South American Geochronology: Radiometric Time Scale for Middle to Late Tertiary Mammal-Bearing Horizons in Patagonia

Abstract. *Radiometric (potassium-argon) age determinations for basalts and tuffs associated with middle to late Tertiary mammal-bearing horizons in Patagonia, southern Argentina, permit refinement of boundaries and hiatuses between beds of Deseadan (early Oligocene) through Friasian (middle to late Miocene) age. At two localities beds of Deseadan age are overlain by basalts, which gave dates of 33.6 and 35.4 million years ago; 34.0 million years ago is tentatively accepted as a terminal date for known Deseadan. At several localities beds of Colhuehuapian age are underlain by basalts, which gave dates ranging from 28.8 to 24.3 million years ago; 25.0 million years is tentatively taken as a basal age for known Colhuehuapian. The paleontological hiatus between known Deseadan and known Colhuehuapian is thus in the order of 9.0 million years. Two tuffs from the Santa Cruz Formation (Santacrucian) gave ages of 21.7 and 18.5 million years. Plagioclase and biotite concentrates of an ignimbrite from the Collón Curá Formation (Friasian) gave ages ranging from 15.4 to 14.0 million years.*

It is well established that South America was an island continent during most, if not all, of the Tertiary Period (65 through 2 million years ago) (*1*). As a result of this long isolation, the South American land mammal fauna developed in isolation and is dominated by autochthonous groups. The unique nature of this terrestrial fauna and lack of two-way continental faunal interchanges until the latest Tertiary make paleontostratigraphic intercontinental correlations difficult if not impossible. The isolation ended only a few million years ago, when the Panamanian land bridge came into existence, uniting the two Americas. Thereafter the fossil record reveals an intermingling of the long-separated North and South American faunas.

Despite these drawbacks, a relative time scale for mammalian faunal succession within South America is now generally agreed on (*2–6*) (Fig. 1). This time scale has been based largely on stratigraphic tie-ins with the "Patagonian" marine beds (conventionally assigned a latest Oligocene or earliest Miocene age). The terrestrial beds above and below these marine deposits are correlated with geochronologic time units largely on the basis of stage of evolution and overall distinctness of, or similarity between, the contained mammalian faunas. Lack of extensive interdigitations of fossiliferous marine and nonmarine strata in South America has deterred further refinement.

Radiometric age determinations for strata associated with Tertiary mammal-bearing horizons and calibration of land mammal ages in terms of a radiometric time scale, as has been done for North America (*7*), were almost nonexistent for the South American Cenozoic. The third best Cenozoic mammal record in the world thus stood virtually outside the growing framework of radiometric dating (*8*).

During January and February 1975, key middle to late Tertiary mammal-bearing localities were visited in Patagonia, southern Argentina (Fig. 2). Volcanic rocks associated with known mammal-bearing horizons and suitable for radiometric analysis were collected (*9*) and dated by the ^{40}K-^{40}Ar method by G.H.C. and R.E.D. (Table 1).

A basalt capping beds of Mustersan (conventionally middle Eocene) age at Cerro del Humo (Fig. 2) gave a date of 2.2 million years ago (sample KA 2945 in Table 1). This basalt is related to Plio-cene-Pleistocene volcanism documented for this area (*10*) and has no bearing on the age of the underlying Tertiary series.

Between the Deseadan (conventionally early Oligocene) and Colhuehuapian (conventionally late Oligocene) horizons at the Great Barranca south of Lago Colhué-Huapí, Cerro Blanco (Fig. 2), and the south side of the Valle Hermoso are intercalated basalt flows. In all cases the beds overlying these basalts are referable to the Colhué-Huapí Formation (*2*).

Two separate basalts between the Deseadan and Colhuehuapian horizons at the west end of the Great Barranca south of Lago Colhué-Huapí gave dates of 28.8 (KA 2919) and 24.3 (KA 2942) million years ago; a third basalt from Cerro Blanco gave a date of 35.4 million years ago (KA 2920) (Table 1). Samples KA 2919 and KA 2942 are taken to represent minimal (basal) ages from known Colhuehuapian, while KA 2920 apparently lies conformably on the Deseadan horizon at this locality. A basalt (KA 2943) capping the Deseadan horizon at the east end of the Great Barranca gave a date of 27.7 million years ago (Table 1). This basalt is apparently of pre-Colhuehuapian age, as are KA 2919 and KA 2942.

Two basalts from Pico Truncado (Fig. 2) gave dates of 33.6 (KA 2917) and 27.6 (KA 2918) million years ago (Table 1). The first basalt conformably overlies rocks of Deseadan age, and the second lies 37 m up section from the first. These basalts bracket an apparently unfossiliferous tuff that occurs between rocks with Deseadan and Colhuehuapian faunas.

Two periods of volcanic activity are recorded by these basalts, one around 34 to 35 million and the other around 25 to 29 million years ago. A terminal date of 34.0 million years ago is tentatively accepted for known Deseadan, while 25.0 million years is tentatively taken to represent a basal age for known Colhuehuapian (Fig. 1). The paleontological hiatus between known Deseadan and known Colhuehuapian faunas is thus in the order of 9.0 million years.

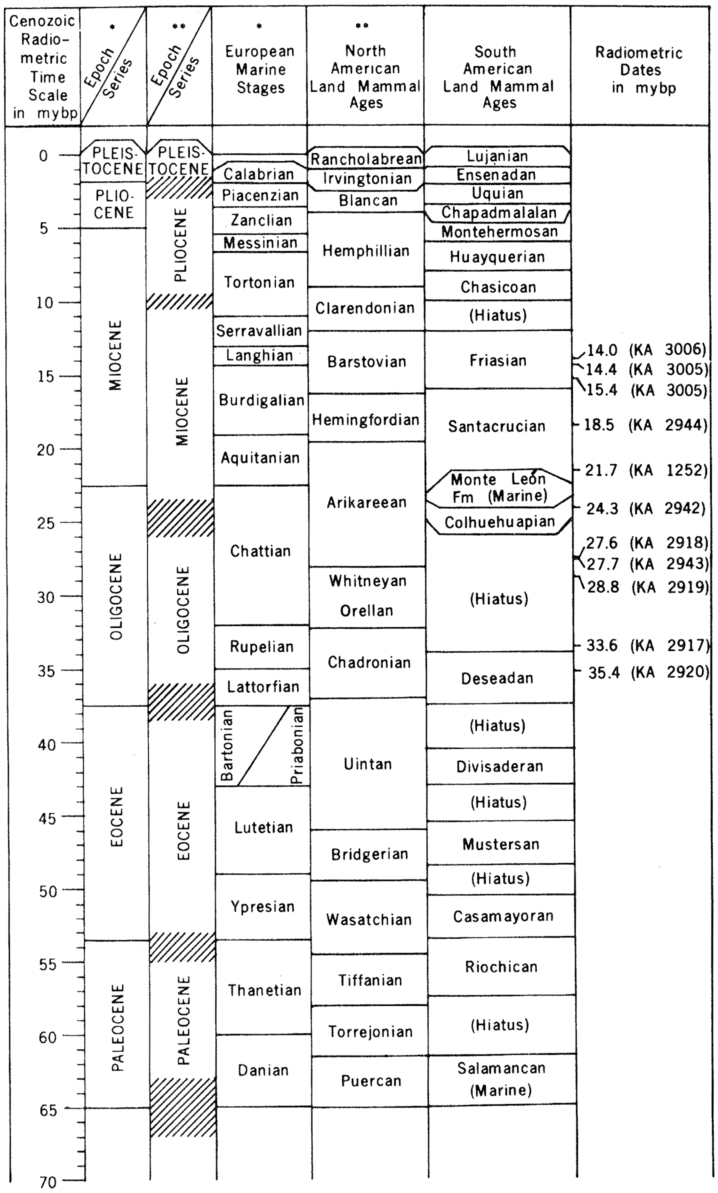
The few known deposits of Colhuehuapian age are conventionally included in the heterogeneous Tobas de Sarmiento (*11*) or Sarmiento Group (*12*), which includes beds of Casamayoran (conventionally early Eocene), Mustersan, Deseadan, and Colhuehuapian age (*13*). Colhuehuapian deposits were formed locally in depressions, and in places can be seen passing without noteworthy unconformity into the overlying Patagonian marine beds (*3*).

The marine beds comprising the Patagonian Stage (generally believed to be latest Oligocene or earliest Miocene in age) are now thought to represent two or possibly three distinct formations ranging in age from Eocene to Miocene. Three formations have been characterized on the basis of their molluscan faunas (*14*)—the Monte León Formation (late Oligocene), the Estratos con *Monophoraster* y *Venericor* (late Eocene), and the San Julián Formation (early or middle? Eocene). The Monte León and San Julián formations are recognized (*15*) largely on the basis of their discontinuous distribution and lithologic differences; their planktonic foraminifera indicate a similar age, correlative with the late Chattian Stage (upper Oligocene) of Europe (*15, 16*).

The Monte León Formation conformably underlies the Santa Cruz Formation along the Atlantic coast between Monte León and the mouth of the Río Gallegos (*14*). To the north of this region, between Camarones and Trelew, especially in the lower valley of the Río Chubut, marine sediments occur with cetaceans and penguins similar to those of the Monte León Formation, with which they correlate in time (*14*). The latter represent the marine beds that conformably overlie the Colhué-Huapí Formation. The Colhué-Huapí beds everywhere underlie the base of these marine beds, but with no marked hiatus, so it is possible that the earliest of these marine beds do, in part, overlap the latest Colhuehuapian in time, although this has not been established as fact (*3*).

It must be emphasized that there is no continuous section in which the Colhué-Huapí, Monte León, and Santa Cruz formations occur together. The Colhué-Huapí beds occur below the Monte León marine equivalent in the lower course of the Río Chico, while the Santa Cruz Formation overlies the Monte León Formation only along the coastal region of southern Santa Cruz (*17*). Furthermore, the Colhuehuapian and Santacrucian (conventionally early to middle Miocene) mammals are recognizably different, but the average difference is so slight that they suggest closely successive stages of the same general fauna despite the apparent intercalation of marine beds between them. The time represented by these marine beds cannot be very long, geologically speaking, and is certainly shorter than any of the major hiatuses recognized in the Eocene or Oligocene series (*3*). The mammal faunas from the Trelewense (conventionally late Colhuehuapian) near Gaiman, Chubut Province, along the Río Chubut, and Notohipidense (conventionally early Santacrucian) near Lago Argentino, Santa Cruz Province, have yet to be adequately compared; they may prove contemporaneous or nearly so. For these reasons, the justification for recognizing a Colhuehuapian age distinct from that of the Santacrucian has been queried (*4*).

The lower Santa Cruz Formation is more than 800 m thick in the west and thins to some 200 m along the Atlantic coast in the southern part of Santa Cruz Province (*18*). Its deposition seems to have been relatively rapid. Local facies are sometimes distinguishable, but no real sequence of faunal change has been demonstrated. Although the fauna was remarkably uniform, doubtless evolutionary advance may be identified by the application of more refined field and laboratory methods (*3*). It has been suggested that the very rich Santa Cruz fauna may not be of one age (*8*). If the eastward thinning of the Santa Cruz For-



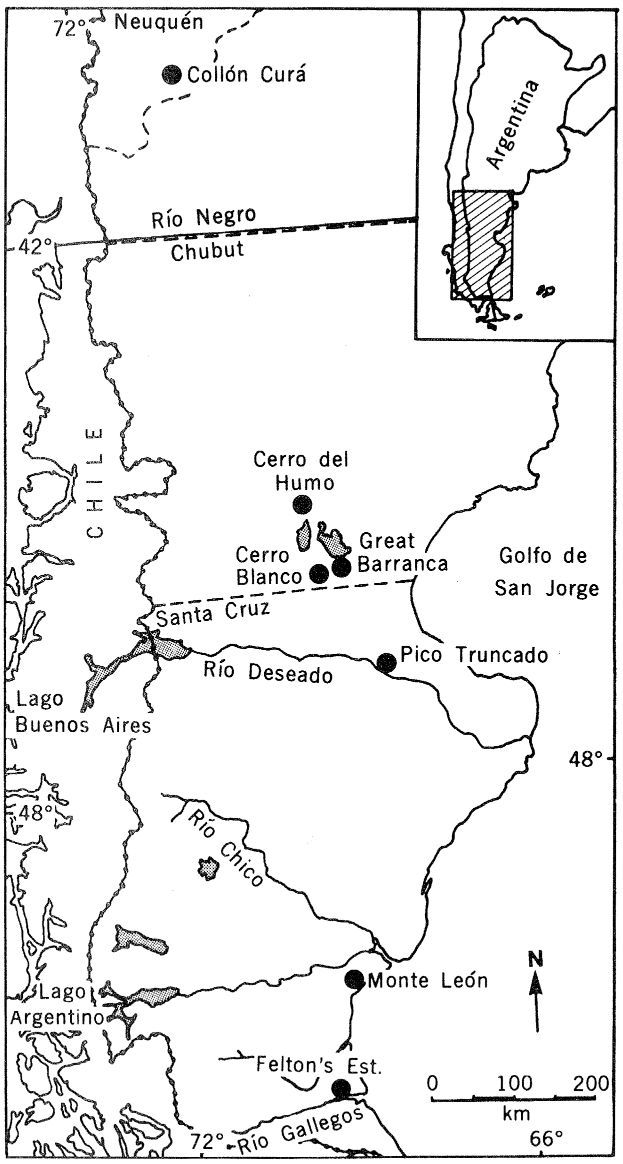


Fig. 1 (left). Cenozoic radiometric time scale and chronostratigraphy showing approximate correlations of South American land mammal ages and marine stages with North American land mammal ages and European marine stages. (*) From Berggren and Van Couvering (*16*); (**) from Savage (*20*); *mybp*, million years before present. Fig. 2 (right). Map of Patagonia, southern Argentina, showing mammal-bearing fossil localities (●) for which radiometric dates are available.

Table 1. Analytical data. Samples and locations are described in (9). Calculations are based on $^{40}K/K = 1.18 \times 10^{-4}$ and radioactive decay constants $^{40}K_{\lambda} = 5.480 \times 10^{-10}$ year^{-1}; $^{40}K_{\lambda_\beta} = 4.905 \times 10^{-10}$ year^{-1}; and $^{40}K_{\lambda_E} = 0.575 \times 10^{-10}$ year^{-1}.

Sample location	Sample number	Dated material	Sample weight (g)	K (%)	Radiative ^{40}Ar ($\times 10^{-11}$ mole/g	Atmospheric ^{40}Ar (%)	Age ($\times 10^6$ years)
1. Near Felton's Estancia	KA 1252	Tuff plagioclase concentrate	2.3538	0.180	0.695	88.0	21.7 ± 0.3
2. Monte León	KA 2944	Whole rock tuff	4.16945	2.327	7.4939	36.7	18.5 ± 0.2
3. Pico Truncado	KA 2918	Whole rock basalt	1.77600	0.642	3.0983	54.5	27.6 ± 0.4
3. Pico Truncado	KA 2917	Whole rock basalt	1.22563	1.056	6.2061	28.7	33.6 ± 0.4
4. Cerro Blanco	KA 2920	Whole rock basalt	2.21030	1.199	7.4281	28.8	35.4 ± 0.4
5. Great Barranca	KA 2942	Whole rock basalt	5.06278	0.890	3.774	41.9	24.3 ± 0.5
5. Great Barranca	KA 2942R	Whole rock basalt	6.15202	0.890	3.748	38.9	24.3 ± 0.5
5. Great Barranca	KA 2943	Whole rock basalt	4.84600	1.661	8.045	23.9	27.7 ± 0.6
5. Great Barranca	KA 2919	Whole rock basalt	2.02351	0.717	3.6082	88.6	28.8 ± 0.9
6. Cerro del Humo	KA 2945	Whole rock basalt	5.50445	1.591	0.611	68.4	2.21 ± 0.06
7. Río Collón Curá	KA 3006	Biotite from ignimbrite	1.16299	5.933	14.497	57.8	14.0 ± 0.3
7. Río Collón Curá	KA 3006R	Biotite from ignimbrite	0.55865	5.933	14.548	59.8	14.1 ± 0.3
7. Río Collón Curá	KA 3005R	Plagioclase concentrate from ignimbrite	6.04476	0.649	1.629	29.4	14.4 ± 0.3
7. Río Collón Curá	KA 3005	Plagioclase concentrate from ignimbrite	5.24695	0.649	1.745	27.2	15.4 ± 0.3

mation is due to erosion (*18*), the probability that the fossils from the coastal area, where most of the collecting has been done, are of essentially the same age is increased (*8*).

The only probable distinction yet made between Santa Cruz local faunas is that certain beds at high elevation in the foothills near Lago Pueyrredón yielded a fauna with several distinct species. If ecological differences do not account for this, the fauna may be younger than the typical (coastal) Santa Cruz fauna (*19*). This distinction has led to the suggestion that the Santa Cruz and Collón Curá faunas may have overlapped in time (*8*).

Until recently, the only radiometric date available for the whole of the Argentine mammal-bearing Tertiary was based on a plagioclase concentrate obtained from a tuffaceous matrix from the inside of a glyptodont (order Edentata) carapace. The specimen was collected from the Santa Cruz Formation along the north side of the Río Gallegos between Felton's Estancia and Cabo Buen Tiempo (Cape Fairweather) (Fig. 2) (*7*). This date, 21.7 million years ago (KA 1252), correlates with the late Arikareean (early Miocene) land mammal age of North America and the Aquitanian marine stage of Europe (*20, 21*).

A second date of 18.5 million years ago (KA 2944) was obtained for a tuff from 116 m above the base of the Santa Cruz Formation at Monte León (Fig. 2, Table 1). This sample is from a level (> 100 m) stratigraphically above KA 1252, which is consistent with the somewhat younger age. Sample KA 2944 is a fine-grained vitric tuff, and some argon loss due to devitrification of the glass is also possible. These two dates (mean = 20.1 million years ago) indicate that at least the greater part, if not all, of the coastal Santa Cruz Formation is of Aquitanian age (Fig. 1).

A few small local faunas occur in the time interval between Santacrucian and Chasicoan (conventionally early Pliocene). The Collón Curá Formation occurs just east of the Andes in northwestern Patagonia, Neuquén Province, and attains a thickness of 1000 m in places (*8*). These beds are similar in age and origin to the pre-Andean Santa Cruz Formation of southern Patagonia. Three local faunas have been described from the Collón Curá Formation—the Río Collón Curá, the Río Frias, and the Río Mayo. Roth (*22*), who found the beds and faunas, and Ameghino (*23*) agree that they were of Santacrucian age. Later students (*3, 24, 25*) believed them to be somewhat younger. Kraglievich (*24*) based an age on each (for example, Colloncurense, Friasense, and Mayoense), although this arrangement has not been followed by subsequent workers (*3*). Kraglievich (*24*) may well have been right in his belief that more than one land mammal age should be recognized in this part of the sequence, but the data are inadequate for judgment (*8*). These three local faunas are currently regarded as Friasian (conventionally late Miocene) in age (Fig. 1), with the Collón Curá local fauna representing the earlier part of that age and the Río Mayo local fauna the later (*5*). It is particularly unfortunate that the Friasian is so poorly defined, because the best-known northern fauna, the La Venta of Colombia, appears to correlate with some part of it (*8*).

Biotite and plagioclase concentrates from an ignimbrite underlying the mammal-bearing tuff horizon in the Collón Curá Formation along the Río Collón Curá were dated and gave ages ranging from 14.0 (KA 3006) to 15.4 (KA 3005) million years (*N* = 4, mean = 14.5 million years) (Table 1). These dates correlate with the Barstovian land mammal age in North America and the latest Burdigalian to Langhian marine stage of Europe (Fig. 1).

It now appears probable that the Colhuehuapian (including Trelewense), Santacrucian (including Karaikense, Pinturense, Notohipidense, and Astrapothericulense), and Friasian (including Colloncurense and Mayoense) are based on a successive and relatively continuous evolutionary sequence without such hiatuses as those recognized between the lower Tertiary mammal ages (*5, 17*). For this reason and because of the precise stratigraphic tie-ins of the Santa Cruz and Colhué-Huapí beds with the "intervening" late Chattian Monte León marine beds, the Colhuehuapian age is assigned to the late Oligocene and the rest of the successive units, representing the Santacrucian and Friasian, to the Miocene (*17*). These age assignments are corroborated by the new radiometric dates (Fig. 1 and Table 1).

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9. The rock samples dated were of two types: (i) tuffaceous sediments from fossiliferous horizons and (ii) basalts interbedded in tuffaceous fossil horizons or filling channels cut into them. The tuff samples are all fine-grained, often with extensive to total devitrification of the glass. Because they are predominantly water-laid deposits, detrital contamination of the tuffs with older rocks is present in some samples. For these reasons the tuffs are not as reliable as the basalts for radiometric age determinations. The basalts generally show only minor alteration and have given consistent results. Unfortunately, basalts are rare in the stratigraphic sequence, deterring construction of a complete time scale based solely on radiometric age determinations of this rock type.

   Location 1: Near Felton's Estancia. Tuff (KA 1252) collected from Santa Cruz Formation along north bank of Río Gallegos, between Felton's Estancia and Cabo Buen Tiempo, Santa Cruz Province [see (*7*)].

   Location 2: Monte León. Tuff (KA 2944) from Santa Cruz Formation. Sample collected 116 m above contact of Monte León Formation (marine) and overlying Santa Cruz Formation (terrestrial). For stratigraphic section see (*2*, p. 114, figure 133).

   Location 3: Pico Truncado. Samples collected from amphitheater on east side of Pico Truncado. Sample KA 2917 (basalt) was collected from east wall of amphitheater, 37 m above contact of *Pyrotherium* beds (Deseadan horizon) and argiles fissilaires. Basalt overlies Deseadan horizon and corresponds to horizon d of profile 10 in (*26*) and to toba litoidea (*2*, figure 115). Sample KA 2918 is from a second basalt collected 37 m up section from KA 2917, and occurs between horizons e and f of profile 10 in (*26*) and immediately below rodados cuaternarios (*2*, figure 115).

   Location 4: Cerro Blanco. Basalt (KA 2920) is from between Deseadan and Colhuehuapian horizons on west face of Cerro Blanco (*2*, p. 40).

   Location 5: Great Barranca south of Lago Colhué-Huapí. Samples KA 2919 and KA 2942 are from separate isolated channel basalts at west end of Great Barranca (Fig. 2). Both basalts occur between Deseadan and Colhuehuapian horizons; KA 2919 was collected about 100 m northwest of KA 2942. These basalts correspond to manto de teschenita (*2*, figure 104), manto de roca magmatica (*2*, figure 105), and level j, profile 1, in (*26*). Sample KA 2943 is a basalt capping the Deseadan horizon toward the east end of Great Barranca, about 4 km east of the sites where KA 2919 and KA 2942 were collected.

   Location 6: Cerro del Humo. Basalt (KA 2945) capping meseta and directly overlying Mustersan horizon (*Astraponotus* beds). Corresponds to horizon g, profile 6, in (*26*); upper basalt (*2*, figure 117), and basalt in profile 1 and map (*10*, p. 43).

   Location 7: Río Collón Curá. Type locality of Collón Curá Formation, on west bank of Río Collón Curá, on National Route 40, 34 km north of where it crosses National Route 237, Neuquén Province. Ignimbrite lying directly below mammal-bearing tuffaceous horizon was dated.
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Kinetic Resonance Raman Spectroscopy: Dynamics of Deprotonation of the Schiff Base of Bacteriorhodopsin

Abstract. *We have developed a kinetic technique, combining resonance Raman spectroscopy and variable-speed continuous flow methods, to study molecular dynamics of isolated sites in macromolecules. Kinetic resonance Raman spectra of the retinylidene chromophore of bacteriorhodopsin have been obtained and the dynamics of the deprotonation of the Schiff base linkage is discussed.*

Kinetic studies on reaction intermediates by vibrational spectroscopy have been severely limited, mainly because of the difference in the time scale for most kinetics and the time needed to obtain a vibrational spectrum. Vibrational spectra have, therefore, been obtained on molecular systems either before they are altered or after they have reached a steady state. In this report we describe a kinetic technique that combines resonance Raman spectroscopy and continuous flow methods (*1*, *2*) with variable speeds which allows us to study rapid kinetics of molecular species. We have performed these kinetic experiments on bacteriorhodopsin using all the advantages inherent in vibrational spectroscopy.

In recent years, resonance Raman spectroscopy has become the method of choice for obtaining vibrational spectra of specific sites in macromolecular systems. This is done by selectively enhancing vibrational modes coupled to electronic transitions. When the exciting radiation from a tunable laser is within or near an absorption band, the resonance enhanced spectra are due mainly to the vibrational modes of the chromophore which couples to this absorption band. At Cornell we have used this technique to study the structure and the function of rhodopsins. Rhodopsin is a membrane glycoprotein and is the primary molecule in visual excitation. It absorbs a photon, converting the photonic energy into chemical energy which is used to generate a neural response to the brain (*3*). The active site of all rhodopsins contains the retinylidene chromophore (a form of vitamin A) covalently linked by a Schiff base to the ϵ-amino group of a lysine residue. By selectively enhancing the vibrational spectrum we were able to suggest that the Schiff base linkage in rhodopsin is protonated (*4*). This has been subsequently confirmed by other workers (*2*, *5*). Furthermore, we were also able to show that the Schiff base in bacteriorhodopsin is also protonated and that it can be deuterated (*6*).

Bacteriorhodopsin, which was discovered by Oesterhelt and Stoeckenius (*7*), is contained in the plasma membrane of the bacterium *Halobacterium halobium*. It has been shown that the biological role of bacteriorhodopsin is that of an energy converter. It acts as a light-driven proton pump (*8*), converting light energy into a vectorial proton gradient across the bacterial cell membrane. This proton gradient is used to generate chemical energy in the form of adenosine triphosphate (ATP) when the bacteria are deprived of oxygen. Bacteriorhodopsin and visual pigments are similar in that they not only use the retinylidene chromophore in their photochemically active sites but also have strikingly similar spectral and kinetic properties (*9*, *10*). Bacteriorhodopsin has a well-defined biological role, whereas the biological role of rhodopsin in visual transduction is not known. Thus bacteriorhodopsin, because of its similarities and differences, is an ideal model system to try to elucidate the biological role of visu-