

Reports

Venus: Identification of Banded Terrain in the Mountains of Ishtar Terra

Abstract. *High resolution images obtained with the Arecibo radar system at a wavelength of 12.6 centimeters reveal numerous parallel 10- to 20-kilometer-wide bands of high radar backscatter situated on and oriented parallel to the major mountain ranges of the Ishtar Terra region of Venus. Geometric and morphological characteristics suggest that the bands represent Earth-like tectonic deformational features, such as folds and faults.*

The smaller bodies of the inner solar system (the moon, Mercury, and Mars) are each characterized by a single, globally continuous lithospheric plate dating to the first half of solar system history (1, 2). In contrast, Earth, which is approximately twice the radius of the largest of these small bodies, has many laterally moving lithospheric plates, large portions of which are less than 200 million years old. Conduction dominates the transfer of heat through the lithospheres of the smaller terrestrial planets, while lithospheric plate recycling is the dominant mechanism on Earth (3).

Venus is of extreme interest in understanding the thermal and tectonic evolution of the planets because it is approximately the same size and density as Earth and is Earth's closest planetary neighbor. The Pioneer mission to Venus provided a near-global topographic map of the planet with an average horizontal resolution of about 100 km and an average vertical resolution of about 200 m (4, 5). Analysis of the global physiography shows that approximately 8 percent of the surface lies more than 1.5 km above

the mean planetary radius. This highland terrain is concentrated in several areas, the three most distinctive being Ishtar Terra, Aphrodite Terra, and Beta Regio (5). Although the physiography of Venus can be broadly characterized, the Pioneer Venus data are of insufficient resolution to identify specific geologic processes responsible for physiographic provinces and major topographic features. Thus the question of the presence of plate tectonics and associated features on Venus is a subject of intense debate (3, 6-10). Critical to the understanding of the tectonic style of Venus is the origin of the major mountain ranges on Ishtar Terra (Figs. 1 and 2). These regions are unlike high topography on the moon, Mars, and Mercury, which is predominantly associated with large volcanoes or the rims of large circular impact basins (1). Akna Montes trend north-northeast and are about 1000 km long and up to 300 km wide. Freyja Montes are continuous with Akna, but trend east-west, extending more than 700 km and rising to similar elevations. Maxwell Montes trend approximately northwest in central

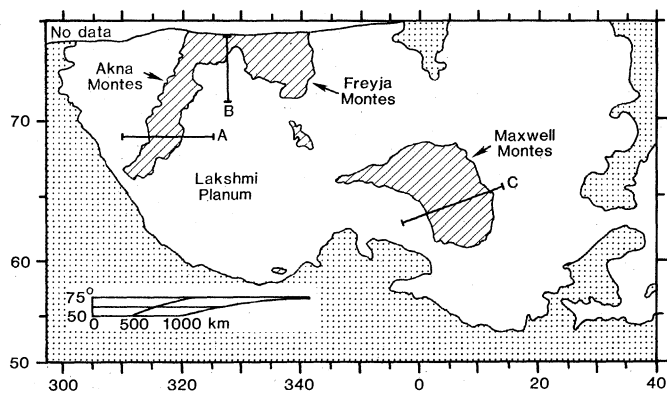
Ishtar Terra, are about 1000 km long and up to 500 km wide, and rise more than 11 km above the mean planetary radius.

Recently, images of the Ishtar Terra region were obtained with the 12.6-cm-wavelength radar system at Arecibo Observatory in Puerto Rico (Fig. 3 and cover). These images, which map the backscatter cross section per unit area (surface reflectivity), have resolutions of 3 km (11), a significant improvement over previous Earth-based images (12). Because the sub-Earth point on Venus is restricted to $\pm 9^\circ$ of the equator, the angle at which the surface is illuminated by the incident radar wave varies from near zero close to the sub-Earth point to a value approximately equal to the latitude at high latitudes. Appropriate scattering laws as a function of incidence angle and methods of data acquisition and display were discussed by Campbell and Burns (12). At the latitudes of Ishtar Terra (55° to 75° N), the slope of the scattering law increases so that both small-scale (wavelength-size) surface roughness and changes in mean surface slope could be important. The average scattering properties of the planet have been removed (12) so that the images show the ratio of the received power to that corresponding to the average scattering behavior of Venus.

The images show the major features of Ishtar Terra known from previous Earth-based observations (12, 13), including Lakshmi Planum, a 1200-km region of low backscatter, and a series of regions of very high backscatter dominated by the Maxwell, Akna, and Freyja ranges (Figs. 1 to 3 and cover). More significantly, however, the new higher resolution images reveal that the regions of very high backscatter are characterized by a series of linear bands that are generally parallel to the long axis of the mountain ranges.

Akna Montes, extending along the western edge of Lakshmi Planum, rise abruptly from the southwestern edge of Ishtar Terra to an elevation 6 to 7 km above the mean planetary radius within a horizontal distance of less than 100 km. The broad cross-sectional topographic form (Fig. 2A) shows that the mountains are somewhat asymmetric with steeper slopes toward Lakshmi Planum to the east. They extend northeastward in a slightly arcuate band 100 to 300 km in width and turn north-northeastward at about 69° N, continuing in this direction until merging with the generally east-west trending Freyja Montes. The height and width of Akna vary along the strike of the range. Topography is highest along the southern section, where three

Fig. 1. Mountains of western Ishtar Terra (mercator projection). Ishtar Terra is outlined by a 1.5-km elevation contour that defines the base of the highlands province on Venus (5). Dotted regions lie below this altitude. The base of Maxwell Montes is outlined by a 4.5-km elevation contour. All other mountains are outlined by a 4.0-km contour. Bars labeled A, B, and C correspond to profiles shown in Fig. 2. Elevations are kilometers above mean planetary radius (6051.5 km) (4).



broad highs reach an elevation of 6 to 7 km. Maximum elevations are not directly correlated with the width of the range; at the southernmost peak the width is about 100 km while at the northern peak ($\sim 69^\circ\text{N}$) the width is about 300 km. The highest point in Akna Montes lies on this latter peak, where there is a very small area 7 to 8 km in elevation. The northern section of the Akna is predominantly 4 to 6 km in elevation.

Topographic patterns also differ between the northern and southern sections of the Akna Montes. In the south the 5- to 6-km elevation forms a continuous band along the range, while to the north this band breaks into a series of small, linear to arcuate patches. The high resolution radar images (Fig. 3) show a distinctive set of high backscatter bands extending along the strike of the entire range, curving eastward at the northern end of Akna to merge into similar banded terrain in Freyja Montes. The bands begin abruptly at the southwestern edge of Ishtar Terra, where there are at least six parallel bands with widths of 10 to 20 km. These merge into two to three major bands of very high backscatter, and this major textural pattern extends the full length of the southern arcuate portion of Akna Montes. As Akna Montes turn northward and the terrain decreases in elevation, the bands become somewhat less distinct but can still be traced into Freyja Montes. To the east the banded texture disappears near the base of the mountains and is not obvious in Lakshmi Planum. To the west bands of comparable length and width but lower backscatter are visible to the edge of Ishtar Terra, a distance of about 400 km. Pioneer Venus data (4, 14) show that the southern portion of Akna is characterized by very high reflectivity and root-mean-square slope values. North of about 69°N , these values are lower.

Pioneer Venus data on Freyja Montes are not complete (4, 5). Available topographic data show the range to be hook-shaped, with the major trend extending east to west along the northern edge of Lakshmi Planum for over 500 km and curving toward the south at the eastern end of Lakshmi Planum. Along the east-west portion the topography is a complex series of peaks and depressions with diameters of approximately 100 km. Peaks rise locally to 6 to 7 km and adjacent lows extend to 3.5 to 4 km (Fig. 2B). The eastern portion of Freyja is higher and consists of a major high region about 200 km in diameter that turns southward and is surrounded by smaller hills and depressions. The high resolu-

tion images reveal that the linear east-west portion of Freyja is dominated by the same type of banded texture seen in Akna Montes (Fig. 3). This terrain is 200 to 300 km wide and is composed of up to 15 bright bands separated by bands of lower backscatter. High backscatter bands are 10 to 20 km wide and up to several hundred kilometers long. The bands of highest backscatter are generally correlated with the highest topography. The high terrain 300 km in width at the eastern end of Freyja is characterized by high backscatter, but the patterns are dominated by shorter linear segments arrayed in a variety of directions. Pioneer Venus data (4, 14) show that most of Freyja is dominated by high reflectivity and root-mean-square slope values. The high topography along the eastern end appears to be characterized by relatively lower root-mean-square slope and reflectivity values than the surrounding mountains. A narrow

(100 to 150 km wide), relatively low (1 to 2 km above Lakshmi Planum) mountain range extends southward along the eastern edge of Lakshmi, curving eastward to merge into Maxwell Montes.

Maxwell Montes are located in east-central Ishtar Terra. They rise from a low point along eastern Lakshmi Planum and extend east-northeast for about 300 km until converging with the main north-northwest-trending mountain range (Fig. 1 and cover). The main part of Maxwell Montes is a massive mountain some 600 to 700 km long and 300 to 400 km wide and rising more than 11 km above the mean planetary radius. The profile of the mountain is asymmetric, with the steepest slopes along the western side (Fig. 2C). At the northern and southern ends of the main mountain range the topography descends to 2 to 2.5 km, 1 to 2 km below the main plateau. The high resolution images show levels of backscatter and a banded texture comparable to

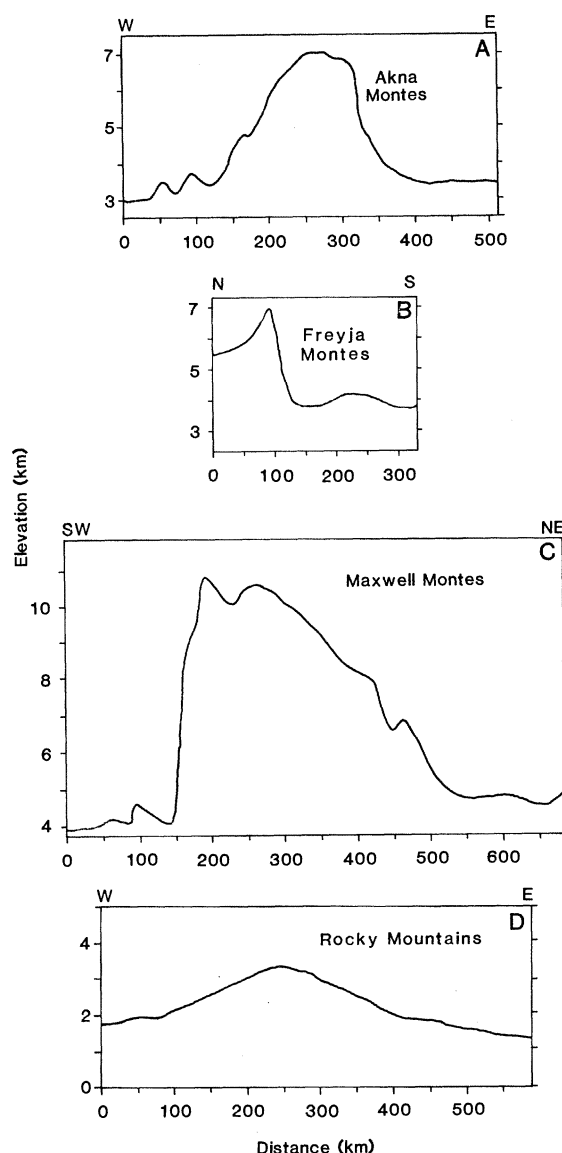
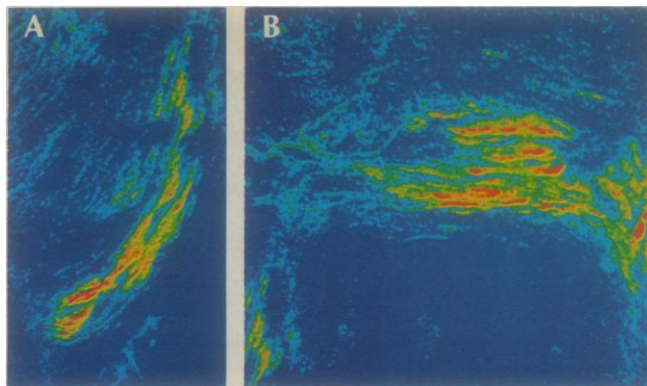


Fig. 2. Topographic profiles of Akna, Freyja, and Maxwell Montes (A to C), shown with 50:1 vertical exaggeration and compared to the profile of the Rocky Mountains of Colorado (D) (21). Elevations for the venusian mountains are kilometers above mean planetary radius (4); elevations in (D) are kilometers above sea level and are averaged over one-quarter degree.

Fig. 3. Radar images of (A) Akna Montes (65.0° to 72.4° north latitude, 310° to 322° longitude) and (B) Freyja Montes (70° to 76° north latitude, 318° to 342° longitude). The blue areas represent regions of normal backscatter; the green and yellow areas, regions of high backscatter; and the red areas, regions of very high backscatter. The banded terrain is parallel to the strike of the mountainous topography and shows the highest backscatter in the mountain regions.



those of the Akna and Freyja montes (cover). The distinctive banded terrain is concentrated in west-central Maxwell, the highest region of the mountain range, and trends parallel to the long axis. On the northern and southern slopes (at lower elevations) the banded terrain merges into mottled regions of high backscatter cross section. To the east on the lower slopes the well-developed banded terrain is replaced by a circular feature over 100 km in diameter. The main portion of Maxwell Montes has high reflectivity and root-mean-square slope values (4, 14). Banded terrain is also evident along the mountain range at the southern edge of Lakshmi Planum.

A number of hypotheses can be proposed to explain the nature and origin of the high backscatter bands, including formation or modification by such basic geological processes as wind activity, mass wasting, volcanism, and tectonism. Eolian processes can sort sedimentary particles into linear bands (dunes) of various grain sizes that often are oriented parallel to the slope. However, the wide spacing of these bands and the possibility that eolian erosion on Venus is less efficient than on Earth (15) suggest that eolian activity is not the primary process responsible for the bands. Volcanic processes can produce lava flow units that differ from the surrounding terrain in composition, surface roughness, and topography, causing variations in the backscatter cross section and thus in discriminability in radar images. In addition, lava flows 10 to 20 km wide and hundreds of kilometers long are known for the moon (16) and Mars (17), and some authors (5) have proposed a volcanic origin for Maxwell Montes. However, most lava flows are oriented normal to the strike of the regional slope, while the vast majority of the bands described here run parallel to the strike. Mass wasting processes produce a varie-

ty of features on Earth, such as slumps and talus aprons, which contain variations in grain size and local slope and are oriented parallel to regional slopes. The steep slopes of the venusian mountains would seem to make them susceptible to mass wasting and erosional processes, although the nature of these processes on Venus is not known. The extremely linear and continuous nature of many of the bands over hundreds of kilometers, however, suggests that mass wasting processes are not the primary cause of their origin, although such processes may have played a role in their enhancement. Deformational features on Earth (folds and faults) are often extremely linear, and a combination of formational and degradational (erosional) processes can produce major belts of linear high topography that have been observed as banded terrain in radar images. The Basin and Range province of the western United States, for example, is characterized by a broad topographic high several hundred kilometers wide and by a series of linear mountains produced by extension and block faulting, with dimensions comparable to those of some parts of the banded terrain on Venus. The Appalachian Mountains of the eastern United States form a broad, linear topographic high approximately 1500 km long and 100 to 200 km wide. The Appalachians contain a system of folds and faults formed at an ancient convergent plate boundary in a compressional tectonic regime and subsequently exposed by erosion. Fold wavelengths and fault separation distances are typically 5 to 20 km. These features are oriented parallel to the topographic trend of the mountain range and appear as banded terrain in radar images (18).

The close correlation of the banded terrain with the mountainous topography, the parallelism of topography and bands, and the continuous nature and

regular spacing of the bands lead us to conclude that deformational processes may account for the banded terrain of Ishtar Terra. These characteristics are more comparable to plate tectonic-related features on Earth, such as folded mountain belts, than they are to most features known on the smaller terrestrial planets. The exact nature of potential deformational or tectonic processes remains unclear because of the lack of sufficient resolution to distinguish geologic details and because of the poor understanding of possible tectonic processes on Venus (3, 8, 9). Indeed, deformation associated with viscous relaxation of mountainous topography and enhanced by the high temperature of near-surface rocks (19, 20) may be a factor in the formation of the bands. A more quantitative assessment of the geometry and textural patterns of the banded terrain may provide information to further distinguish potential modes of formation of these distinctive features.

D. B. CAMPBELL

National Astronomy and Ionosphere Center, Arecibo Observatory, Arecibo, Puerto Rico 00613

J. W. HEAD

Department of Geological Sciences, Brown University, Providence, Rhode Island 02912

J. K. HARMON

A. A. HINE

National Astronomy and Ionosphere Center, Arecibo Observatory

References and Notes

1. J. W. Head and S. C. Solomon, *Science* **213**, 62 (1981).
2. S. C. Solomon, *Geophys. Res. Lett.* **5**, 461 (1978).
3. _____ and J. W. Head, *J. Geophys. Res.* **87**, 9236 (1982).
4. G. H. Pettengill *et al.*, *ibid.* **85**, 8261 (1980).
5. H. Masursky *et al.*, *ibid.*, p. 8232.
6. J. W. Head, S. E. Yuter, S. C. Solomon, *Am. Sci.* **69**, 614 (1981).
7. R. E. Arvidson and G. F. Davies, *Geophys. Res. Lett.* **8**, 741 (1981).
8. W. M. Kaula and R. J. Phillips, *ibid.*, p. 1187.
9. R. J. Phillips, W. M. Kaula, G. E. McGill, M. C. Malin, *Science* **212**, 879 (1981).
10. G. W. Brass and C. G. A. Harrison, *Icarus* **49**, 86 (1982).
11. The 3-km resolution is defined in terms of the ambiguity function of the radar system function (12). Line pair resolution would be approximately 6 km.
12. D. B. Campbell and B. A. Burns, *J. Geophys. Res.* **85**, 8271 (1980).
13. D. B. Campbell, R. B. Dyce, G. H. Pettengill, *Science* **193**, 1123 (1976).
14. G. H. Pettengill, P. G. Ford, S. Nozette, *ibid.* **217**, 640 (1982).
15. B. White, *Icarus* **46**, 226 (1981).
16. G. Schaber, *Geochim. Cosmochim. Acta* **1** (Suppl. 4) 73 (1973).
17. _____, K. C. Horstman, A. L. Dial, Jr., *ibid.* **3** (Suppl. 10), 3433 (1978).
18. J. P. Ford, *Am. Assoc. Pet. Geol. Bull.* **64**, 2064 (1980).
19. J. Weertman, *Phys. Earth Planet. Inter.* **19**, 197 (1979).
20. S. Solomon, S. K. Stephens, J. W. Head, *J. Geophys. Res.* **87**, 7763 (1982).
21. W. H. Diment and T. C. Urban, *U.S. Geol. Surv. Geophys. Invest. Map GP-933* (1981).
22. We thank the staff of the Arecibo Observatory for their assistance in data collection; Barbara

Burns for many contributions to the project; Sean Solomon, Rob Sullivan, James Garvin, Maria Zuber, and Gordon Pettengill for reviews of the manuscript; and Sue Sharpton, Mary Ellen Murphy, and Sam Merrell for manuscript preparation. The National Astronomy and Ionosphere Center is operated by Cornell University

under contract with the National Science Foundation and with support from the National Aeronautics and Space Administration. A portion of the work was supported by NASA grant NGR-40-002-088 to J.W.H.

9 December 1982; revised 18 April 1983

Tobermorites: A New Family of Cation Exchangers

Abstract. *Tobermorites have cation-exchange and selectivity properties intermediate between those of clay minerals and zeolites. Aluminum-substituted tobermorites in particular show high selectivity for cesium. This new group of cation exchangers may find applications in catalysis and in nuclear and hazardous waste disposal.*

Tobermorite, $\text{Ca}_5\text{Si}_6\text{H}_2\text{O}_{18} \cdot 4\text{H}_2\text{O}$, is a naturally occurring hydrous calcium silicate in calc-silicate rocks. Of the various hydrous calcium silicates, the tobermorite group (1) is the most important in cement hydration. Isomorphous substitution of aluminum for silicon in the dreiketten of tobermorite has been observed (2), and we recently reported cation-exchange and Cs^+ -selective properties of the aluminum-substituted tobermorite (3). We report here the discovery of tobermorites as a new family of exchangers. Clay minerals and zeolites act as cation exchangers, sorbents, and molecular sieves which have myriad applications in catalysis, nuclear and hazardous waste disposal, and waste-water treatment. Tobermorites have layer structures similar to those of 2:1 clay minerals (4), but the structure varies

with the chemical composition as well as with the nature of the synthesis (5). Wieker *et al.* (6) recently elucidated the structures of synthetic tobermorites, using solid-state high-resolution ^{29}Si nuclear magnetic resonance spectroscopy. The chemical composition and structure of tobermorites are important in their cation-exchange and selective properties.

We synthesized tobermorites from many starting materials at 80° to 200°C. Zeolites, such as clinoptilolite from Idaho, phillipsite from Nevada, and Linde 3A, were used as some of the silica-alumina sources. Other materials such as amorphous SiO_2 (−400 mesh); quartz (crystalline SiO_2) (−325 mesh); $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$; $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$; and NaOH also were used (Table 1). Teflon capsules were used for synthesis at 85°

and 180°C at saturated steam pressure in a pot furnace; polyethylene bottles were used for synthesis at 80°C in an oven; and gold capsules were used at 180° and 200°C in cold-seal vessels under a confining pressure of 30 MPa. The solids were removed from the capsules or bottles and washed with deionized water prior to x-ray diffraction analysis (XRD), scanning electron microscopy (SEM), cation exchange, and cesium sorption measurements. The normal, anomalous, or mixed behavior of the tobermorites was determined by heat treatment at 300°C for 20 hours, after which they were examined by XRD (5). Tobermorites are described as normal if the basal spacings decreased to 10 Å or less after heating to 300°C and anomalous if they did not shrink below 11 Å under these conditions. The term "mixed tobermorite" is used for products containing both normal and anomalous tobermorites.

We measured the cation-exchange capacity (CEC) of the various products by using a modified version of the method of Dolcater *et al.* (7). A known weight (10 to 50 mg) of each sample was washed twice with 3N KCl, then washed three times with 0.01N KCl to remove excess KCl and to prevent hydrolysis of K^+ from the exchange sites (a correction was made for excess 0.01N KCl, which was determined by weighing); the K^+ was displaced from the exchange sites with four washings of 1N CsCl (1/2 hour

Table 1. Cation exchange capacities and selective cesium sorption properties of synthetic tobermorites. Abbreviations: SS, saturated steam; T_{Al} , aluminum-substituted tobermorite; A, anomalous; C, crystalline; PC, poorly crystalline (became amorphous at 300°C); M, mixed; VC, very crystalline as determined by XRD; amor., amorphous; N, normal; ND, none detected.

Sample No.	Initial sample mixture	Temperature (°C); pressure; duration (days) of treatment	Mineralogy by XRD after treatment	Cation exchange capacity (meq/100 g)	Cesium sorption K_d (ml/g) from solution*	
					0.02N CaCl_2	0.02N NaCl
1	420 mg $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$ + 39.6 mg $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ + 76.8 mg CaO	180°; SS; 1	T_{Al} (A, C), calcite†	182±	4,144 ± 626	2,683 ± 106
2	420 mg $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$ + 39.6 mg $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ + 76.8 mg CaO	85°; SS; 4	T_{Al} (PC), calcite	164±	756 ± 7	654 ± 9
3	210 mg $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$ + 5.3 mg kaolinite + 38.4 mg CaO	180°; 30 MPa; 14	T_{Al} (M, VC), calcite	146	14,240	
4	45.9 mg phillipsite + 16 mg amor. SiO_2 + 38.4 mg CaO	200°; 30 MPa; 28	T_{Al} (A, VC)	148±	20,370 ± 1,985	8,930
5	22.2 mg Linde 3A + 34.8 mg amor. SiO_2 + 38.4 mg CaO	200°; 30 MPa; 28	T_{Al} (A, VC)	158±	6,328 ± 258	3,670
6	50.7 mg clinoptilolite, Idaho, + 10.4 mg amor. SiO_2 + 38.4 mg CaO	200°; 30 MPa; 28	T_{Al} (A, VC), xonotlite, calcite	80±	9,150	4,412 ± 157
7	2.22 g Linde 3A + 3.48 g amor. SiO_2 + 3.84 g CaO + 24 g NaOH	80°; SS; 22	T_{Al} (N, PC), calcite	144±	461 ± 15	484 ± 18
8	5.04 g CaO + 5.4 g amor. SiO_2 + 32 g NaOH	80°; SS; 12	12.6-Å tobermorite (N, VC), calcite	130±	42	51 ± 2
9	38.4 mg CaO + 49.3 mg quartz (−325 mesh)	200°; 30 MPa; 28	Tobermorite (A, VC), xonotlite	48	120	190
10	38.4 mg CaO + 49.3 mg quartz (−325 mesh)	200°; 30 MPa; 28	Xonotlite (VC), quartz	12	8	ND

*Plus or minus sign denotes standard deviation (N weighting) based on three or four replicates. †Calcite is a common constituent of hydrous calcium silicate synthesis. ‡Average of duplicate determinations.