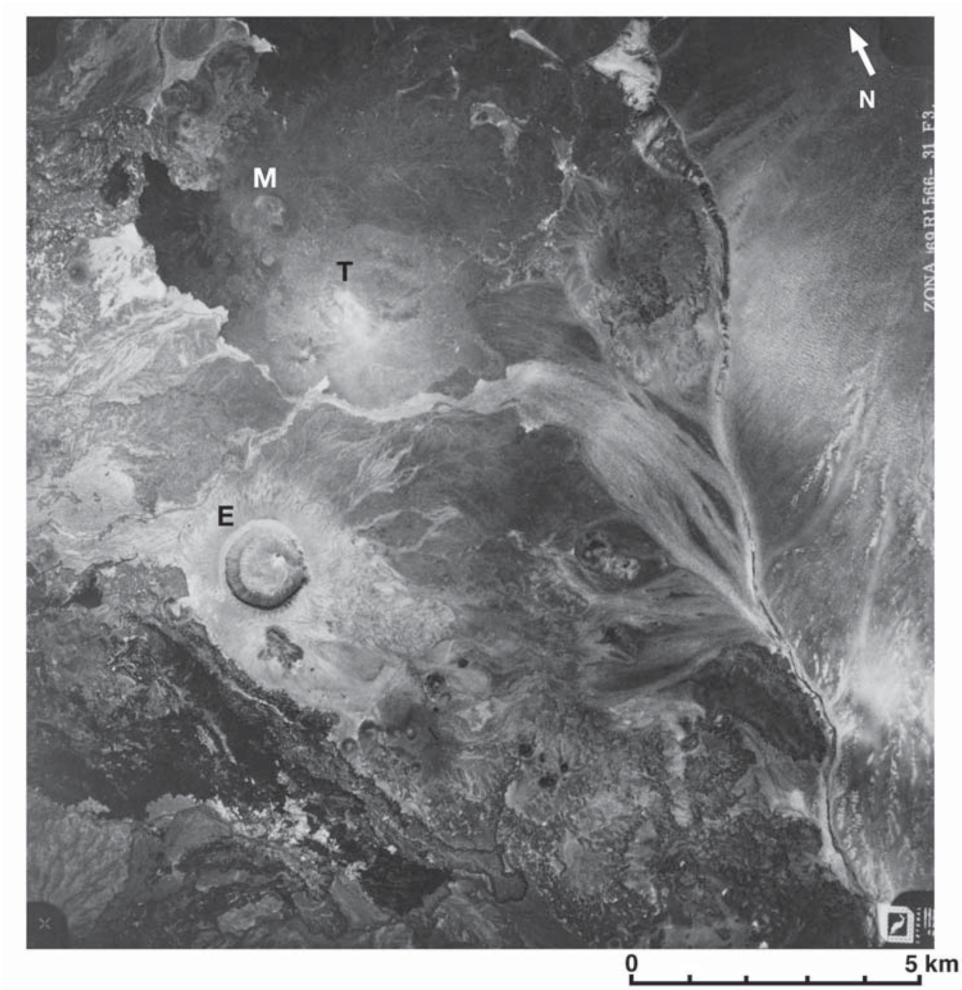

Figure A1. Aerial photo of the Pinacate volcanic field, showing Crater Elegante (E), Tecolote (T), and Mayo (M) Cones. Image is courtesy Arizona State University Space Photography Laboratory.

4.3 Based on your observations of the cone complex and pyroclastic material, describe the eruption mechanisms responsible for the deposits. How do you think the eruption evolved through time?

Returning to the vans, leave the campground and head west to Cerro Colorado.

Mile 230 **Stop 9.** View of Cerro Colorado to the north. Note the relief of the structure and dip of the bedding.
Mile 233 **Stop 10. North rim of Cerro Colorado.**

Cerro Colorado is >27,000 yr old, based on Ar/Ar dating of overlying lapilli. The crater is ~1000 m in diameter, with the crater floor lying >100 m below the highest point on the south rim. The morphology of the crater records multiple centers of activity. Note the presence of Diaz Playa to the north of Cerro Colorado.

EXERCISE 5. Cerro Colorado.

Walk down a few meters inside the crater rim onto the benches to examine rim deposits.

5.1 Describe the characteristics of these deposits (clast types, bedding, dip, etc.).

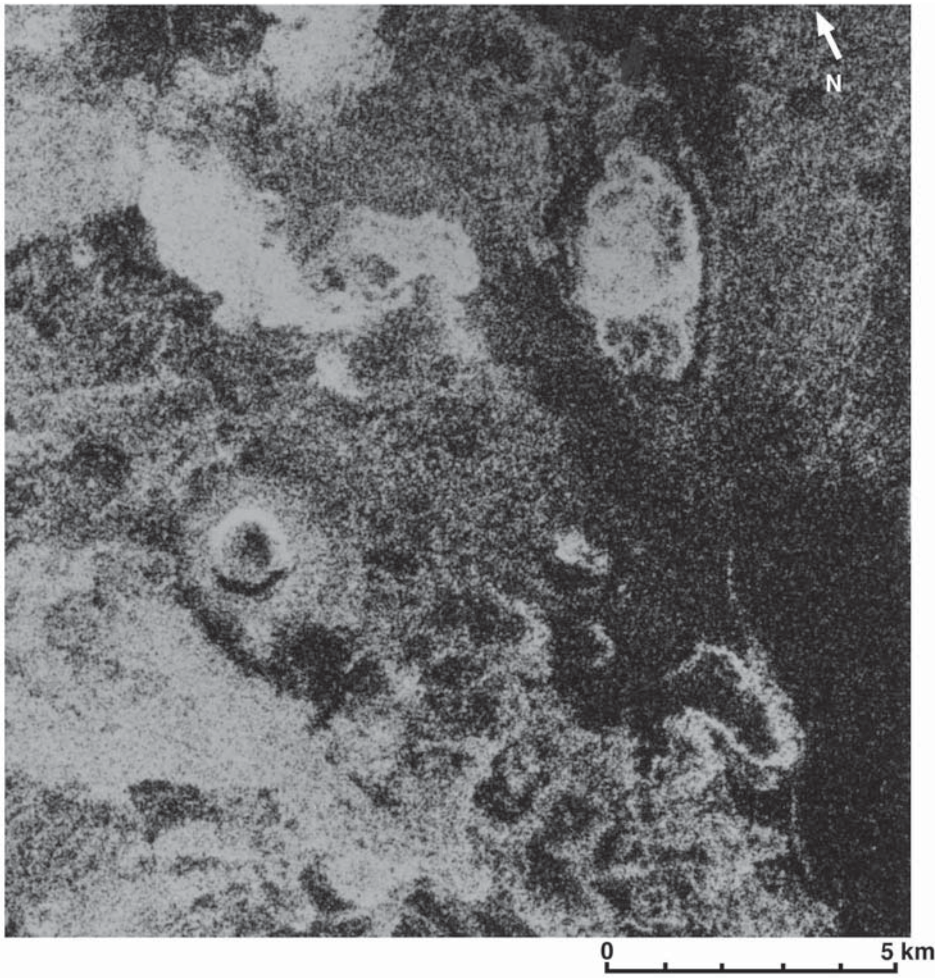

Figure A2. Spaceborne Imaging Radar (SIR)-A radar image of the Pinacate volcanic field, showing Crater Elegante, and Tecolote and Mayo Cones (cf. Fig. A1). Image is courtesy Arizona State University Space Photography Laboratory.

5.2 How were these deposits formed?

5.3 What do the lithic clasts say about the pre-eruption environment?

5.4 How do these deposits differ from those at Elegante?

Looking down into the crater, note the pinkish tan deposits exposed at the bottom of the crater's north wall. These are mudstones, which probably represent preexisting playa deposits.

5.5 What does the morphology of the crater interior suggest regarding the focus of eruptive activity?

Return to the crater rim. Walk counterclockwise around to the northwest part of the rim. Note the presence of long-wavelength radial dune forms on the outer flanks. Examine the deposits in the crater wall.

5.6 What do these deposit characteristics suggest about their mechanism of emplacement?

5.7 What do your observations of cone relief, deposit characteristics, and bedding dip suggest about eruption style and the role of external water? What type of feature is Cerro Colorado?

Return to the crater rim and head back to the vans.

5.8 Locate Cerro Colorado on the radar image (front cover). Explain the radar-dark apron.

5.9 Study the radar image to determine the locations of major craters. Given what you now know about the formation of volcanic craters at Pinacate, what inferences might you make about the paleohydrology of this region?

5.10 How might one distinguish between impact craters and volcanic craters such as Cerro Colorado and Crater Elegante in remotely sensed data?

Lunch at the vans. We will leave Cerro Colorado and head north out of the Reserve.

Mile 234 Head north through Playa Diaz.
Mile 239 Head north on cinder road.
Mile 240 Exit Pinacate Biosphere Reserve. Join Route 2 heading east.
Mile 272 Turn left at junction with Route 8. Head north through Sonoyta to border.
Mile 274 Border crossing. Reverse the outbound route to return to Tempe.

Reference Reprints Included in This Guidebook. ***(These appear courtesy of the Arizona Geological Survey.)***

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Instructor's Answer Key

EXERCISE 1. Remote sensing of the Pinacate region.

1.1 What are the anastamosing channels in the southeast portion of the image? **Riverbed/washes/drainage channels.** What causes the bright radar return?
Surfaces that are 'rough' at the scale of the radar appear bright in radar images (L band: 23.5 cm, C band: 4–8 cm). At this locality cobbles and gravels in riverbeds, vegetation, and the clinkery tops of 'a'ā lava flows appear bright.

1.2 What might compose the broad, dark patterned surface in the far southwest of the image?
Dunes, composed of sand-sized particles smaller than the wavelength of radar, and dusty playa deposits appear dark in these images.

1.3 What causes the reddish hues in the image?
Differences in radar reflectivity caused by variations in the sizes of sediment types (boulders and cobbles to sand, silt and dust).

1.4 Within the main volcanic area, how many prominent (>500 m diameter) craters can you identify? Comment on the variations in morphology and crater floor brightness/color.
10–15. Most have some combination of radar bright and dark surfaces, indicating rough/smooth and/or scattering/absorbing surfaces.

1.5 What are the lobate, bright yellowish features prominent in the eastern part of the field? **Lava flows.** What is the cause of their radar brightness?
The surface roughness of the flows. The rough, clinkery surface of 'a'ā flows results in a brighter radar return than the smooth, flat surface of pāhoehoe flows.

1.6 What are the abundant circular red features? Why are they red?
Cinder cones. Oxidized scoria reflects strongly at longer wavelengths (2–2.5 microns).

1.7 Note that many of the craters and other features that are prominent in the radar image are less distinct in visible to near infrared wavelengths. Why is much of the volcanic field dark?
Basalt has low reflectivity and is spectrally flat (has little variability) in the vis-NIR region, appearing dark. In contrast, basalt can be bright or dark in radar depending on its form ('a'ā—bright, pāhoehoe—intermediate, cinders and ash—dark).

1.8 What is the material making up the yellowish surface to the southwest?
Quartz-rich dunes. Quartz is whitish in visible light.

EXERCISE 2. Crater Elegante.

2.1 Describe the deposits in terms of their components, bedding structures, dip, etc.
Tuff breccia: Thinly bedded outward-dipping layers showing dune-forms, pinch and swell structures, bombsags (indicating sticky and cohesive material), poorly sorted, sometimes reverse-graded. Poorly indurated, partly palagonitized. Juvenile material: tan basaltic ash – vitric/vesicular.
Lithic material: predominantly angular basaltic bocks, 50% derived from exposed precursor lava flows and 50% from deeper in volcanic pile. Lithics include quartzofeldspathic sand, silt, clay, few pebbles/cobbles forming pale buff matrix. Low porosity and permeability indicate a "dryer" eruption relative to Cerro Colorado.

2.2 What eruption mechanism do these deposits represent?
Surge deposits produced in explosive phreatomagmatic activity. Relatively little H_2O – only partial palagonitization/induration; no accretionary lapilli; little construction around crater.

2.3 What do you notice about the structure in the opposite wall?
Bedding dips change; reddish in color; presence of dikes/intrusions (Devil's pitchfork).

2.4 Describe the material comprising the highest point of the rim. **Tuff breccia (32 ka).** How does it differ from that found elsewhere? What is the relationship of this structure to the crater?
The larger, juvenile, vesicular, oxidized, deformed spatter is part of a ca. 430 ka cinder cone. The initial magmatic volatile-driven phase, prior to onset of phreatomagmatic activity and formation of crater, can be seen in the younger gray cinders exposed in the south wall of the crater. For sequence of eruptions at Elegante see Gutmann (2002).

2.5 Based on everything you've observed, what type of feature is Elegante? How did it form?
Elegante has been called a maar, tuff-ring and mini-caldera. It has a complex history and multiple formative events. The eruption started with lava effusion, then explosive construction of the cinder/scoria cone commenced. At some point groundwater gained access to the magma and more powerful phreatomagmatic explosions occurred, producing the tuff breccia. Probably eruption and collapse (deepened and widened the crater) occurred roughly synchronously.

2.6 Examine the enlargement of the radar image covering Elegante (Fig. 3). Explain the variation in radar brightness in the crater floor.
Dark area represents the smooth/absorbing playa deposit in the center. Brighter regions are rougher floor/talus deposits.

2.7 What features does Elegante have or lack compared to impact craters?
Open-ended question: Has lavas, scoria cone, steep walls, depth/diameter ratio (d/D)=0.15 (cf. 0.1 for impacts). Lacks: overturned beds, etc.

EXERCISE 3. Lava flows.

3.1 Locate the pāhoehoe flow. Note the surface textures. What is its stratigraphic relationship and age relative to the ‘a‘ā flow?
Pāhoehoe lies below the ‘a‘ā and is therefore older.

3.2 From the radar image, what can you say about the abundance of pāhoehoe flows relative to ‘a‘ā in the Pinacate volcanic field?
‘A‘ā is far more abundant.

EXERCISE 4. Mayo Cone.

4.1 Describe the characteristics of the pyroclastic material comprising the cone's outer flanks. How does this differ from the material you saw at Elegante?
Vesicular, scoriacous, juvenile lapilli. Larger than the juvenile material (ash-sized) at Elegante.

4.2 Describe the characteristics of the pyroclasts and deposits within the interior of the breached cone.
Large bombs up to ~0.5 m and larger. Some breadcrusted, some deformed. Dense, poorly vesicular, juvenile.

4.3 Based on your observations of the cone complex and pyroclastic material, describe the eruption mechanisms responsible for the deposits. How do you think the eruption evolved through time?
(1) Initial lava effusion (magma contained too few volatiles to exsolve sufficiently to fragment magma), or alternatively, the initial lava effusion was essentially degassed during storage or ascent, and it was only as the eruption progressed that more volatile-rich magma was tapped for stage 2 – Note that the results of these processes are more clearly visible at La Laja Cone. (2) Transition to strombolian activity (ascent of a more volatile-rich magma, including exsolution, bubble growth and fragmentation). (3) Transition back to effusion as volatiles become exhausted, lava piles up inside cone, cone is breached, and lava flows off to the west. (4) Lava cooling and crystallization in vent/conduit induces further exsolution in liquid phase, and final late-stage ejection of large, dense bombs, producing spatter collars on cone tops and around interior vents. There are some small, late explosion pits in Mayo and Tecolote Craters.

EXERCISE 5. Cerro Colorado.

5.1 Describe the characteristics of these deposits (clast types, bedding, dip, etc.).
Palagonitized tuff with diverse lithics. Well indurated. Laterally extensive (along crater rim), normally graded beds, with steep outward dips. Accretionary lapilli present. Lithics include quartzofeldspathic gravels.

5.2 How were these deposits formed?
Fall deposits, from phreatomagmatic explosions.

5.3 What do the lithic clasts say about the pre-eruption environment?
Rounded lithics indicate fluvial environment.

5.4 How do these deposits differ from those at Elegante?
More indurated/palagonitized, accretionary lapilli—more water involved in explosions. Beds are planar and laterally extensive (absence of duneforms, etc.) indicating fall not surge deposits.

5.5 What does the morphology of the crater interior suggest regarding the focus of eruptive activity?
Scalloped margins and inward dipping beds suggest several foci of activity.

5.6 What do these deposit characteristics suggest about their mechanism of emplacement?
Turbulent emplacement produced differential deposit thicknesses (dunes), i.e., they are surge deposits. (One of only a few known localities for longitudinal dunes w/surge deposits.)

5.7 What do your observations of cone relief, deposit characteristics, and bedding dip suggest about eruption style and the role of external water? What type of feature is Cerro Colorado?
Larger accumulation of material at rim suggests sticky, cohesive material. More water (than Elegante) also indicated by accretionary lapilli and palagonitization/induration. Surface water (rather than groundwater) may have been involved here. Cerro Colorado is a tuff cone.

5.8 Locate Cerro Colorado on the radar image (front cover). Explain the radar-dark apron.
Smooth, flat-lying apron of fine pyroclastics from Cerro Colorado.

5.9 Study the radar image to determine the locations of major craters. Given what you now know about the formation of volcanic craters at Pinacate, what inferences might you make about the paleohydrology of this region?
Ideas: Water was displaced by the growing volcanic field and concentrated around the north and east margins, where the maars and tuff rings/cones are located. Alternatively, magma could have pierced a unit of water-saturated sand and gravel in an abandoned channel of Sonoyta River, Strombolian activity and lava flows would have changed to phreatomagmatic activity and maar formation (Jahns, 1959; Gutmann, 2002).

5.10 How might one distinguish between impact craters and volcanic Craters such as Cerro Colorado and Crater Elegante in remotely sensed data?
Cerro Colorado has significant accumulation of material in cone, would be easier than Elegante to distinguish from an impact crater. Scalloped margins might also provide a clue. Cerro's floor is only 10 m below surrounding terrain, in contrast to impact craters. Multispectral imaging data could also yield clues as to composition and hence point to a volcanic vs. impact origin. Many other points can also be made here, as for 2.7.

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