Subterranean Waterworks of Biblical Jerusalem: Adaptation of a Karst System

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Ancient Jerusalem has long been known to possess a system of subterranean waterworks by which the spring of Gihon, which issues outside the walls, could be approached from within the city, and its waters diverted to an intramural pool. Most scholars regarded these waterworks as man-made, but the techniques of underground orientation and ventilation employed by the builders, as well as the numerous anomalies and ostensible mistakes in design, mystified investigators. Geological investigation has revealed the waterworks to be part of a well-developed karst system, a network of natural dissolution channels and shafts, in the limestone and dolomite underlying the city. Thus, it was not through primary planning but by means of skillful adaptation of these pre-existing natural features that the city was ensured of a dependable water supply during both war and peace. Likewise, knowledge of the subterranean access may have played a role in David's capture of the Jebusite city.

THE CANAANITE AND SUBSEQUENT ISRAELITE CITY OF JERUSALEM ("the City of David") was built on a narrow, southward sloping spur of the Temple Mount, flanked on the west by the Tyropoeon Valley and on the east by the Kidron Valley. The only perennial water source nearby is the Gihon Spring, which issues in a cave on the western bank of Kidron Valley, at the foot of the eastern slope of the City of David. To use the water from the spring the ancient inhabitants constructed, in chronological order, three water supply systems: Warren's Shaft Installation (WSI), the Siloam Channel, and Hezekiah's Tunnel (HT). The Siloam Channel carried artificially raised spring water southward alongside the valley, outside the walls. The WSI and HT are subterranean systems. Their plans and methods of construction have puzzled archeologists and historians since their discovery in the 19th century, and they are the subject of my investigation.

Plan of the Waterworks

Warren's Shaft Installation was discovered by Charles Warren in 1867 (*1*) and comprehensively described by Vincent (*2*). The system was "rediscovered" in 1980 by the City of David Archaeological Project (CODAP) (*3*), which cleaned out and provided access to all parts of the installation. This waterworks was built in two levels, connected by a vertical shaft, known as Warren's Shaft (WS) (Fig. 1). The lower level consists of a horizontal tunnel that brought water from the Gihon Spring to the bottom of the shaft. The shaft itself served as a well through which water was hauled up to the upper level. Its lower part, cleaned out by CODAP in 1981, was found to continue downward for another 2.7 m below the level of the tunnel that connects it to the Gihon Spring. The upper level of the installation consists of a tunnel leading from the top of the shaft upward into the city. A dead-end shaft (DES), today filled, descends from under the top of the upper tunnel (3 in Fig. 1). Another passage (7 in Fig. 1) leads from the top of the shaft in the opposite direction and emerges on the eastern slope, outside the ancient Israelite city wall.

Hezekiah's Tunnel (Fig. 2) is a subterranean aqueduct that carries the waters of the Gihon to an open reservoir in the Tyropoeon Valley, which at the time was within the walled perimeter of the city. The tunnel was discovered by Robinson and Smith in 1838 (*4*) and described in meticulous detail by Vincent (*2*).

The construction of Hezekiah's Tunnel is mentioned in the Old Testament and in Ecclesiasticus (*5*). It was built by King Hezekiah, about 700 B.C., in preparation for an impending siege by the Assyrians. Its purpose was to divert the waters of Gihon into a reservoir inside the city, thus providing a secure water supply in case of siege and denying it to the enemy. The builders immortalized the successful completion of the project in the famous Siloam Inscription, written in ancient Hebrew script on the tunnel wall (*6*). From this inscription we learn that the tunnel was dug by two teams working toward each other from both ends.

Anomalies and Questions of Construction

The design of the waterworks is puzzling. Although its fundamental purposes are clear there appears to be no logic behind some choices of routes, slopes, and dimensions of the tunnels, the unnecessary hewing in harder bedrock, and the construction of apparently useless components, all of which required vastly superfluous excavation. Furthermore, at least with respect to WSI, the installation is notably inconvenient to use. The more prominent anomalies in the waterworks are outlined in Figs. 1 and 2. The majority of scholars have tended to regard the waterworks as entirely manmade and therefore to ascribe the anomalies to human intent or error. The following explanations have been suggested for some of them:

Clermont-Ganneau (*7*) proposed that the southern bend in the tunnel was necessary to avoid the desecration of passing underneath the tombs of the House of David, whereas the northern bend of the tunnel was planned to meet a certain well within the city. However, the tombs in question are probably not royal (*8, 9*), and no well was encountered anywhere along the tunnel. Vincent (*2*) suggested that the frequent meandering near the meeting point of the teams is due to "false echoes" from the axes, which misdirected the workmen, and their "nervous haste" toward the imminent meeting.

As to WSI, Vincent (*2*) thought that the unnecessary prolongation of the curved upper tunnel was designed to moderate its slope. Simons (*8*) suggested that the scarp in the middle of the tunnel was a defense measure and that the exit to the eastern slope was especially

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made for the disposal of excavation waste. Vincent (*2*) regarded the DES as an early attempt to reach the Gihon water level, discontinued because the workmen encountered hard rock that they could not penetrate. This interpretation was later adopted by Hecker (*10*) who brought up more geological arguments which, as found by the present investigation, were based on an incorrect interpretation of the actual stratigraphic setting. In the absence of convincing explanations the ostensible flaws in design were often dismissed as "mistakes" or attributed to careless engineering (*2, 8, 11*).

Besides the aforementioned anomalies, the construction of the waterworks raises questions regarding technical means. The builders must have been faced with at least two crucial problems: the first was ventilation, indispensable for miners working at the blind end of a narrow passage and moreover using oil-burning lamps; the second was accurate underground orientation, especially important in the construction of HT, where two teams progressed toward a planned meeting point from opposite directions. Next to nothing is known of the surveying methods and mining techniques available at the time, but because instruments could not have been but primitive and inaccurate, both ventilation and orientation appear to have been insurmountable obstacles.

Sulley (*12*), followed by Amiran (*13*) and Issar (*14*), suggested that the builders of HT may have followed a natural fissure. The present investigation provides a lithological and stratigraphical background, and documents the presence of a well-developed natural karst system (dissolution and channeling by ground water) in the limestone and dolomite hill on which the city was built, thus providing clues to many of the anomalies, as well as to the technologic questions.

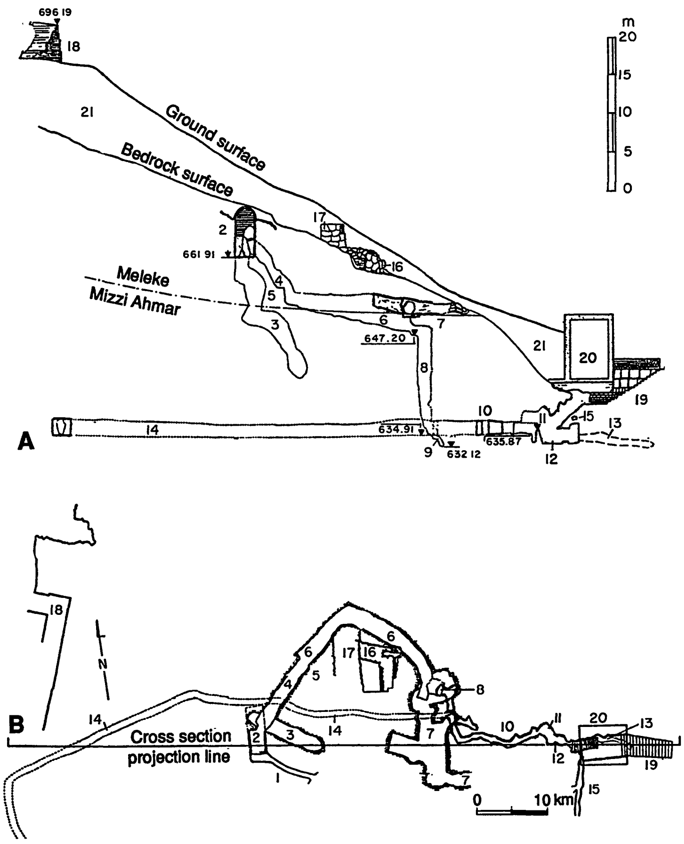

Fig. 1. (**A**) Cross section and (**B**) plan of Warren's Shaft Installation (WSI), modified after Vincent (*2*), Kenyon (*10*) and Shiloh (*3*). Note the position of the boundary between the Meleke and the Mizzi Ahmar strata (Fig. 2A). Key: 1, entrance corridor; 2–6, upper tunnel; 2, vaulted chamber; 3, dead-end shaft; 4, steep tunnel; 5, scarp; 6, inclined tunnel; 7, passage with blocked exit; 8, Warren's Shaft; 9, sinkhole termination; 10, lower tunnel; 11, cave of Gihon; 12, Gihon Spring; 13, defunct outlet of Gihon to Kidron Valley; 14, Hezekiah's Tunnel; 15, head of Siloam Channel; 16, Canaanite (Jebusite) city wall; 17, Israelite city wall; 18, Hasmonean tower; 19, staircase; 20, modern building; and 21, unconsolidated and partly stratified debris. The main apparent anomalies in WSI are the dead-end shaft (3), which appears to have no function; the very steep inclination (33°) of the upper part (4) of the upper tunnel; the 2.7-m vertical scarp at the bottom of the steep section (5); the curved pathway of the upper tunnel (4 and 6), which increases its length from a possible 25 m to an actual 42 m; the excessively spacious dimensions (6 m high and 4 to 6 m wide) of the gallery at the lower end of the inclined tunnel (6); the passage (7) that leads from the upper tunnel outside to the eastern slope, which is a potential flaw in the city's defenses. Far from being a plumbline cylindrical well, the 12.3 m long Warren's Shaft is dangerous to approach, irregularly shaped, lined with calcareous crusts, and has a projecting ledge in its lower third, interfering with the hauling path. The extra length of the shaft (9) below the level of the lower tunnel (10), which is unneeded for hydrostatic purposes.

Geological Aspects of the Waterworks

The spur of the City of David is a downfaulted block of Cenomanian-Turonian formations dipping 10° to 15° to the southeast. The lower part of the spur is built of Mizzi Ahmar dolomite and its upper part of Meleke limestone (Fig. 3). Several minor faults, each with a throw of 20 to 30 m, transect the area. Two sets of vertical joints, one trending roughly north-south and the other north 70° east, can be discerned. The upper level of WSI is within the Meleke, whereas the lower half of the DES, as well as WS and HT along their entire lengths, are within the Mizzi Ahmar (Figs. 1A and 3).

The Mizzi Ahmar consists of homogeneous, fine-crystalline, dense, very hard dolomite, composed of a uniform mosaic of subhedral to euhedral crystals, about 40 μm across. The rock is practically impervious, with an average porosity of 2.6% and a permeability of 0.13 millidarcys. The Meleke is a fossiliferous limestone, with fossil fragments making up about 30% of the rock. The original matrix consisted of very fine-grained lime mud, parts of which have recrystallized into a dense mosaic of anhedral calcite. The extent of matrix recrystallization determines the hardness of the rock, its resistance to weathering, and its overall morphology. Thus, where recrystallization is more pervasive, the unit is hard and cliff-forming. The Meleke is very porous (8 to 15%) and permeable (135 millidarcys). Porosity was created mainly by dissolution and leaching of biogenic fossil fragments.

Both the Mizzi Ahmar and the Meleke have been affected by karst, though in different styles, according to their lithologic properties and stratigraphic relations. In the Meleke permeability is isotropic, and water can move relatively freely in all directions, whereas the Mizzi Ahmar is practically impervious. Consequently, water reaching the base of the Meleke is forced to continue its flow along the boundary between the two formations. This enhances dissolution and channeling along and above the contact at the expense of the less resistant Meleke, resulting in the development of caves along the contact. In the impervious Mizzi Ahmar, dissolution occurs along more permeable boundaries such as bedding planes, faults, and joints. Once an initial dissolution channel is formed, it draws more water and is continuously enlarged, forming joint-controlled vertical dissolution shafts connecting narrow, subhorizontal flow nets and conduits.

Karst in the Judea Group and in the Jerusalem Waterworks

The Judea Group carbonates have been repeatedly affected by karst-forming processes during the 90 million years since their formation (*15*). The most intensive phase occurred following the

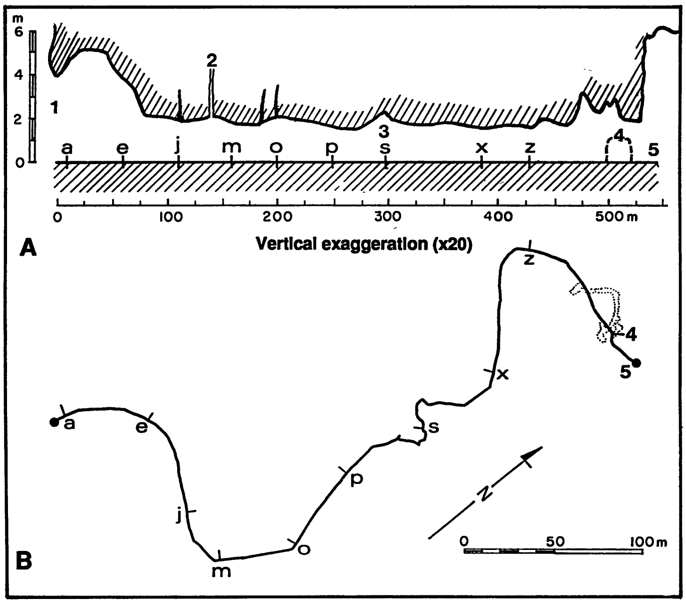

Fig. 2. (**A**) Longitudinal profile and (**B**) plan of Hezekiah's Tunnel; modified after Vincent (*2*). The letters a to z mark Vincent's reference points. Note the following anomalies: the winding route, which increases the distance between its ends from a rectilinear 320 m to a flow distance of 533 m; the variable height of the ceiling, mostly hewn to a height of 1.7 to 2.0 m, but rough and irregular along sections that are higher, especially in the southernmost 70 m, where it attains 5.08 m near the exit. The floor of the tunnel runs smoothly at a 0.06% average slope, descending a mere 0.32 m between entrance and exit—an accuracy that discounts the probability that anomalies are due to incompetence or carelessness. Key: 1, outlet to Tyropoeon Valley; 2, blocked sinkhole in ceiling; 3, hewers' meeting point; 4, entrance to Warren's Shaft; and 5, Gihon Spring.

late Cenozoic uplift (*16*). Karst development was further enhanced during the pluvial interludes of the Pleistocene, which were characterized by high rainfall and rich vegetation (*17*). Around Jerusalem, karst in correlative rock units is particularly well developed east of the regional water divide, where one finds some of the largest caves in the country (*18, 19*), as well as karst-controlled aquifers and springs (*20, 21*). Effects of these karst-forming episodes can also be seen in Jerusalem. Karst features in the Mizzi Ahmar include irregular solution cavities, small caves, and short shafts filled with dark brown loams and breccias. Jerusalem number 4 water well, located in the Ben-Hinnom Valley, encountered a loss-of-circulation zone in the Mizzi Ahmar section, indicating the existence of large cavernous openings in the subsurface. Caves in the Meleke are common along the southern bank of Ben-Hinnom Valley, the larger ones occurring near the Monastery of Haqaldama, close to the confluence of the Ben-Hinnom and Kidron valleys.

Many karst features, small- and large-scale, are visible in the waterworks. Warren's Shaft, with its irregular shape and the calcareous crusts that coat its walls, is a natural sinkhole. The shaft developed along a joint, which can be traced along its entire length. Its bottom is tapering and funnel-shaped, with rough walls, entirely similar to the natural termination of a karstic sinkhole. A fragment of calcareous crust was analyzed for carbon-14 but contained none (*22*), indicating that the crust is older than 40,000 years. The shaft can therefore not be manmade. According to Vincent's description of the nearby DES (*2*), which noted its irregular shape, its rough walls, natural encrustations and gradual downward narrowing, this feature is likewise a natural karstic sinkhole. The passage from the top of WS to the eastern slope, which follows a series of interconnected caves in the Meleke, is also an obvious dissolution channel on top of the Mizzi Ahmar.

The Gihon Spring itself, which issues in a natural cave, is an expression of the karst in the area. "Gihon" is most aptly translated as "gusher," describing the pulsating regime of a water source that gushes forth intermittently. Nowadays the spring flows sparingly and no longer gushes, but its pulsating nature is mentioned in sources as late as the end of the 19th (*23, 24*) and the beginning of the 20th century (*2*). Pulsating flow is caused by the periodic charge and discharge of a subterranean siphon, typical of karst terrains. Additional noteworthy karst features in HT are several small caves located south of the cave of Gihon (*2*), and another large sinkhole opening in the ceiling of HT, located 142 m east of the southern end of the tunnel (2 in Fig. 2A) (*2, 25, 26*).

A Scenario for the Construction of the Waterworks

The apparent "mistakes" in the waterworks are so fundamental and numerous that it is unlikely that they were deliberately planned. Previous authors tried to rationalize each anomaly individually instead of looking for a common reason. A reexamination of the waterworks suggests that it was fashioned essentially by skillful enlargement of natural (karstic) dissolution channels and shafts and their integration into a functional water supply system.

The construction of HT could therefore have proceeded along the lines of the following scenario: A natural dissolution channel ran a winding course under the hill (Fig. 2B), connecting an opening on the east slope of the Tyropoeon Valley with the Gihon Spring, through the lower tunnel of WSI, but not at the right slope to convey water. It may have been large enough for a man to crawl through from end to end (at least the Gihon-WS section was already passable), or otherwise it was first enlarged sufficiently to ascertain that it did indeed connect with Gihon. Once the connection was established, massive two-way tunneling, as related in the Siloam

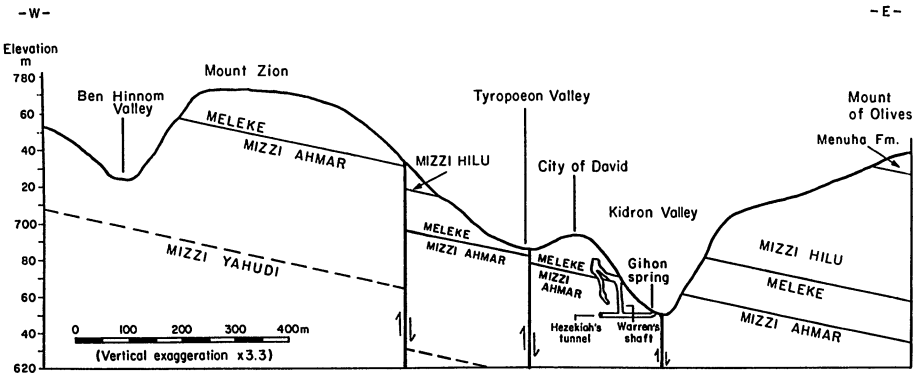

Fig. 3. East-west geological profile through the City of David showing the waterworks with respect to the lithostratigraphic units.

Inscription, could be launched with assurance of success. After the linkup the slope of the channel was reversed by careful downward cutting to the desired level and inclination. This had to be done with precision, most likely by a single team of workers who progressed from the spring downward. This mode of construction is also hinted at in the Old Testament. The final stage of the work was to raise the ceiling to the desired height, leaving the original ceiling undisturbed where it was high to begin with. Most of these unnecessarily high sections (>2 m) (Fig. 2A) consist of rough bedrock and are evidently relics of the original dissolution channel. Smoothly hewn sections of the ceiling mark segments where the original ceiling was too low. This seems a straightforward explanation for the irregular height of the tunnel (Fig. 2A). If correct, it follows that the original southern entrance to the channel may have been up to 5 m above the elevation of the Gihon.

It was possible to hew the tunnel under dry conditions because until its slope was reversed the waters of Gihon flowed out through the Siloam Channel (*2, 3, 8*) which begins 2.38 m above the Gihon's level of issue (*27*) (15 in Fig. 1A). The water could be raised to this level by a dam, which blocked the lower tunnel of WSI (*2*). After HT was completed the dam was removed and the water flowed into the reservoir in the Tyropoeon Valley.

A similar scenario can be inferred for the construction of WSI. Originally the upper tunnel was a dissolution channel with its entrance upslope the hill and its exit downslope, connecting several caves along the way. Two sinkholes, DES and WS, branched down from it. By exploring the recesses of the cave of Gihon, the ancients found the fissure leading up to the WS sinkhole, and by careful downcutting they made it into a roughly level conduit through which the water of Gihon could flow to the bottom of WS, which now could serve as a well shaft. On their way the hewers encountered the branching fissure that led all the way to Tyropoeon and which in due time became HT, as described above. The bottom of WS was sealed to prevent downward leakage of water, and the caves of the upper level were made passable by filling (or at least covering) the pitfall of the DES, and safe from invaders by blocking and concealing the eastern exit. It appears that the configuration of most of the natural elements was not significantly altered, which is why this installation contains so many apparent "mistakes" and is so inconvenient to use.

This interpretation, based on the finding of pre-existing karst features, provides a unified explanation for the apparent errors in design, and explains how the builders overcame the problems of underground orientation and ventilation. Because the miners were guided by existing passageways, the orientation issue did not even arise. Ventilation was supplied by the natural conduits and sinkholes, which were interconnected and open to the atmosphere, providing the airflow without which underground tunneling operations would have been impossible.

Biblical Texts and the Proposed Scenario

A passage in Chronicles reads, "And he, Hezekiah, stoppered the upper outlet of Gihon's waters and straightened them down westward of the City of David" (*28*). The structure of the Hebrew sentence allows for the reading "upper Gihon" instead of "upper outlet of Gihon," an ambiguity that has led several scholars (*2, 13, 29*) to infer the presence of an "upper" and a "lower" Gihon spring. It was even postulated that the lower exit of HT (whose original ceiling is actually 5 m higher than the level of the spring) might be the inferred "lower Gihon." The correct reading, however, admirably fits the scenario presented here (accepting that "straightened" is the term used for "guided along a precise slope," which is too technical for archaic Hebrew). It also comes as a sensible sequel to the foregoing verse: "And a host of people gathered and they stopped all the springs, and the brook that ran in the midst of the land" (*30*)—describing the sealing of Gihon's entrance into the Siloam Channel and the channel's outlets into the natural streambed of Kidron (*8*).

In Samuel occurs a somewhat obscure text describing the capture of Jerusalem by David and his men: "And David captured the fortress of Zion, which is the City of David. And David said on that day: Whosoever strikes a Jebusite and touches the *tsinnor*, and the lame and the blind that are hated of David's soul. Wherefore it is said: a blind and a lame [person] shall not enter the house" (*31*). Chronicles presents a different version: " . . . and David captured the fortress of Zion, which is the City of David. And David said: Whosoever is first to strike a Jebusite shall be chief and captain. So Joab the son of Tseruyah went up first, and became chief" (*32*). Considering both narratives, the crux centers around the term *tsinnor*, which has been traditionally interpreted as pipe or gutter. Several scholars (*2, 8*) have interpreted the combined texts in the sense that Joab daringly entered Gihon, found Warren's shaft (the *tsinnor*), clambered up, and surprised the defenders. On the other hand, Shiloh (*3, 33*), quoting authorities, pointed out that hewn waterworks are unknown in the pre-Israelite cities of the country, and that WSI could therefore not have existed at the time.

Linguistic issues aside, the present investigation establishes that ancient (Jebusite) Jerusalem could be entered from at least two extramural points on the eastern hillside: the cave of Gihon, and the upper tunnel of WSI, which both connected to pre-existing natural passages, but whose whereabouts was most likely known only to insiders. Thus, if anything, the present findings provide support to Joab's exploit (the capturing of Jerusalem by using a hidden passage), based on geologic fact rather than on linguistic assumptions.

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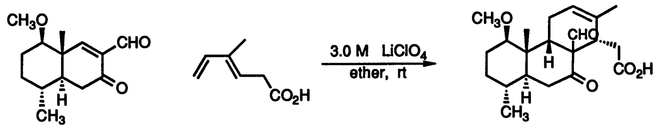
The Atom Economy—A Search for Synthetic Efficiency

BARRY M. TROST

Efficient synthetic methods required to assemble complex molecular arrays include reactions that are both selective (chemo-, regio-, diastereo-, and enantio-) and economical in atom count (maximum number of atoms of reactants appearing in the products). Methods that involve simply combining two or more building blocks with any other reactant needed only catalytically constitute the highest degree of atom economy. Transition metal–catalyzed methods that are both selective and economical for formation of cyclic structures, of great interest for biological purposes, represent an important starting point for this long-term goal. The limited availability of raw materials, combined with environmental concerns, require the highlighting of these goals

THE CONTINUING SOPHISTICATION IN AND EVER CHANGING landscape of molecular targets for a myriad of applications ranging from biology to materials science requires a continuing evolution of synthetic methods. A key goal must be synthetic efficiency in transforming readily available starting materials to the final target. Selectivity—chemo- (functional group differentiation), regio- (orientational control of two reacting partners), diastereo- (control of relative stereochemistry), and enantio- (control of absolute stereochemistry)—has been the prime focal point because it defines the overall length of a sequence of reactions that constitutes a synthetic strategy (*1*). The success of the selective synthetic methods that have been developed is readily apparent by the ever more complex targets, exemplified by the successful synthesis of palytoxin, an extremely potent marine toxin of 128 carbons, 64 of which are stereogenic centers, that has more than two sextillion possible stereoisomers (*2*).

In the quest for selectivity, a second feature of efficiency is frequently overlooked—how much of the reactants end up in the product, a feature we might refer to as atom economy. Consider regioselective methylenation with methyltriphenylphosphonium bromide, wherein a mass of only 14 out of 365 is transferred. The importance of this reaction cannot be overstated; we tolerate its uneconomical use of mass because it solves a selectivity problem we could not resolve otherwise. An alternative process that is both selective and atom economical remains a challenge. The ideal reaction would incorporate all of the atoms of the reactants. Major benefits that derive from such processes include more effective use of limited raw materials and decreased emissions and waste disposal. Such reactions do exist in our repertoire of synthetic methods. Most noteworthy among the classical reactions are the [$4n + 2$] electron cycloaddition, represented by the Diels-Alder reaction (Eq. 1; rt = room temperature) (*3*) and the aldol condensation (Eq. 2; TBDMS = *tert*-butyldimethylsilyl, THF = tetrahydrofuran, i-C_3H_7 = isopropyl) (*4*),



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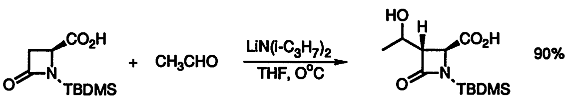

(2)

although the latter normally requires a stoichiometric amount of base "catalyst." A primary goal is the evolution of synthetic methods requiring only catalytic quantities of "activators." The ability of transition metal complexes to activate organic molecules makes them attractive prospects for developing catalytic processes with high atom economy. This concept is already embodied in important industrial processes such as Ziegler-Natta polymerization (*5*) and hydroformylation (*6*). However, little or no attention has been focused on developing such methods for the synthesis of complex molecular architecture or for intramolecular processes. This article examines these latter efforts with an emphasis on carbocyclic ring construction. All of the reactions involve simple summation of the reacting partners to form products, and any additional reagents are used only in catalytic quantities to serve as true catalysts, that is, substances that promote chemical change without being altered themselves.

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