floating at a constant altitude within 100 m (pressures between 534 and 542 mbar). Vertical velocities of the atmosphere were from +0.5 to −0.8 m sec^{-1} (*1*). Nevertheless, measured temperatures varied between two adiabats separated by 0.6 K (eight data counts) and moved between these limits four times in 20 minutes. This establishes a rough time scale of about 300 seconds for the variation. Since the vertical velocity of the atmosphere relative to the balloon in this frame was typically −0.5 m sec^{-1}, a time scale of 300 seconds corresponds to a scale size of approximately 150 m if the variations are a result of air parcels of differing temperature sweeping down past the balloon.

Because the amplitude of temperature variation seen in this frame with relatively small vertical motion of the atmosphere is higher than in some other frames with higher vertical velocities, we considered the possibility that the gondola wake was influencing the temperatures. Our analysis suggests that the gondola wake probably did not influence the temperature data. In frames with higher vertical velocities, such as B 39 and B 55 (Fig. 3, A and B), influence of the gondola wake is improbable because the wake is swept mainly upward or downward rather than to the side. In these cases, temperature influences of the balloon wake are possible.

In frame B 50 (Fig. 3D, 32.46 hours U.T.), except for the last two data points, the data lie close to an adiabat that is 0.2 K warmer than the reference adiabat. The maximum deviation from the reference adiabat is 0.7 K. The vertical wind velocities relative to the balloon were −0.4 to +1.25 m sec^{-1} (*1*), with the higher velocities occurring late in the frame when temperatures were drifting off the adiabat. These four frames illustrate the diversity of the temperature data and perhaps will give some clues as to the mechanisms of the convective heat transport processes in the clouds. Although not yet analyzed in as much detail, the VEGA-1 data appear to be similar in these respects.

Near the end of the VEGA-2 mission, when the balloon was advancing well into the dayside of Venus (solar zenith angle near 64°), measured temperatures were as high as 12 K above the reference adiabat. This was during a period of low vertical wind velocities (0.1 to 1 m sec^{-1}). Initially, the high temperatures seemed to indicate that the balloon had moved out of the air mass in which it rode 30 percent of the way around Venus and entered a new, warmer air mass. However, it now appears that these higher temperatures were a result of direct solar heating of the sensor on the dayside. The sensors were nickel-resistance elements within a thin (50-μm) sandwich of amber-colored polyamide plastic (*7*). Assuming that the sensor solar absorptivity is 0.5 and that the infrared emissivity is 0.8, it was estimated that solar heating would raise the sensor temperature at this solar zenith angle by 12 K at $w_r = 0.1$ m sec^{-1} to 5 K at $w_r = 1$ m sec^{-1}, with convective heat transfer to the atmosphere limiting the temperature error. Thus solar heating of the sensor can explain the observed higher temperatures, and data taken on the dayside will have to be interpreted with this effect taken into account.

In summary, the principal results of the early analysis of the VEGA balloon data pertaining to thermal structure of the middle cloud layer of Venus are as follows. (i) Temperatures correlated highly with pressures in the vertical excursions of the two balloons. (ii) The two balloons were immersed in air masses differing consistently in temperature at a given pressure by about 6.5 K over a range of longitudes from about 180°E to 70°E. (iii) The atmosphere was close to adiabatic in the middle cloud region, confirming earlier probe soundings. (iv) Small deviations from a single adiabat occurred, suggesting the presence of discrete, small-scale air masses of differing thermal history. (v) Comparisons of data from the two balloons with data from earlier probe soundings suggest variations in the thermal structure with time and position that were not suspected a decade ago.

REFERENCES AND NOTES

1. R. Z. Sagdeev *et al.*, *Science* **231**, 1411 (1986).
2. B. Ragent and J. Blamont, *J. Geophys. Res.* **85**, 8089 (1980).
3. M. Ya. Marov, *Annu. Rev. Astron. Astrophys.* **16**, 141 (1978).
4. A. Seiff *et al.*, *J. Geophys. Res.* **85**, 7903 (1980).
5. V. S. Avduevskiy *et al.*, in *Venus*, D. M. Hunten, L. Colin, T. M. Donahue, V. I. Moroz, Eds. (Univ. of Arizona Press, Tucson, 1983), p. 281.
6. A. Seiff, *ibid.*, p. 215.
7. R. S. Kremnev *et al.*, *Science* **231**, 1408 (1986).
8. J. Blamont *et al.*, *ibid.*, p. 1422.
9. See figure 14 of (*4*).

10. Supported in part by National Aeronautics Space Administration Ames Research Center and the Jet Propulsion Laboratory.

23 October 1985; accepted 24 January 1986

Implications of the VEGA Balloon Results for Venus Atmospheric Dynamics

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Both VEGA balloons encountered vertical winds with typical velocities of 1 to 2 meters per second. These values are consistent with those estimated from mixing length theory of thermal convection. However, small-scale temperature fluctuations for each balloon were sometimes larger than predicted. The approximate 6.5-kelvin difference in temperature consistently seen between VEGA-1 and VEGA-2 is probably due to synoptic or planetary-scale nonaxisymmetric disturbances that propagate westward with respect to the planet. There is also evidence from Doppler data for the existence of solar-fixed nonaxisymmetric motions that may be thermal tides. Surface topography may influence atmospheric motions experienced by the VEGA-2 balloon.

THE VEGA VENUS BALLOON MISSION was designed to determine atmospheric characteristics at the float altitude of the balloons in terms of horizontal and vertical winds, thermal structure, and cloud properties, with a goal of learning more about important dynamical processes. In this paper we discuss possible interpretations of certain aspects of the data, with the caveat that any conclusions are preliminary.

Vertical momentum and heat transport, which are derived from products of vertical velocity with horizontal wind and temperature, respectively, are among the principal quantities that determine the characteristics of the general circulation. Thus the VEGA balloon vertical wind data are of considerable interest. The initial balloon float altitudes near 53 km are in the region of the atmosphere identified by the VEGA-2 lander (*1*) and Pioneer Venus (*2*) as having

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nearly neutral static stability, that is, nearly adiabatic lapse rate of temperature. It is in such neutrally stable regions where relatively large vertical winds are expected. The balloons commonly encountered vertical winds that exceeded 0.5 m sec^{-1}, with peak amplitudes reaching 2.5 to 3.5 m sec^{-1} (*3*). It is known from Pioneer Venus data that the vertical variation in the predominant east-west (zonal) wind is close to zero where the static stability is small near 53 km altitude (*4*), a result that is almost certainly due to intense vertical transport in that region. Besides their importance for vertical heat and momentum transport, large vertical velocities in the neutrally stable region can affect the circulation by generating atmospheric waves as convective motions penetrate surrounding regions of the atmosphere having relatively high static stability. Such waves can propagate to other regions of the atmosphere and may therefore affect momentum distributions at levels well away from the neutrally stable region.

There are two probable causes for the neutral stability region in the middle cloud and the associated small variation in the zonal wind with altitude. One is shear instability, that is, a dynamical instability resulting when the ratio of the square of the Brunt-Vaisalla frequency (*5*) to the square of vertical gradient of the zonal wind is less than 0.25. When this instability occurs, the expected result is a region of nearly neutral static stability and small vertical gradient in the zonal wind, even though the initial state may have had large values for both these quantities. A second cause is thermal convection induced by radiative heating of the middle cloud levels by atmospheric layers below (*6*). At present we cannot evaluate the relative importance of these processes; however, the following statements can be made.

Amplitudes of the observed vertical winds are generally consistent with those estimated from thermal convection mixing length theory, which gives an estimate of average values of quantities associated with convective eddies (*7*):

$$|w| \sim \left(\frac{Fgl}{4\rho c_p T}\right)^{1/3} \approx 1 \text{ m sec}^{-1} \qquad (1)$$

where w is vertical wind, F is convective heat flux taken to be the global average net solar heat flux at 54 km (40 W m^{-2}), g is the gravitational acceleration, ρ is density at the float altitude of the balloon, c_p is specific heat at constant pressure, and T is temperature corresponding to ρ. The reason for choosing the global average net solar heat flux as the appropriate value for F is as follows. At any given level in the atmosphere, there must be a global average energy balance between the net downward solar flux and the sum of the net upward flux of infrared radiative energy and upward convective energy flux. If the middle cloud layer is opaque to infrared radiation, most of the upward energy transport would be due to thermal convection. We have assumed that essentially all the net upward infrared flux is absorbed, so that all the energy transport is by convection; however, even if just a substantial fraction of the energy transport is by convection, the order of the estimate for w will not change greatly. Because the infrared radiative flux depends on temperature, and temperature does not vary greatly with horizontal position in the lower Venus atmosphere, the global average is a good approximation for the infrared flux, and by the above energy balance argument this must be equal to the global average net solar flux. The mixing length, l, was chosen as 5 km (about the thickness of the neutrally stable layer), but a mixing length of 1 km reduces the estimate for $|w|$ by less than a factor of 2. The wind velocities are generally consistent with the estimate of 1 m sec^{-1} (Fig. 1). Although mixing length theory successfully estimates the typical values of $|w|$ encountered, some of the larger vertical winds with magnitudes above about 2 m sec^{-1} seen by VEGA-2 may be due to other processes (see later discussion).

From mixing length theory, the average magnitude of temperature fluctuations corresponding to vertical winds of 1 m sec^{-1} can also be estimated (*7*):

$$\Delta T \sim \frac{8T|w|^2}{gl} \approx 7.5 \times 10^{-2} \text{ K} \qquad (2)$$

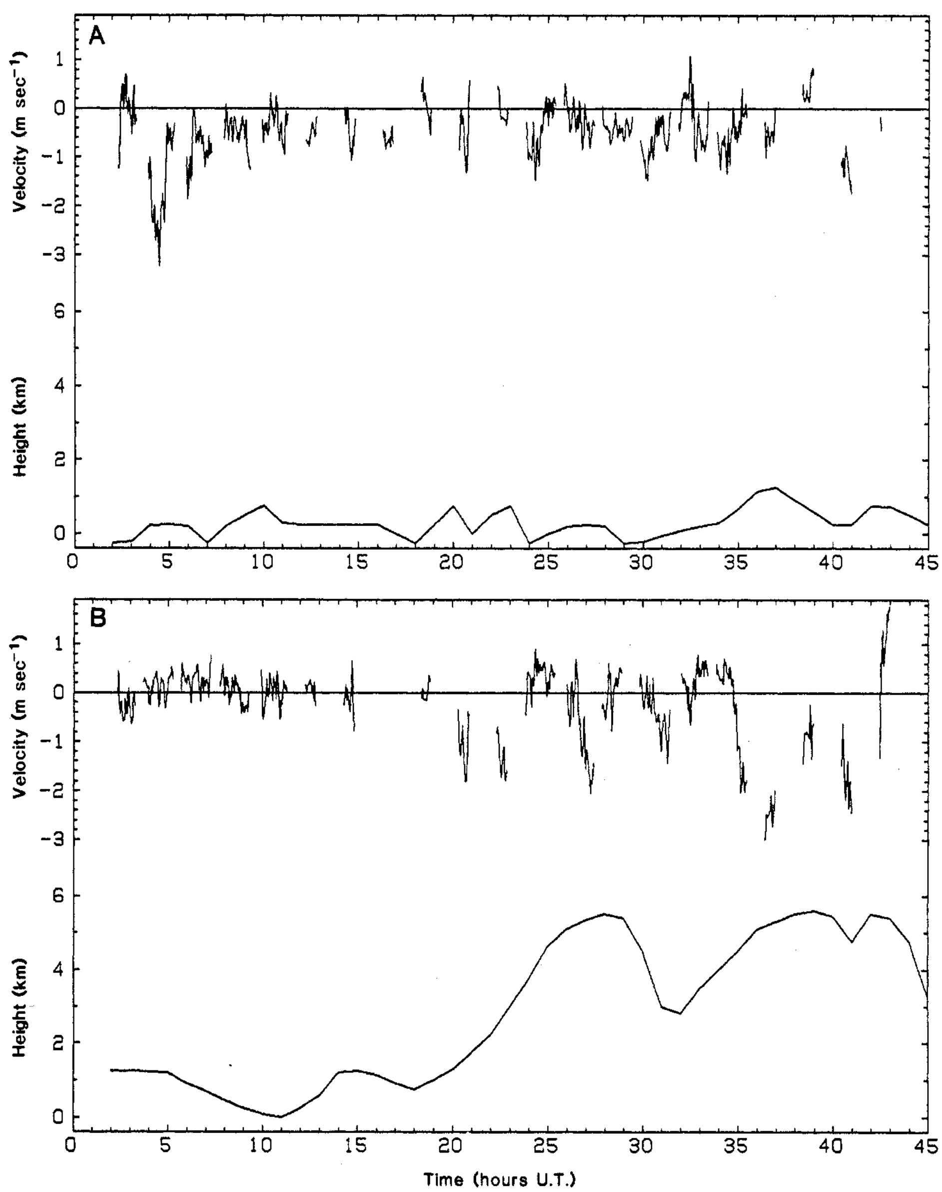

Fig. 1. Comparison of temporal history of atmospheric vertical winds with estimated surface topography. Topography curves, which are referenced to a planetary radius of 6051 km, represent only an envelope of the actual terrain, which may be much more jagged. (A) VEGA-1; (B) VEGA-2.

Thus, according to mixing length theory, average convective temperature fluctuations are of the order of 0.1 K. To date, four individual frames of data (each frame is a half hour of data) have been analyzed in terms of temperature fluctuations (*1*). Two frames indicate fluctuations about a reference adiabat of the order of 0.1 K, but the two others apparently have temperature fluctuations of approximately 0.5 K and 0.7 K.

Another aspect of the vertical winds encountered by the balloons is an apparent predominance of downward winds (*3*). This is probably not a property of the atmosphere but instead a consequence of the balloons floating in the upper regions of a neutrally stable layer (*1*). The rapid increase of static stability with altitude above 55 km acts as an "upper lid" to motions within the neutrally stable zone, since vertical velocities are reduced as static stability increases. Thus it is in the upper regions of the neutrally stable layer where a downward vertical wind would usually be associated with convergence of the horizontal winds, with upward vertical velocity corresponding to horizontal divergence (*8*). Under these conditions the balloon tends toward areas of downwelling and is advected away from areas of upflow, thereby leading to a bias in the vertical wind sampled.

The offset in the temperature-pressure relation between VEGA-1 and VEGA-2 (*1*), corresponding to a consistent potential temperature difference (temperature difference on constant pressure surface) of about 6.5 K, implies one or more possible situations; (i) there are measurable hemispheric asymmetries between the northern and southern hemispheres over the approximate 14° latitude separation of the balloons, or (ii) temporal or longitudinal variations, or both, exist in the state of the atmosphere. At present it is impossible to rule out any of the above possibilities as being at least partially responsible for the observed offset. However, as discussed above, the potential temperature offset of about 6.5 K is much larger than can be accounted for by turbulent mixing processes in the neutrally stable layer. Hence it must be concluded that larger scale (that is, synoptic or planetary-scale) processes are responsible. A zonally averaged hemispheric asymmetry of the observed magnitude is not likely. The meridional temperature gradient on a constant pressure surface derived from the potential temperature offset and latitude separation of the balloons is an order of magnitude larger than meridional temperature gradients estimated from the vertical derivative of the zonally averaged meridional momentum equation. Thus synoptic or planetary-scale eddy disturbances probably account for the major part of the temperature difference between the balloons. Such eddies must have vertical length scales on the order of the thickness of the neutrally stable layer or larger in order that their amplitude not be severely diminished across this region. In addition, they must propagate in the zonal direction with approximately the same speed as the mean zonal wind and have a lifetime greater than 1 week in order that the potential temperature difference between the balloons remain essentially unchanged over the observation periods.

There is evidence for either solar-fixed or planet-fixed large-scale eddy motions from the Doppler data (*9*). There is a relatively smooth variation of the Doppler residuals between Venus midnight and dawn, such that the Doppler residuals for both balloons are of similar magnitude and of the same sense (*9*). One model for interpreting the Doppler data suggests an increase in the zonal wind of approximately 3 m sec^{-1} from midnight to dawn. It is the fact that the residual curve for each balloon is similar over the entire longitude range which suggests that the balloons have encountered either a solar-fixed or planet-fixed disturbance of planetary-scale wavelength. The most probable form of stationary disturbance having planetary length scale is a solar-fixed thermal tide, although surface topography may influence the atmosphere at the balloon float altitudes (see below). Semidiurnal thermal tides have been identified in the Venus atmosphere by the Pioneer Venus orbiter infrared radiometer above 65 km (the lowest altitude sensed by this instrument) (*10*).

One of the most intriguing aspects of the data has to do with large amplitude changes in the measured quantities observed between 35 and 40 hours universal time (U.T.) for VEGA-2. Doppler residuals for VEGA-2 increase considerably between 35 and 40 hours U.T. (*9*), so that the maximum indicated change in horizontal velocity may be many times 10 m sec^{-1}. At the same time that the Doppler residuals dramatically increase, there are large excursions in pressure and temperature (*3*). The VEGA-2 balloon lost superpressure near 700 mbar, which amplified the effects of actual changes in the atmosphere (*8*). Nevertheless, atmospheric vertical winds had their largest amplitudes and longest duration between 35 and 40 hours U.T. for VEGA-2 (Fig. 1). VEGA-1 did not observe an analogous set of events. Although VEGA-1 saw large excursions of pressure and temperature together with large vertical winds between 4 and 5 hours U.T. and near the end of the mission (*3*), the Doppler residuals for VEGA-1 never exhibited excursions anywhere near the magnitude of the maximum VEGA-2 Doppler residual excursion (*9*). Aside from a period between 4 and 5 hours U.T. and perhaps one surrounding 41 hours U.T. in which downdrafts of approximately 2 m sec^{-1} lasted for nearly 1 hour, the vertical winds for VEGA-1 did not exhibit a prolonged period of either intense downwelling or upwelling. On the other hand, there were several periods of intense downdrafts experienced by VEGA-2 before 35 hours U.T. that lasted for an hour or more. These episodes of strong downdrafts are reflected in the pressure and temperature data (*3*). It can be seen from the pressure and temperature time histories of the balloons that VEGA-2 generally experienced larger excursions in both these quantities than did VEGA-1. These excursions are a measure of the magnitude and duration of vertical winds encountered.

The temporal behavior of the data for VEGA-2 between 35 and 40 hours U.T., and perhaps the downdrafts of more than 1 m sec^{-1} beyond 20 hours U.T., may reflect an influence of surface topography on atmospheric motions. Figure 1 presents an approximate envelope of the cross section of surface topography overflown by each balloon in conjunction with the atmospheric vertical winds. The position of each balloon relative to the surface of Venus was estimated from the known injection coordinates and by assuming a constant zonal wind with no meridional wind. One-way Doppler measurements provided the average value of the zonal wind for each balloon (*9*), while the surface heights relative to 6051 km radius were obtained for the computed balloon trajectory from data obtained by the radar altimeter on board the Pioneer Venus orbiter (*11*).

There are three important points with regard to Fig. 1. First, the set of events for VEGA-2 described above evidently occurs over the mountainous terrain known as Aphrodite. Second, the terrain overflown by VEGA-2 during the second half of the mission has much more vertical relief than that overflown by VEGA-1; there does not appear to be any particular influence of topography on the atmospheric motions encountered by VEGA-1. Finally, although VEGA-2 crossed the morning terminator at about the same time that it passed over the peaks in Aphrodite, it is unlikely that the terminator crossing has special significance. VEGA-1 also crossed the terminator but did not experience unusual atmospheric conditions. If the topography associated with the Aphrodite region does influence the wind and temperature fields at the VEGA-2 balloon float altitude, then it would appear that two mechanisms could be responsible. One possibility, which appears to be rather unlikely, is an active volcano. One of the difficulties associated with such an explanation is why a volcanic eruption would cause the balloon to sink. The more likely explanation is some form of mountain or lee wave. Such waves can produce intense perturbations in the terrestrial atmosphere well above the tropopause (*12*), and gravity waves forced by topography are important momentum sources in the stratosphere and mesosphere (*13*).

Although the appropriate calculations have not yet been done for Venus, Schubert and Walterscheid (*14*) have shown that for vertically dependent Venusian static stability and mean zonal wind profiles certain gravity waves forced at the surface are capable of reaching the atmosphere at or above cloud level. They did not consider waves that are stationary with respect to the surface, but their calculations did indicate that at a given wave frequency there were particular horizontal wave numbers for which amplitudes could be considerably amplified in the upper atmosphere relative to the surface forcing. There is no a priori reason to believe that such would not be the case as well for stationary waves.

An estimate of the terrain slope required to produce vertical winds of the magnitudes observed at the balloon float altitudes can be obtained as follows. The vertical wind at the surface is the product of the surface horizontal wind, u, and the terrain slope, α, which is the ratio of terrain height to horizontal scale. Suppose that there are particular gravity waves for which $R_w = 1$, where R_w is the ratio of the quantity $\rho^{1/2}|w|$ at the balloon float altitude to that at the surface. Values of R_w up to order 10 were computed under certain conditions by Schubert and Walterscheid (*14*). Using R_w we can estimate what terrain slope is required at a given value of the surface wind in order that vertical winds at the balloon altitude are of the order of 2 to 3 m sec^{-1}. Choosing $u = 1$ m sec^{-1} (*15, 16*) and $R_w = 1$ gives a value for α of about 0.3, which is equivalent to a 1-km rise in 3 km. This is a slope much steeper than that indicated by the topography envelope given in Fig. 1 but one that is realized over horizontal distances of several miles in rugged terrestrial mountain ranges. A value for R_w of 10 gives a value for α of about 0.03, which is a modest slope for high mountain ranges. Thus mountain forcing of the cloud level atmosphere appears to be feasible, but obviously more work needs to be done before we can be confident that such an effect actually exists.

REFERENCES AND NOTES

1. V. M. Linkin *et al.*, *Science* **231**, 1420 (1986).
2. A. Seiff *et al.*, *J. Geophys. Res.* **85**, 7903 (1980).
3. R. Z. Sagdeev *et al.*, *Science* **231**, 1411 (1986).
4. G. Schubert *et al.*, *J. Geophys. Res.* **85**, 8007 (1980).
5. The square of the Brunt-Vaisalla frequency is defined as $(g/T)(dT/dz - \Gamma)$, where Γ is the adiabatic temperature lapse rate and z is altitude. Other quantities are defined in the text.
6. J. B. Pollack, O. B. Toon, R. Boese, *J. Geophys. Res.* **85**, 8223 (1980).
7. J. Cox and R. Giuli, *Principles of Stellar Structure* (Gordon and Breach, New York, 1968), vol. 1.
8. V. M. Linkin *et al.*, *Science* **231**, 1417 (1986).
9. R. A. Preston *et al.*, *ibid.*, p. 1414.
10. J. T. Schofield and F. W. Taylor, *Q. J. R. Meteorol. Soc.* **109**, 57 (1983).
11. H. Masursky *et al.*, *J. Geophys. Res.* **85**, 8232 (1980).
12. D. K. Lilly and P. J. Kennedy, *J. Atmos. Sci.* **30**, 1135 (1973).
13. D. C. Fritts, *Rev. Geophys. Space Phys.* **22**, 275 (1984).
14. G. Schubert and R. L. Walterscheid, *J. Atmos. Sci.* **41**, 1202 (1984).
15. C. C. Counselman III, S. A. Gourevitch, R. W. King, G. B. Loriot, *J. Geophys. Res.* **85**, 8026 (1980).
16. V. S. Avduevskii *et al.*, *Cosmic Res.* **14**, 622 (1977).

17. Supported in part by NASA Ames Research Center and the Jet Propulsion Laboratory.

23 October 1985; accepted 24 January 1986

Southern Hemisphere Origin of the Cretaceous Laytonville Limestone of California

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New paleomagnetic, paleontologic, and stratigraphic data from outcrops of the Laytonville Limestone (101 to 88 million years old) support a Southern Hemisphere origin. A paleomagnetic megaconglomerate test is statistically significant and suggests magnetization at 14° ± 5° south, predating Late Cretaceous to Eocene (70 to 50 million years ago) accretion. Rapid Kula plate movement or the existence and demise of a now vanished oceanic plate (or both) are required to accommodate the greater than 50° of poleward displacement implied by the paleomagnetic data. This rapid motion brings into question the validity of a "speed limit" for absolute plate velocity based on present-day plate motions.

Pioneering work of Alvarez *et al.* (*1*) centered on a paleomagnetic and paleontologic study of two blocks of red pelagic limestone contained in the Franciscan central mélange belt near Laytonville, California. Study of the abundant foraminifera of the Laytonville Limestone determined that the northern LL-2 block is middle Cenomanian in age [97 to 95 million years old (Ma)] (*2*) whereas the southern LL-1 block is latest Albian in age (101 Ma). Evolutionary trends in the foraminiferal species within the LL-2 section were thought to be distinctive enough to determine stratigraphic polarity. The 101- to 95-Ma interval is entirely contained within the Cretaceous normal polarity superchron; therefore, the paleolatitude of Laytonville Limestone deposition could be determined specifically by paleomagnetic analysis, assuming magnetization shortly after deposition. In their paleomagnetic analysis, Alvarez *et al.* concluded that the Laytonville Limestone acquired its magnetization at 17° ± 7° (95 percent confidence interval) *south* paleolatitude.

Some workers expressed doubt as to whether the foraminiferal trends visible in the sections were distinct enough to permit determination of stratigraphic polarity (*3*). At the heart of the debate was the assumption that the implied convergence rates of 24 to 60 cm per year between the plate carrying the Laytonville Limestone and North America were unrealistically high. This was especially so because if it is arbitrarily assumed that the Laytonville Limestone outcrop LL-2 is overturned, the results of Alvarez *et al.* can be neatly incorporated into extant northern Pacific basin plate models (*3*).

We report new paleomagnetic and paleontologic data from previously unstudied outcrops of Laytonville Limestone. The new outcrops occur as blocks containing as much as 25 m of continuous section enclosed in mélange, and are located close to the outcrops studied by Alvarez *et al.* (Fig. 1B). Several distinct biozone boundaries are crossed within individual continuous blocks, providing unambiguous facing directions. Together with new data from the outcrops originally studied by Alvarez *et al.*, these new studies confirm a Southern Hemisphere origin for the Laytonville Limestone.

The Franciscan Complex in northern California consists of three major tectonic belts

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