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TITLE: DIVERGENCE AND VORTICITY IN THE ROCKY MOUNTAIN PLATEAU CIRCULATION

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Divergence and Vorticity in the Rocky Mountain Plateau Circulation

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I. Introduction

Mountainous regions of major areal extent have the potential to produce systematic regional circulations with day to night reversals. During the day the elevated land mass absorbs solar energy and serves as a warm spot relative to the surrounding air at the same altitude. This creates a general low level convergence into the area of elevated topography. At night, cooling at ground level reverses the thermal circulation to outflow from the high ground. The pattern of convective cloudiness that forms during the day over mountainous areas in summertime serves to enhance the effect. Release of latent heat in the cloud-forming condensation processes during the day warms the atmosphere above the mountains. Similarly, evaporative cooling occurs in this area at night. Tang and Reiter (1984) found evidence of this diurnally varying Plateau circulation over the massive and high Tibetan plateau. Reiter and Tang (1984) report a similar pattern over the Rocky Mountains in the Summer season. In the other seasons of the year the effect is swamped by migratory synoptic scale circulation features. Reiter and Tang develop the 850 mb geopotential height pattern by upward hydrostatic adjustment of surface pressures from 44 stations in the mountain west. They performed the analysis on a record of seven July periods between 1975 and 1982. They present the 850 mb height fields for 3-hourly intervals throughout the diurnal period.

Figure 1 shows streamlines estimated from Reiter and Tang's Figure 2 by simply adopting a 45^{o} cross isobar wind. Figure 1a represents the time of maximum outflow and 1b the time of maximum convergence. The reversing wind patterns described in Fig. 1 have helped explain some otherwise mysterious wind soundings. For example, Barr and Clements (1981) present data on a 1.5 km deep layer of vigorous easterly wind over the Piceance Basin of Western Colorado during two nights when conventional analyses all suggested weak southwesterly flow. Fig. 2 shows the temporal trend of low level wind directions at the Piceance Basin site compared with winds derived from Reiter and Tang's pressure analyses. Both reflect a fairly rapid evening transition from westerly to easterly. Differences in timing aren't too important considering that the Reiter-Tang pressure fields are based on an ensemble while the Piceance Basin observations are for particular nights.

Based on evidence similar to that described above and the enormous practical implications of a systematic plateau circulation in the Rocky Mountain regions of Colorado, Wyoming, New Mexico and Utah, collaborators from Colorado State University and Los Alamos National Laboratory designed an experimental program to observe evidence of the plateau circulation directly in the wind field. An array of 13 wind and temperature sensors were deployed at exposed locations on mountain peaks from Steamboat Springs, CO south to Santa Fe, NM and west to Grand Mesa, CO. The object of the study was to place the sensors at exposed locations out of local drainage winds and, hopefully free of local aerodynamic recirculations so that they would respond to the larger scale plateau circulation winds. The mountain peaks were used as very tall proxy towers. In this way some hypotheses on the existence and properties of the Rocky Mountain plateau circulation could be tested continuously during a two month period of expected maximum influence. The cost for this deployment was a small fraction of the cost to maintain an array of upper air soundings. Positive results from this relatively inexpensive experiment can be used to justify a more elaborate array of soundings. Details of the Rocky Mountain Peak Experiment (ROMPEX) are described by Sheaffer (1986).

This paper describes an effort at empirical analysis of the available ROMPEX wind data with emphasis on the divergence and vorticity magnitudes and, in a few cases, patterns.

II. Estimates of the Magnitude of the Plateau Circulation

It is instructive to estimate the magnitudes of the pressure gradient forces and the resulting wind fields in order to look for consistencies with the Reiter and Tang analyses and to see how the plateau circulation compares with synoptic influences on the wind and pressure fields. Whiteman and McKee (1978) and Whiteman (1981, 1982) report the results of three-hourly temperature soundings up to 6 km MSL over several locations in the Colorado Rockies. They show a deep convective boundary layer in the summer from 2 to 4 km above the main Rocky Mountain "plateau" (2 km MSL). At night a deep stable layer develops to altitudes as high as 2 km above the plateau. Based on a summary of warm season soundings, we have constructed a crude conceptual model of the relative heating and cooling above the plateau relative to the atmosphere above the surrounding plains. Fig. 3 shows schematically the evolution of temperature profiles during the day and the subsequent night. An ambient tropospheric potential temperature profile of +3°C per km is imposed. This compares with the standard atmosphere and is reflected in many of the observed profiles. If the boundary layer over the plains does not exceed the 2 km height of the plateau, then we may examine perturbations to the ambient profile created in the boundary layer over the plateau. The convective boundary layer creates a shallow superadiabatic layer beneath a zone of constant potential temperature, the top of which is determined by the intersection of the ambient profile with the selected isentrope. Typical daytime warming leads to an average increase in potential temperature of 2 to 3°C over a layer 2 to 3 km in depth. Hydrostatic estimates of pressure at the height of the plateau surface are on the order of a few mb lower over the warm plateau than over the plains at the same height, assuming no pressure differential at 6 km MSL. Nighttime cooling over the plateau creates a similar plateau-plain pressure differential of about 2 mb. This pattern agrees very well with the contours of the 850 mb surface analyzed by Reiter and Tang.

We are further interested in the wind speed that results from a 2 mb pressure difference over the approximately 500 km radius of the Rocky Mountain plateau. Recognizing that even though we are dealing with a temporally evolving boundary layer flow on a relatively small scale, the simplicity of the geostrophic approximation is irresistible and the approximation will produce the expected order of magnitude of the winds. Substituting into $u_g = \frac{\partial P/\partial n}{\rho f}$ the values 210 Pa over 5×10^5m, $\rho \cong 1$ kg/m^3 and $f = .94 \times 10^{-4}$ s^{-1} yields $u_g = 4.5$ m/s. Accounting for Ekman layer reduction in speed as well as the fact that throughout most of the day the driving force is evolving and has a magnitude less than the maximum, we can suggest that the plateau circulation has speeds of a few meters per second.

We can go one step further and estimate the expected vorticity and divergence from the wind field estimated in this section. Assuming a cross-isobar flow angle of 45^{o}, a reasonable value for the lower boundary layer over rough terrain, and a net velocity of 3 m/s, we can evaluate equations (1) and (2) over a circle of 500 km diameter. This yields values for both divergence and vorticity of $1.7 \times 10^{-5}\ s^{-1}$. This agrees within a factor of 2 with the values for the purest cases of plateau circulation in the ROMPEX data described in Section III.

The estimates are admittedly quite rough and not intended to represent any simulation effort. Instead, they are presented to show as directly as possible that the typical heating and cooling of the plateau boundary layer gives rise to the observed magnitude of pressure and wind which, in turn reflect the correct magnitude of vorticity and divergence. More detailed modeling efforts are described by Sang and Reiter (1982).

The difficulty in diagnosing the Plateau circulation can be seen by comparing the pressure gradient driving force for this system with synoptic pressure gradients. Above we have estimated a gradient of 2 mb over a 500 km lateral distance. This is equivalent to the weakest of synoptic pressure gradients in summer. In the presence of a front or cyclonic disturbance, summertime pressure gradients are more typically 10 mb over the same distance while a storm in winter will be double the value. Hence the local forcing can range from one half the total forcing down to a 10% perturbation. In the presence of the strong mixing, advection and alteration of the diurnal heating/cooling by clouds and widespread precipitation that occur in migratory synoptic systems, it is likely that the local forcing would be further diminished. Thus, it appears that the plateau circulation can be expected to be a major factor in Rocky Mountain transport wind fields only in favorable periods in the summer.

III. Analysis of Data

A. Calculation of Divergence and Vorticity

A line integral method for estimating divergence and vorticity was introduced by Ceselski and Sapp (1975) and applied by Schaefer and Doswell (1979) and; more recently, by Shapiro and Zamora (1984). In this method the integrals:

$$D = \frac{\partial \mu}{\partial x} + \frac{dv}{dy} = \frac{1}{A} \int_c v_n \, ds \qquad (1)$$

$$\zeta = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = \frac{1}{A} \int_c v_p \, ds \qquad (2)$$

are evaluated around the minimum geometry for a closed curve, a triangle. In (1)and (2), A is the area enclosed by the path c, v_n and v_p are the velocity components normal to and parallel to the path, and ds is an increment of the curve c. Fig. 4 shows the array of triangles created from the available wind stations for the August 1985 period from the ROMPEX data set. Since each triangle yields an estimate of D and ζ the calculation produces a field of divergence and vorticity for each time period. In most of the analysis described below the spatial averages of D and ζ are used. Two periods; were selected for analysis based on the completeness of the data records; July 10-20 and August 8-September 7. Hourly values of divergence and vorticity were calculated.

One of our objectives is to look for diurnal variation in the area-averaged divergence and vorticity. In the absence of disturbance by migratory synoptic scale circulations, the expected pattern of the plateau circulation is inflow or convergence during the day and outflow or divergence at night. The time and space scale of the convergence-divergence cycle is large enough to expect an influence of the Coriolis force some would also expect cyclonic circulation in the daytime with anticyclonic circulation at night.

B. Interpretation of the Time Series

Figure 5 presents time series plots of the spatial mean convergence and vorticity patterns. Although there appear to be diurnal variations it is clear that there is variability on other time scales. July 12, 15, 16 and 20; Aug. 26, 27, 30 and September 2 appear to offer the clearest cases of a diurnal pattern in both dynamical parameters. The other days are all strongly influenced by other circulations. There also appears to be a phase shift in which the vorticity lags the divergence by about three hours. We must keep in mind that Figure 4 refers to the mean properties over the entire observational array. There are many cases where the plateau circulation is dominant over the southern portion of the array while synoptic winds predominate in the north.

In order to look more specifically for the diurnal cycle in the somewhat noisy time series of Fig. 4 we used a Fast Fourier transform calculation to produce the power spectra of Figs. 6 and 7. Figure 6 displays the spectra for divergence (6a) and vorticity (6b) for the 10-day July period while Figs. 7a,b show the same quantities for a thirty day August-Sept. period. The dominant feature of each of the spectra is the peak at the diurnal frequency of 1.16×10^{-5} Hz. An apparent secondary peak at 2.5×10^{-5} Hz is most likely the result of the nonsinusoidal shape of the dominant diurnal cycle being expressed in sinusoidal basis functions.

The August record shows a broad secondary maximum at a period of 4-5 days that doesn't appear in the July record. We suspect that this is the synoptic scale variation. The August record is barely long enough to suggest this spectral feature and the July record clearly is too short. Reiterating, the major features that appear in the power spectra of divergence and vorticity time series are distinct peaks at the diurnal frequency. These dynamical parameters are exhibiting the day to night reversals suggested by the plateau circulation hypothesis.

C. Time and Space Dependence

Figures 8 and 9 present patterns of divergence and vorticity, respectively, for a 27 hour period identified as a case of good plateau circulation on July 19-20, 1985. Anticyclonic and divergent circulations are denoted as light stippled areas. There are several points to make regarding the patterns.

1. There are no pure region-wide patterns of all one sense. There are pockets of divergence in predominantly converging flow and vice-versa. The same holds for vorticity.

2. The area coverage for divergence (anticyclonic vorticity) includes most of the area at night and shrinks to a minor coverage during the day.

3. There is a measure of continuity in the evolution of the patterns with time although there are exceptions.

4. This case is dominated by strong nocturnal divergence in the northeast corner of the grid. This is not true of other cases. This area received heavy rainfall during the afternoon thunderstorms and could be a source of strong evaporative cooling at night.

IV. Conclusions

Early results from analysis of the ROMPEX data set suggest that a plateau circulation with characteristic dimensions of 500 km is a factor in the summertime wind fields over Colorado, Wyoming and New Mexico. Also, the deployment of sensors in exposed locations on mountain peaks appears to yield a representative sample of the regional scale circulation reflected in reasonable temporal and spatial patterns of derived quantities. The kinematic flow properties of divergence and vorticity are excellent diagnostics for interpreting the plateau circulation in the ROMPEX data set. Both parameters exhibit a clear diurnal variability as well as a suggested synoptic scale variability. The phase of the variations as well as the amplitudes are consistent with estimates based on the thermal forcing and resulting pressure fields. A comparison of forces suggests that the plateau circulation can represent everything from a dominance of the observed wind (when synoptic gradients are very weak) to an insignificant perturbation under vigorous synoptic flow.

The practical implications of the circulation are significant. As in the case of the Piceance Basin observations described in Section I, transport winds can be in the opposite direction to those indicated by synoptic analysis exclusive of the circulation domain. The diurnal reversal characteristic suggests that pollutant plumes may pass a particular location more than once.

The majority of cases exhibit spatial structure in the convergence field. Although the mean value for a particular day may represent convergence, for example, there are persistent and sometimes migratory pockets of divergence in the observation array. It is tempting to speculate on the relationship of such space-time variations to the vigor of mountain thundershowers. Those of us who live in the mountains often observe quite abrupt changes in the character of the local thunderstorm environment as if an extensive field of deep convection were squelched by a somewhat sudden subsidence. I will suggest that some important variations in the precipitation patterns and subsequent deposition patterns in summer depend on the plateau circulation.

The results from ROMPEX are demonstrating quite clear evidence of a component of the wind field that exhibits properties of the plateau circulation postulated by Reiter and Tang. It is appropriate to devise more elaborate experiments that may rely on vertical soundings of wind and temperature and, perhaps tracer releases. I encourage the continued effort in modeling the system that is currently under way at Colorado State University.

References

Barr, S. and Clements, W. E., "Nocturnal Wind Characteristics in High Terrain of the Piceance Basin, Colorado," Proc. Second Conf. on Mtn. Meteorol., Steamboat Springs, CO, Nov. 1981, Amer. Meteorol. Soc., 6 pp.

Ceselski, B. F. and Sapp, L. L., "Objective Wind Field Analysis Using Line Integrals," Mon. Wea. Rev., 103, 89-100, 1975.

Reiter, E. R. and Tang, M., "Plateau Effects on Diurnal Circulation Patterns," Mon. Wea. Rev., 112, 638-651, 1984.

Sang, J.-G. and Reiter, E. R., "Model-Derived Effects of Large-Scale Diurnal Thermal Forcing on Meteorological Fields, Arch. Met. Geoph. Biokl., A31, 185-203, 1982.

Schaefer, J. T. and Doswell, C. A. III, "On the Interpolation of a Vector Field," Mon. Wea. Rev., 107, 458-476, 1979.

Schaefer, J., draft report on ROMPEX, Colo. St. Univ., 1986.

Shapiro, M. and Zamora, R., "Diagnostic Divergence and Vorticity Calculations Using a Network of Mesoscale Wind Profilers," Proc. 10th Conf. on Wea. Forecasting and Anal., June 1984, Clearwater, FL, Amer. Meteorol. Soc., 386-391.

Tang, M. and Reiter, E. R., "Plateau Monsoons of the Northern Hemisphere: A comparison Between North America and Tibet," Mon. Wea. Rev., <u>112</u>, 617-736, 1984.

Whiteman, C. D., and McKee, T. B., "Air Pollution Implications of Inversion Descent in Mountain Valleys," Atmos. Env., 2151-2158, 1978

Whiteman, C. D., Personal Communication, Jan. 1981, "Airsonde Data, Oil Shale Tract C-a August 1980"

Whiteman, C. D., "Breakup of Temperature Inversions in Deep Mountain Valleys: Part I. Observations, J. Appl. Meteorol., <u>21</u>, 270-275, 1982.

Figures

1. Estimated 850 mb wind fields at a) 0500 MST and b) 1700 MST derived from the height fields described by Reiter and Tang (1984).

2. Comparison of observed low level wind directions at a Piceance Basin site with directions estimated from Rieter and Tang for the appropriate location.

3. Schematic diagram of the thermal inequalities that drive the plateau circulation.

4. Diagram of the network of ROMPEX stations in Colorado and New Mexico and the triangles selected for estimating divergence and vorticity.

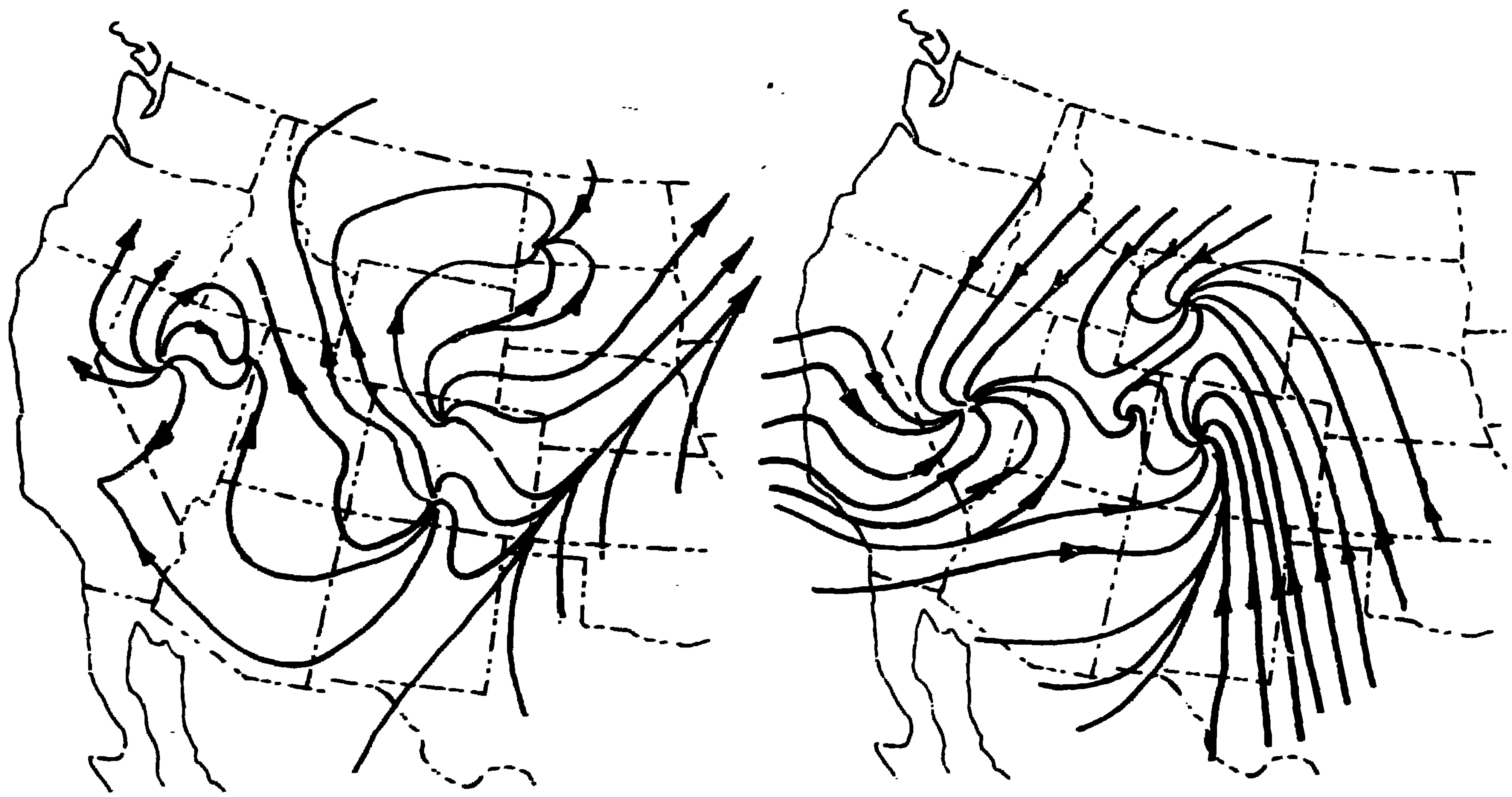
5. Time series of space-averaged divergence and vorticity from the ROMPEX network.

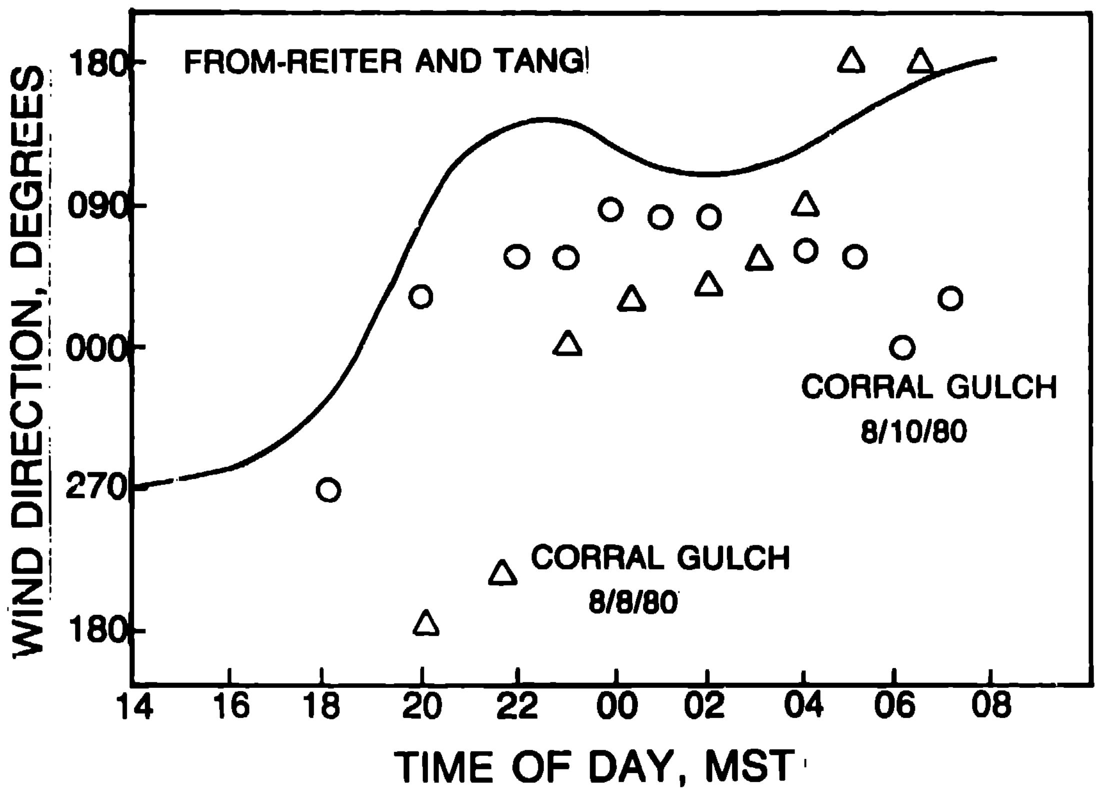
6. Spectra of a) Divergence and b) vorticity for a 10-day July 1985 period.

7. Spectra of a) Divergence and b) vorticity for a 30-day August-September, 1985 period.

8a-8j. (top) Divergence patterns at three-hour intervals for a 27-hour case during strong diurnal influence. Light stippled areas are divergent while dark shading is convergence. Contours are at values of $1 \times 10^{-4}\ s^{-1}$.

9a-9j. (bottom) Vorticity patterns corresponding to Fig. 8. Light stippling represents anticyclonic vorticity. Contours are at values of $1 \times 10^{-4}\ s^{-1}$.





FROM-REITER AND TANG
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CORRAL GULCH
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TIME OF DAY, MST

Fig 2

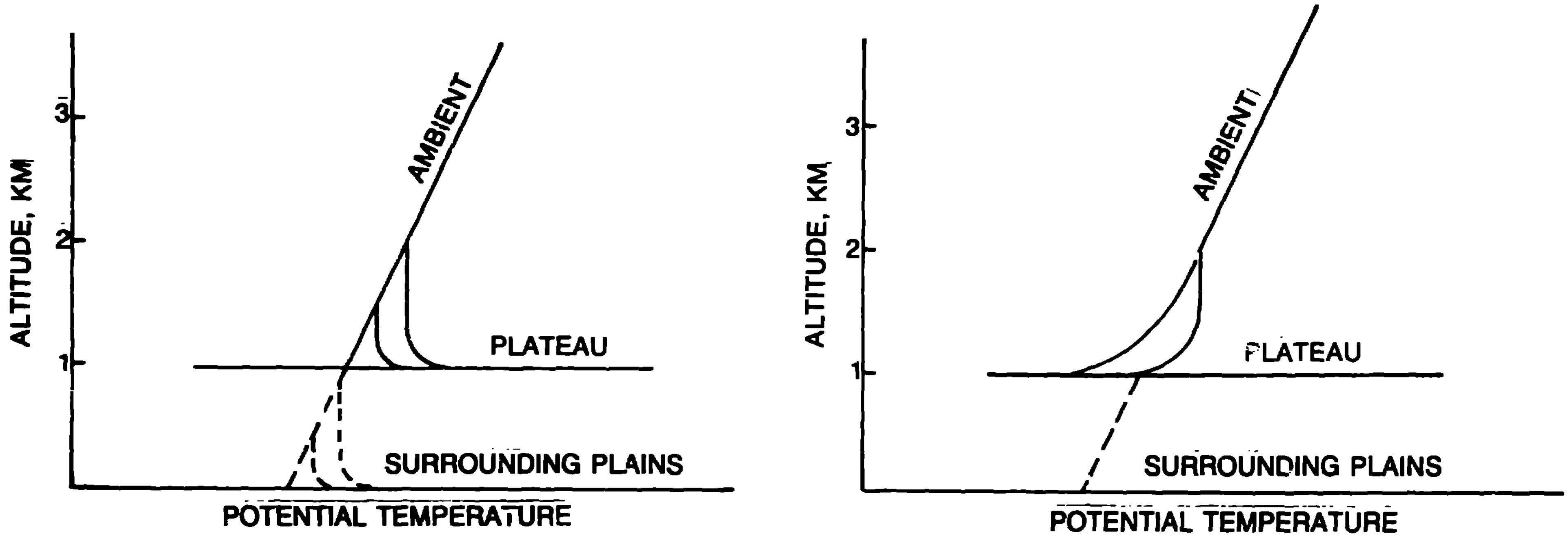
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Fig 3

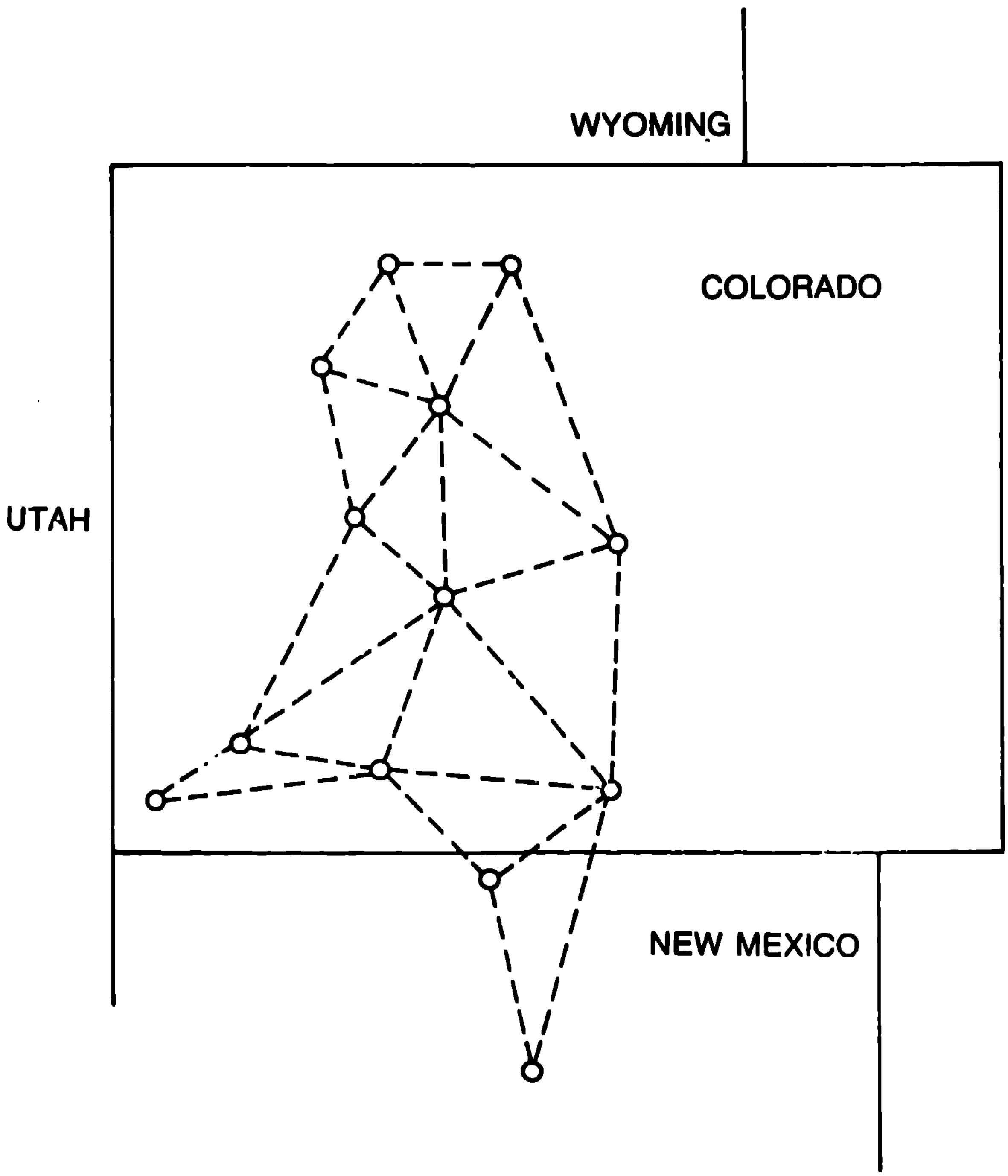
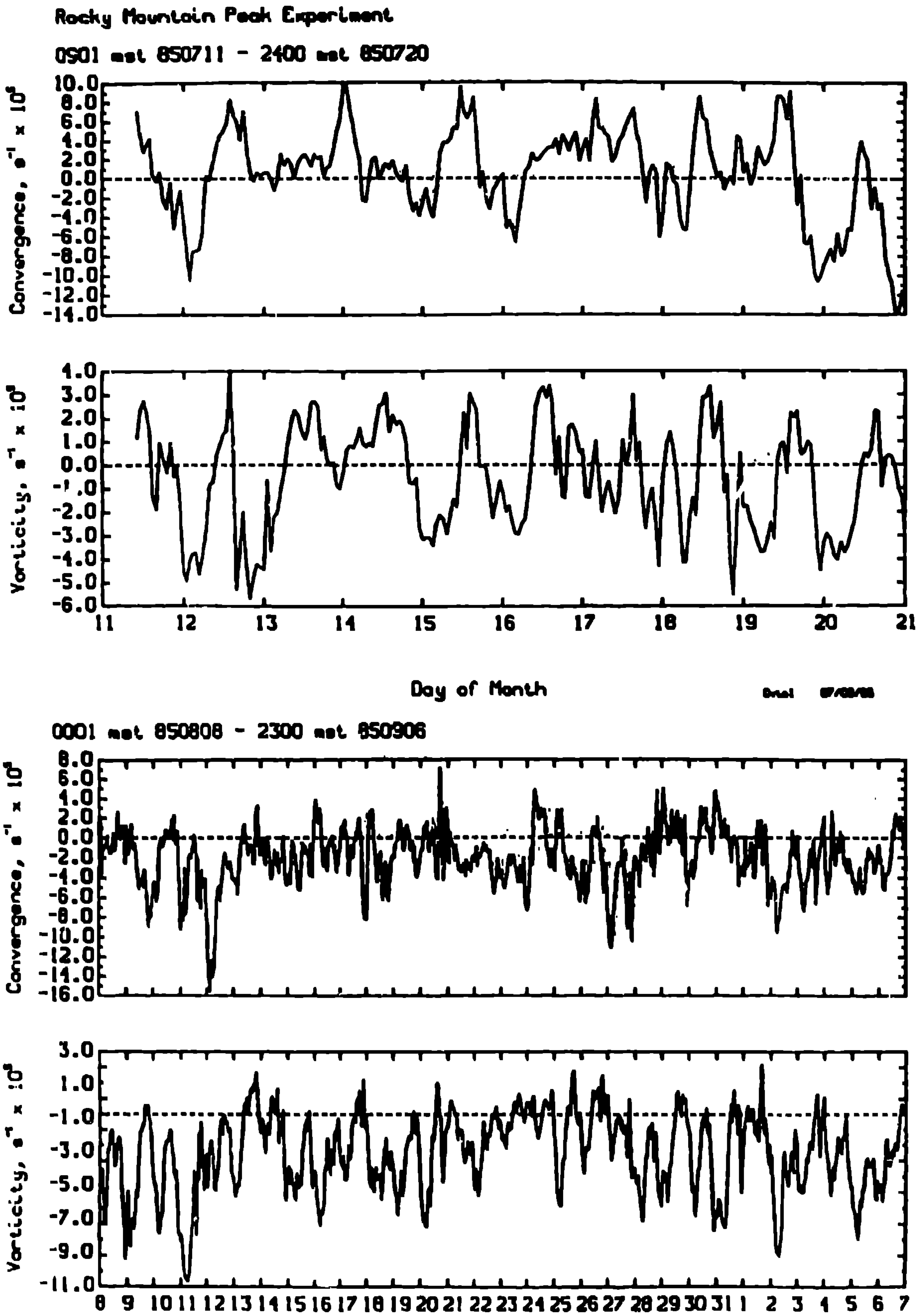


Fig 4


Rocky Mountain Peak Experiment
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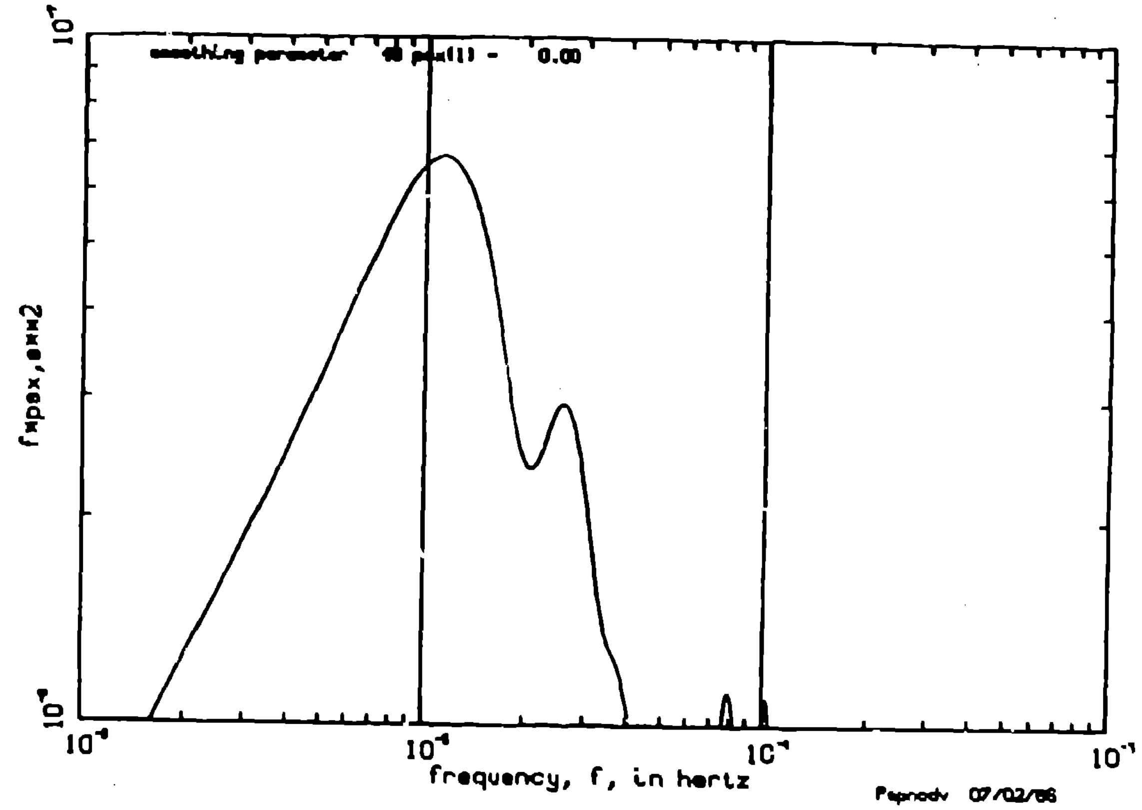
Convergence, s⁻¹ x 10⁵
Vorticity, s⁻¹ x 10⁵
Day of Month
0001 mst 850808 - 2300 mst 850906
Convergence, s⁻¹ x 10⁵
Vorticity, s⁻¹ x 10⁵

Fig 5

Rocky Mountain Peak Experiment

Spectral Estimates

Divergence 0901 mst 850711 - 2400 mst 850720



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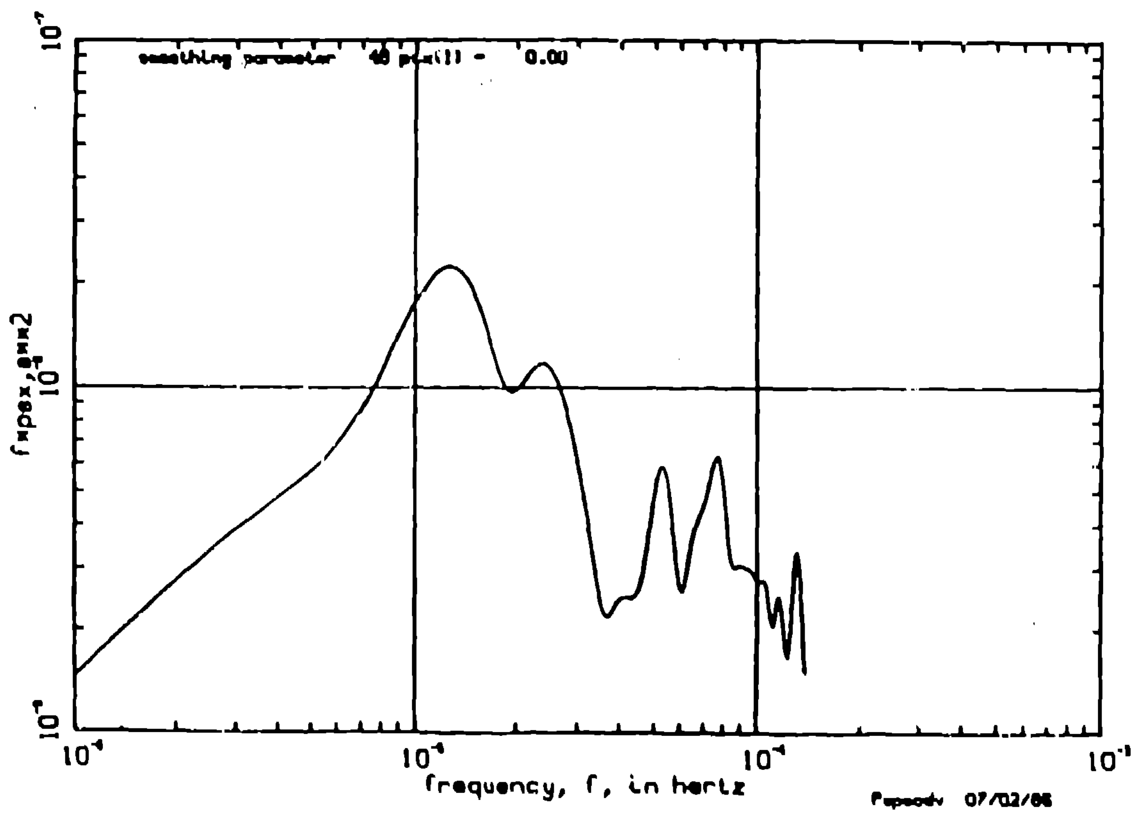
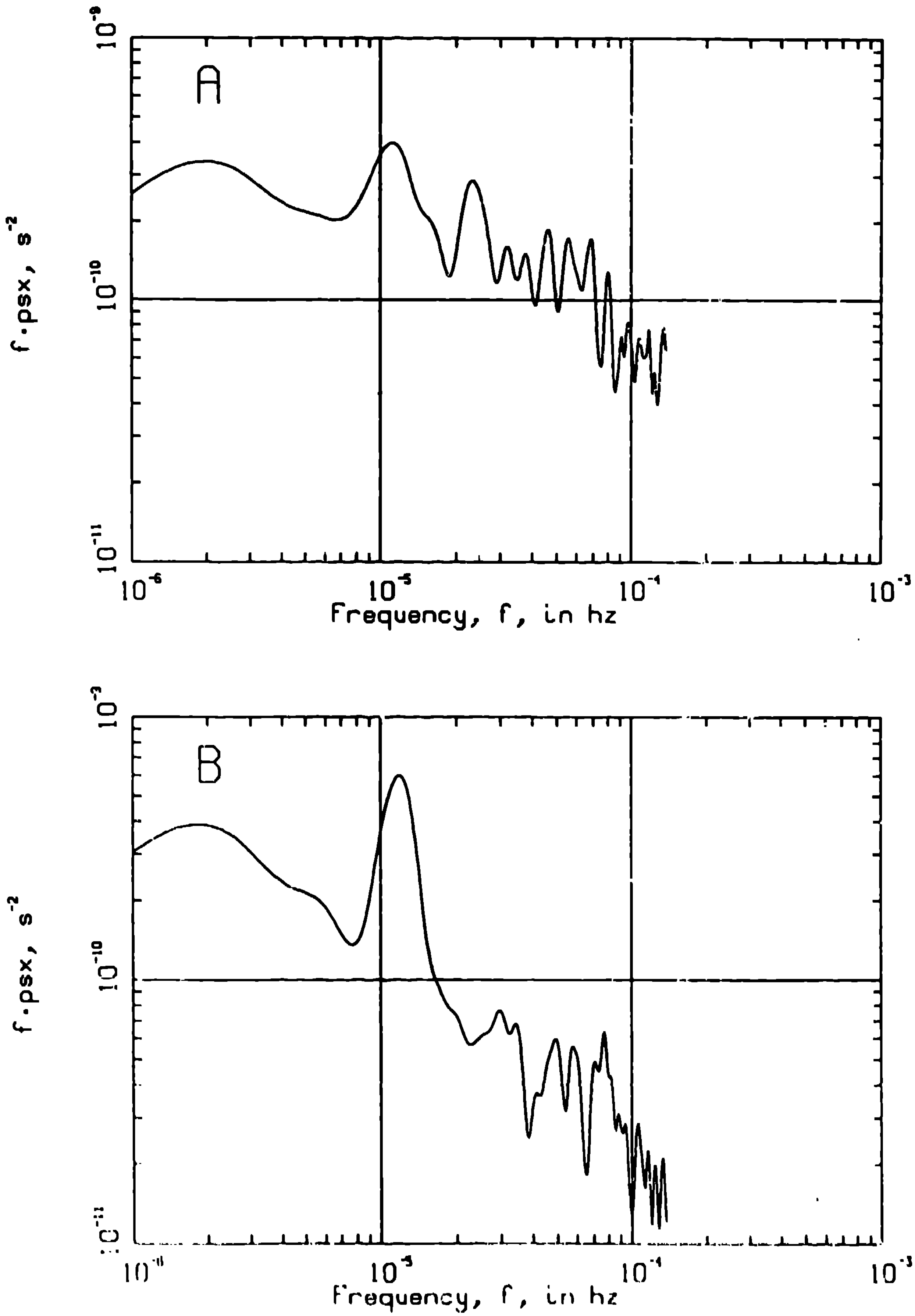


Fig 6



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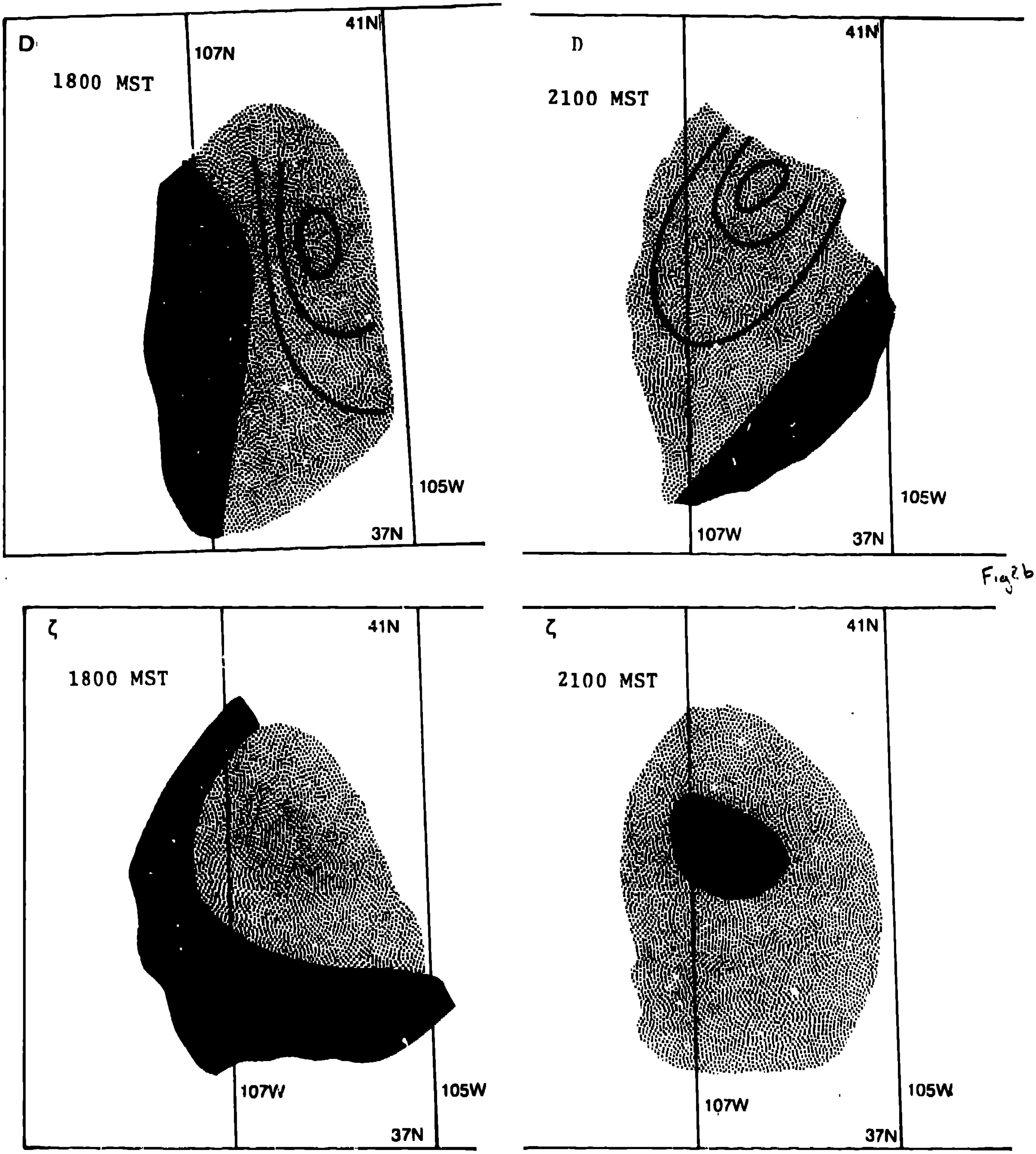
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Fig2b

Fig9b

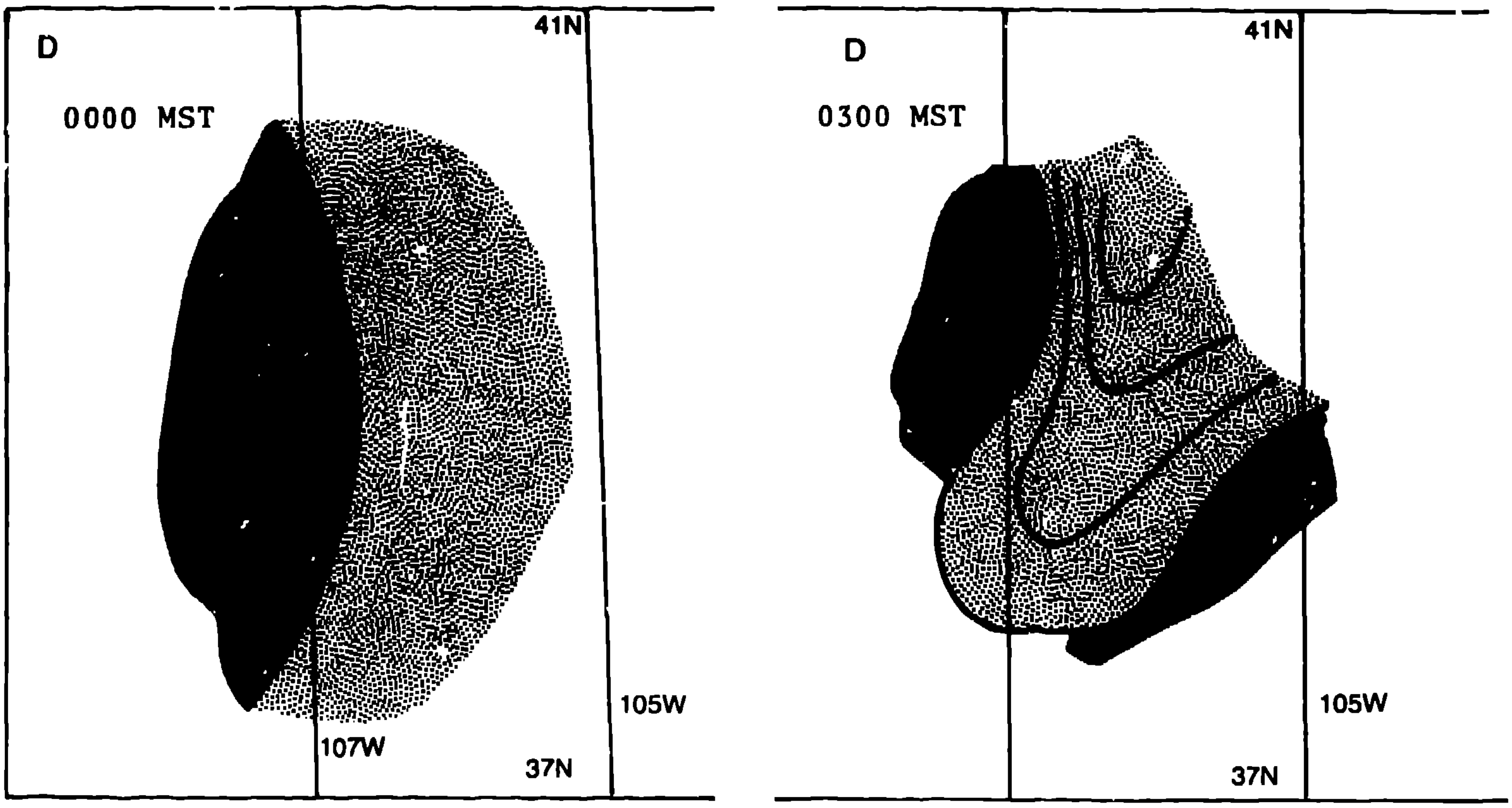
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Fig 8d

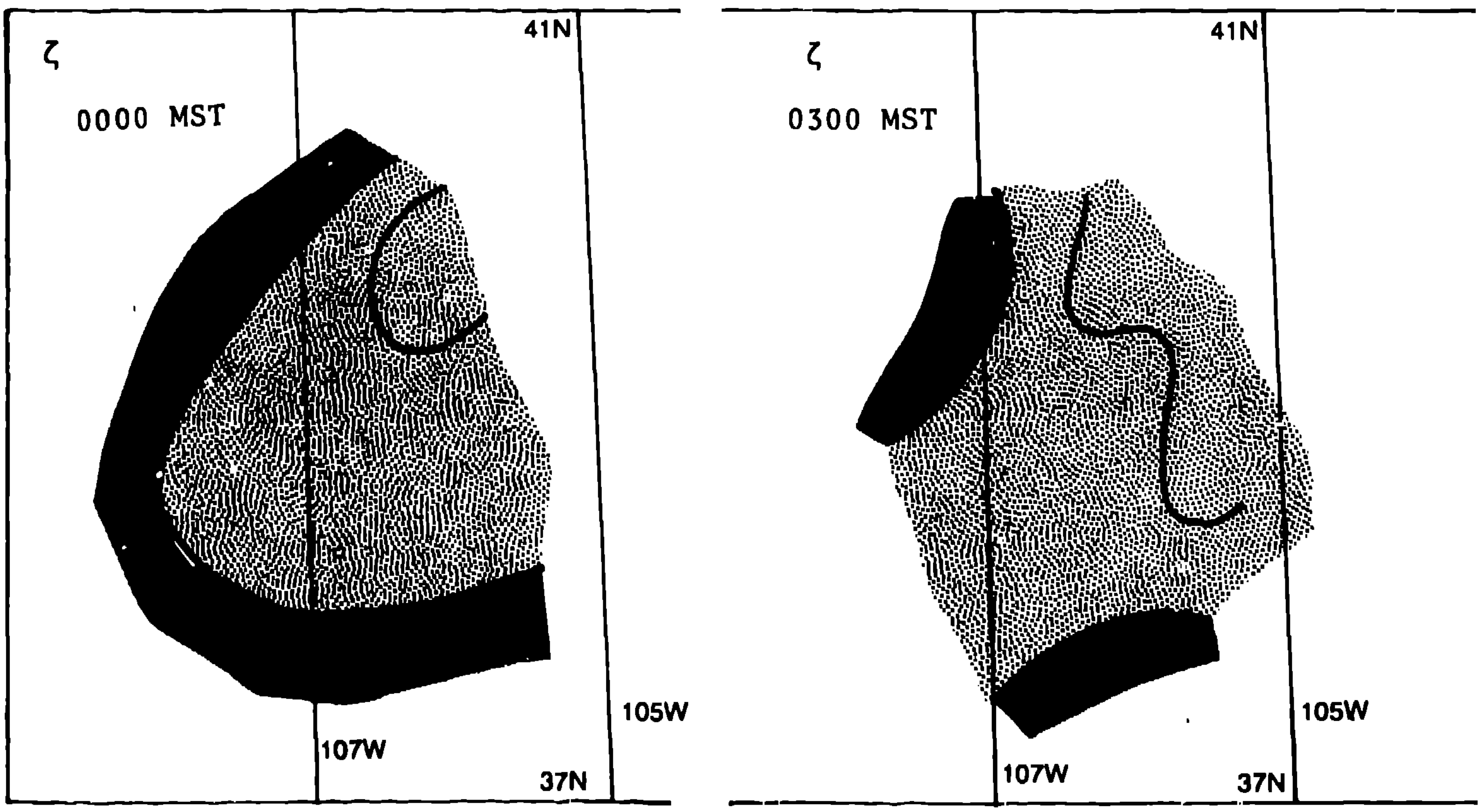
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Fig 9d

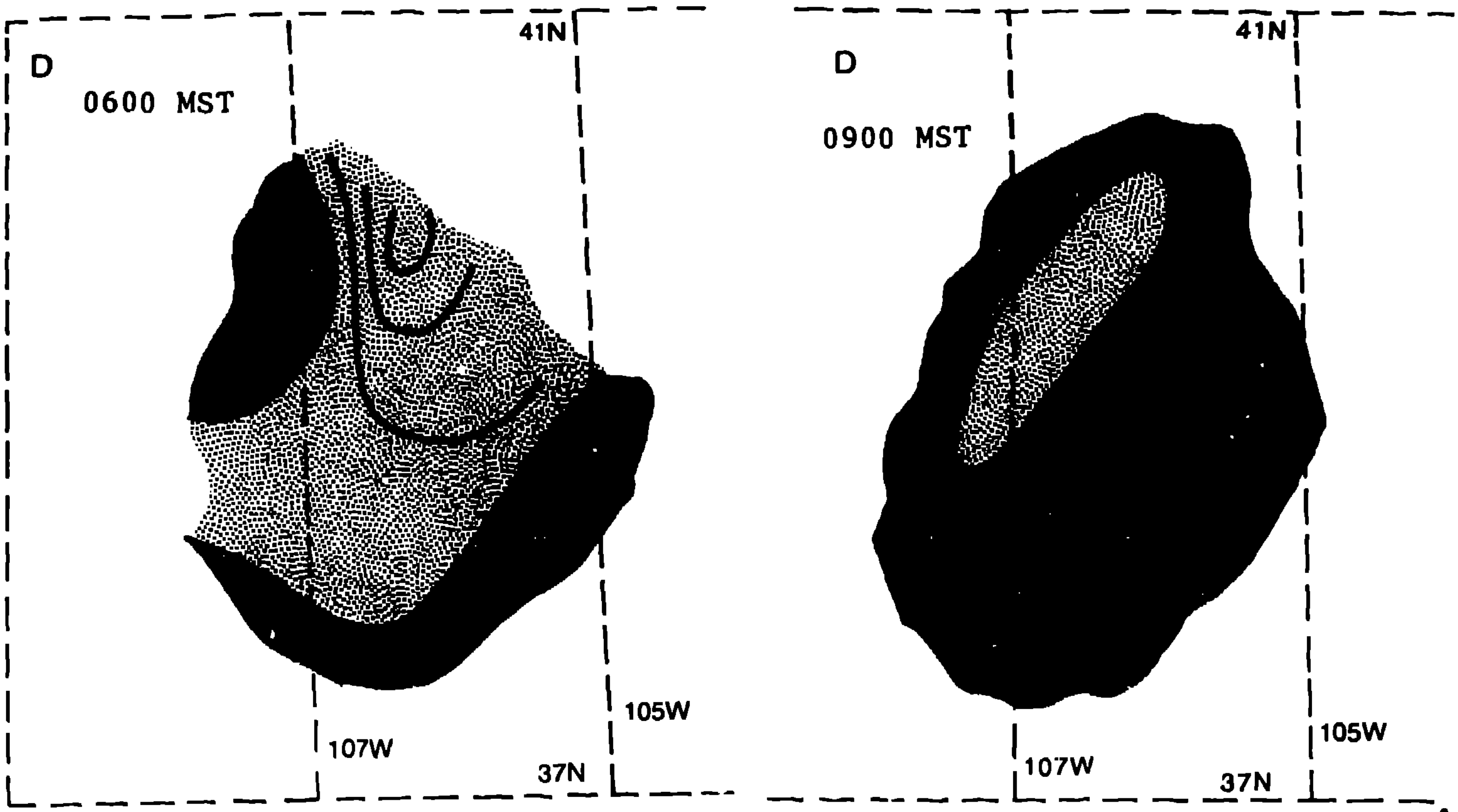
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Fig 8

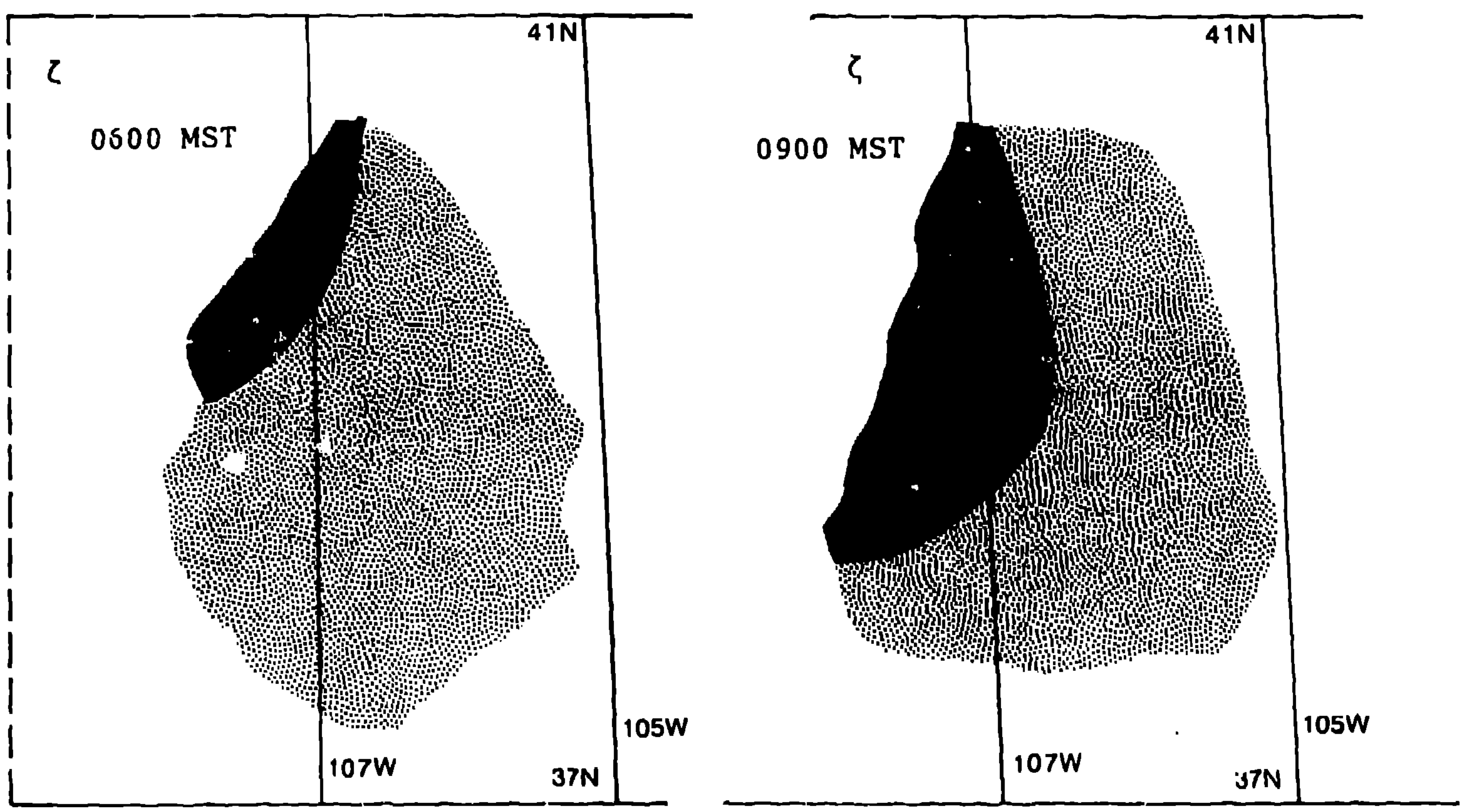
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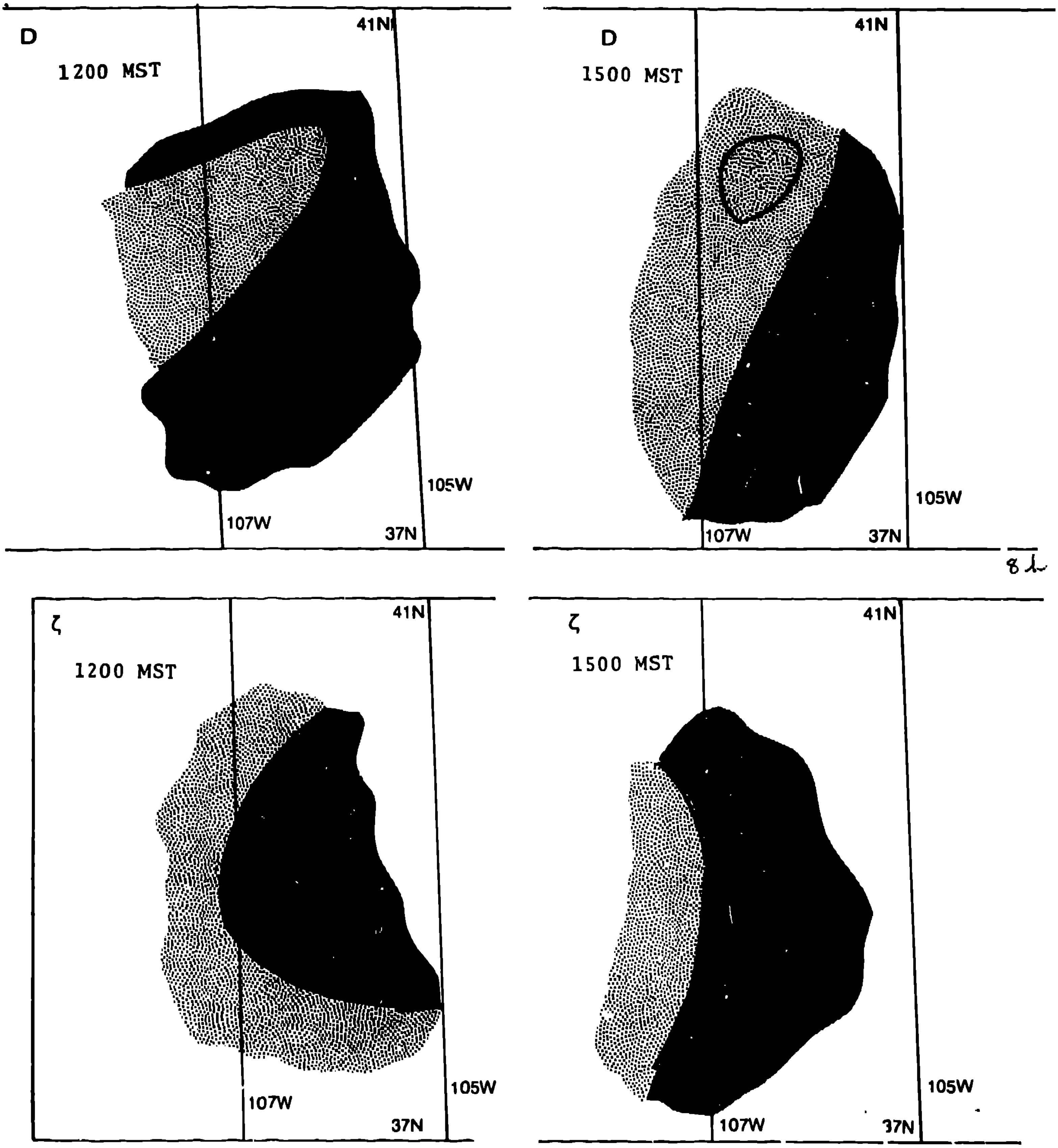
Fig 9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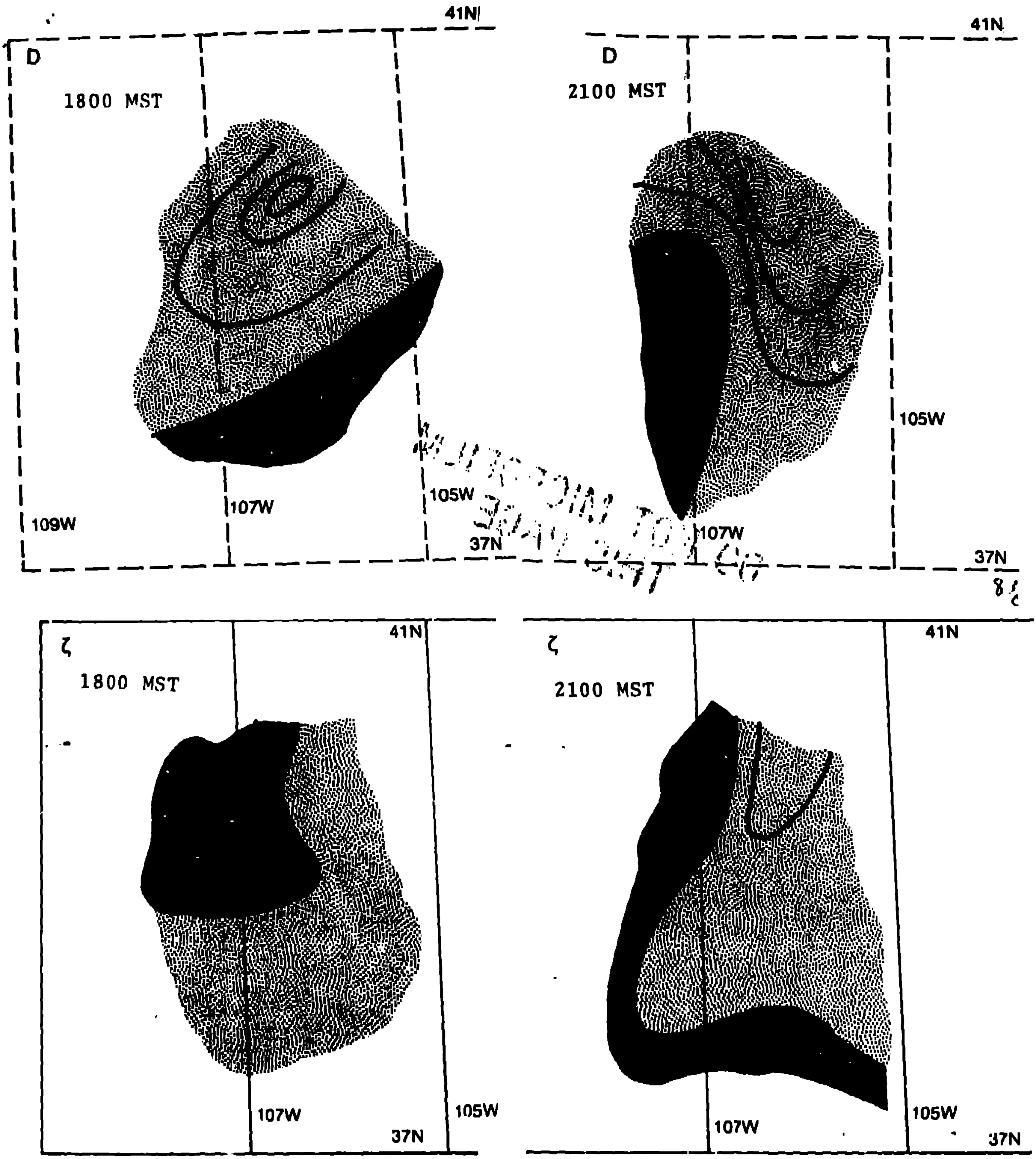
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