FORUM

Eocene continental climates and latitudinal temperature gradients: Comment and Reply

COMMENT

Gregory J. Jordan
*Department of Plant Science, University of Tasmania,
G.P.O. Box 252C, Hobart, Tasmania 7001, Australia*

Greenwood and Wing's (1995) use of leaf physiognomy to show relatively equable high-latitude continental climates during the Eocene is invalid because their method is based on a circular argument. Their physiognomic arguments can be logically reduced to using the assumption that the modern and Eocene relationships between mean annual temperature (MAT) and cold month mean temperature (CMMT) were the same to show that these relationships were much the same. My argument is as follows:

(1) Greenwood and Wing (1995) attempted to predict both MAT and CMMT from the same data.

(2) It is reasonable to assume that MAT is much more likely to be a primary determinant of physiognomy than CMMT. MAT ($r^2 = 0.89$) has a highly significantly stronger relationship ($p \approx 0.001$ using a bootstrap analysis) with physiognomy than CMMT ($r^2 = 0.79$) in the CLAMP data set (Wolfe, 1993) on which the models were based.

(3) MAT and CMMT are strongly correlated ($r^2 = 0.84$) in the CLAMP data base. This correlation means that it is possible to make predictions of modern CMMT from the CLAMP data set, even if there is no independent information about CMMT. This is equivalent to predicting MAT, then predicting CMMT from these predictions. Modern CMMT can, in fact, be predicted within the CLAMP data set from the predictions of MAT ($r^2 = 0.783$).

(4) The physiognomic models of Wing and Greenwood (1993) used by Greenwood and Wing (1995) do not in fact extract independent information about mean annual temperature (MAT) and cold month mean temperature (CMMT) because one cannot predict CMMT more accurately from the physiognomy than from the estimate of MAT. The physiognomic models predict CMMT to almost exactly the same accuracy ($r^2 = 0.791$) as regression on the estimated MAT. This difference is unlikely to be significant ($p \approx 0.8$, using a bootstrap analysis as in point 1). Also analysis of Wolfe's (1993) physiognomic ordination space based on the same data suggests that there is no useable independent information about CMMT independent of MAT. If the space is rotated so that one axis matches the vector of best fit for MAT, and CMMT is predicted on the physiognomy excluding this MAT axis, then there is no significant relationship between CMMT and the physiognomy.

(5) Because there is no independent information about equability, the models cannot predict CMMT unless the correlation between MAT and CMMT is constant. The results of the general circulation models (Sloan and Barron, 1992, Sloan, 1994) discussed by Greenwood and Wing (1995) imply that the relationship between MAT and CMMT was different in the past. Using Wing and Greenwood's (1993) models to prove that this is untrue is circular, because these models assume that the relationships between MAT and CMMT were the same in the Eocene as they are now.

The presence of many sites from the Eocene with similar "predictions" of CMMT does not strengthen Greenwood and Wing's (1995) argument, because the errors are systematic: Similar predictions of MAT will always lead to similar estimates of CMMT because the predicted CMMT is based on the predicted MAT.

Other problems associated with the predictions of equability include the unknown effects of photoperiod and other factors on physiognomy. All this means that the only new evidence for equability presented by Greenwood and Wing (1995) is the presence of palms. The actions of extinction and evolution mean that the use of a single taxon in a nearest living relative approach is a perilous approach to paleoclimate.

REFERENCES CITED
Greenwood, D. G., and Wing, S. L., 1995, Eocene continental climates and latitudinal temperature gradients: Geology, v. 23, p. 1044–1048.
Sloan, L. C., 1994, Equable climates during the early Eocene: Significance of regional paleogeography for North American climate: Geology, v. 22, p. 881–884.
Sloan, L. C., and Barron, E. J., 1992, A comparison of Eocene climate models to quantified paleoclimatic interpretations: Palaeogeograpy, Palaeoclimatology, Palaeoecology, v. 93, p. 183–202.
Wing, S. L., and Greenwood, D. R., 1993, Fossils and fossil climates: The case for equable continental interiors in the Eocene: Philosophical Transactions of the Royal Society of London Series B, v. 341, p. 243–252.
Wolfe, J. A., 1993, A method of obtaining climatic parameters from leaf assemblages: U.S. Geological Survey Bulletin 2041, 71 p.

REPLY

Scott L. Wing
Department of Paleobiology, NHB121, Smithsonian Institution, Washington, D.C. 20560
David Greenwood
Department of Environmental Management, Victoria University of Technology, P.O. Box 14428, M.M.C., Melbourne, Victoria 3000, Australia

We thank Jordan for pointing out that within the CLAMP data set of Wolfe (1993) there is no correlation of cold month mean temperature (CMMT) with physiognomy once the effects of mean annual temperature (MAT) have been removed. We agree with Jordan that predictions of paleo-CMMT based on physiognomy/climate correlations in the CLAMP data set presume the same relationship between MAT and CMMT in the past as in the present.

Although Jordan has made a useful statistical point, this in no way changes the nature of the geological and paleoclimatological problem we addressed (Greenwood and Wing, 1995). The "problem" is to explain the overwhelming paleontological evidence for warm winter conditions at high latitudes and in continental interiors at middle latitudes during the Eocene. As Jordan has pointed out, our estimates of Eocene CMMT were based on the implicit assumption that CMMT and MAT had the same relationship in the Eocene as in the present. As there is little dispute that polar ice caps and mid-latitude temperature seasonality are more developed now than in the Eocene, our estimates of CMMT for the Eocene are almost certainly too low, a point which we made in our paper: "Particularly at high latitudes, nearest living relative–based minimums of the CMM[T] are probably more reliable than those based on physiognomy" (Greenwood and Wing, 1995, p. 1045). If our statistical procedure led to underestimates of Eocene CMMT, then Eocene climates were likely even more equable than we suggested, and the need for an explanation is that much greater.

Jordan is incorrect in stating that we used a single taxon in our floristic approach; we used the distribution of cycads, gingers, and tree ferns in addition to that of palms. Furthermore, as we pointed out in our paper, extant tribes and probably genera of palms were present by the Eocene. In order for an extant group of palms to have had highly frost-tolerant Eocene species, one would have to propose the evolution of physiological mechanisms of frost tolerance within some sublineages of the group during the globally warm early Cenozoic, then the preferential extinction of those cold-hardy sublineages during the cooler and more seasonal late Cenozoic. This improbable and ad hoc explanation would have to be invoked independently for each of the extant groups of palms present at

middle to high latitudes in the Eocene, minimally the tribes Lepi-docaryoideae, Arecoideae, Nypoideae, Caryotoideae, and Cory-phoideae, and possibly as many as ten extant genera. (See Daghlian, 1981, for a review of the fossil record of palms.) Although it is well known that paleoclimatic inferences based on relictual or undiverse living taxa can be misleading (e.g., Wolfe, 1979), this is not the case with palms.

In sum, although the relationships between physiognomy and CMMT observed in the CLAMP data set probably should not be used to make quantitative estimates of paleo-CMMT, the distribu-tion of palms and other frost-sensitive plant and animal taxa pro-vides many independent lines of strong evidence that middle and high latitude temperature minimums in the Eocene were much warmer than at present, and that temperatures far below freezing were either absent, or confined to as yet unsampled parts of high-latitude continental interiors. These observations require climato-logical explanation.

REFERENCES CITED

Daghlian, C. P., 1981, A review of the fossil record of Monocotyledons: The Botanical Review, v. 47, p. 517–555.
Greenwood, D. R., and Wing, S. L., 1995, Eocene continental climates and latitudinal temperature gradients: Geology, v. 23, p. 1044–1048.
Wolfe, J. A., 1979, Temperature parameters of humid to mesic forests of eastern Asia and relation to forests of other regions of the Northern Hemisphere and Australasia: U.S. Geological Survey Professional Paper 1106, 37 p.
Wolfe, J. A., 1993, A method of obtaining climatic parameters from leaf assemblages: U.S. Geological Survey Bulletin 2040, p. 1–71.

Early Precambrian gneiss terranes and Pan-African island arcs in Yemen: Crustal accretion of the eastern Arabian shield

COMMENT

Peter R. Johnson
U.S. Geological Survey Mission, PO Box 1488, Jiddah 21431, Saudi Arabia
I. C. F. Stewart
BOX 1352, Saudi Aramco, Dhahran 31311, Saudi Arabia

Windley et al. (1996) supplied critical information for ongoing terrane analysis in the Arabian-Nubian shield, but their correlation of two terranes in Yemen with the Afif and Ar Rayn terranes in Saudi Arabia and their use of the name *Nabitah suture* for the fault zone between two of the terranes is premature because of problems about some key tectonic relations in Saudi Arabia. The Nabitah suture is named after the ultramafic-decorated Nabitah fault, which all workers in the region map south to about 18°N (Fig. 1). It has not been mapped farther south either because the fault changes char-acter or because it is absent in a large segment of plutonic rocks comprising the Tarib batholith. In Saudi Arabia it is difficult to establish that the fault truly represents a suture, that is, separates crustal units marked by different geologic histories. On the one hand, amphibolite-grade metamorphic assemblages (Simons, 1985) and somewhat evolved lead isotopes (Stoeser and Stacey, 1988) are present in rocks east of the fault in contrast to greenschist facies and oceanic leads west of the fault, whereas north-striking bedding and north-trending gently plunging lineations characterize the rocks on either side of the fault, suggesting that the rocks do not have dif-ferent deformation histories.

Correlation of the Afif terrane with rocks in Yemen is prob-lematic because the location of the terrane in southern Saudi Arabia is uncertain. The terrane may extend south of the Mulhah fault (Fig. 1) along the eastern side of the Asharah fault (Stoeser and Stacey, 1988), an interpretation that is attractive because the Asharah fault is on line with the suture located between Hajjah and Sada in Yemen. However, detailed mapping indicates that the Asharah fault separates stratigraphically related rocks and is not a terrane boundary (Carten and Tayeb, 1989). Aeromagnetic data suggest that the Ar Rayn terrane is truncated southeast of the ex-posed shield by a strike-slip fault of the Najd system (Fig. 1) (John-son and Stewart, 1995). It is well known that the Najd fault system severely disrupts amalgamated terranes in the Saudi Arabian shield. Consequently, the extension of the Ar Rayn terrane into Yemen shown in Figure 1 in Windley et al. (1996), which necessitates cross-ing at least two Najd fault zones, requires further validation before it can be accepted.

Ambiguity about tectonic relations in the eastern part of the Saudi Arabian shield causes additional correlation problems. Wind-ley et al. (1996) summarized selected results indicating that the Abt schist belongs to a west-dipping subduction zone. This conclusion is doubtful because the polarity of the Suwaj arc, immediately west of the Abt schist (Fig. 1), is unknown and that of the Siham arc farther west was east dipping (Agar, 1985). Other workers relate the schist to a subduction zone dipping east beneath the Ar Rayn terrane (Stacey et al., 1984; Al-Shanti and Gass, 1983), a model supported by structural relations inferred from aeromagnetic data (Johnson and Stewart, 1995).
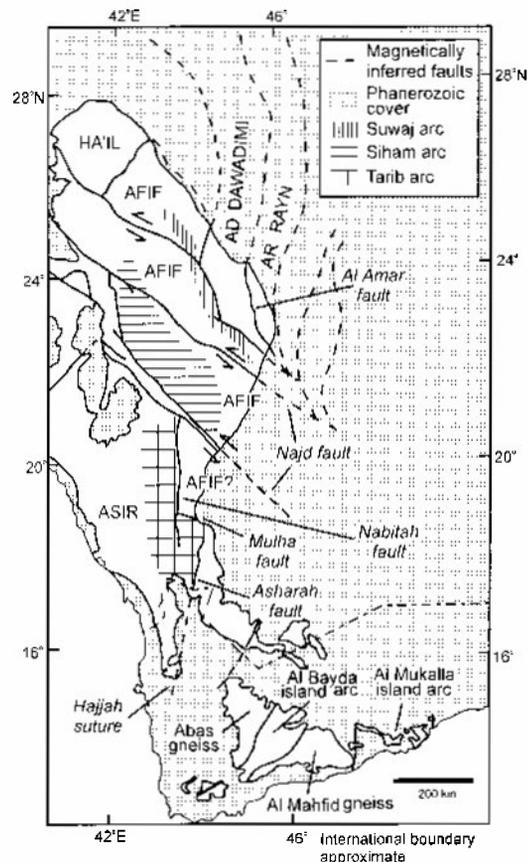

Figure 1. Map of Precambrian terranes in Saudi Arabia and Yemen. Yemeni data after Windley et al. (1996); Saudi terranes after Johnson et al. (1987); basement faults in central Arabia after Johnson and Stew-art (1995). Note queried identity of terrane east of the Nabitah fault—for reasons, see text.

REFERENCES CITED
Agar, R. A., 1985, Stratigraphy and paleogeography of the Siham group: Direct evidence for a late
Proterozoic continental microplate and active continental margin in the Saudi Arabian shield:
Journal of the Geological Society [London], v. 142, p. 1205–1220.
Al-Shanti, A. M., and Gass, I. G., 1983, The upper Proterozoic ophiolitic mélange zones of the
easternmost Arabian shield: Journal of the Geological Society [London], v. 140, p. 867–876.
Carten, R. B., and Tayeb, J., 1989, Geology of the Halahila mineral belt, southeast Asir, Kingdom of
Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Technical Record
USGS-TR-10-1, 76 p.
Johnson, P. R., and Stewart, I. C. F., 1995, Magnetically inferred basement structure in central Saudi
Arabia: Tectonophysics, v. 245, p. 37–52.
Johnson, P. R., Schneibner, E., and Smith, E. A., 1987, Basement fragments, accreted tectonostrat-
igraphic terranes, and overlap sequences: Elements in the tectonic evolution of the Arabian
shield: Washington, D.C., American Geophysical Union, Geodynamics Series, v. 19, p. 323–343.
Simons, F. S., 1985, Geologic map of the Wadi Bishah quadrangle, sheet 20F, Kingdom of Saudi
Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM 97,
scale 1:250 000.
Stacey, J. S., Stoeser, D. B., Greenwood, W. R., and Fisher, L. B., 1984, U-Pb geochronology and
geological evolution of the Halaban–Al Amar region of the eastern Arabian shield, Kingdom
of Saudi Arabia: Journal of the Geological Society [London], v. 141, p. 1043–1055.
Stoeser, D. B., and Stacey, J. S., 1988, Evolution, U-Pb geochronology, and isotope geology of the
Pan-African Nabitah orogenic belt of the Saudi Arabian shield, in El-Gaby, S., and Greiling,
R. O., ed., The Pan-African belt of Northeast Africa and adjacent areas: Braunschweig, Wies-
baden, Germany, Friedrich Vieweg and Sohn, p. 227–288.
Windley, B. F., Whitehouse, M. J., and Ba-Bttat, M. A. O., 1996, Early Precambrian gneiss terranes
and Pan-African island arcs in Yemen: Crustal accretion of the eastern Arabian shield: Geology,
v. 24, p. 131–134.

REPLY

Martin J. Whitehouse
Naturhistoriska Riksmuseet, Box 50007, S-104 05 Stockholm,
Sweden
Brian F. Windley
Department of Geology, University of Leicester, Leicester LE1 7RH,
United Kingdom
Mahfood A. O. Ba-Bttat
Arab Petroleum Services Company Ltd., P.O. Box 48, Aden, Yemen

We welcome the constructive comment by Johnson and Stewart on our terrane analysis of the Arabian Nubian shield in southern Saudi Arabia and Yemen (Windley et al., 1996), and we agree that long-distance correlation of terranes across areas of limited exposure and/or poor geologic characterization can be highly speculative. Their comments address a small part of our paper in which we propose correlation of two terranes in northwestern Yemen with possible counterparts in Saudi Arabia, and we address their points below.

In our paper (Windley et al., 1996), we argued that isotopic data on three newly delineated terranes in central southern Yemen (Abas, Al-Bayda, and Al-Mahfid) preclude their correlation with any of the continental terranes characterized in the eastern part of the Arabian Nubian shield in Saudi Arabia. Because these Yemen terranes lie approximately along north-south strike of the boundaries between terranes in Saudi Arabia, two correlation scenarios may be envisaged. Juxtaposition of Yemen terranes against those in Saudi Arabia might have taken place by strike-slip movement along presently undocumented faults belonging to the northwest-southeast–trending sinistral Najd system south of 18°N. This would place any possible southward extension of the Nabitah suture zone and the flanking Asir and Afif terranes farther to the east than proposed by Windley et al. (1996), but would not account for the consistent change in structural trend from north-south in Saudi Arabia to northeast-southwest in Yemen. Furthermore, this scenario would imply possible correlation of the Afif terrane of Saudi Arabia with one of the newly characterized terranes in Yemen, a correlation that is not supported by the isotopic data (Agar et al., 1992; Windley et al., 1996). Thus we prefer a regional change of strike of the terrane boundaries as suggested by the aeromagnetic data of Johnson and Stewart (1995). In this second scenario (Windley et al., 1996), terrane correlation into north-western Yemen is predicated upon the

identification of an inferred southward extension of the Nabitah suture and its flanking terranes.

Johnson and Stewart rightly point out that it is difficult to trace the Nabitah suture zone south of ca. 18°N because of the Tarib batholith and that considerable ambiguities exist in the interpretation of geological observations from southern Saudi Arabia that relate to the identification of the Asir and Afif terranes. Furthermore, they question interpretation of the Nabitah fault zone itself as a terrane suture. However, we consider that the contrast in metamorphic grade (Simons, 1985) and lead-isotopic signature (Stoeser and Stacey, 1988) across the fault in Saudi Arabia represents somewhat more convincing evidence in favour of a terrane boundary than the counter argument of Johnson and Stewart based upon a potentially coincidental structural similarity.

The documentation in Yemen of a major belt of ophiolites north-northeast of Sada (Michel et al., 1989) and the south-south-westerly continuation of this belt to Hajjah (Windley et al., 1996) is clear evidence for a major suture directly along strike of the Asharah fault of southern Saudi Arabia, which Quick (1991; not cited by Johnson and Stewart) marked as the boundary between Asir and Afif on the basis of the Pb-isotopic interpretation of Stoeser and Stacey (1988), and which therefore can be equated with the Nabitah suture. Unambiguous correlation of the suture identified in Yemen with the Nabitah suture of Saudi Arabia must of course rely upon further isotopic and geological characterization of the flanking terranes, but in the current absence of such studies, or the suggestion by Johnson and Stewart of an alternative terrane correlation, our original speculation appears reasonable and hopefully will stimulate such investigations.

We agree with Johnson and Stewart that correlation of the Ar Rayn terrane of Saudi Arabia with the Abas terrane of Yemen (Windley et al., 1996, Fig. 1), which is loosely based upon inferred structural trends derived from aeromagnetic data (Johnson and Stewart, 1995), is highly speculative. In our original paper, we point out that there are substantial differences in geology between these two terranes, which appear to preclude such a correlation.

Finally, Johnson and Stewart raise the question of subduction zone polarity in the Arabian Nubian shield. Windley et al. (1996) followed the interpretation of Quick (1991, and references therein) that the Abt schist belongs to a west-dipping subduction zone. We do not find the lack of evidence for subduction polarity in the Suwaq arc farther to the west to be a particularly compelling argument against this. Additionally, we have no problem accommodating this observation with that of eastward-directed subduction in the Siham arc (Agar, 1985) and point out that in any complex terrane accretion scenario, it is quite possible that opposite subduction polarities might be observed in different arcs (Hamilton, 1988).

REFERENCES CITED
Agar, R. A., 1985, Stratigraphy and paleogeography of the Siham group: Direct evidence for a Late
Proterozoic continental microplate and active continental margin in the Saudi Arabian shield:
Journal of the Geological Society [London], v. 142, p. 1205–1220.
Agar, R. A., Stacey, J. S., and Whitehouse, M. J., 1992, Evolution of the southern Afif terrane—A
geochronologic study: Jeddah, Saudi Arabia, Directorate General of Mineral Resources
Open-File Report DGMR-OF-10-15, 41 p.
Hamilton, W. B., 1988, Plate tectonics and island arcs: Geological Society of America Bulletin, v. 100,
p. 1503–1527.
Johnson, P. R., and Stewart, I. C. F., 1995, Magnetically inferred basement structure in central Saudi
Arabia: Tectonophysics, v. 245, p. 37–52.
Michel, J. C., Corp, J. C., Lescuyer, J. L., and Odent, B., 1989, Mineral master plan: France, Bureau
de Recherches Géologique et Minière, 540 p.
Quick, J. E., 1991, Late Proterozoic transpression of the Nabitah fault system—Implications for the
assembly of the Arabian Shield: Precambrian Research, v. 53, p. 119–147.
Simons, F. S., 1985, Geologic map of the Wadi Bishah quadrangle, sheet 20F, Kingdom of Saudi
Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM 97,
scale 1:250 000.
Stoeser, D. B., and Stacey, J. S., 1988, Evolution, U-Pb geochronology and isotope geology of the
Pan-African Nabitah orogenic belt of the Saudi Arabian shield, in El-Gaby, S., and Greiling,
R. O., eds., The Pan-African belt of northeast Africa and adjacent areas: Braunschweig, Wies-
baden, Germany, Friedrich Vieweg and Sohn, p. 227–288.
Windley, B. F., Whitehouse, M. J., Ba-Bttat, M. A. O., and Rex, D., 1996, Early Precambrian Gneiss
blocks and Pan-African island arcs in Yemen: Terrane accretion of the eastern Arabian shield:
Geology, v. 24, p. 131–134.