ic evolution, and its possible effect on organic evolution (*20*), is an integral part of Phanerozoic earth history, and that gas bubbles in fossil amber, with much more work, may provide an indication of ancient atmospheric composition.

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21. We are indebted to R. M. Garrels for suggesting this study, to E. Roedder for encouragement, to J. Langenheim (Dominican 1 and 3 and modern resin) and F. Carpenter (Baltic and Cedar Lake) for providing amber samples, to C. Remington for helping us to locate samples, and to J. M. Hayes, L. Kump, and M. Baur for criticisms and suggestions. We also thank E. Faller, J. Leventhal, M. Wasserman, D. Rye, and R. Mahrt for technical assistance.

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The 1987 Whittier Narrows Earthquake in the Los Angeles Metropolitan Area, California

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The Whittier Narrows earthquake sequence (local magnitude, M_L = 5.9), which caused over $358-million damage, indicates that assessments of earthquake hazards in the Los Angeles metropolitan area may be underestimated. The sequence ruptured a previously unidentified thrust fault that may be part of a large system of thrust faults that extends across the entire east-west length of the northern margin of the Los Angeles basin. Peak horizontal accelerations from the main shock, which were measured at ground level and in structures, were as high as 0.6*g* (where *g* is the acceleration of gravity at sea level) within 50 kilometers of the epicenter. The distribution of the modified Mercalli intensity VII reflects a broad north-south elongated zone of damage that is approximately centered on the main shock epicenter.

The moderate-sized (M_L = 5.9) Whittier Narrows main shock, which occurred in the east Los Angeles metropolitan area at 7:42 (PDT) on 1 October 1987, caused three direct fatalities and substantial damage in many communities in Los Angeles and Orange counties (*1*). The main shock was located at 34°3.0′N, 118°4.8′W, 3 km north of the Whittier Narrows (*2, 3*) and at the northwestern end of the Puente Hills (Fig. 1). The depth of focus of the main shock is estimated to have been 14 ± 1 km. The epicenters of the aftershocks form an approximately circular pattern that is centered at the epicenter of the main shock and has a diameter of 4 to 5 km (Fig. 2); the hypocenters define a surface that dips gently to the north. The spatial extent of the aftershock zone is smaller than for most M_L = 5.9 main shocks. By comparison, the 1986 North Palm Springs earthquake (M_L = 5.6) had an aftershock zone of 9 km by 16 km (*4*). The focal mechanism of the main shock, which was derived from first motion polarities, has two nodal planes, that is, possible fault planes, that strike east-west and dip 25° to the north and 65° to the south. The maximum compressive stress is estimated to trend 163° (south-southeast) and plunge 6° (*5*). The spatial distribution of the hypocenters of the main shock and aftershocks as well as the focal mechanism of the main shock indicates that the causative fault is a gently north-dipping thrust fault with an east-west strike that is located at depths from 11 to 16 km. No surface rupture for the Whittier Narrows earthquake has been documented (*6*).

The Whittier Narrows earthquake was located near the subsurface intersection of the west-northwest striking Whittier fault and the east-west striking thrust faults of the southern margin of the Transverse Ranges. Where it is best exposed in the Puente Hills, the Whittier fault is dominantly a northeast-dipping strike-slip fault with a small reverse component. The Whittier Narrows main shock was not caused by slip on the Whittier fault because it ruptured a gently dipping thrust fault with an east-west strike. The seismogenic potential of such thrust faults has long been recognized farther to the north along the exposed frontal fault system of the Transverse Ranges. For instance, the 1971 (M_L = 6.4) San Fernando earthquake occurred along the frontal fault system (*7*).

The spatial distribution of hypocenters of the main shock and aftershocks indicates that the Whittier Narrows earthquake sequence ruptured a thrust fault beneath the uplifted Elysian Park–Montebello Hills and Puente Hills. These uplifts are surface expressions of anticlines that are part of a large and mostly buried antiform (an anticline in which the stratigraphy is uncertain).

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This antiform is the result of folding in the hanging wall of a buried system of thrust faults and extends from the Puente Hills in the east through Santa Monica to the Santa Barbara Channel Islands in the west (Fig. 1). The Montebello and Elysian Park anticlines have formed above shallow thrust faults that did not rupture in the Whittier Narrows main shock. The zone of thrust faults making the antiform and higher anticlines has been identified in the northwest Los Angeles basin through seismotectonic analysis of small earthquakes (*3*). The moderate-sized 1973 (M_L = 5.9) Point Mugu and the 1979 (M_L = 5.0) Malibu earthquakes occurred along thrust or reverse faults at the base of the regional antiform (*8*, *9*). Thus the antiform appears to be the shallow crustal expression of a system of seismogenic thrust faults that is capable of generating moderate-sized destructive earthquakes along the northern edge of the basin. The Whittier Narrows earthquake indicates that active thrust faulting associated with this fault system extends farther to the southeast, and into the Los Angeles basin, than previously thought.

The focal mechanism of the main shock was also determined by modeling long- and short-period teleseismic P and S waves. This focal mechanism is very similar to the focal mechanism that was obtained from the local data (Fig. 2). The teleseismic records can also be matched if we assume that the main shock actually was a double event or had two separate source areas. The first source area is the gently dipping fault plane that was defined by the local seismological data (Fig. 2). The second source area is a more steeply dipping fault that is located at shallower depth and 2 km to the south of the first source. These observations and the distribution of aftershock hypocenters and focal mechanisms suggest that the fault of the main shock may have a listric shape, such that the dip of the fault becomes shallower at greater depths.

The recorded teleseismic amplitudes correspond to a seismic moment of 1.0×10^{25} dyne-cm (*10*). An independent determination of the moment is obtained by least-squares fitting of the observed strain offsets that were recorded by a 14-station dilatometer network in California to those expected from an elastic dislocation model of the event. This method indicates a total moment of 1.1×10^{25} dyne-cm (*11*). These estimates are approximately 15 times smaller than the seismic moment of the 1971 San Fernando earthquake (*12*).

The largest aftershock (M_L = 5.3), which occurred at 3:59 (PDT) on 4 October 1987, was located 3 km to the northwest of the main shock's epicenter. In contrast with the main shock, the focal mechanism of the largest aftershock shows mostly strike-slip movement with a small reverse component on a steeply dipping northwest-striking plane. The focus is located at a depth of 12 ± 1 km, which is within the hanging wall of the thrust fault and 2 to 3 km above the rupture surface of the main shock. The locations of the two largest and numerous smaller aftershocks define a north-northwest–striking, steeply dipping fault that forms the western edge of the aftershock distribution of the main shock (Fig. 2). The spatial distribution of aftershock hypocenters indicates that this steeply dipping fault is present within both the hanging and the foot wall, and the main shock slip thus may have terminated against this fault. The dynamic stress loading from the main shock may have triggered the largest aftershock on this steeply dipping fault.

Several hundred accelerograms of ground motion were obtained both at ground-level stations (Fig. 3) and at structural stations mostly in high-rise buildings (*13*). Horizontal peak accelerations ranged up to 0.6*g* within 50 km of the main shock epicenter. For most ground-level stations, the duration of strong ground shaking was 2 to 4 seconds. The nearest strong motion station to the epicenter (Garvey Reservoir) was situated approximately 3 km away on bedrock. Peak accelerations at this site were 0.47*g* horizontal and 0.38*g* vertical. The distribution of high peak accelerations around the main shock epicenter was asymmetric; accelerations were higher than average to the south and north as well as to the west in the center of the Los Angeles basin and to the northwest in the middle of the San Fernando Valley (Fig. 3). Peak acceleration values are not available yet from recorders located to the east within 25 km of the epicenter, however. The pattern of seismic radiation from the main shock rupture and local site effects, which were caused partly by a southwesterly thickening prism of sedimentary rock and by the distribution of unconsolidated fluvial sediments in the Los Angeles basin and the San Fernando Valley (*14*), could have contributed to this asymmetric distribution. Detailed studies of the accelerograms, the site geology, and damage to structures are needed to understand better this distribution.

The city of Whittier experienced ground shaking of modified Mercalli intensity (MMI) VIII, which was the highest intensity reported. The oldest structures, built between 1900 and 1920 in the old Whittier commercial district, the historic uptown, suffered the most damage. This area also suffered severe damage in the 1929 Whittier earthquake (*15*), which may have been on the Norwalk fault. Most of the greater Los Angeles metropolitan area experienced MMI of VI or VII (Fig. 1). The region with MMI of at least VII shows an asymmetric distribution with a broad north-south elongated zone of damage approximately cen-

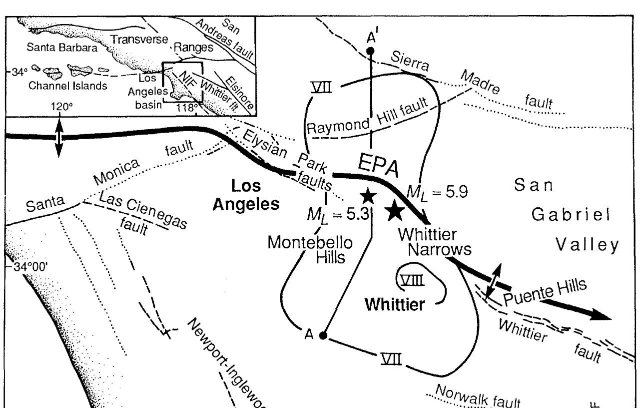

Fig. 1. An overview of the Los Angeles basin, southern California (location map in the upper left corner; NIF is the Newport-Inglewood fault). Epicenters of the Whittier Narrows main shock (M_L = 5.9) and largest aftershock (M_L = 5.3), and preliminary modified Mercalli intensity contours of VII and VIII are shown. Faults from (*23*) are shown as dotted lines where concealed by alluvium or late Tertiary deposits, dashed lines where inferred, or solid lines where exposed. Faults located to the south of the epicenter of the Whittier Narrows earthquake accommodate mostly strike-slip movement, whereas faults that are located to the north accommodate mostly reverse or thrust movement. The axis of the Elysian Park–Montebello Hills and Puente Hills antiform (EPA) is indicated with a thick curved line. (Lower right) An approximate geologic cross section (A–A') where LCF is the Las Cienegas fault adjacent to the EPA; WF is the Whittier fault; EPF is the proposed Elysian Park thrust fault; RHF is the Raymond Hill fault; SMDF is the Sierra Madre fault; and MOF is the Montebello oil field. The closed circles indicate top of basement as determined by gravity; solid lines with arrows indicate thrust faults; dashed lines with arrows indicate reverse, normal, or strike-slip faults. Ages of the sedimentary rocks that form the Elysian Park antiform are indicated to the left in the cross section.

tered on the epicenter of the main shock.

During the last decade, many man-made structures in the Los Angeles metropolitan area have been instrumented with extensive arrays of strong motion accelerographs to record the accelerations that they experience from ground shaking during earthquakes (*13*). During the Whittier Narrows main shock, these arrays recorded the detailed time history of longitudinal, transverse, and torsional mode accelerations in high-rise buildings in downtown Los Angeles. For instance, a 33-story, steel-frame office tower 17 km west of the epicenter experienced a maximum horizontal acceleration of 0.21*g* at ground level and of approximately 0.24 to 0.26*g* on the 12th and 13th floors. The 32nd floor had a peak acceleration of 0.19*g*. Several buildings on the campus of California State University, Los Angeles, which is 10 km west of the epicenter, sustained damage. A damaged, nine-story reinforced concrete building on campus experienced 0.4*g* acceleration at its base. This acceleration is similar to the peak acceleration that damaged the similarly designed Imperial County Services building in El Centro during the 1979 Imperial Valley earthquake (M_L = 6.6). In the Whittier Narrows earthquake, however, the duration of the ground shaking was somewhat shorter and with less long-period energy than in the 1979 earthquake.

The largest horizontal peak acceleration reported so far (0.63*g*) was in a ten-story reinforced concrete apartment building in the heavily damaged uptown section of Whittier, 10 km south of the epicenter. The high-rise sustained no significant damage (*13*). To date, only this one set of acceleration records is available from the area of severe damage in Whittier. Hence, it is not yet possible to tell whether the excessive damage in Whittier at a large distance from the main shock epicenter was caused by an anomalous site or source effect or whether it simply indicates that the many old (1900 to 1920) buildings in Whittier were particularly susceptible to earthquake damage. The second highest peak acceleration (0.62*g*) that was recorded 44 km away in Tarzana, San Fernando Valley, is an anomalous record because it is three to four times larger than accelerations recorded elsewhere at similar epicentral distances (Fig. 3).

Because the rupture of the thrust fault during the main shock did not break the surface, the Whittier main shock probably caused less ground shaking and property damage than would be expected in a similar magnitude earthquake that ruptured the surface. For instance, the (M_L = 6.4) San Fernando earthquake ruptured from 14-km depth up to the surface whereas the Whittier Narrows earthquake only ruptured from approximately 16-km depth up to about 11-km depth, if we assume that the aftershock zone defines the extent of rupture. The largest peak acceleration (1.25*g* at Pacoima Dam) during the 1971 San Fernando earthquake (*12*) can be compared to the 0.47*g* horizontal peak acceleration at Garvey Reservoir.

The Whittier Narrows earthquake was neither predicted nor preceded by obvious earthquake precursors such as significant changes in the rate of occurrence of small earthquakes in the Los Angeles basin (*16–19*). Between 1970 and 1987 seven other $M_L \geq 5.0$ earthquakes occurred west of the San Andreas fault in southern California. These earthquakes are distributed over a large geographic area and are generally associated with low slip-rate faults (*20*). Over the last century, moderate-sized earthquakes have occurred more frequently on thrust faults in the Transverse Ranges than along north-northwest striking strike-slip faults

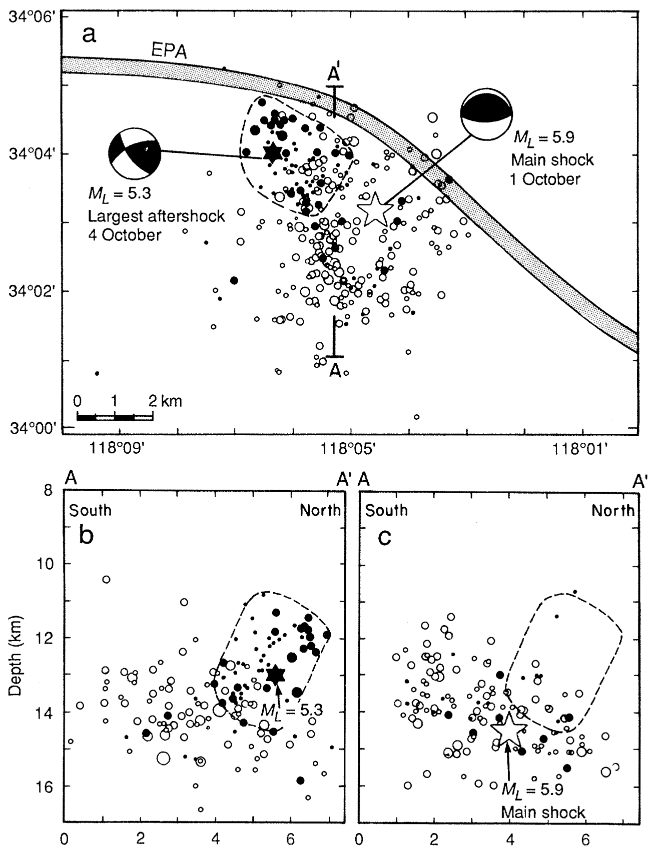

Fig. 2. Map (a) and cross sections (b and c) of the main shock (shown as an open star) and aftershocks. Open circles represent epicenters of all aftershocks that were recorded by the Southern California Seismic Network and the University of Southern California Los Angeles Basin Seismic Network before 10:59 (UT) 4 October 1987, the time of the largest (M_L = 5.3) aftershock. Closed circles represent epicenters of aftershocks that occurred after the largest aftershock (shown as a closed star) and before 12 October 1987. Lower hemisphere focal mechanisms from first motion polarities, where compressive quadrants are black and dilational quadrants are white, are shown for the main shock and largest aftershock in (**a**). Dashed curve that encloses the aftershock zone of the largest aftershock is also shown in cross sections (b) and (c). The shaded heavy curve (EPA) is the axis of the Elysian Park antiform. (**b**) Aftershocks located to the west of line A–A′ with depth error less than 0.5 km projected onto line A–A′. (**c**) Main shock and all aftershocks located east of the line A–A′ with depth error less than 0.5 km projected onto line A–A′.

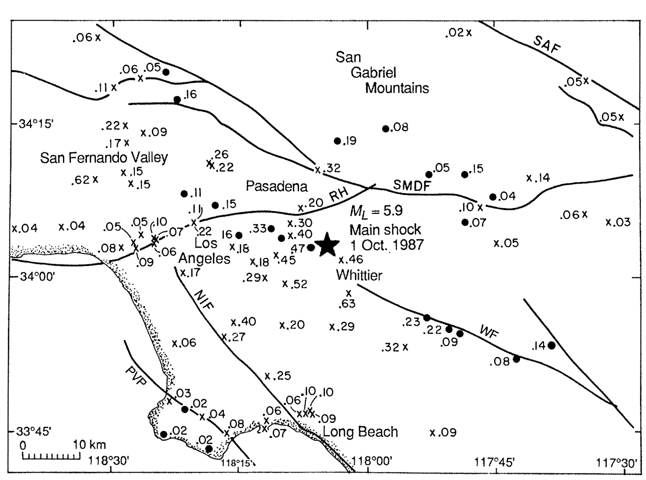

Fig. 3. Map showing peak horizontal ground-level accelerations from unrotated accelerograms of the main shock (shown by a star) that were recorded at stations operated by the U.S. Geological Survey and the California Division of Mines and Geology. Accelerations are given as a fraction of *g*, the acceleration of gravity at sea level. Closed circles indicate hard-rock sites and crosses indicate soft-rock sites. Abbreviations as in Fig. 1; SAF is the San Andreas fault; and PVP is the Palos Verdes fault.

such as the Elsinore-Whittier fault system and the Newport-Inglewood fault zone, which strike subparallel to the San Andreas fault.

The strike-slip faults are typically well exposed at the surface, and earthquake hazards can be quantified through detailed studies of fault slip rates (*21*). In some areas, reverse or thrust faults of the Transverse Ranges are also exposed at the surface and can be studied in the same manner as strike-slip faults. In contrast, the Whittier Narrows earthquake indicates that a system of buried thrust faults presents additional potential earthquake hazards to the Los Angeles metropolitan area. These faults are at depths of 10 to 15 km within the crystalline basement and below a thick sedimentary rock section. The deformational history recorded in the sedimentary rocks commonly contains information about the offset and slip rate on these buried thrust faults (*22*). Furthermore, spatial distribution of small earthquakes (*3*) as well as secondary structural features within the sedimentary rocks may provide clues as to the size and segmentation of these buried thrust faults. Thus it may be possible to quantify the potential earthquake hazards from these buried thrust faults.

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1. Preliminary assessments of damage, made by the California Office of Emergency Services, are $252 million to private property and $106 million to local government facilities. These damage estimates are 50 times as large as the damage caused by the comparably sized 1984 Morgan Hill (M_L = 6.2) earthquake, which occurred in a much less densely populated area.
2. The main shock and its aftershock were recorded by the Caltech–U.S. Geological Survey southern California seismic network and the University of Southern California, Los Angeles, basin seismic network. In addition, several portable instruments were deployed to record aftershocks. The P and S wave arrival times at 80 of these seismic stations were inverted for hypocentral parameters, two crustal velocity models, and a set of station delay by the use of the VELEST computer algorithm (S. Roecker and W. L. Ellsworth, personal communication). The resultant velocity models are similar to those of (*3*). The first motion polarities that were recorded at these seismic stations were used to determine focal mechanisms for the main shock and 38 aftershocks. The orientations of the nodal planes were determined by the use of a grid-searching algorithm [P. Reasenberg and D. Oppenheimer, *U.S. Geol. Surv. Open-File Rep. 85-739* (1985), p. 46].
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5. The focal mechanisms of main shock and 38 magnitude 2.2 or higher aftershocks were inverted with the techniques of A. J. Michael [*J. Geophys. Res.* **89**, 1171 (1984)] to determine the deviatoric stress regime that best explains the data. Inverting the focal mechanisms for a stress field that is both uniform in space and constant in time results in a maximum compression axis that trends 163° (south-southeast) and plunges 6° and a most tensional stress axis that trends 50° (northeast) and plunges 66°. These orientations have a 95% confidence limit of ±20°. The magnitude of the intermediate deviatoric stress is near zero. The orientation of the maximum horizontal compressional axis (which in this case is also the maximum compressional axis) is rotated to the west from the maximum compressive stress that was determined for the western Los Angeles basin (*3*).
6. Geologic surface expression of the main shock appears to be limited to secondary nontectonic breaks that were caused by ground acceleration. Mapped faults in the vicinity of the epicenter and area of greatest cultural damage were field checked; no tectonic slippage was observed. Numerous ground cracks were observed along the base of the Puente Hills between Turnbull Canyon and Norwalk Boulevard. Although this area does contain the west-northwest extension of the Whittier fault, breakage was limited to slope failures that included extensional cracks along slope contours, minor landslides, and earthfalls. Surface cracks were also observed in relatively flat-lying areas of artificial fill (Worsham Creek oil field) and areas with shallow water table (Whittier Narrows golf course). Steep slopes in the area from the San Gabriel Mountains near Pasadena on the north to the Puente Hills south of Whittier suffered minor failures. Reporting of ground cracks near Whittier may partly reflect local hillside housing development and the extensive field search for surface rupture in that area.
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16. Seismicity rates before the Whittier Narrows earthquake were calculated for earthquakes ($M_L \geq 2.5$) in the entire Los Angeles Basin, the Newport-Inglewood fault zone, and the northern section of the Elsinore fault zone. Aftershocks were removed from the data set by a computer algorithm (*17*). The statistical significance of the resulting rate fluctuations in these zones was assessed relative to a Poisson model of occurrence (*18*). The results indicate that there were no significant (n = 325; $P > 0.1$; where n is the number of events and P is the probability) rate fluctuations in the Los Angeles Basin during the 13.5-year interval before the main shock. In the North Elsinore fault zone, the seismicity rate decreased abruptly from approximately 6.0 earthquakes per year before 1983 to 2.6 earthquakes per year from 1983 to the time of the main shock. However, this decrease is not significant at the P = 0.1 level, in view of the low total number (57) of earthquakes that occurred there. Within the Newport-Inglewood fault zone, rate fluctuations were also not significant (n = 71; $P > 0.1$) during the 13.5-year interval. These results are consistent with those obtained for other moderate-sized earthquakes in California. Seismicity rates remained essentially constant during comparable intervals prior to the 1986 North Palm Springs (M_L = 5.6) earthquake, the 1984 Morgan Hill (M_L = 6.2) earthquake, and the 1979 Coyote Lake (M_L = 5.9) earthquake (*19*).
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RNA as an RNA Polymerase: Net Elongation of an RNA Primer Catalyzed by the *Tetrahymena* Ribozyme

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A catalytic RNA (ribozyme) derived from an intervening sequence (IVS) RNA of *Tetrahymena thermophila* will catalyze an RNA polymerization reaction in which pentacytidylic acid (C_5) is extended by the successive addition of mononucleotides derived from a guanylyl-(3′,5′)-nucleotide (GpN). Cytidines or uridines are added to C_5 to generate chain lengths of 10 to 11 nucleotides, with longer products being generated at greatly reduced efficiency. The reaction is analogous to that catalyzed by a replicase with C_5 acting as the primer, GpNs as the nucleoside triphosphates, and a sequence in the ribozyme providing a template. The demonstration that an RNA enzyme can catalyze net elongation of an RNA primer supports theories of prebiotic RNA self-replication.

SELF-SPLICING OF THE *Tetrahymena thermophila* precursor ribosomal RNA is mediated by the intervening sequence (IVS) portion of the RNA molecule. Splicing proceeds by two transesterification (phosphoester transfer) reactions. The first, attack by guanosine at the 5′ splice site, generates a 5′ exon with a free 3′ OH

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