ground-water tables, the paleoliquefaction record along the present coast is probably complete only for the last 2000 years, intermittent for the period 2000 to 5000 years ago, and may be extremely limited for earlier times.

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15. Atlantic seaboard is used to refer to the east coast of the United States extending from Long Island to southern Florida.
16. To establish a comprehensive control data, we first focused on the identification and characterization of liquefaction sites in the Charleston area. Criteria to distinguish seismically induced liquefaction features from other features that look similar but are not seismic in origin were also developed. See G. Maurath and D. Amick, in *Proceedings of the Second International Conference on Case Histories in Geotechnical Engineering*, St. Louis, MO, 1 to 5 June 1988 (University of Missouri–Rolla, Rolla, MO, 1988); D. Amick, G. Maurath, R. Gelinas, *Seismolog. Res. Lett* **61**, 117 (1990).
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A Water Storage Adaptation in the Maya Lowlands

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Prehispanic water management in the Maya Lowlands emphasized collection and storage rather than the canalization and diversion accentuated in highland Mexico. Reexamination of site maps of the ancient Maya city of Tikal, Guatemala, has revealed an important, overlooked factor in Maya centralization and urban settlement organization. In a geographical zone affected by an extended dry season and away from permanent water sources, large, well-planned reservoirs provided resource control as well as political leverage.

THE SETTLEMENT PATTERN OF THE ancient Maya, a civilization identified with a dispersed support population, continues to perplex Mesoamericanists (*1*, *2*). Occupying central and northern Guatemala and adjacent areas of Mexico, Belize, and Honduras (Fig. 1), southern Maya Lowland cities contrast with other great experiments in Mesoamerican urban statecraft—Monte Albán (*3*), Teotihuacán (*4*, *5*), Tenochtitlán (*5*, *6*). Although as advanced as these more nucleated and ordered ancient settlements of highland Mexico, the lowland Maya urban aggregate differed in population density and spatial organization. One condition separating these two settlement adaptations is the availability of water.

Water availability limits the location of permanent populations. In highland Mexico, rainfall is less annually abundant than in the southern Maya Lowlands, but perennial drainages and year-round springs allow the deliberate diversion of water to nearby settlements (*5*, *7*). Although more precipitation may fall in the Maya area, little permanent external drainage exists (*8*). Water management in the Maya Lowlands emphasized collection over diversion, source over allocation.

Most studies of water management in preindustrial states emphasize water allocation rather than water sources and their abundance (*9*). With the use of previously published contour maps, a study of large Classic Period Maya cities (A.D. 250 to 900) was initiated, focusing on water sources (*10*). Examination of the ancient reservoir

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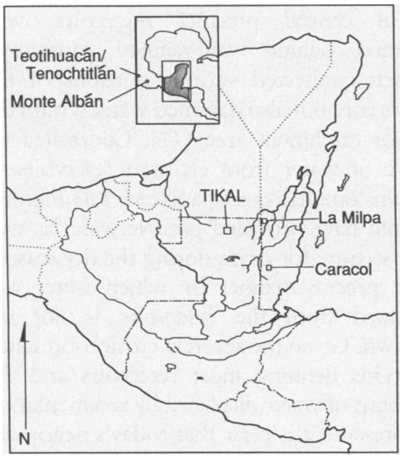

Fig. 1. Map of the Maya area, showing the location of Tikal and other sites mentioned in the text.

technology in the tropical wet-dry forests of the southern Maya Lowlands reveals that rainwater storage basins were the major source of water for many sites during a 4-month dry season. The planning and placement necessary for the substantial reservoir construction at Tikal, Guatemala (*11*), the best documented large community in the Maya Lowlands, demonstrates the significance of collection and storage and suggests centralized water management. This centralization, evidenced by the size, location, and density of reservoirs within the spatial core of the city, also implies political and economic control by an elite, a previously unexamined urban perspective.

Three factors support this centralization hypothesis at Tikal: (i) a pronounced dry season, (ii) the construction of reservoirs as sole water sources, and (iii) the resulting water control. Tikal has been carefully surveyed and excavated during the last 40 years (*11–13*). Although one of the largest Classic Period cities, it is not unique in the southern Maya Lowlands in having neither rivers nor springs. Most Maya cities of Tikal's complexity, if not its size, are located on natural promontories away from permanent water sources (*14*).

Climatic fluctuations have occurred during the last 2000 years (*15*), but the present-day climate is a close analogue to Classic Period conditions. Together with monthly rainfall and evapotranspiration rates as well as seepage data, estimates have been made of the amount of water available to a consuming population during the dry season (Table 1) (*11*). Precipitation rates today range from 1350 to 2000 mm per year in the northcentral Petén, Guatemala (*10, 16, 17*), with a 4-month period of annual drought.

Reservoirs were constructed at Tikal to cope with this seasonal unavailability of water. Six major reservoir catchment areas or drainage divides drain the summit of this human-modified watershed and range in area from 9 to 62 ha (Fig. 2). The runoff from these surfaces easily filled the associated reservoirs. All sizable catchment areas eventually terminated in *bajo*-margin reservoirs or natural *aguadas* (depressions near the edge of a *bajo*), ultimately leading into the flanking *bajos* (large, seasonally inundated, internally drained swamps).

Three reservoir types have been documented within the catchment areas: (i) central precinct reservoirs, (ii) residential reservoirs, and (iii) *bajo*-margin reservoirs (Table 1). This typology, based principally on reservoir location but also on amount of water contained, reflects centralization.

Central precinct reservoirs are located within the summit epicenter (*13*). The Causeway, Palace, Temple, Hidden, and a newly identified reservoir (behind the north end of the Maler Causeway) retain runoff from the largest and most completely paved reservoir catchment area. Also within the central precinct reservoir sphere is the Floodgate holding tank, a little understood feature draining into the larger Causeway Reservoir (Fig. 3). More than 900,000 m^3 of water could be collected from the entire catchment annually (based on 1500 mm of rainfall per year). These features were near the largest public architecture at the site and probably had a symbolic function in associating elite authority with the elaborate display of water control (*18*). The central precinct reservoirs also appear to have stored major water reserves for the seasonal replenishment of the *bajo*-margin reservoirs (*19*) (Figs. 3 and 4).

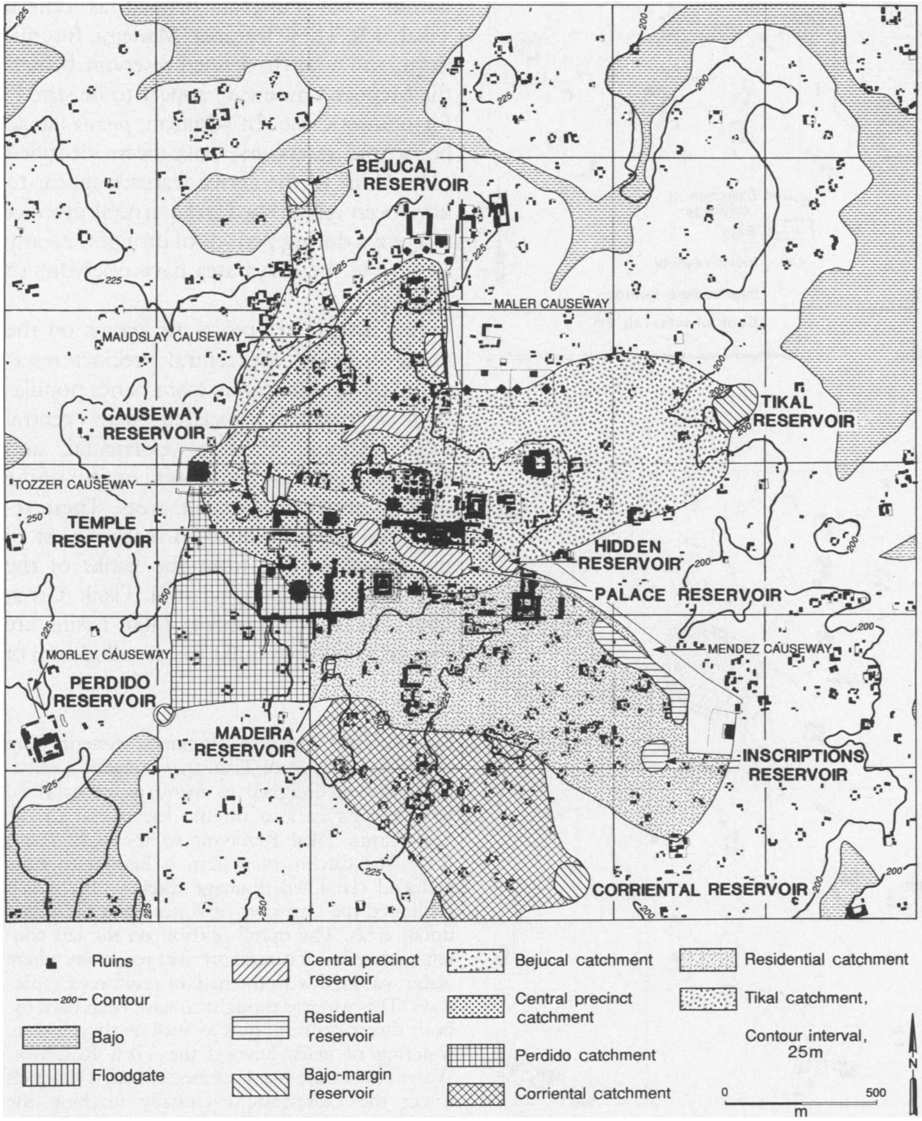

Fig. 2. Main catchments. Map showing the central 9 km^2 of Tikal (*11*). The six central shaded areas are rainwater collection catchments. The Tikal, Corriental, Perdido, and Bejucal catchments each drain into their respective *bajo*-margin reservoirs. The catchments shown are the largest by far at Tikal, though other smaller more localized catchments exist. Some of these are located within larger catchments, others outside. All catchments are derived from contour lines taken from the detailed Tikal maps as well as comments about and drawings and photographs of Tikal (*10–12*).

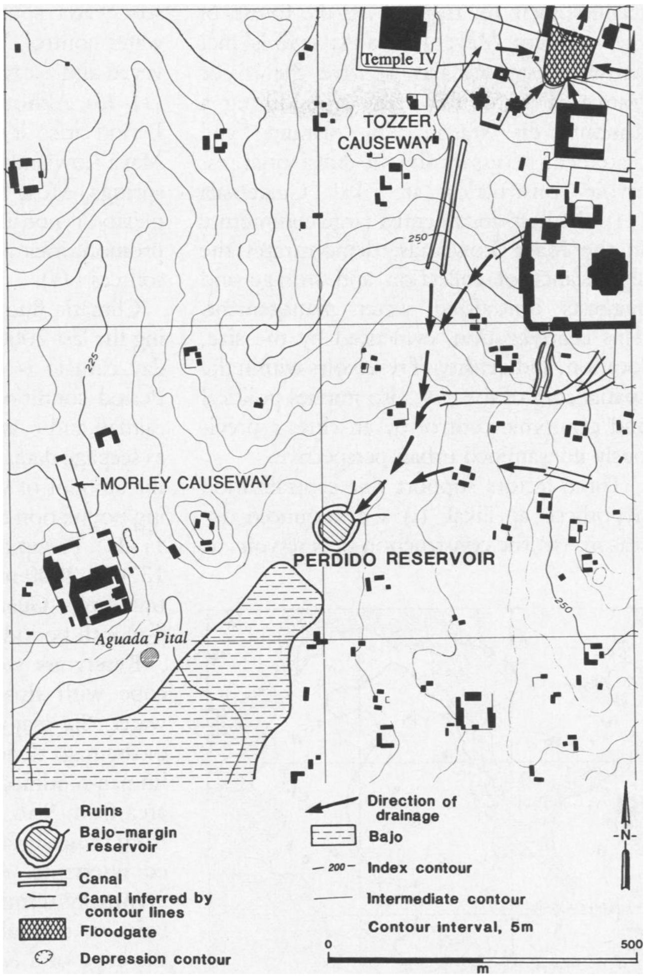

Fig. 3. Perdido reservoir catchment system. Map showing a section of Tikal that includes a canal system designed to transport rainwater from the paved area in the upper right (central precinct) to the *bajo*-margin Perdido Reservoir located at the bottom (*11*). Water stored in the reservoir is hypothesized to have kept the *bajo*-margin fields further south moist. The canal system is derived from structures, contour lines, and quarry marks visible on the detailed Tikal maps (*10*) as well as from comments made by the preparers of the maps (*11*). Part of the captured rainwater flowed north into the "Floodgate" (upper right), a recently identified central precinct holding tank where water was held until it was needed in an area further east (*10*). This holding tank may have been used to keep debris out of the larger, more permanent Causeway Reservoir (not shown) in the central precinct. Three small but centrally located structures are positioned in the channel leading into the Causeway Reservoir on the northern margins of the Tozzer Causeway. These structures are conjectured to have been pylons designed to support a weir or perishable dam.

All central precinct reservoirs were formed behind well-defined causeways, which connected various portions of the city's core but also dammed water within the major catchment area (*11*). Controlled release of water from elevated reservoirs to downslope flanks and adjacent *bajo* margins would have provided potable water as well as moisture for crops during the dry season. The precise manner by which water was released from the reservoirs is not yet known. Given the severely erosion-breached margins defining most reservoirs and the amount of water displaced by sedimentation at present, it is clear that today's nearly dry tanks once held much more water (*10, 11*).

Residential reservoirs are located downhill from the central precinct within the most densely populated zone immediately outside the epicenter's public architecture, within what Puleston defined as central Tikal (*13*). These features (Madeira, Inscriptions, and a newly defined reservoir behind the Méndez Causeway) appear to be strictly for domestic use. In addition, *pozas* (small household reservoirs) have been identified (*11*). None of the above features appear to have been replenished from central precinct reservoirs during periods of drought. Nearly all sites in the Maya area have reservoirs of this type.

Bajo-margin reservoirs are basins on the scalar order of the central precinct reservoirs, but located away from dense population aggregates associated with central Tikal. Bejucal, Perdido, Corriental, and Tikal reservoirs are the termini of four of the major reservoir catchment areas. These receptacles are positioned to receive most of the runoff issuing from the flanks of the promontory defining central Tikal. Given their size and placement, these basins are viewed as holding tanks for the allocation of

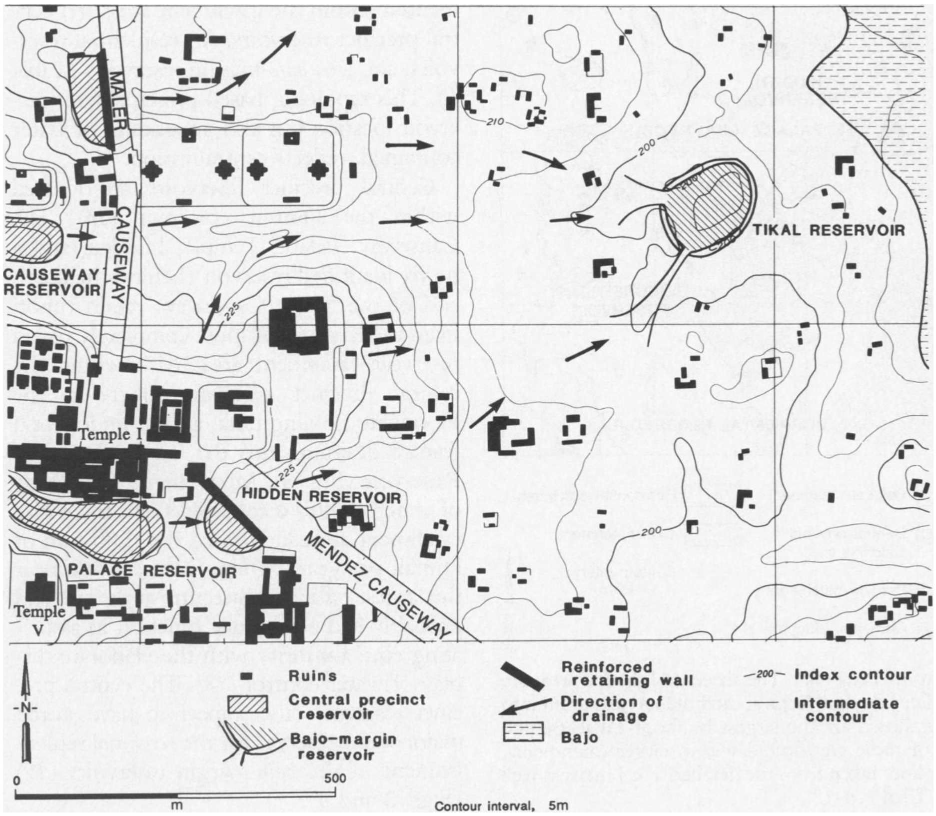

Fig. 4. Tikal reservoir catchment system. Map showing a section of Tikal that includes a catchment system designed to move water collected from the paved area on the left (west) to the *bajo*-margin Tikal Reservoir to the right (east) (*11*). The catchment system is known to have included clay-lined drainage ditches (*16*) which facilitated the transport of water from the paved uphill areas. The uphill portion on the left contains a number of central precinct reservoirs where water was held with the help of reinforced causeways. This water is thought to have been used for both direct consumption as well as the ultimate watering of fields beyond the Tikal Reservoir. Water could have been released through channels under the causeways, eventually reaching the Tikal Reservoir by means of the clay-lined ditches. There, water was held until needed for the *bajo*-margin fields. This elaborate system is suggested by the relative locations of causeways, the central precinct reservoirs, and the *bajo*-margin reservoirs (*10*). The contour lines suggested a general pattern of drainage consistent with this system.

Table 1. Reservoir and catchment dimensions. The table lists the critical dimensions of reservoirs and their catchments. *Pozas* are small, localized reservoirs associated with structures. *Aguadas* and other small reservoirs are not associated with structures. These latter two reservoir types compose a small fraction of the water available to Tikal and would be subject to early dry-season desiccation as a consequence of elevated evapotranspiration rates and their shallow depth. The second column shows the total number of reservoirs for each category. The third column shows the range of total reservoir capacity based on a low figure derived from extant capacity (*11*) and a high figure obtained from projected volumes (*10*). Ranges estimated for each reservoir in a category are summed. The fourth column gives the total surface area of the catchments in each category. Note that the *bajo*-margin reservoirs drain the Tikal, Corriental, Perdido, and Bejucal catchments, yet have a capacity of approximately half that of the central precinct reservoirs. This is a function of differing catchment seepage rates (*11*). Totals of annual rainwater accumulation collected by catchments in each category are based on 1500 mm per year of rainfall, adjusted by the amount of rain lost to seepage and multiplied by total catchment surface area. Seepage rates are determined independently for each catchment. All figures are based on calculations done by Gallopin (*10*) using the detailed maps of Tikal (*11*).

Reservoir type	No.	Reservoir capacity (m^3)	Catchment area (ha)	Rainfall (m^3/year)
Central precinct	6	105,108–243,711	61.90	928,500
Residential	3	42,647–133,921	56.37	603,324
Bajo-margin	4	48,956–172,149	125.63	1,379,322
Pozas	47	8,581–12,867	37.96	379,508
Aguada, other	15	1,450–4,956	16.71	174,974

water to agricultural fields, presumed—but not identified—on the borders of the *bajos* (*19, 20*).

Elsewhere in the southern Maya Lowlands, large tracts of raised or drained fields have been recorded in similar settings (*21, 22*). Sedimentation would have been greatest at the margins of the *bajos*, where steep-sided promontories graded into the gentle slope of a *bajo*, burying evidence of ancient fields. A millennium of accelerated infilling has occurred since Tikal flourished. Given the desiccation of *bajos* during the dry season, water in *bajo*-margin reservoirs may have kept raised fields moist and productive throughout the year. The absence of household groups around *bajo*-margin reservoirs may suggest that water entering them was polluted by passing through residential areas upslope. However, the recollection of the resource indicates a deliberate but subsequent use.

Other sites provide information on water collection and storage in the Maya area (*22, 23*). Two promising sites in western Belize are Caracol (*24*) and La Milpa (*25*), cities with large reservoirs away from permanent water sources and located at the summits of man-made watersheds. Western Belize, together with northeastern Guatemala, was a seat of early state-level Maya development and florescence.

Obviously, sites located near permanent sources of water or associated with large household *chultunes* (constricted orifice cisterns) (*26*) were less influenced by the centralizing forces affecting reservoir-dependent populations. However, in those areas of the southern Maya Lowlands without such water sources and with an abundant though seasonal rainfall, reservoir management may also have centralized population aggregates.

Drennan has recently argued that labor-intensive agricultural practices precipitated dispersed settlement in Mesoamerica (*1*). Further, he considers settlement compaction a normal condition and dispersion an anomaly. Whether or not early canal irrigation schemes of highland Mexico were a less labor-intensive means of production than terrace or drained-field agriculture of the lowland Maya (*8*), the different strategies for controlling water coincide with the different settlement adaptations. Urbanism, a function of many centralizing forces, is difficult to analyze in the Maya area because the settlement design is less nucleated than that of most early states. An early dependence on reservoirs and *aguadas* may have contributed to a dispersed population aggregate.

During the Late Classic Period, however, the Maya significantly expanded central precinct monumental architecture, resulting in quarries that may have become central precinct reservoirs. These reservoirs in turn promoted a degree of centralization and urban compaction on an otherwise dispersed settlement landscape. At Tikal, water management allowed resource control and therefore political control by a central-precinct elite. Reservoirs, which act as nodes in attracting population in seasonally water-scarce areas (*27*), are an underrecognized centralizing stimulus.

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Large Protein-Induced Dipoles for a Symmetric Carotenoid in a Photosynthetic Antenna Complex

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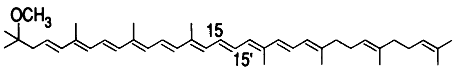
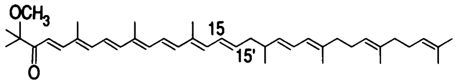
Unusually large electric field effects have been measured for the absorption spectra of carotenoids (spheroidene) in the B800–850 light-harvesting complex from the photosynthetic bacterium *Rhodobacter sphaeroides*. Quantitative analysis shows that the difference in the permanent dipole moment between the ground state and excited states in this protein complex is substantially larger than for pure spheroidene extracted from the protein. The results demonstrate the presence of a large perturbation on the electronic structure of this nearly symmetric carotenoid due to the organized environment in the protein. This work also provides an explanation for the seemingly anomalous dependence of carotenoid band shifts on transmembrane potential and a generally useful approach for calibrating electric field–sensitive dyes that are widely used to probe potentials in biological systems.

CAROTENOIDS ARE WIDELY DISTRIBUTED in nature and serve a wide range of functions (*1*). They are especially important in photosynthetic systems where they serve the dual functions of light harvesting and photoprotection (*2*). In addition to these important physiological roles of carotenoids, shifts in the absorption spectra of carotenoids have been widely used to measure transmembrane potentials and the electrogenicity of charge separation steps (*3*). Underlying the utility of these band shifts is quantitative information on the change in dipole moment, $\Delta\mu_A$, and the change in polarizability, $\Delta\alpha$, for these chromophores in their specific protein environment; to date, there is relatively little direct information on these essential properties. In the course of investigating the effects of applied electric fields on the absorption and emission spectra of bacteriochlorophyll a (BChl a) in photosynthetic antenna complexes (*4*), we examined the Stark effect spectrum in the region of the carotenoid absorption bands. Unusually large effects were observed, and these are shown to result from the interaction between the chromophore and the organized environment in the protein. The direct determination of electro-optic parameters for these polyene chromophores by Stark effect spectroscopy provides some of the quantitative basis needed for the evaluation of carotenoid band shifts under physiological conditions.

The B800–850 (LHII) antenna complex from purple nonsulfur bacteria such as *Rhodobacter sphaeroides* has been characterized in detail with respect to composition (*5, 6*), electronic absorption and emission spectroscopy (*7*), BChl a Stark effect spectroscopy (*4*), and energy transfer (*8*). This complex is the major pigment-bearing protein in the membranes of these organisms. Diffraction-quality crystals of B800–850 from different bacteria have been prepared by several groups (*9*), but a structure is not yet available. The complex consists of BChl a and carotenoid chromophores in a 2:1 ratio (*6*), which are complexed with a pair of α-helical transmembrane polypeptides (*10*). The chemical identity of the carotenoids present depends on the growth conditions: under anaerobic growth conditions, the dominant carotenoid is spheroidene; under semiaerobic growth conditions, spheroidenone accumulates with the exact fraction present dependent on the level of O_2 during cell growth (*11*).



Spheroidene



Spheroidenone

It is generally agreed that the carotenoids in the B800–850 complex are all-*trans* (*12*) and that their transition dipole moments, which are roughly parallel to the long molecular axis, lie approximately 45° to 50° away from the plane of the membrane (*13*). The carotenoids function both to transfer energy to the lower energy BChl a components and to quench potentially reactive and destructive BChl a triplet states, should they be formed (*2, 8*).

Stark effect spectroscopy can provide direct information on $\Delta\mu_A$, $\Delta\alpha$, and field-dependent changes in oscillator strength (due to transition polarizability and hyperpolarizability). If these effects are independent of each other, then for an immobilized isotropic sample, changes in dipole moment lead to band-broadening (second derivative–shaped features in the Stark effect spectrum), changes in polarizability lead to band shifts (first-derivative effects), and changes in oscillator strength produce zeroth and first-derivative effects (*14*). The apparatus for measurement of electric field effects and the determination of $|\Delta\mu_A|$ and the angle ζ_A between $\Delta\mu_A$ and the transition moment have been described (*15*).

All Stark effect spectra were found to scale quadratically with the externally applied electric field as expected for an isotropic, immobilized sample. Derivatives of the absorption spectra were obtained either directly from the data (generally smoothed with a Savitsky-Golay moving window or Fourier filtering) or the data were fitted to a combination of skewed Gaussian bands, followed by numerical differentiation. Contributions of zeroth, first, and second derivatives to the

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