# Shifts in late Paleozoic atmospheric circulation over western equatorial Pangea: Insights from pedogenic mineral $\delta^{18}O$ compositions

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## ABSTRACT

**The $\delta^{18}O$ values of pedogenic calcites, phyllosilicates, and iron (oxyhydr)oxides from fossil soils throughout the southwestern United States show systematic paleolatitudinal and temporal trends that indicate a significant change in soil moisture conditions and atmospheric circulation patterns over southwestern Euramerica throughout latest Pennsylvanian and Early Permian time. A progressive depletion of as much as 6‰ in mineral $^{18}O$ values with increasing distance northward (to 10°) of the paleoequator indicates a weakening or disruption of zonal easterly flow over the study area by latest Pennsylvanian time. Furthermore, elevated $\delta^{18}O$ values suggest a proximal source of paleoprecipitation over the study area, perhaps due to initiation of reversed equatorial flow over tropical southwestern Euramerica. Coupling of the geographic and temporal trends defined by pedogenic mineral $\delta^{18}O$ values with those defined by climatically sensitive paleosol pedotypes in the study area, along with overall elevated mineral $\delta^{18}O$ values, provides some of the strongest evidence that Northern Hemisphere monsoonal circulation was well established over Pangea by Early Permian time.**

**Keywords:** paleosols, oxygen isotopes, atmospheric circulation, Permian, monsoon.

## INTRODUCTION

Late Paleozoic construction of Pangea is thought to have profoundly altered atmospheric circulation over tropical regions, given the effects of orogenic belts and large land masses on wind patterns (Rowley et al., 1985; Kutzbach and Gallimore, 1989; Patzkowski et al., 1991; Parrish, 1993). Pennsylvanian to Early Permian uplift of the Himalayan-scale Allegheny and Ouachita Mountains in equatorial Pangea likely disrupted westward flow in the Intertropical Convergence Zone, creating a rain shadow on the lee side of the highlands (Fig. 1). If hypothesized large-scale monsoonal circulation developed over Pangea's Northern Hemisphere in the late Paleozoic, moist tropical air masses would have been diverted away from the equator toward mid-latitude regions (Fig. 1; Kutzbach and Gallimore, 1989; Parrish, 1993). In addition, receding epeiric seaways along western equatorial Pangea during Early Permian time would have significantly diminished any regional moisture sources in that area (Ziegler et al., 2002). In response to these shifts in large-scale atmospheric circulation and moisture availability, climate in the tropics—and western equatorial Pangea in particular (Parrish, 1993)—would have become progressively more dry throughout the late Paleozoic.

The shift away from a tropical ever-wet climate to drier conditions at equatorial latitudes (10°N–10°S) predicted by these climate models is recorded by the low-latitude distribution of Permian–Pennsylvanian geologic (e.g., coals, red beds, eolian deposits, evaporites, and fossil soils) and paleobotanical climate indicators (Parrish, 1993; Rees et al., 2002; Ziegler et al., 2002). This long-term aridification trend and its relationship to shifts in atmospheric circulation, proximity to moisture source, and changes in isotopic composition of paleoprecipitation should also be recorded by the stable isotopic composition of minerals that formed in fossil soils throughout western equatorial Pangea (cf. Amundson et al., 1996; Stern et al., 1997; Yapp, 2000; Deutz et al., 2001; White et al., 2001). To date, however, stable isotopic proxy records of late Paleozoic paleoprecipitation and atmospheric circulation over Pangean low latitudes have not been developed.

In this paper we use the geographic distribution of the $\delta^{18}O$ values of calcites, phyllosilicates, and Fe-(oxyhydr)oxides that formed in fossil soils (paleosols) across western equatorial Pangea to test the shifts in atmospheric circulation predicted by climate models. Our results indicate a strong component of reversed equatorial flow (i.e., winds coming from the west) over the tropics during the late Paleozoic, a component only recently predicted by Early Permian climate models (Gibbs et al., 2002). The isotopic proxy records, when integrated with the geographic and temporal distribution of paleosol pedotypes throughout the study area, suggest that monsoonal atmospheric circulation was well established over the Pangean Northern Hemisphere by Early Permian time.

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## METHODS

Calcite, phyllosilicate, and Fe-oxide samples were collected from paleosols within latest Pennsylvanian (Virgilian) through Early Permian (Wolfcampian and Leonardian) terrestrial successions in Utah, New Mexico, Arizona, Colorado, Texas, and Oklahoma. Micritic calcite exhibiting pedogenic micromorphologies (Brewer, 1964) and no evidence of secondary dissolution and reprecipitation (cf. Deutz et al., 2001) were microsampled for isotopic analysis. Pedogenic phyllosilicates were isolated from bulk paleosol matrix using physical and chemical separation techniques (discussed in Tabor et al., 2002). Fe-oxides from permineralized hematite and goethite root and branch axes were chemically pretreated to remove contaminants and analyzed for pure oxygen isotope endmember oxyhydroxides following the mass-balance method of Yapp (2000). Oxygen of phyllosilicates and Fe-oxides was extracted for isotope analysis following the method of Clay-

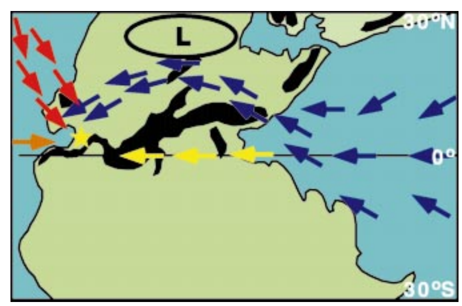


**Figure 1. Paleogeographic reconstruction of late Pennsylvanian–Early Permian Pangea (30°N–30°S). Light blue—ocean and inland seas; light green—land; black—major late Paleozoic highlands (>1000 m); star represents location of Texas study area. Blue arrows represent monsoonal atmospheric circulation proposed for this time period, whereas yellow arrows represent undisturbed zonal easterly flow in Intertropical Convergence Zone (Parrish, 1993; Rowley et al., 1985). Red arrows represent possible northwesterly extension of westerlies (Otto-Bliesner, 1998). Orange arrow indicates superimposed regional-scale, westerly circulation over Midland Basin proposed by this study.**

ton and Mayeda (1963) at Southern Methodist University with an analytical uncertainty, based on replicate analyses of samples and quartz standard NBS 28, of ±0.2‰, whereas oxygen of pedogenic calcites was extracted following the methods of Tabor et al. (2002) at the University of California, Davis, with an analytical uncertainty, based on replicate analyses of samples and calcite standard NBS 19, of ±0.2‰.

## ISOTOPIC RELATION BETWEEN PRECIPITATION AND PEDOGENIC MINERALS

The $\delta^{18}O$ values of pedogenic minerals can be used to define changes in the $\delta^{18}O$ composition of paleoprecipitation ($\delta^{18}O_{precip}$) and in atmospheric circulation given three main factors: (1) pedogenic minerals form in oxygen isotope equilibrium with soil water (Cerling and Quade, 1993; Yapp, 1993, 2000; Savin and Hsieh, 1998; Hsieh et al., 1998); (2) the $\delta^{18}O$ values of pedogenic minerals and meteoric precipitation are strongly correlated (Lawrence and Taylor, 1971; Cerling and Quade, 1993; Amundson et al., 1996; Savin and Hsieh, 1998); and (3) precipitation $\delta^{18}O$ relations have been shown to be correlated with atmospheric circulation patterns and air-mass rainout history (Rozanski et al., 1993; Amundson et al., 1996).

In general, the $\delta^{18}O$ values of pedogenic calcite record the $\delta^{18}O$ composition of soil water during the dry season (Quade et al., 1989), whereas the $\delta^{18}O$ values of pedogenic phyllosilicates and Fe-oxides record the $\delta^{18}O$ composition of soil water during the wetter part of the year (Hsieh and Yapp, 1999; Stern et al., 1997). Soil processes such as evapotranspiration and mixing of precipitation with antecedent moisture, especially in the upper portions of soil profiles, however, may modify the $\delta^{18}O$ composition of soil water from that of local precipitation (Hsieh et al., 1998; Savin and Hsieh, 1998). Pedogenic mineral $\delta^{18}O$ values, in particular carbonates from semiarid to arid regions, thus may be enriched relative to mean $\delta^{18}O_{precip}$ (Quade et al., 1989; Stern et al., 1997; Deutz et al., 2001). Studies of pedogenic carbonates in semiarid regions, however, have documented that calcite $^{18}O$ values generally reflect $\delta^{18}O_{precip}$ values and record temporal changes in paleoprecipitation $\delta^{18}O$ compositions (Amundson et al., 1996; Deutz et al., 2001).

## RESULTS

The $\delta^{18}O$ values of latest Pennsylvanian (Virgilian) through Early Permian pedogenic calcites, phyllosilicates, and Fe-oxides exhibit consistent geographic trends (Fig. 2). The $\delta^{18}O$ values of earliest Early Permian (Wolfcampian) pedogenic calcites show a progressive depletion of as much as 6‰ (−1.2‰ ± 2‰ at 0° to −7.8‰ ± 0.9‰ at ~8°N) with increasing distance northward from the paleoequator (Fig. 2A). Geographic trends cannot be evaluated in the $\delta^{18}O$ values of Leonardian calcites given their restriction to equatorial paleolatitudes.

The $\delta^{18}O$ values of latest Pennsylvanian through early Early Permian (Wolfcampian) pedogenic phyllosilicates and Fe-oxides exhibit a geographic trend of decreasing values (4‰ and 3‰, respectively) over an ~5° range of paleolatitude northward from the equator, similar to that defined by calcite $\delta^{18}O$ values (Figs. 2B and 2C). The $\delta^{18}O$ values of Leonardian phyllosilicates and Fe-oxides come from paleoequatorial sites, and overlap within analytical uncertainty. In addition to exhibiting geographic trends, the $\delta^{18}O$ values of all three pedogenic minerals from paleoequatorial sites show a temporal trend of increasing values (from 0.7‰ to 1.5‰) from the latest Pennsylvanian through to the Early Permian.

Measured pedogenic mineral $\delta^{18}O$ values are considered to record soil water conditions, and in turn mean $\delta^{18}O_{precip}$, during their formation in Permian–Pennsylvanian soils. This assumption is reasonable, given the low-grade diagenetic history of the studied paleosols (e.g., Ruppel and Hovorka, 1995) and the preservation of clay mineralogical trends in the studied paleosols analogous to those observed in modern weathering profiles (Tabor et al., 2002). Moreover, pedogenic minerals were sampled systematically from paleoprofiles in order to minimize the effects of environmentally induced fractionation on $\delta^{18}O_{soil\ water}$ compositions (see Deutz et al., 2001), and to maximize the analysis of purely pedogenic fractions (i.e., sampling of noncarbonate minerals from paleosol Bt horizons). In this paper we use the measured $\delta^{18}O$ values of pedogenic minerals from the paleosols to infer relative changes in $\delta^{18}O_{soil\ water}$ and paleo-$\delta^{18}O_{precip}$ throughout the study area rather than to estimate absolute shifts in paleo-$\delta^{18}O_{precip}$. This approach minimizes the potential for erroneous estimates of paleo-$\delta^{18}O_{precip}$ due to the effects of environmental modification of $\delta^{18}O_{soil\ water}$ compositions and the large uncertainties of temperatures of mineral formation.

## ATMOSPHERIC CIRCULATION OVER WESTERN EQUATORIAL PANGEA

The magnitude of the paleogeographic trend in $\delta^{18}O$ values of pedogenic calcites, phyllosilicates, and Fe-oxides, and the inferred latitudinal trend in paleo-$\delta^{18}O_{precip}$ could be interpreted to record latitudinal temperature gradients (cf. Fricke and O'Neil, 1999) during the latest Pennsylvanian through earliest Early Permian (Wolfcampian). Paleomagnetic reconstructions, however, indicate that the study area remained within the tropics throughout this time period (Scotese, 1984; M. Steiner, 2000, personal commun.). Modern surface temperature gradients in the tropics are negligible, resulting in weak correlation between present-day $\delta^{18}O_{precip}$ and latitude within the tropical belt (Rozanski et al., 1993; Fricke and O'Neil, 1999). The latitudinal decrease in inferred $\delta^{18}O_{precip}$ thus is not consistent with zonal easterly flow over the western Pangean tropical belt (herein referred to as southwestern Euramerica), and requires weakening or disruption of zonal flow beginning sometime prior to the latest Pennsylvanian. Further evidence for deviation from zonal flow over the study area is the significantly more positive $\delta^{18}O$ values of the pedogenic carbonates ($\delta^{18}O$: −7.8‰ to +0.5‰), phyllosilicates ($\delta^{18}O$: +16.4‰ to +22.1‰), and Fe-oxides ($\delta^{18}O$: −0.4‰ to 1.8‰) that formed at paleoequatorial latitudes than would be anticipated for minerals that formed from meteoric waters with an eastern Tethyan water vapor source. Rather, measured $\delta^{18}O$ values overlap with those of modern pedogenic minerals ($\delta^{18}O$ of ~+14‰ to +24‰) that form in tropical island or coastal zone soils from locally derived precipitation that has undergone a low degree of rainout (Lawrence and Taylor, 1971; Cerling and Quade, 1993).

The source of this disruption in zonal flow could have been uplift of equatorial highlands or the onset of Northern Hemisphere monsoonal circulation, both of which have been inferred for the origin of the long-term aridification trend defined by depositional and paleontologic proxies from low-latitude Pangea. If an Intertropical Convergence Zone (ITCZ) existed over the Pangean supercontinent, then uplift of the Alleghenian and Ouachita Mountains at equatorial latitudes (Fig. 1) in the Pennsylvanian through Early Permian would have weakened zonal flow and created a rain-shadow effect in southwestern Euramerica. The tropical latitudes of southwestern Euramerica would have received lower levels of annual precipitation due to rainout on the eastern slopes of the highlands. The $\delta^{18}O_{precip}$ in the tropical Pangean rain shadow would have become $^{18}O$ depleted as the highlands were uplifted, analogous to the present-day western Andean rain shadow, where $\delta^{18}O_{precip}$ is 10‰–18‰ depleted compared to the Atlantic Ocean source.

Development of monsoonal circulation in the late Paleozoic would have created large low-pressure thermal cells over Pangean mid-latitudes that in turn would have diverted moist tropical air masses of the ITCZ away from the equator (Fig. 1). Similar to the effects of a tropical western Pangean rain shadow on paleoprecipitation, rainfall levels and $\delta^{18}O_{precip}$ in the study region would have decreased significantly due to intense rainout

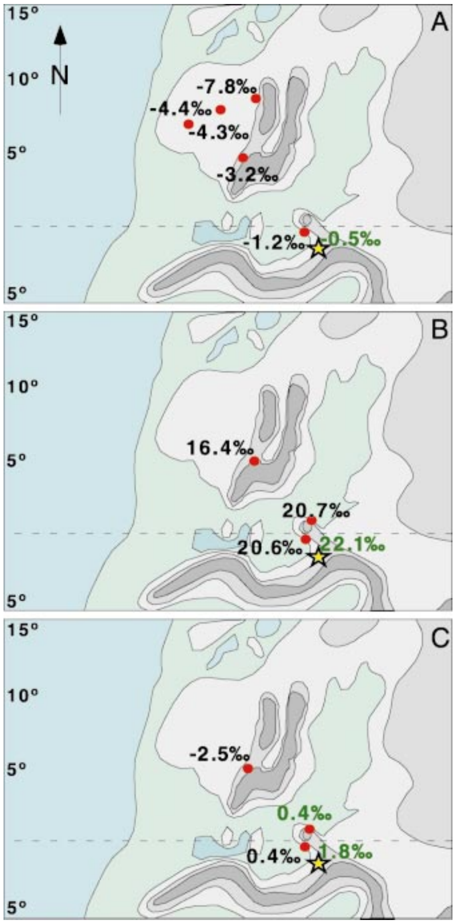


**Figure 2. Oxygen isotopic composition of pedogenic calcite (A), phyllosilicates (B), and Fe-oxyhydroxides (C) from Permian–Pennsylvanian strata of southwestern United States. Isotope data are plotted on paleogeographic base maps of Ziegler et al. (1996). Locations of study areas are shown by red dots. Data in black are latest Virgilian and Wolfcampian, data in green are Leonardian. Calcite $\delta^{18}O$ values are relative to Vienna Peedee belemnite, and phyllosilicate and Fe-oxyhydroxide $\delta^{18}O$ values are relative to Vienna standard mean ocean water. Panthalassan ocean and deep-water basins are darker blue; inland seas (Delaware, Midland, and Paradox) are lighter blue areas west of study area, whereas light, medium, and dark gray areas are emergent coastal (<200 m), upland (200–1000 m), and mountain (1000–2000 m) regions, respectively, within study area. Yellow star represents approximate location of Dallas, Texas. A–C in Figures 2 and 3 show fixed position of epeiric seaways: seaways receded during Permian–Pennsylvanian and contributed, at least in part, to regional dryness (Ziegler et al., 2002).**

upon the eastern and interior continental regions (Parrish, 1993). Notably, the $^{18}O$-depleted precipitation values called upon by these two circulation models are in sharp contrast to the more positive paleo-$\delta^{18}O_{precip}$ ($\sim -0.5$‰ to $-5.5$‰ at 25 °C) inferred from the most equatorial paleosol mineral $\delta^{18}O$ values (Fig. 2).

Rather, the pedogenic mineral $\delta^{18}O$ values from paleoequatorial latitudes of southwestern Euramerica indicate a more proximal source for precipitation than the Tethys ocean. The western Panthalassan ocean or the inland seas along western tropical Pangea (Midland and Delaware Basins; Figs. 1 and 2) could have provided proximal water vapor sources that would have undergone limited rainout prior to delivery to the study region. This proposed scenario, however, requires that reversed equatorial flow developed over southwestern Euramerica. Numeric and lithology-based climate models (e.g., Parrish, 1993; Kutzbach and Gallimore, 1989) for Pangea have generally indicated that easterly air flow in the tropical belt remained intact until monsoonal circulation strengthened in the Middle to Late Triassic, given the lack of sufficient pull created by late Paleozoic low-pressure zones to initiate westerly flow. Reversed equatorial flow in the Permian and draw of moisture from western sources, however, may have been facilitated by the low-pressure zones created by uplift of air masses over the equatorial highlands (Rowley et al., 1985; Otto-Bliesner, 1998; Gibbs et al., 2002).

In the context of the previously discussed models of atmospheric circulation over southwestern Euramerica, the latitudinal decrease in $\delta^{18}O_{precip}$ inferred from pedogenic mineral $\delta^{18}O$ values could record several influences. Meridional flow initiated at the equator could have developed in response to weakened zonal easterly flow, leading to progressive downflow depletion in $\delta^{18}O_{precip}$. Alternatively, the observed latitudinal trend could record the influence on northern study sites of precipitation from different sources, e.g., an increased contribution of isotopically depleted rainfall and a decreased contribution from less isotopically depleted, more proximal western sources. The $^{18}O$-depleted precipitation could have been delivered to the northern parts of the study area by the descending arm of a summer monsoonal circulation system or through capture of the westerly jet stream moving in to fill the vacuum produced over the tropical highlands. Pedogenic mineral $\delta^{18}O$ values cannot be used to distinguish unequivocally between these influences given the limits of their geographic distribution.

The pedogenic mineral $\delta^{18}O$ values, when coupled with the geographic distribution of paleosol pedotypes in the study area, however, support the establishment of Northern Hemisphere monsoonal circulation by latest Pennsylvanian to Early Permian time. We have recognized eight pedotypes that have paleoclimatic significance based on the macromorphologic and micromorphologic characteristics and chemical indices of Permian–Pennsylvanian paleosols in the southwestern United States. Trends in the geograph-

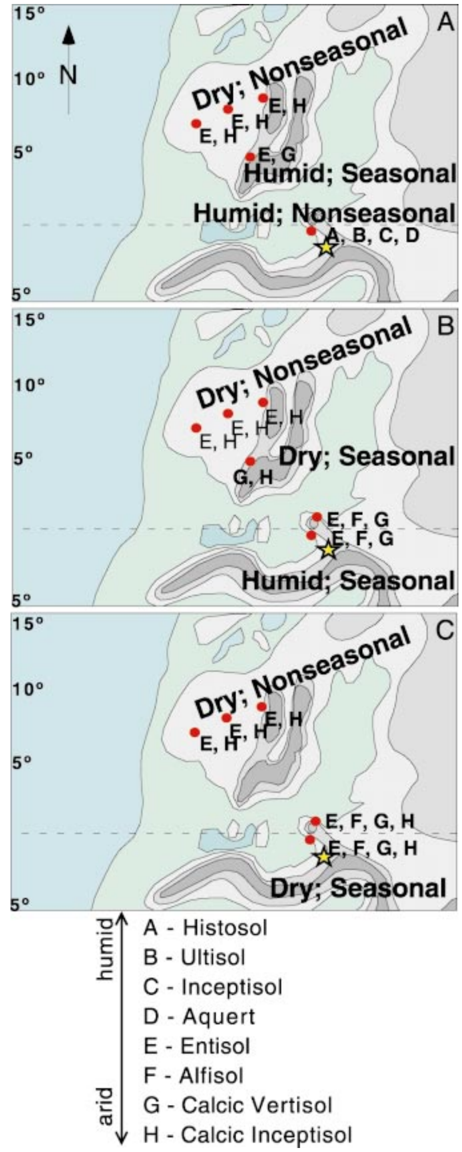


**Figure 3. Distribution of pedotypes from Upper Pennsylvanian, Virgilian (A), Lower Permian, Wolfcampian (B), and Lower Permian, Leonardian (C) terrestrial successions of study area. Pedotypes define range of soil moisture conditions, and by inference, regional climate conditions. See Figure 2.**

ic and temporal distribution of these pedotypes throughout the study area (Fig. 3) indicate a shift from wet seasonal climates in the latest Pennsylvanian to increasingly more seasonal and dry climatic conditions throughout Early Permian time for paleoequatorial latitudes. Paleosols record increasingly drier conditions and progressively decreased seasonality toward northern sites in western equatorial Pangea (Fig. 3). In addition to the effects of receding epeiric seas during Early Permian time (Ziegler et al., 2002), these trends are also anticipated for monsoonal circulation. The pedogenic mineral $\delta^{18}O$ proxy for reversed equatorial flow over the tropical belt of southwestern Euramerica, in conjunction with the pedotype distribution, provides some of the strongest evidence for monsoonal circulation being well established over the Pangean Northern Hemisphere by latest Pennsylvanian–Early Permian time (Parrish and Peterson, 1988).

The observed temporal increase in pedogenic mineral $\delta^{18}O$ values from paleoequatorial sites could be interpreted as increases in mean surface temperatures between 1.5 and 3 °C from latest Pennsylvanian to Early Permian time. Global warming, however, would likely have led to increased atmospheric water vapor budgets in the tropics and thus increased global mean precipitation. A consequent decrease in $\delta^{18}O_{precip}$ (Dansgaard, 1964) and pedogenic mineral $\delta^{18}O$ values at tropical sites is not supported by the observed temporal $\delta^{18}O$ trend. It is possible that the observed increase in mineral $\delta^{18}O$ values records increased evaporation-induced fractionation of soil waters in response to increasingly drier conditions, perhaps associated with global warming. Given the relationship between modern precipitation amount and $\delta^{18}O_{precip}$ in coastal settings (a 2‰ change per 100 mm change per month; Dansgaard, 1964), an ~75 mm/month decrease in rainfall can be inferred from the temporal increase of 0.7‰ recorded by pedogenic carbonates, which formed in paleosols during periods of low precipitation, and a 1.5‰ increase in phyllosilicates and Fe-oxides, which formed under higher soil moisture conditions. This estimated decrease in rainfall is entirely consistent with the observed temporal distribution of paleosol types (Fig. 3), which indicates a trend toward drier, more arid conditions during Early Permian time (Ziegler et al., 2002).

## ACKNOWLEDGMENTS

We are indebted to the following people for providing an introduction and stratigraphic and paleoecologic framework for the field areas: William DiMichele and Dan Chaney, Department of Paleobiology, Museum of Natural History, Smithsonian Institution; Greg Mack, New Mexico State University; and Douglas D. Ekart, Energy and Geoscience Institute, University of Utah. This research was supported by Grants-in-Aid to Tabor from the Geological Society of America, American Association of Petroleum Geologists, Society for Sedimentary Geology (SEPM), and Sigma Xi, as well as National Science Foundation grant EAR-9814640 to Montañez. We thank David Fastovsky, Gregory Retallack, and Alfred Ziegler for constructive reviews of this manuscript.

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Manuscript received May 16, 2002
Revised manuscript received August 27, 2002
Manuscript accepted September 4, 2002

Printed in USA