Reports

True Polar Wander since the Early Cretaceous

Abstract. *The motions of the lithospheric plates have been reconstructed for three time intervals back to the Early Cretaceous. These displacements were analyzed to determine the best-fitting rigid rotation, which could then be ascribed to true polar wander. The true polar wander so obtained is no larger than a few degrees and is within the magnitude of the uncertainties involved.*

The apparent polar wander paths observed for the lithospheric plates, that is, the movement of the magnetic pole relative to a plate assumed to be fixed, may be due to either or both of two causes: (i) the motion of the plate relative to a fixed magnetic dipole or (ii) the motion of the magnetic axis relative to the lithosphere as a whole. Moreover, since the magnetic axis is assumed to be, on the average, coincident with the spin axis, the second cause implies true polar wandering. It is commonly accepted that at least some of the differences in the apparent polar wander paths of different continents are due to the relative motions of the continents; on the other hand, it has been suggested (*1*) that the comparable lengths of the apparent polar wander paths of the individual continents imply a common cause, true polar wander.

A number of tests have been proposed and applied to separate these two effects. Two attempts were made (*2, 3*) on the assumption that certain points or areas on the globe, namely, the oceanic ridges (*2*) or Antarctica (*3*), were fixed with respect to the spin axis; in both cases, however, it has been argued (*4, 5*) that these assumptions are not justified and that the conclusions that true polar wander had occurred were, at least, ambiguous. In a later proposal McKenzie (*6*) suggested that a vector describing true polar wander could be found from the resultant of the area-weighted vectors representing the angular motion of the paleomagnetic poles for each of the plates. This technique was applied (*5*) for the time interval from the Early Tertiary to the present, and the conclusion was that there has been no significant polar wander.

This report presents the results of another approach to the problem. We have reconstructed the lithospheric plate positions for the Early Tertiary, Late Cretaceous, and Early Cretaceous, using dated marine magnetic anomalies to determine the relative plate positions, then using paleomagnetic poles to fix the position of the spin axis (assuming that the ancient geomagnetic field was, on the average, that of a geocentric, coaxial dipole). Knowing the plate positions at the present and at these earlier times, we were able to construct, for each of the three time intervals, a displacement field which describes the plate motions during an interval.

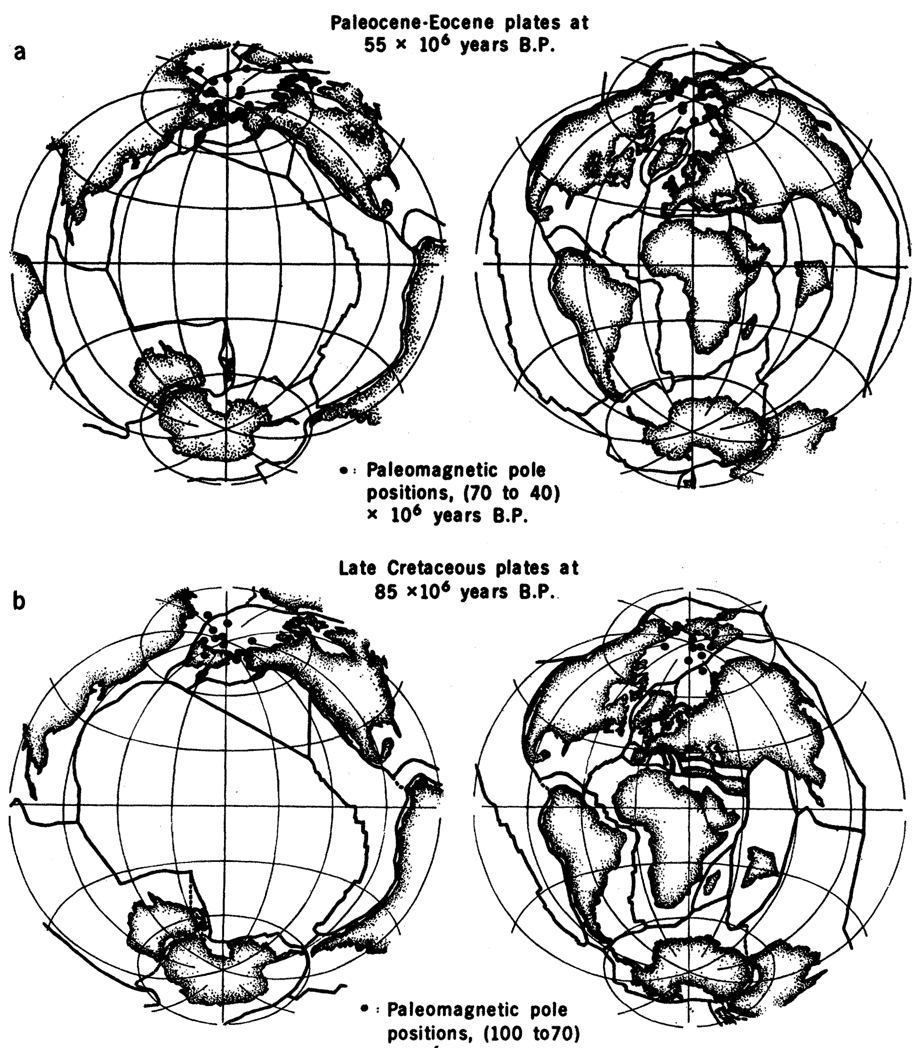

Fig. 1. (a) Paleogeographic map of the plates and plate boundaries for the Early Tertiary. The paleomagnetic poles used for the determination of the mean are plotted. The longitudes are arbitrary. (b) Paleogeographic map of the plates and plate boundaries for the Late Cretaceous. The paleomagnetic poles used for the determination of the mean are plotted. The longitudes are arbitrary.

Scoreboard for Reports: In the past few weeks the editors have received an average of 63 Reports per week and have accepted 11 (17 percent). We plan to accept about 10 reports per week for the next several weeks. In the selection of papers to be published we must deal with several factors: the number of good papers submitted, the number of accepted papers that have not yet been published, the balance of subjects, and length of individual papers.

Authors of Reports published in *Science* find that their results receive good attention from an interdisciplinary audience. Most contributors send us excellent papers that meet high scientific standards. We seek to publish papers on a wide range of subjects, but financial limitations restrict the number of Reports published to about 12 per week. Certain fields are overrepresented. In order to achieve better balance of content, the acceptance rate of items dealing with physical science will be greater than average.

True polar wander has been defined (7) as a bodily shift of the earth relative to its spin axis, and, if it had occurred, it would appear as a special kind of displacement field: a pure rigid rotation about some axis. If no relative motions between plates had occurred but such a rigid rotation of the lithosphere had taken place, it would be observed as true polar wander and the apparent polar wander paths of all continents would coincide. If, on the other hand, no true polar wander but only plate motions relative to each other had occurred, the apparent polar wander paths of different plates would diverge in the geologic past. Our method therefore can be best summarized as finding a best-fitting rotation of the entire lithosphere, and it is this rotation that we attribute to true polar wander. It is crucial for an understanding of our method to realize that in the case of no true polar wander a summation or integration of the displacements of all the plates over the entire surface of the earth would yield a zero global average. In more mathematical terms, such plate motions do not contribute to a first-degree displacement field (a rotation of the entire lithosphere) but instead make up the higher-degree displacement fields such as hemispherical twists or zonal rotations in which the motions are opposite to each other.

The past distributions of the plates are determined from data on sea-floor spreading and paleomagnetic poles. Magnetic anomalies and fracture zones provide information about the relative positions of two adjacent plates separated by a ridge. If either of these two plates can then be related by similar information to a third plate, all three areas are relatively positioned. One follows this procedure until all major regions on the earth are tied into a circuit, with one continent held temporarily fixed and the rest of the plates rotated relative to it. The next step is to provide a fixed reference frame. For this purpose, mean paleomagnetic pole positions were determined for groups of reliable individual poles that were rotated with their respective plates, for the time intervals of (40 to 70) $\times 10^6$, (70 to 100) $\times 10^6$, and (100 to 130) $\times 10^6$ years before the present (B.P.). The virtual paleomagnetic poles that were used to determine the means include a selection of reliable paleomagnetic poles (8) with additions for Australia, Antarctica, India, Madagascar, and the Pacific, and additions for some very recent publications (9). The clusters of poles for these time intervals were found to be tightly grouped for the reassembled plates, with relatively small cones of 95 percent confidence ranging between 4° and 6.5°.

A reconstruction of the major plates and plate boundaries for the Early Tertiary (55×10^6 years B.P.) is shown in Fig. 1a, and the reconstruction for the Late Cretaceous (85×10^6 years B.P.) is shown in Fig. 1b. The relative positions of the plates have been determined from published data (10, 11). The plate configurations before 85×10^6 years B.P. are less well established, in particular because of uncertainties in the positions of the Gondwana continents. Figure 2a is a reconstruction of the major plates and plate boundaries for the Early Cretaceous (115×10^6 years B.P.), with the southern continents approaching the fit of Smith and Hallam (10); Fig. 2b is a similar reconstruction except that the southern continents are approaching the positions favored in an alternate fit by Tarling (12). Active plate boundaries are shown as solid lines; incipient plate boundaries, which will become active within the next period, are shown as dashed lines.

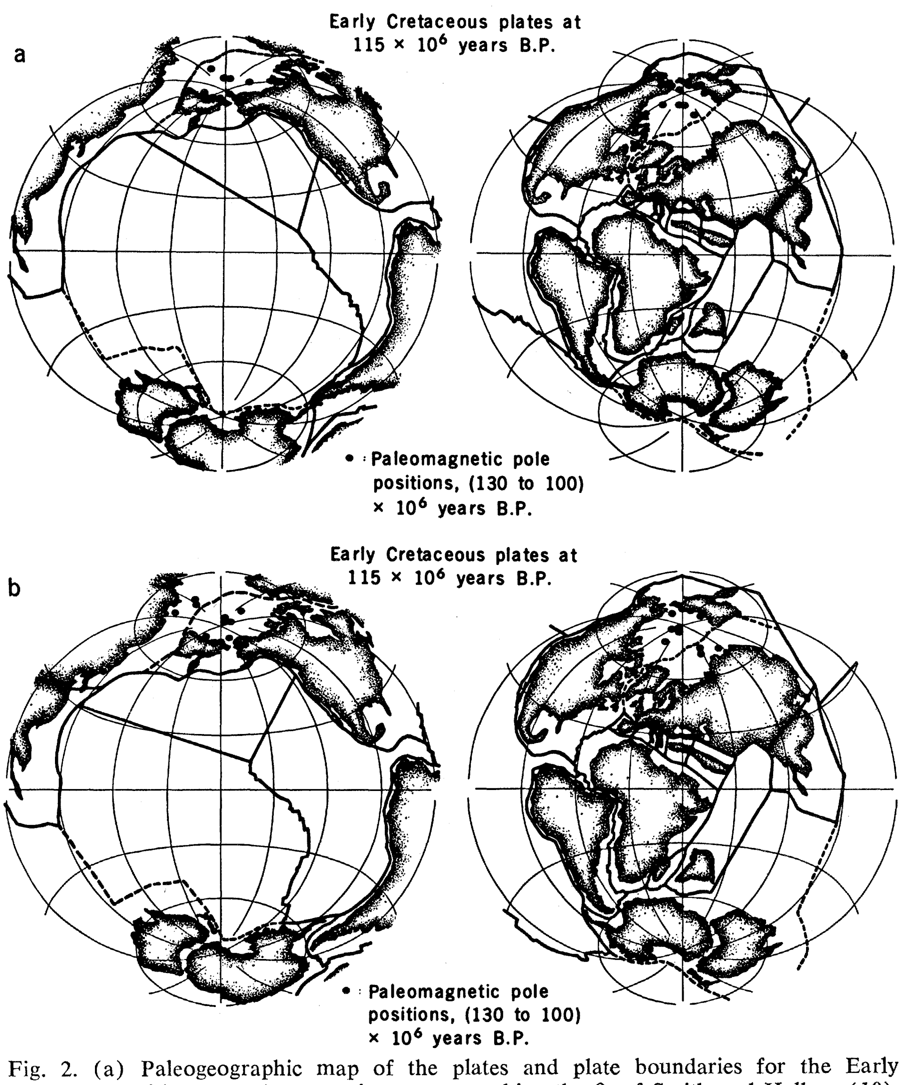

Fig. 2. (a) Paleogeographic map of the plates and plate boundaries for the Early Cretaceous, with the southern continents approaching the fit of Smith and Hallam (10). The paleomagnetic poles used in the determination of the mean are plotted. The longitudes are arbitrary. (b) Paleogeographic map of the plates and plate boundaries for the Early Cretaceous, with the southern continents approaching the fit of Tarling (12). The paleomagnetic poles used for the determination of the mean are plotted. The longitudes are arbitrary.

The plate configurations were evaluated in a coordinate framework fixed by the paleomagnetic data of the reassembled plates. The mean magnetic poles were used to fix the earth's polar axis and to define a Cartesian coordinate system in which latitudes but not longitudes can be determined. The axes lying in the equatorial plane thus must be positioned arbitrarily, and we chose to hold the longitudinal coordinates of North America more or less fixed. This

Table 1. Calculated amounts of true polar wander.

Time interval	Amount of polar wander	Direction relative to North America longitudes (*14*)
Present to 55 $\times 10^6$ years B.P.	2.0°	142°W
(55 to 85) $\times 10^6$ years B.P.	3.2°	177°W
(85 to 115) $\times 10^6$ years B.P.*	7.7°	11°W
(85 to 115) $\times 10^6$ years B.P.†	6.8°	32°W

* Smith and Hallam fit (*10*). † Tarling fit (*12*).

Table 2. Cumulative amounts of true polar wander.

Time interval	Amount of polar wander	Direction relative to North America longitudes (*14*)	α_{95}
Present to 55 $\times 10^6$ years B.P.	2.0°	142°W	4.1°
Present to 85 $\times 10^6$ years B.P.	5.0°	164°W	5.0°
Present to 115 $\times 10^6$ years B.P.*	4.9°	50°W	4.7°
Present to 115 $\times 10^6$ years B.P.†	6.3°	76°W	6.4°

* Smith and Hallam fit (*10*). † Tarling fit (*12*).

arbitrary positioning of the equatorial axes implies an indeterminacy in the longitudinal displacements and indeed allows a rigid rotation of the entire lithosphere. However, this is a rotation precisely about the polar axis and such a rotation is irrelevant for true polar wander, since it leaves the position of the magnetic polar axis relative to the lithosphere as a whole unchanged. Consequently, if we decompose a rigid rotation about a geocentric axis cutting a sphere at arbitrary latitude and longitude into three component rotations about each of the coordinate axes, respectively, we find that only rotations about the two equatorial axes will contribute to true polar wander and that the sum of the squares of these rotations is independent of the arbitrary positioning of the equatorial axes.

The plate reconstructions give us three time intervals over which the displacement field can be evaluated. We developed a mathematical method (*13*) to find the rigid rotation which best fits in a least-squares sense a set of general displacements on a sphere. For example, the change in position of any point on a plate between, say (55 and 85) $\times 10^6$ years B.P., may be defined by a displacement vector ($\bar{F}$), with $\bar{F}$ changing discontinuously at the plate boundaries. If we denote a rigid rotation, corresponding to true polar wander, as a displacement field ($\bar{G}$), we can determine how much of the observed displacement field $\bar{F}$ can be accounted for by a rigid rotation of the entire lithosphere $\bar{G}$, by minimizing the integral

$$(\bar{F} - \bar{G})^2\, ds$$

where ds is an element of surface, and the integration is done over the entire surface of the earth. Further mathematical details have been presented elsewhere (*13*).

The analysis of the displacement field for the three time intervals considered yielded very small rigid rotations $\bar{G}$, an indication of little or no true polar wander. The calculated values are presented in Table 1, where the amount of true polar wander is the length of arc along which the pole moves relative to the whole lithosphere, which is the same amount the lithosphere moves relative to a fixed pole. The cumulative polar wander, found by adding the motion over the time intervals, is given in Table 2, along with the uncertainties (α_{95}) in the mean paleomagnetic pole used for the plate reconstructions (Figs. 1 and 2).

The resultant polar wander is quite small, even over the entire time interval from the present to the Early Cretaceous. This is due to the differences in the direction of movement (Table 1) over the three time intervals. For the time intervals from the present to 55 $\times 10^6$ years B.P. and the present to 85 $\times 10^6$ years B.P., the calculated amounts of true polar wander were within the uncertainty of the mean paleomagnetic pole (Table 2) and thus must be considered insignificant. An analysis of the plate displacements for the earliest time interval considered, (85 to 115) $\times 10^6$ years B.P., was more ambiguous, as uncertainties exist in the positions of the southern continents for that interval. Still, for the longest time interval, from the present to 115 $\times 10^6$ years B.P., the amount of calculated true polar wander is less than the uncertainty in the mean paleomagnetic pole.

The same result was reached (*6*) when Tertiary paleomagnetic data from a majority of plates were analyzed by a different approach (*5, 6*). Our results extend the calculations of true polar wander to the Early Cretaceous. The primary requirement of our method (*13*) is a reliable displacement field all over the earth, including the oceans, since their role in determining the existence of polar wander is great because of their large area. When better Mesozoic sea-floor spreading data become available, it is conceivable that reliable determinations can also be carried out for the earlier Mesozoic periods.

D. M. Jurdy
R. Van der Voo
Department of Geology and Mineralogy, University of Michigan, Ann Arbor 48104

References and Notes

K. M. Creer, E. Irving, S. K. Runcorn, *Philos. Trans. R. Soc. Lond. Ser. A Math. Phys. Sci.* **250**, 144 (1957).
2. E. Irving and W. A. Robertson, *J. Geophys. Res.* **74**, 1026 (1969).
M. W. McElhinny and P. Wellman, *Earth Planet. Sci. Lett.* **6**, 198 (1969).
4. J. Francheteau and J. G. Sclater, *J. Geophys. Res.* **75**, 1023 (1970).
M. W. McElhinny, *Nature (Lond.)* **241**, 523 (1973).
6. D. P. McKenzie, in *The Nature of the Solid Earth*, E. C. Robertson, Ed. (McGraw-Hill, New York, 1972), pp. 334–337.
7. E. Irving, *Paleomagnetism and Its Application to Geological and Geophysical Problems* (Wiley, New York, 1964), p. 131; W. H. Munk and G. J. F. MacDonald, *The Rotation of the Earth* (Cambridge Univ. Press, London, 1960), p. 265.
R. Van der Voo and R. B. French, *Earth Sci. Rev.* **10**, 99 (1974).
9. For additional discussion of Lower Tertiary paleomagnetic poles, see: A. Schult and H. Soffel, *Geophys. J. R. Astron. Soc.* **32**, 373 (197 P. K. S. Raja and J. B. Vise, *Earth Planet. Sci. Lett.* **19**, 438 (1973); E. R. Deutsch, *Can. J. Earth Sci.* **8**, 1542 (1971); P. Wellman, M. W. McElhinny, I. McDougall, *Geophys. J. R. Astron. Soc.* **18**, 371 (1969); W. G. Mumme, *ibid.* **7**, 314 (19 E. Irving, P. M. Stott, M. A. Ward, *Philos. Mag.* **6**, 225 (196 H. Wensink, *Tectonophysics* **17**, 41 (1973). For additional references on Upper Cretaceous paleomagnetic poles, s N. D. Opdyke and W. D. MacDonald, *Earth Planet. Sci. Lett.* **18**, 37 (1973); J. Francheteau, C. G. A. Harrison, J. G. Sclater, M. L. Richards, *J. Geophys. Res.* **75**, 2035 (1970); W. A. Robertson, *J. Geophys. Res.* **68**, 2299 (1963); R. Andriamirado and A. Roche, *C. R. Hebd. Seances Acad. Sci. Ser. D Sci. Nat.* **269**, 16 (19 R. K. Verma and G. Pullaiah, *Earth Planet. Sci. Lett.* **2**, 310 (1967). For additional treatment of Lower Cretaceous paleomagnetic poles, see: K. M. Creer, *Philos. Trans. R. Soc. Lond. Ser. A Math. Phys. Sci.* **267**, 457 (1970); *Ann. Geophys.* **14**, 373 (1958); *Geophys. J. R. Astron. Soc.* **7**, 1 (1962); J. Francheteau, C. G. A. Harrison, J. G. Sclater, M. L. Richards, *J. Geophys. Res.* **75**, 2035 (1970); W. A. Robertson and L. Hastie, *J. Geol. Soc. Australia* **8**, 259 (1962); R. N. Athavale, C. Radhakrishnamurty, P. W. Sahasrabudhe, *Geophys. J.* **7**, 304 (196 G. S. Mital, R. K. Verma, G. Pullaiah, *Pure Appl. Geophys.* **81**, 177 (1970);

C. T. Klootwijk, *Tectonophysics* **12**, 449 (1971).
A. G. Smith and A. Hallam, *Nature (Lond.)* **225**, 139 (1970).
W. C. Pitman and M. Talwani, *Geol. Soc. Am. Bull.* **83**, 619 (1972); J. W. Ladd, thesis; Columbia University (1974); D. P. McKenzie and J. G. Sclater. *Geophys. J. R. Astron. Soc.* **25**, 437 (197 D. P. McKenzie, D. Davies, P. Molnar, *Nature (Lond.)* **226**, 243 (1970); *Geotimes* **18**, 19 (1973); P. Molnar, T. Atwater, J. Mammerikx, S. M. Smith, in preparation; W. J. Morgan, *J. Geophys. Res.* **73**, 1959 (196 R. L. Larson and W. C. Pitman, *Geol. Soc. Am. Bull.* **83**, 3645 (1972);
P. Molnar and L. B. Sykes, *ibid.* **80**, 1639 (19(B. T. Malfait and M. G. Dinkelman, *ibid.* **83**, 251 (197 J. A. Grow and T. Atwater, *ibid.* **81**, 3715 (197 X. LePichon and J. C. Sibuet, *Earth Planet. Sci. Lett.* **12**, 83 (1971).
D. H. Tarling, *Nature (Lond.)* **238**, 92 (1972).
13. D. M. Jurdy and R. Van der Voo, *J. Geophys. Res.* **79**, 2945 (1974); D. M. Jurdy, thesis, University of Michigan (1974).
14. Arbitrary longitudes have been assigned on the basis of the longitudes of North America being approximately fixed.
15. We thank M. Stefanick for his help and Prof. H. N. Pollack, Dr. W. C. Pitman III, and an unknown reviewer for their critical remarks on the manuscript. We thank Drs. J. W. Ladd and T. Atwater who kindly permitted us to use their unpublished data. The contributions of R.V.V. were supported in part by NSF grant GA 38038.

29 August 1974; revised 13 December 1974

Elevated Salivary and Synovial Fluid β_2-Microglobulin in Sjogren's Syndrome and Rheumatoid Arthritis

Abstract. *β_2-Microglobulin is normally present in low concentrations in serum and other bodily fluids. By use of a radioimmunoassay, elevated concentrations of β_2-microglobulin were found in saliva and synovial fluid from patients with Sjogren's syndrome and rheumatoid arthritis, autoimmune inflammatory diseases that attack and destroy the salivary glands and articular tissues, respectively. Elevated β_2-microglobulin concentrations decreased in the saliva of two patients who simultaneously showed a clinical response to systemic treatment. Measurement of β_2-microglobulin in inflammatory fluids may offer a simple method of quantifying local activity in autoimmune states.*

The low molecular weight protein β_2-microglobulin (β_2m) (molecular weight 11,700) is present in low concentrations in normal serum and urine (*1*). It is increased in the serum and urine of patients with renal tubular disorders and in kidney transplant recipients, particularly during rejection crises (*2*). Amino acid sequence analysis of β_2m indicates a close homology with constant region domains of immunoglobulin polypeptide chains (*3, 4*).

β_2-Microglobulin is present on the surface membranes of peripheral blood lymphocytes (*5*). It is synthesized and secreted by lymphocytes as well as by various lymphoid and nonlymphoid tumor cell lines (*5, 6*). It is associated with both thymus-derived (T) and bone marrow–derived (B) lymphocytes since its presence has been demonstrated on thymocytes, thoracic duct lymphocytes, chronic lymphocytic leukemia cells, and cultured lymphoblastoid cell lines (*5, 6*). The latter two are generally considered to represent B cells.

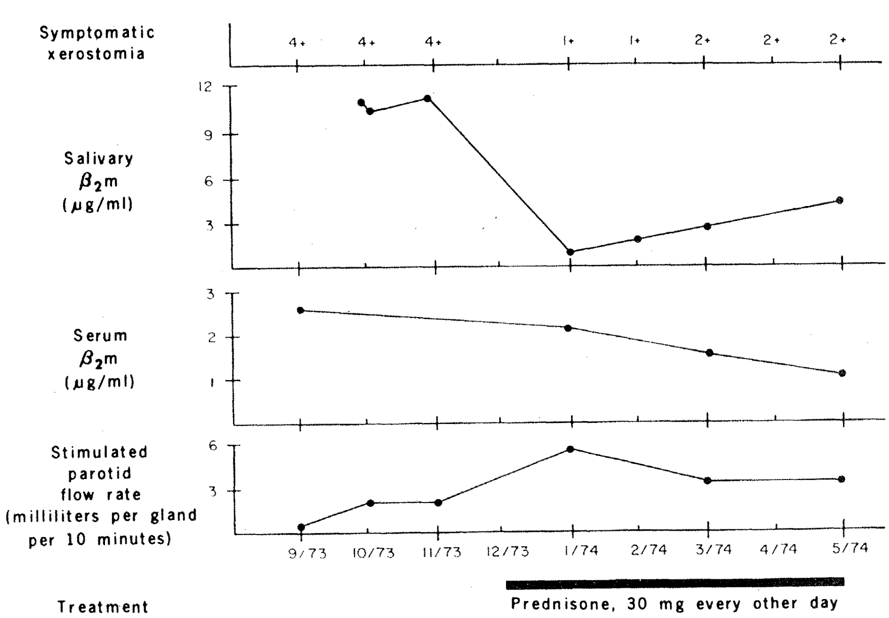

Fig. 1. Changes in clinical status and β_2m concentration in response to corticoid treatment in a patient with Sjogren's syndrome. The scale for symptomatic xerostomia is relative; there was no observation for December 1973.

Although the exact function of β_2m is unknown, it is thought to play a role in immunologic reactions since it is part of the HL-A antigen complex present on the lymphocyte cell surface (*7*). Antiserum to β_2m inhibits the response of lymphocytes to alloantigens in a mixed lymphocyte reaction (*8*). Such antiserums also induce redistribution and aggregation ("capping") of both β_2m and HL-A antigens on the lymphocyte membrane (*7–9*). The "co-capping" of β_2m and HL-A antigens is evidence of their intimate association in the living cell.

Certain autoimmune diseases such as Sjogren's syndrome and rheumatoid arthritis are characterized by intense lymphocytic and inflammatory cell infiltrations of the target tissue sites (*10, 11*). In Sjogren's syndrome, the destruction of the salivary and lacrimal glands by these infiltrates leads to the distressing symptoms of dry mouth and dry eyes (the "sicca complex"). In rheumatoid arthritis, the joint cavity is the target of attack, with cartilage destruction, bone erosion, and joint deformity occurring as a consequence. Immunoglobulins, rheumatoid factor, lymphoid cells, and inflammatory products can often be found in the biological fluids associated with these inflammatory sites, that is, the saliva and synovial fluid (*11, 12*).

A rapid simple method for quantitatively measuring the extent of inflammation in tissue sites would be extremely useful both for diagnosis and for monitoring treatment in these autoimmune and related diseases. We hoped that measurement of β_2m concentrations in inflammatory fluids might provide such a method. Accordingly, we have employed a radioimmunoassay procedure to measure β_2m in saliva and synovial fluid collected from patients with Sjogren's syndrome and rheumatoid arthritis, respectively. β_2-Microglobulin was also measured in the patients' serum and in saliva and synovial fluid collected from a variety of control subjects. Our results suggest that β_2m concentrations are increased in these inflammatory fluids, probably as a consequence of local production by infiltrating cells. Moreover, in two patients with Sjogren's syndrome a clinical response to corticosteroids or immunosuppressive drugs