

Features on Venus Generated by Plate Boundary Processes

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Various observations suggest that there are processes on Venus that produce features similar to those associated with plate boundaries on Earth. Synthetic aperture radar images of Venus, taken with a radar whose wavelength is 12.6 cm, are compared with GLORIA images of active plate boundaries, obtained with a sound source whose wavelength is 23 cm. Features similar to transform faults and to abyssal hills on slow and fast spreading ridges can be recognized within the Artemis region of Venus but are not clearly visible elsewhere. The composition of the basalts measured by the Venera 13 and 14 and the Vega 2 spacecraft corresponds to that expected from adiabatic decompression, like that which occurs beneath spreading ridges on Earth. Structures that resemble trenches are widespread on Venus and show the same curvature and asymmetry as they do on Earth. These observations suggest that the same simple geophysical models that have been so successfully used to understand the tectonics of Earth can also be applied to Venus.

INTRODUCTION

Perhaps the most important question about the evolution of Venus is to what extent its surface is being deformed in the same way as is that of Earth. If it is, then the understanding developed for Earth can be directly used to understand the origin of features on Venus. If it is not, progress is likely to be much slower, because synthetic aperture radar (SAR) images, altimetry with a resolution of 10 km or less and a few low accuracy analyses of the surface composition are not likely to be sufficient to allow an understanding of new tectonic processes to be developed. Such observations would not have been sufficient for Earth, where our understanding of the processes involved depends principally on seismology and palaeomagnetism. Since so few types of information are yet available for Venus, we must argue by analogy and compare features on the two planets at the same scale, observed by similar types of sensors. If they look alike, we argue that they have been produced by similar processes. Though it is clear that such an argument may not be valid, there is at present no obvious alternative.

Before Magellan images and altimetry became available there was considerable controversy about whether there were structures on Venus corresponding to plate boundaries on Earth [Crumpler and Head, 1988; Grimm and Solomon, 1989]. It is now clear that the resolution of these early images was not sufficient to allow this question to be decided one way or the other. But the new higher-resolution data allow a much stronger and more detailed case to be made.

Our object in this paper is to show that there are features on Venus that closely resemble oceanic transform faults, abyssal hills and trenches, and fold mountain belts and transform faults on continents. We have not yet found a convincing example of a spreading ridge or of a basin produced by extension. Such features may be present but are not likely to be easy to map using altimetry and SAR images (see below). Of these structures, only analogs to terrestrial trenches, continental fold belts, and transform faults appear to be widespread on Venus. Features resembling abyssal hills and oceanic fracture zones have so far only been recognized in one region of the planet and extend over an area of about $500 \times 1000 \text{ km}^2$.

TRANSFORM FAULTS AND FRACTURE ZONES

On Earth the most unambiguous method of mapping transform faults depends on offsets in the magnetic anomaly patterns. Until this method came into general use there was some confusion between fracture zones and trenches. Though their topography can be similar, fracture zones tend to be narrower and more symmetric than trenches. The surface expression of the transform part of a plate boundary joining two spreading ridges is a deep linear trough, whose width is about 20–30 km and whose depth is 1–3 km below the ridge axis. The active strike-slip fault is generally near the center of the trough, whose depth below the seafloor changes little as the plate motions transport the seafloor away from the plate boundary. On ridges spreading at less than about 30 mm yr^{-1} half rate the crust along the axis of the fault is as thin as 3 km or considerably less than the oceanic average of 7 km. The thin crust probably results because less melt is produced at the ridge tip next to older, colder, lithosphere. The major cause of the trough is this difference in crustal thickness. On Venus the crustal thickness on transform faults is likely to be reduced by a similar amount where they intersect ridges, but the depth of the trough will be reduced by a factor of about 0.7, the ratio of the density contrasts, because the trough is filled by atmospheric gas, not water.

The SAR on Magellan uses a radar whose wavelength is 12.6 cm and maps a swath width of about 20 km with a resolution of about 75 m [Pettengill *et al.*, 1991]. The images are best compared with those produced by GLORIA, a side scan sonar system that uses a wavelength of 23.1 cm to map

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a 20 km width swath with a similar resolution to the SAR [Somers *et al.*, 1978; Searle, 1986; Mitchell, 1991]. The most important difference between the two systems involves the incidence angle, measured from the vertical. That of the SAR varies slowly with latitude from 17° to 47° [Pettengill *et al.*, 1991] and is essentially constant for an image that spans only a few degrees of latitude. In contrast, that of GLORIA varies strongly with range, from about 30° at the edge of the image nearest the ship to more than 80° at the greatest range. GLORIA images have mostly been obtained for small areas of the seafloor. The only large areas that have been covered are around the United States, and most are dominated by sedimentary features. Though the cost of mapping all the ocean floor with GLORIA would only be about half of the cost of Magellan, it would take about 100 ship years to do so.

Figure 1a shows a GLORIA image of part of the East Pacific Rise where it is offset by the Quebrada and Discovery transform faults [Searle, 1983, 1986]. The half spreading rate of the ridge is about 75 mm yr^{-1} . The bright lineations are reflections from the edges of abyssal hills and are zones of small scale roughness produced by faulting. As the seafloor moves away from the spreading ridge axis, these zones become less reflective as they are covered with sediment. The transform faults are marked by curvature of the margins of the abyssal hills. This curvature is believed to result from

the stress field associated with the ridge-transform fault junction [Crane, 1976; Searle and Laughton, 1977; Lonsdale, 1978; Fox and Gallo, 1984] and is in the same direction as the ridge offset. However, the location of the spreading ridge itself cannot be seen on the GLORIA record.

Similar features to those in Figure 1a are visible on the SAR images of part of the Artemis region of Venus (see Figure 2 for a location map). These show short bright reflectors that are linear over much of the image but sigmoidal where they cross what we believe are fracture zones. These traces are themselves curved. On Earth such curvature arises if the fracture zone is close to the pole of relative rotation between the plates involved or if the direction of spreading changes. It is not clear whether the faults in Figures 1c and 1d are associated with deep troughs, as they would be on Earth. The altimeter has an along-track resolution of about 8 km and an across-track of about 20 km at -40°N [Pettengill *et al.*, 1991] and may be sufficient to map any troughs associated with these transform faults [Ford and Pettengill, this issue].

SPREADING RIDGES

On Earth, separating plate boundaries are marked by topographic ridges whose elevation e is about 4 km above the oldest seafloor [Parsons and Sclater, 1977]. This elevation difference is a direct consequence of the production of plates

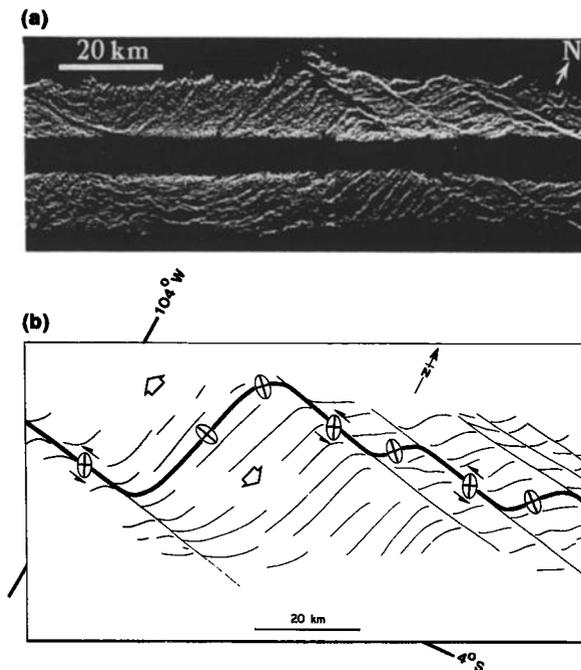
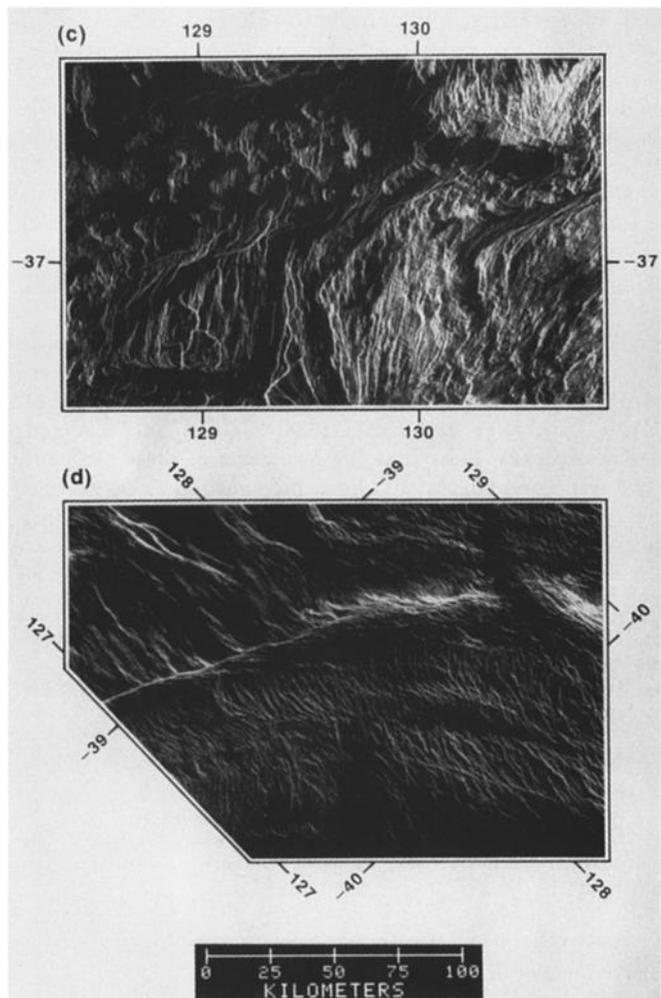


Fig. 1. (a) Two-sided GLORIA image of parts of the Quebrada and Discovery fracture zones on the East Pacific Rise. The ship track is along the middle of the central dark horizontal line. (b) An interpretation of Figure 1a. The fine lines are selected tectonic lineaments, the heavy line is the inferred plate boundary, half arrows show the slip directions, full arrows the spreading directions, and the ellipses the strain [from Searle, 1983]. (c) and (d) SAR images of fracture zones in the Artemis region of Venus. 1° of latitude corresponds to 111 km on Earth and to 105 km on Venus. Figure 1c is from F-MIDR 35S130;1. Figure 1d is from F-MIDR 40S131;1.



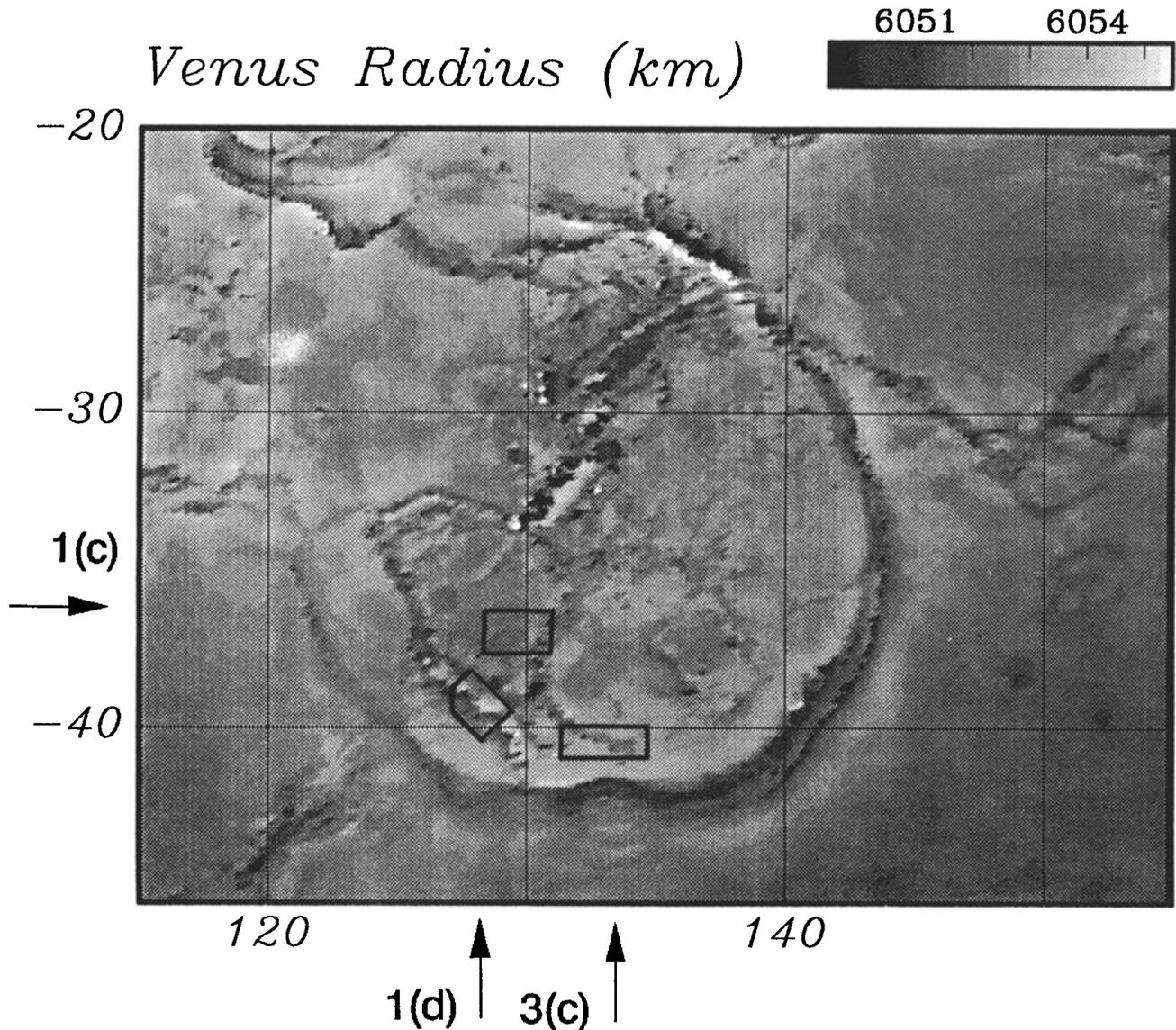


Fig. 2. The topography of the Artemis region, showing the location of Figures 1c, 1d and 3c. The circular depression of radius 1000 km marks the outer boundary of Artemis Corona.

from hot mantle. If T_1 is the mantle temperature, ρ_w is the density of water, ρ_m is the density of the mantle, κ is the thermal diffusivity, α is the volumetric thermal expansion coefficient, d is the thickness, and t is the age of the plate, then

$$e(t) = \alpha \rho_m \left(\frac{(T_1 - T_0)d}{\rho_m - \rho_w} \right) F(t/\tau) \quad (1)$$

where τ is the thermal time constant

$$\tau = \frac{d^2}{\pi^2 \kappa}$$

For Earth, $\rho_w = 1.03 \text{ Mg m}^{-3}$, $T_0 = 0^\circ\text{C}$ and $T_1 \approx 1350^\circ\text{C}$, whereas for Venus, $\rho_w = 0.05 \text{ Mg m}^{-3}$, $T_0 \approx 470^\circ\text{C}$, and T_1 is likely to be similar to that of Earth (see below). These differences alone reduce the value of $e(0)$ from 3.9 km for Earth to 1.75 km for Venus [Kaula and Phillips, 1981]. For oceanic plates on Earth, $d \approx 125 \text{ km}$, but the value of d for Venus is uncertain. If the heat flow through old lithosphere on Venus is required to be the same as that on Earth, or 36 mW m^{-2} , its thickness can only be 84 km and the eleva-

tion of ridge axes above old lithosphere is reduced to 1.2 km. The thermal time constant is also reduced, from 62.8 Ma for Earth to 28 Ma for Venus. Though a lithospheric thickness of 84 km is too small to satisfy the flexural observations, it is too large to allow the heat generated by radioactive decay to escape by conduction through the lithosphere.

The other important cause of topographic variations on Earth is variations in crustal thickness. On Venus, corresponding variations in crustal thickness will produce topographic variations reduced by a factor of $(\rho_m - \rho_w)/\rho_m \approx 0.70$. In contrast, the topography associated with a spreading ridge is reduced by a factor of 0.31 if the lithospheric thickness is 84 km. Hence ridges on Venus may be harder to recognize by their topography compared with those on Earth, because they are smaller both in height and in lateral extent relative to topographic features resulting from crustal thickness variations. Furthermore, terrestrial ridge axes cannot be distinguished from adjacent abyssal hills on the GLORIA images (see Figures 1a and 3a) and are therefore not likely to be visible on the SAR images either. These

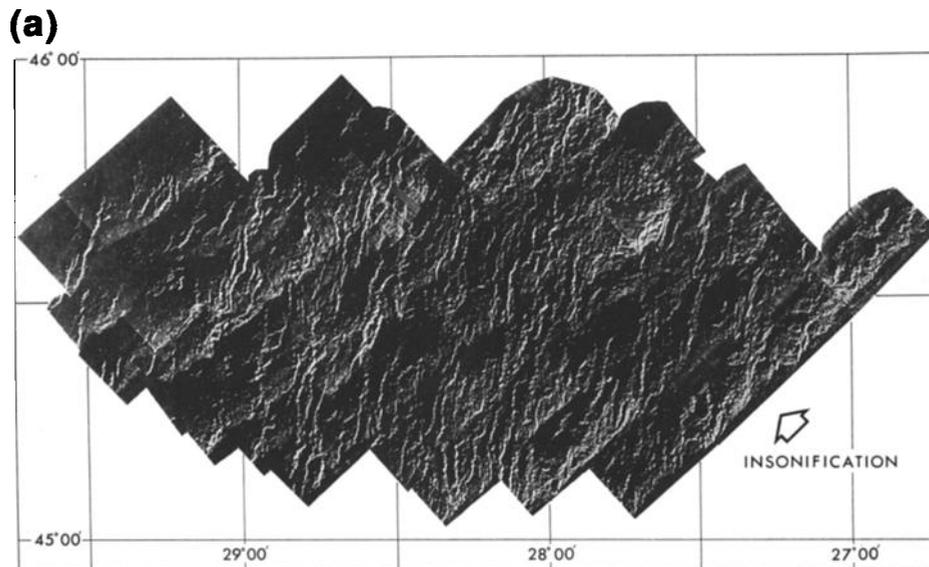


Fig. 3a. Mosaic of GLORIA images on the axis of the Mid-Atlantic Ridge.

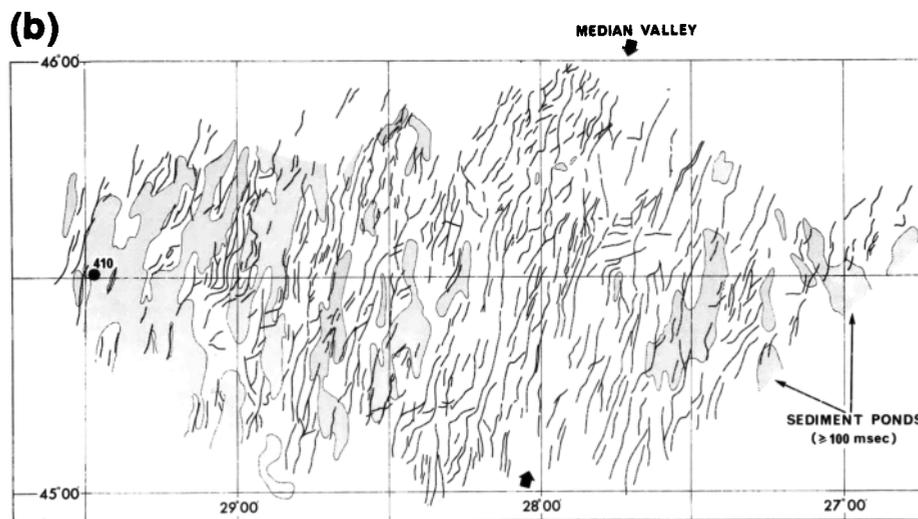


Fig. 3b. An interpretation of Figure 3a showing the main tectonic lineations [Laughton and Searle, 1979].

arguments suggest that active spreading ridges on Venus will not be easy to map: only their linearity and symmetry may distinguish them from other larger features supported by variations in crustal thickness. These arguments probably explain why no convincing examples of spreading ridges on Venus have yet been identified. Nonetheless spreading ridges have probably been responsible for producing the structures in Figures 1 and 3c. As Figure 2 shows, these features occur inside Artemis Corona. Its outer edge is a flexural bulge that is cut by faults that are tangential to the corona and closely resembles the outer rise of terrestrial trenches. Therefore the features that are like abyssal hills may be produced in a tectonic setting like that of back arc spreading on Earth. The abyssal hills in Figure 3a are on either side of a slowly spreading ridge in the North Atlantic that is spreading at 12 mm yr^{-1} half rate [Laughton and Searle, 1979]. The short bright features are thought to arise when short individual spreading centers are staggered within a spreading zone

[Searle and Laughton, 1977]. On fast spreading ridges the bright linear features are continuous over greater distances (see Figure 1a). The existence of features on Venus whose spacing and length is similar to those in the North Atlantic (Figure 3c) suggests that spreading centers have existed on Venus. But the processes that produce the lineations on Earth are not yet well understood, and it is therefore not clear whether the Venusian ridges were also slowly spreading. There are no obvious linear symmetric features visible on the altimetric profiles associated with the lineations in Figures 1c, 1d, and 3b, so it is not clear whether the ridges that produced the lineations are still active. In the absence of erosion, the roughness responsible for the radar reflections will persist indefinitely.

A striking feature of spreading ridges on Earth is that they are the major volcanic features of the planet and produce basaltic magma at a rate of about $20 \text{ km}^3 \text{ yr}^{-1}$. The composition of this basalt is distinctive in having uniform

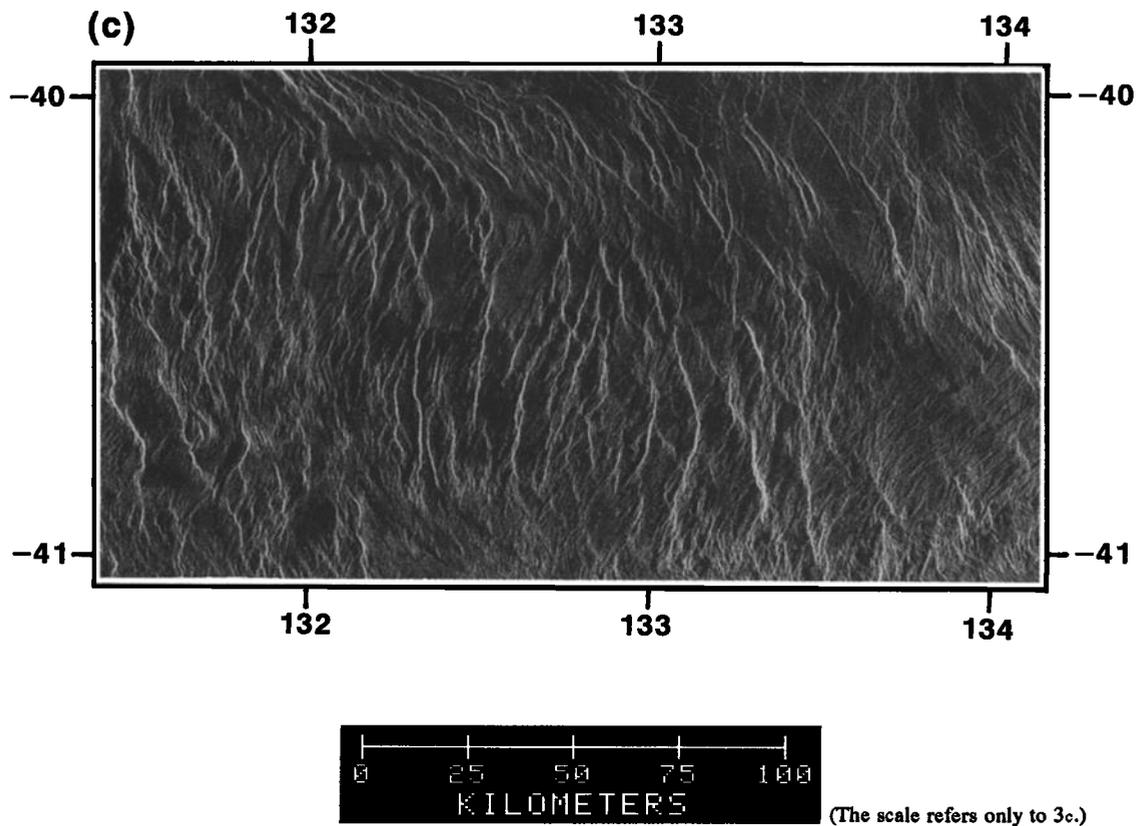


Fig. 3c. A SAR image from F-MIDR 40S131;1 of part of the Artemis region (see Figure 2 for the location).

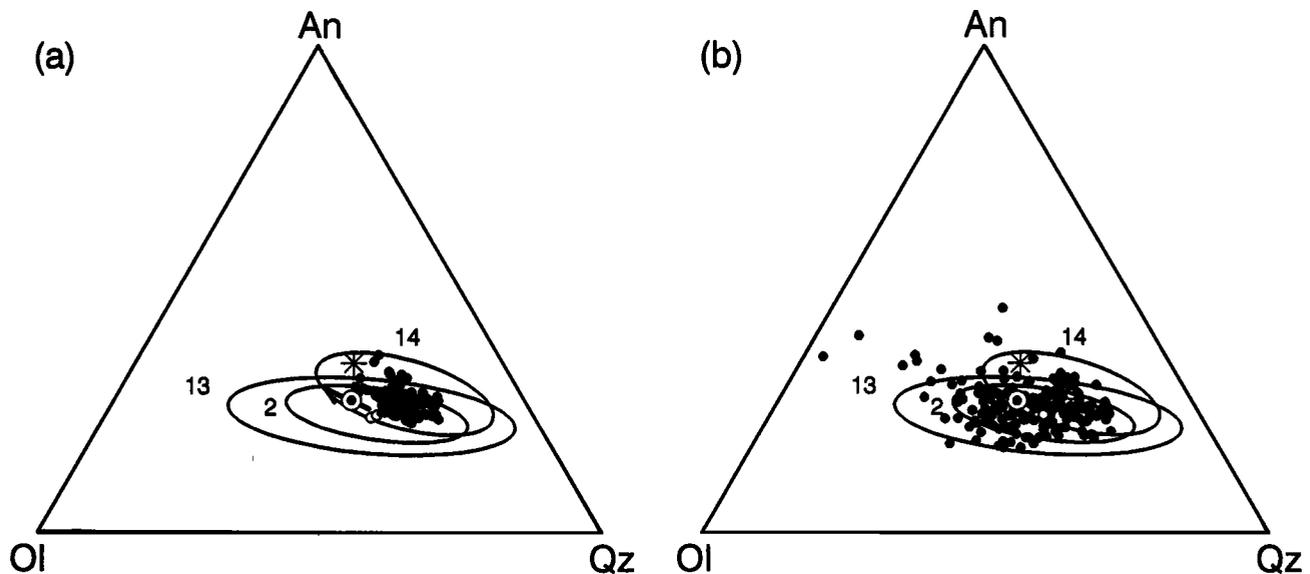


Fig. 4. Projections onto the olivine-anorthite-quartz face from the diopside apex of the tetrahedron of *McKenzie and Bickle* [1988]. The location of the points in this tetrahedron depends only on the concentration of SiO_2 , Al_2O_3 , FeO , MgO and CaO in the rock, and is independent of that of Na_2O and K_2O . The points corresponding to the compositions measured by Venera 13 and 14 and Vega 2 [Surkov *et al.*, 1984, 1986] are shown with open circles at the center of ellipses, numbered 13, 14, and 2, respectively, produced by projecting the five-dimensional hyperellipsoid calculated from the standard errors given by Surkov *et al.* The heavy line and the solid dot at the center of a circle show the point average and the point and depth average composition, respectively, generated by adiabatic decompression to the surface when the potential temperature is 1330°C , calculated from the parameterisation of *McKenzie and Bickle* [1988] and *Watson and McKenzie* [1991]. The star shows the average composition of cumulus gabbro from the Semail ophiolite [Pallister, 1984]. The Venus compositions are compared with (a) mid-ocean ridge basalt (MORB) measured on dredged and drilled samples (R. S. White *et al.*, submitted manuscript, 1992), (b) magmas from oceanic islands and seamounts (D. McKenzie and R. K. O'Nions, manuscript in preparation, 1992), (c) Miocene and younger magmas from western Turkey [McKenzie and Yilmaz, 1990], and (d) Jurassic melts from the North Sea [Latin *et al.*, 1990].

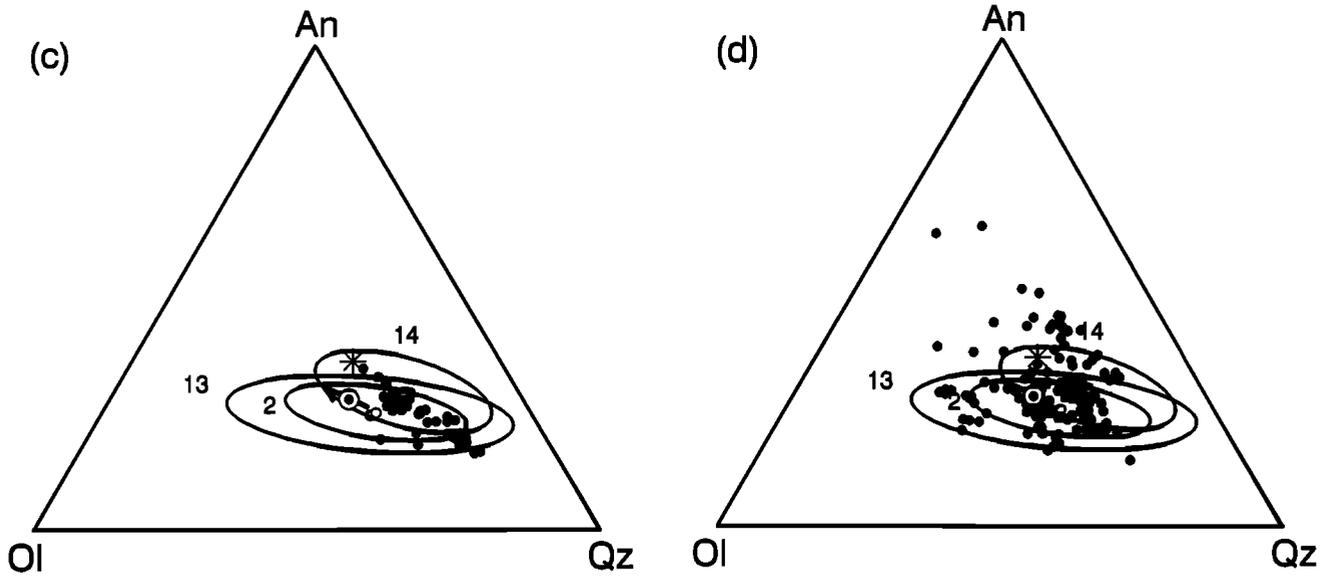


Fig. 4. (continued)

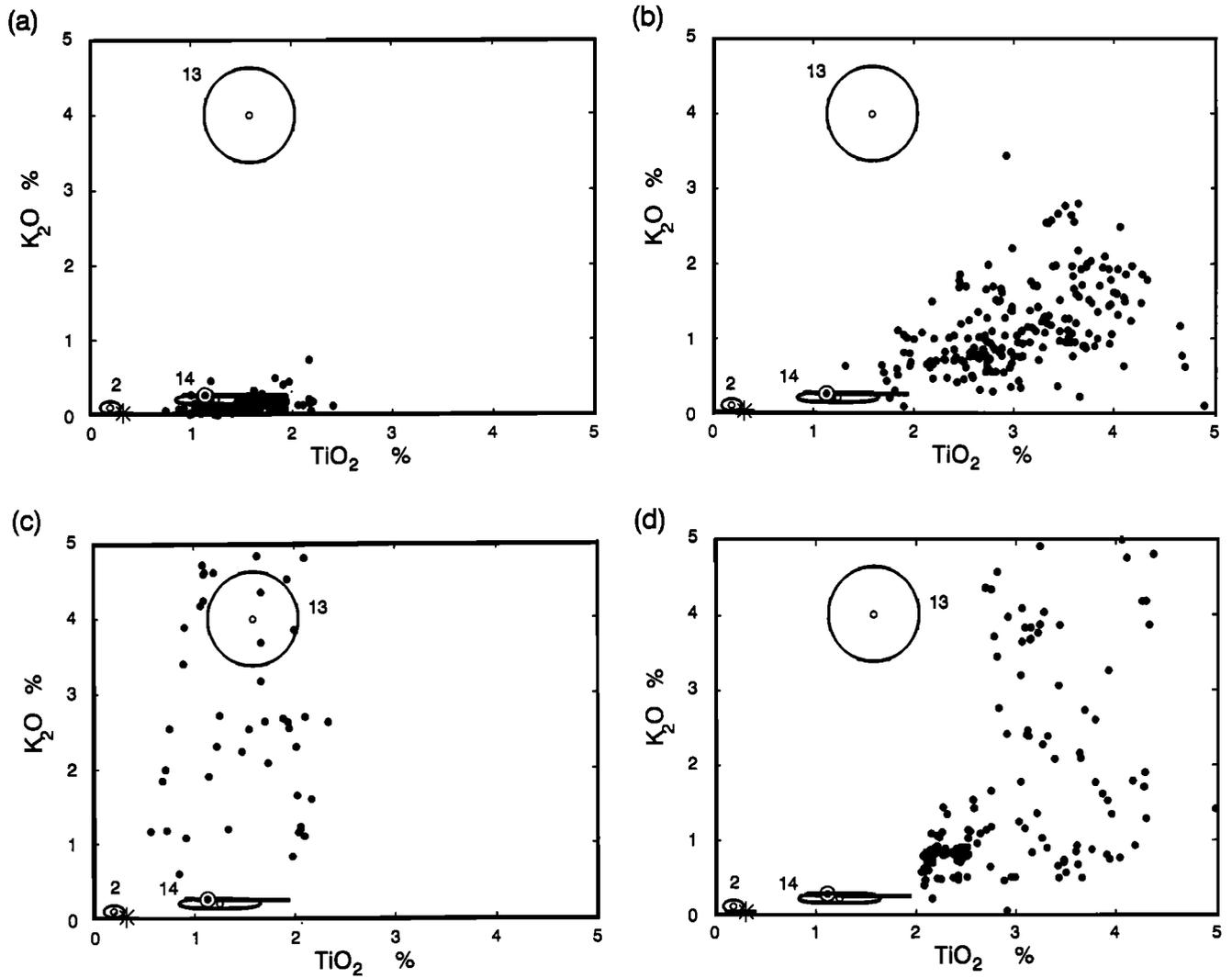


Fig. 5. K_2O as a function of TiO_2 for the same magmas as in Figure 4. The ellipses correspond to one standard deviation. The magmas plotted in Figures 5a-5d are the same as those in Figures 4a-4d.

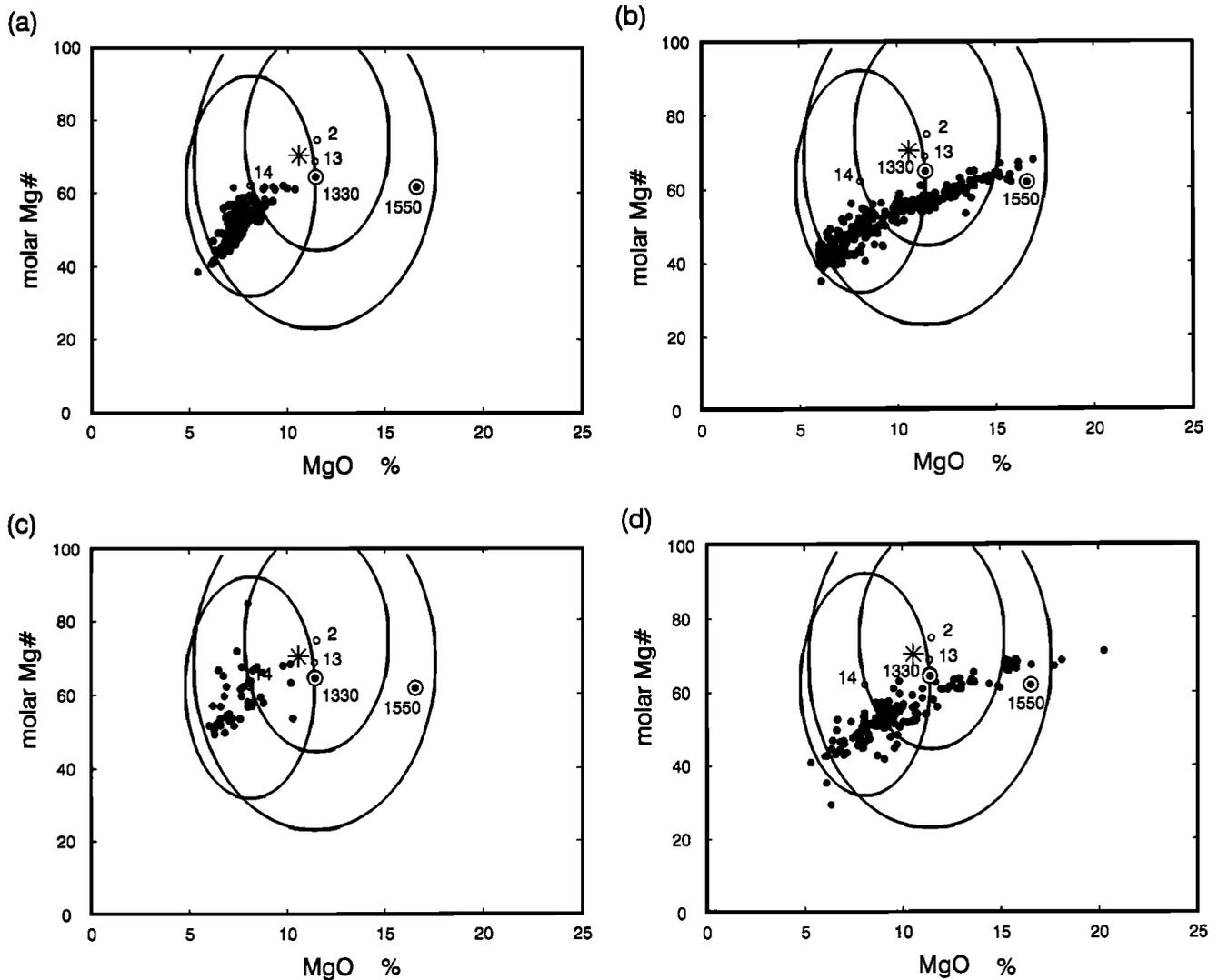


Fig. 6. Modal Mg# as a function of MgO concentration for the same magmas as in Figure 4. The ellipses correspond to one standard deviation. The magmas plotted in Figures 6a-6d are the same as those in Figures 4a-4d.

and low concentrations of TiO_2 and K_2O . Analyses of rocks from Earth and Venus [Surkov *et al.*, 1984, 1986] are compared in Figures 4-6. Figure 4 shows that the concentrations of SiO_2 , Al_2O_3 , $\text{FeO}+\text{MgO}$, and CaO are similar to those from a variety of tectonic settings on Earth and are therefore little help in deciding how such rocks were produced on Venus. However, as Pearce *et al.* [1975] have pointed out, the concentrations of TiO_2 and K_2O are more diagnostic. Figures 4-6 shows that the concentrations of all elements except S analyzed by Venera 14 are similar to those of basalts from spreading ridges. This agreement suggests that the basalt covering the lower plains is formed by adiabatic decompression and that the upwelling mantle comes within about 10 km of the surface. It also suggests that the source is like that of Earth and has the composition of a garnet peridotite. The TiO_2 and K_2O concentrations depend strongly on the total amount of melting, which is in turn controlled by the upper mantle temperature. The agreement between the Venera 14 and MORB compositions suggests that the upper mantle temperature on Venus is similar to that of 1330°C for Earth.

The analysis from Venera 13 differs both from basalts from spreading ridges and from basic melts from oceanic islands in having a $\text{K}_2\text{O}/\text{TiO}_2$ ratio of 2.5. Similar high values are found in some continental volcanics on Earth. Figure 5c shows that basic magmas from western Turkey have similar concentrations of K_2O and TiO_2 to that of Venera 13, but that those from the Jurassic volcanics from the North Sea in Figure 5d are richer in TiO_2 . On Earth, magmas associated with island arcs commonly have lower concentrations of TiO_2 relative to that of K_2O than do similar rocks from other environments, probably because TiO_2 is retained by amphibole in the source regions. Amphibole can exist only if water is present in the source, and on Earth the water required is transported into the mantle beneath island arcs by subduction. Subduction of oceanic crust was occurring beneath western Turkey until about 5 Ma, but ceased in the North Sea region at least 200 Ma before the volcanics in Figure 5d were produced. It is somewhat surprising that water should be present in the mantle of Venus when there is so little in its atmosphere. However, in addition to the $\text{K}_2\text{O}/\text{TiO}_2$ ratio of Venera 13, the presence of water within Venus is also

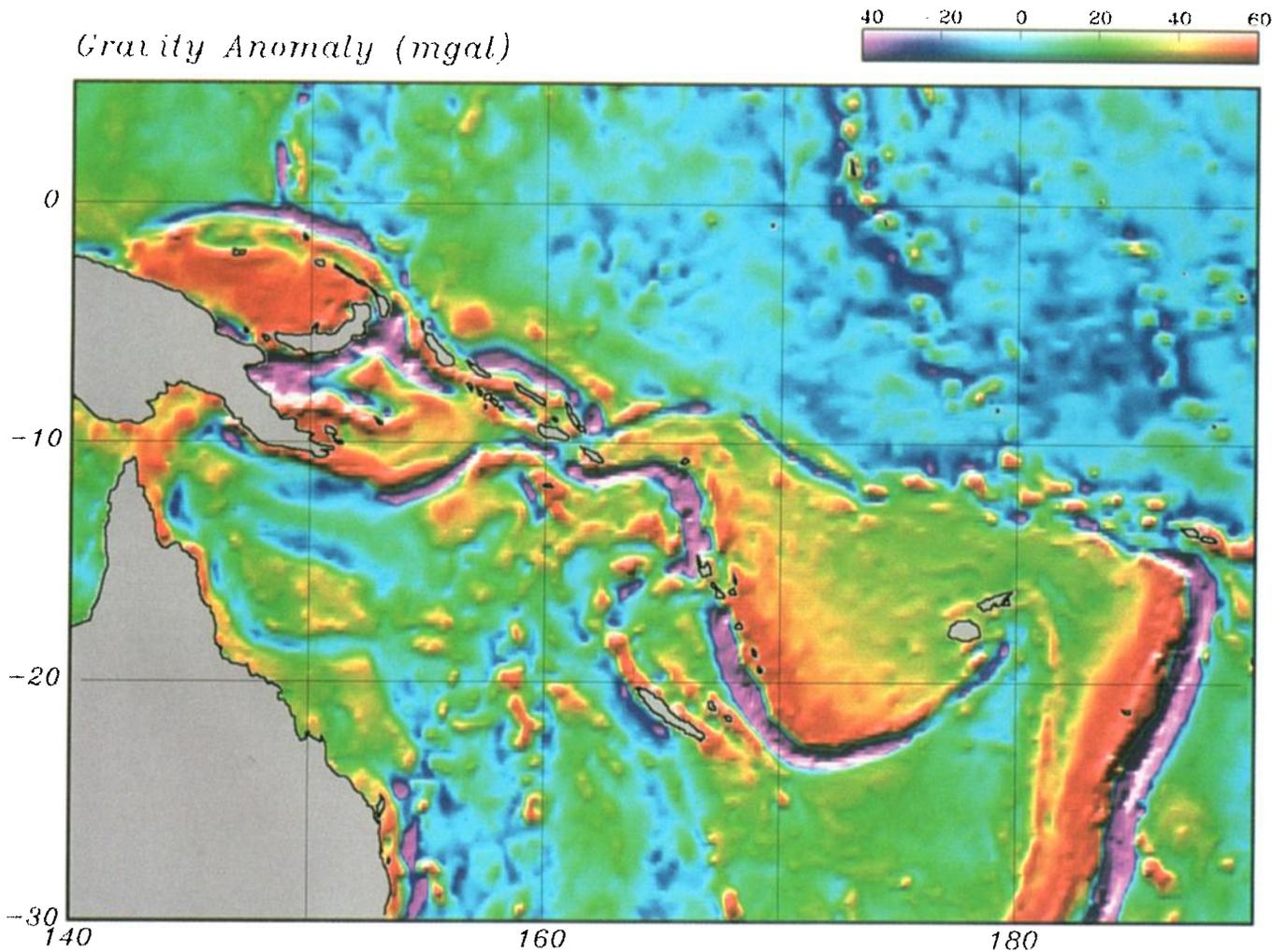


Plate 1a. The gravity field of the region between New Guinea and Fiji, calculated from the satellite altimetry [Hazby, 1987].

suggested by the existence of the high-viscosity melts that are inferred to have produced the pancakelike domes [Head *et al.*, 1991; M^cKenzie *et al.*, this issue]. These domes are probably made of rhyolite, a high-viscosity magma that contains about 70% SiO₂. The production of such magmas on Earth involves the removal of Al₂O₃, FeO, MgO, CaO, and some SiO₂ by crystal settling, to leave behind a melt that is rich in SiO₂. This process is only possible if the viscosity of the silica-rich magma is sufficiently low to allow crystal settling. On Earth its viscosity is reduced by a factor of about 10⁸ by the presence of water. When the magma is erupted, the water is exsolved from the magma and the viscosity increases. The same behaviour can account for the pancakelike domes on Venus, because the surface pressure is not sufficiently high to prevent exsolution of water.

The composition of the rock analysed by Vega 2 from the northern slope of Aphrodite Terra [Surkov *et al.*, 1986] contains less TiO₂ than any of the four basalt types shown in Figures 4 and 5. As Surkov *et al.* [1986] remark, in this respect, and in its low K₂O content, it resembles a gabbro. The average composition of the cumulus gabbro from the Oman [Pallister, 1984] is shown as a star in Figures 4 and 5. Only the concentration of CaO, of 7.5 ± 0.7% for Vega 2 and 14.6% for the Oman gabbro, is significantly different. Such

a difference is not surprising if the Vega 2 sample contains an appreciable fraction of cumulus gabbro, since cumulus rocks are usually strongly heterogeneous. The rock composition at the Vega 2 landing site is therefore consistent with the exposure of cumulus rocks at the surface in the more elevated regions of Venus.

Another useful quantity that can be calculated from the oxide concentrations is the magnesium number Mg#, defined by

$$\text{Mg\#} = \frac{100[\text{MgO}]}{[\text{MgO}] + [\text{FeO}]}$$

where the brackets indicate molar concentrations. On terrestrial ridges, partial crystallization reduces the Mg# of the magma from its initial value of about 65 to values between 60 and 40 (Figure 6). This reduction occurs because magnesium is preferentially removed by the crystallization of olivine and pyroxene. Figure 6 compares the Mg# calculated for the basalts at the three landing sites with those from a number of terrestrial environments. The error ellipses for the Venusian samples are large, and Figure 6 shows that basalts from any of the four tectonic environments are similar to those from Venus. Only the material sampled by Venera 14 suggests that some crystallization may have occurred before eruption.

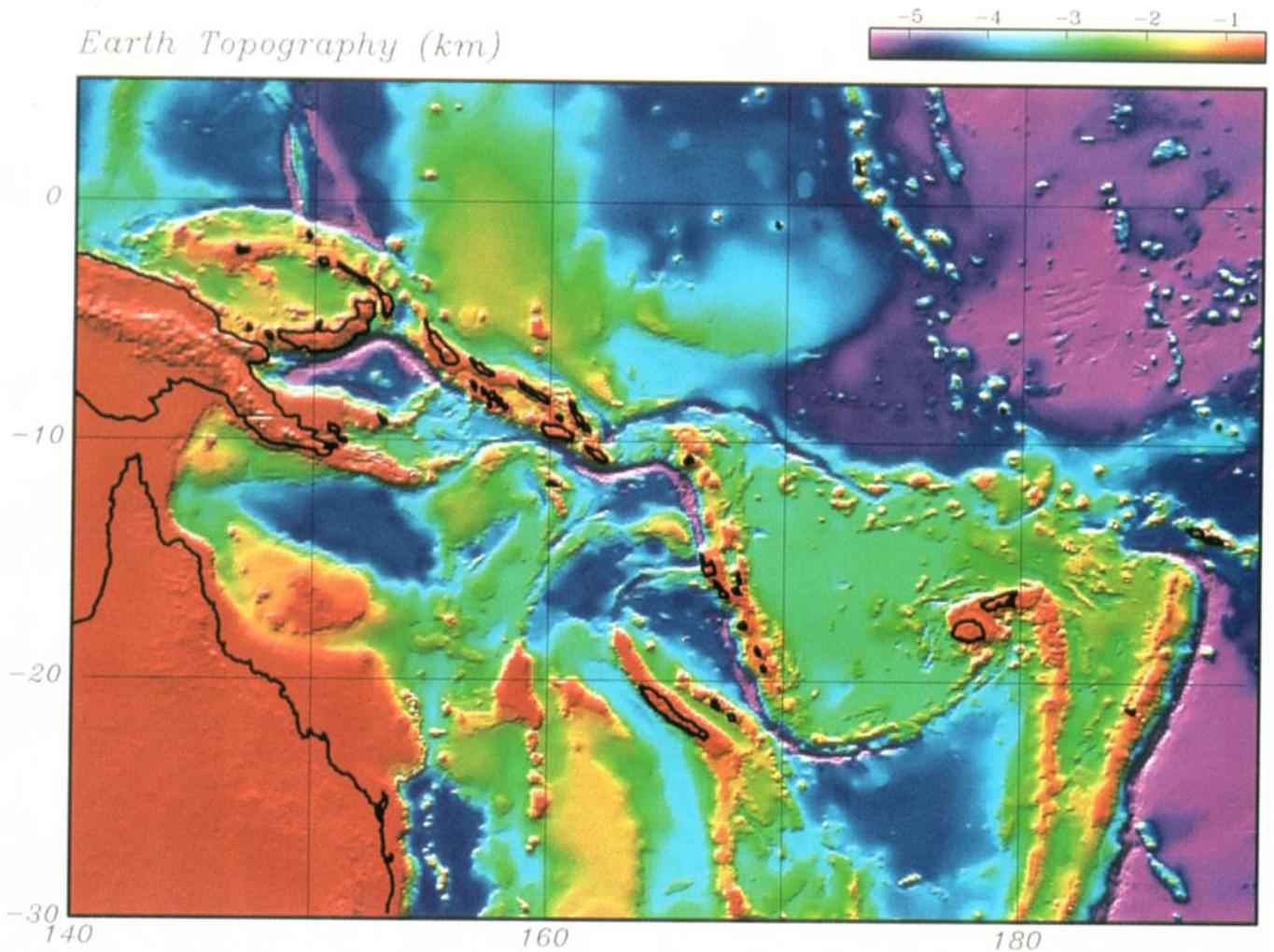


Plate 1b. The topography of the region between New Guinea and Fiji.

TRENCHES AND FOLD BELTS

On Earth the rate of plate production on ridges is the same as the rate of consumption, either by trenches in oceanic regions or by thrusting and folding in continental regions. Unlike trenches, where the relative movement between adjacent plates is largely taken up on a single large thrust, shortening in continental regions occurs within zones whose width can be as great as 2000 km. The processes that occur within these continental zones must take up the relative motion of the plates on either side but cannot be predicted in detail from a knowledge of this motion. Though the reason for this difference in behavior is not properly understood, it is believed to be connected to the difference in homologous temperature $\theta = T/T_S$, where T is the temperature of the material and T_S is the temperature at which melting begins, both measured in degrees Kelvin, between oceans and continents. To the first approximation the creep properties of materials are controlled by the value of θ . Because the melting point of mantle material is greater than is that of continental crust, the oceanic plates are stronger and are more likely to deform by brittle failure than are continental plates whose crust is thicker and weaker. The surface

temperature of Venus is about 470°C, or close to the brittle-ductile transition for Earth's mantle. If the mantle material of the two planets is indeed the same, as the basalt compositions suggest, then, since the surface temperature is higher on Venus, fold and thrust belts should be more widespread than they are on Earth.

The first SAR images of Venus from Magellan [Solomon *et al.*, 1991] showed that fold belts were widely distributed in some parts of Venus but did not find any convincing evidence of trenches. The greater coverage now available, and particularly the high-resolution altimetry, shows clearly that troughs whose shape is similar to that of terrestrial trenches also exist on Venus. Plate 1 and Figure 7 show a comparison of gravity calculated from altimetry [Harby, 1987] and topography in the East Indies region with that from eastern Aphrodite on Venus, with sketch maps of the major tectonic features. On Earth the topography near trenches is strongly affected by variations in crustal thickness. If these were absent the topography would closely resemble the gravity field, with 1 km of topography corresponding to 140 mGal when the topography is above sea level and to 100 mGal when it is submarine. The structures shown in Plate 1c and Figure

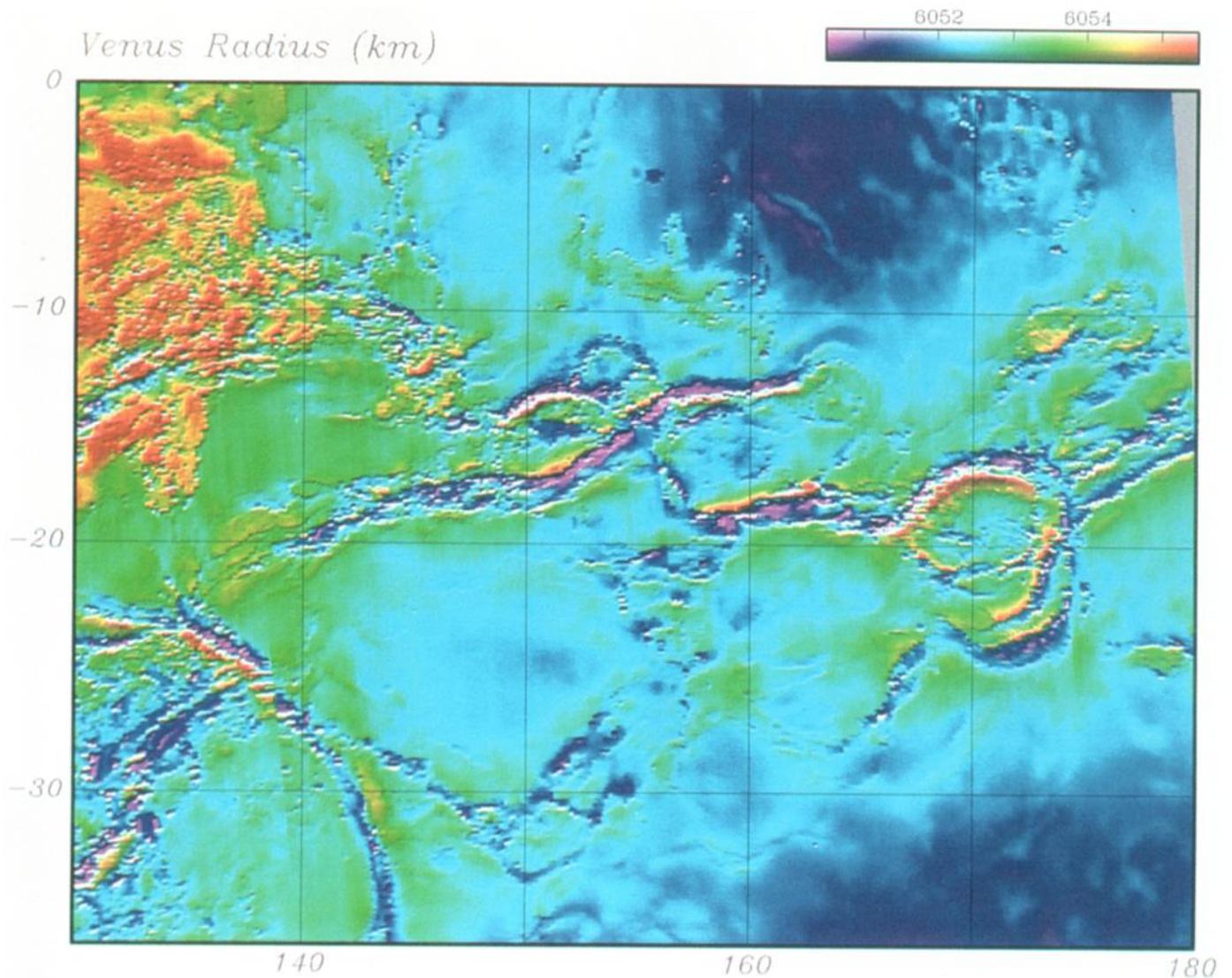


Plate 1c. Altimetry of the eastern part of the Aphrodite region.

7b resemble trenches on Earth. They are curved, with the high topography on the concave side. Both the high and low topography is strongly asymmetric. Trenches in the East Indies have a complicated geometry, because there are several small plates in the area whose movement is not closely related to the relative motion of the two large plates involved, the Pacific and Australian plates. Similar complexity exists on Venus, where the SAR images from Magellan show that extensive normal faulting occurs, associated with the flexure of the plate that is being subducted. The images of these faults are similar to GLORIA images of comparable structures on Earth [Masson *et al.*, 1990]. One important difference is that there is no evidence of magmatism being associated with subduction on Venus. Such a difference is to be expected, since melt generation beneath island arcs on Earth is believed to be caused by water transported into the mantle by the plate that is being subducted. When the water is released, it lowers the melting temperature of the mantle and generates wet magmas. The same process cannot operate on Venus because there is no water on its surface. Water may be present in the mantle of Venus but

is not concentrated in the mantle beneath trenches by subduction. If the large amplitude asymmetric features in Plate 1c and Figure 7b are indeed trenches, then they must terminate on transform faults, as do similar features on Earth. A number of such faults are sketched in Figures 7a and 7b. In Plates 1b and 1c they are marked by narrow troughs in the bathymetry and topography.

DISCUSSION AND CONCLUSIONS

We believe that all three types of plate boundary exist on Venus, but at present there is no way of knowing whether any of these structures is active. In the absence of erosion the features by which all three types of plate boundary have been recognized will persist indefinitely. The only evidence of their age depends on the crater density on the surface of Venus [Phillips *et al.*, 1991], which suggests that the mean age of its surface is about 0.4 Ga. This estimate lies between that of 0.06 Ga for Earth's oceans and a radiometric age of about 2.0 Ga for its continents. Plate tectonic motion is one of several processes that could cause the surface age of Venus to be so different from its planetary age of about 4.5

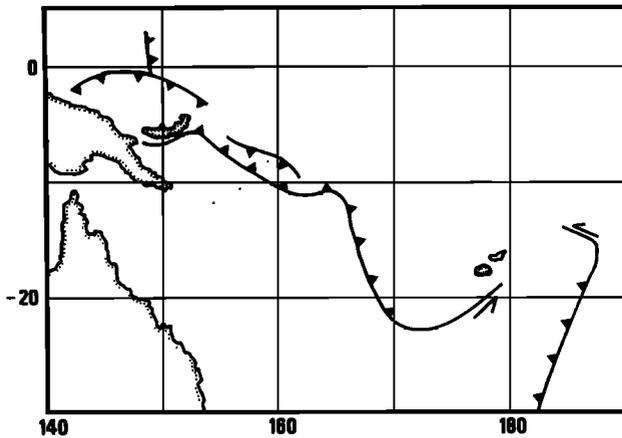


Fig. 7a. A sketch map of the major tectonic features [Abers and McCaffrey, 1988; Cooper and Taylor, 1989; Louat and Pelletier, 1989; Maillet et al., 1989; Wells, 1989] of Plates 1a and 1b.

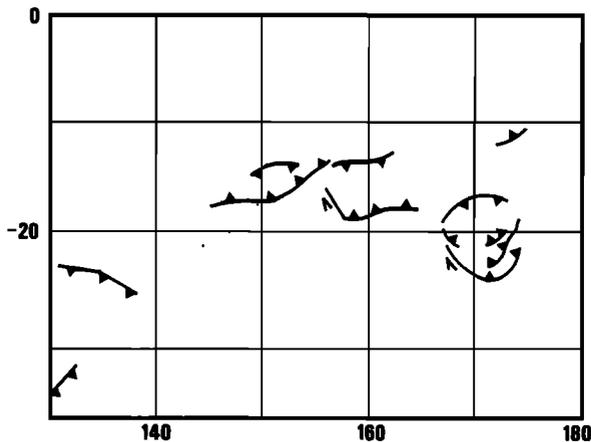


Fig. 7b. A sketch map of the tectonic features of Plate 1c.

Ga. However, its global importance in resurfacing the planet is likely to be minor, because Phillips et al. [1991] found no systematic variations in crater density with position. Such variations would be obvious if the Venusian lithosphere was formed on spreading ridges and aged as it moved towards the subduction zones, in the same way as it does on Earth.

Transform faults and abyssal hills on Venus have only been clearly recognized within the Artemis region, though features that somewhat resemble those illustrated in Figures 1 and 3 do exist elsewhere. The bright lineations in these images result from small rough escarpments. Since these can easily be buried by lavas, and perhaps even by tuff falls [Surkov et al., 1984], abyssal hills and transform faults could underlie the smooth plains that cover so much of the surface, though there is no evidence that they in fact do so. In contrast there are many large scale features that resemble trenches: those illustrated in Figure 7b and Plate 1c were chosen because their topography most closely resembles that of similar structures on Earth. Since there are so many trenches on Venus, there must be an equally widespread process that generates new surface. Other than plate generation by spreading ridges, the only other process

that does so that can be recognized on the SAR images is dyke emplacement. Many areas of the planet show evidence of extension by dyke intrusion that is not confined to narrow linear belts, as it is on Earth's ridges. Similar distributed extension does occur on Earth's continents but is generally taken up at the surface by normal faulting rather than dyke intrusion. It will not be straightforward to estimate the change in surface area produced by dykes on Venus, because their surface expression is so easily removed by later lava flows.

The examples of plate boundaries on Venus illustrated in Figures 1, 3, and 7 and Plate 1 show that such structures are not confined to Earth. Ridges and transform faults appear to be much less common on Venus than they are on Earth and for this reason were not discovered until most of the planet had been imaged. Trenches, however, are widespread, and detailed comparison of their topography with those on Earth should provide constraints on the rheology of the Venusian lithosphere.

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