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The Genesis and Collapse of Third Millennium North Mesopotamian Civilization

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Archaeological and soil-stratigraphic data define the origin, growth, and collapse of Subir, the third millennium rain-fed agriculture civilization of northern Mesopotamia on the Habur Plains of Syria. At 2200 B.C., a marked increase in aridity and wind circulation, subsequent to a volcanic eruption, induced a considerable degradation of land-use conditions. After four centuries of urban life, this abrupt climatic change evidently caused abandonment of Tell Leilan, regional desertion, and collapse of the Akkadian empire based in southern Mesopotamia. Synchronous collapse in adjacent regions suggests that the impact of the abrupt climatic change was extensive.

Akkadian empire. Much of the data are derived from Tell Leilan, one of the three large third millennium cities on the Habur Plains (Fig. 3). This site occupied 75 to 100 hectares at maximum size and was dominated by a 15-hectare Acropolis that today rises 20 m above plain level. Occupied from the mid-sixth millennium B.C., Tell Leilan became a major center in the mid-third

The origins and early history of southern Mesopotamian civilization, the third millennium B.C. irrigation-based cities and states of Sumer and Akkad, have been a major archaeological research enterprise for the past century (1, 2). Recently, archaeological inquiry has returned to two poorly understood questions that first attracted attention 50 years ago. The first is the problem of secondary state formation, or when, how, and why the prestate societies of regions adjacent to pristine civilizations were transformed into state-level societies (3–6). The developmental history of Sumer's northern neighbor, Subir, or Subartu, the rain-fed cereal agriculture Habur Plains of northeastern Syria (Figs. 1 and 2) (7, 8), provides a means to examine these questions. The second problem is state collapse, or when, how, and why stable or expanding early civilizations suddenly disintegrated and, after a period of instability, were replaced by new state organizations, often controlled by new ethnic groups (9, 10). The sudden collapse of the Akkadian empire at ~2200 B.C. (11) is the earliest historical example of this problem.

In this article we present archaeological and climatic data that define four stages for state formation, consolidation, imperialization and collapse of Subir, and its dynamic interaction with southern Mesopotamia that resulted in the disintegration of the

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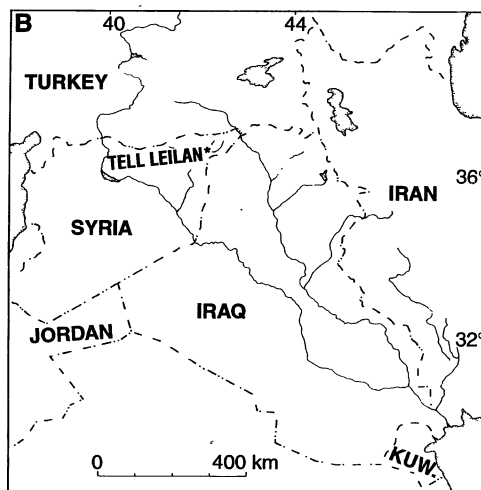
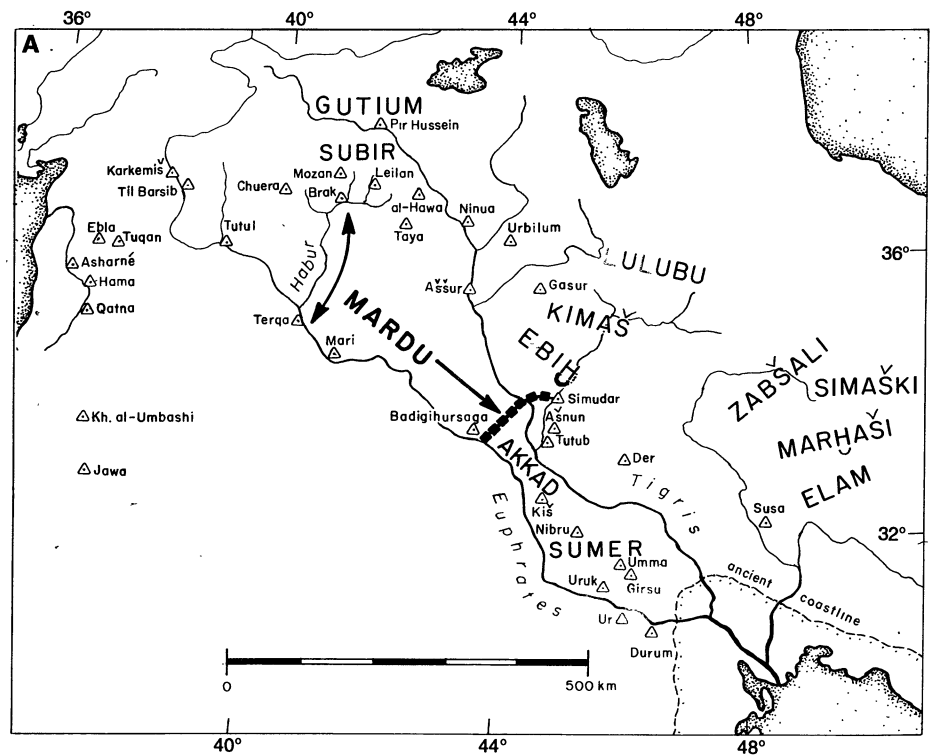


Fig. 1. (A) Syro-Mesopotamia, 2600 to 2000 B.C. Major urban centers of southern Mesopotamia (Sumer and Akkad) and Habur Plains (Subir), and adjacent ancient toponyms. Arrows indicate tribal pastoralist Amorite (Sumerian MARDU) seasonal north-south transhumance inferred before Habur hiatus 1 and subsequent movement down the Euphrates and Tigris floodplains. The Repeller of the Amorites wall of fortresses was constructed ~2054 to 2030 B.C. from Badigihursaga to Simudar to control Amorite infiltration. **(B)** Modern political units of southwest Asia and location of Tell Leilan in Syria.

millennium B.C. and the political capital of the region in the early second millennium B.C. (12, 13).

We conducted excavations in eight Tell Leilan horizontal exposures and soundings through stratified deposits, which yielded architectural, ceramic, faunal, and floral data. A series of 26 conventional and accelerator mass spectrometry radiocarbon dates were derived from seed and wood samples from the Tell Leilan Acropolis and Lower Town South residential area (Table 1 and Fig. 4). In addition we conducted two regional surveys that illuminate regional settlement patterns for the genesis and collapse of Subir's third millennium urban settlement.

Additionally, we studied datable, soil-stratigraphic units sealed below third millennium occupations within 6-m-deep trenches at six loci at the perimeter of Tell Leilan. The micromorphological and physicochemical properties of these units define alterations in hydrologic regime and soil conditions diagnostic of significant climatic changes. To correlate geological events and social responses within the archaeological record, we present dated regional socioeconomic and climatic data. These data define

the major effects of an abrupt climatic change at ~2200 B.C., namely imperial collapse, regional desertion, and large-scale population dislocation.

Stage 1—Secondary State Formation

From the first settlement in the sixth millennium B.C. until the 26th century B.C., Tell Leilan was a small agricultural community typical of dispersed settlements in the rain-fed north Mesopotamian plains (14). During the Tell Leilan IIIc period (~2600 to 2400 B.C.), settlement patterns on the Habur Plains and the adjacent Assyrian steppe were radically altered with the sudden emergence of indigenous state-level society, as seen in the large planned city at Tell Leilan and the reorganization of settlements across the region. Settlement at Tell Leilan expanded more than sixfold within 200 years; the city grew from a 15-hectare Acropolis-based settlement, to ~100 hectares comprising the Tell Leilan Lower Town (excavation operations 2, 3, 5, 7, and 8) and extended settlements to the west (excavation trench D3) and east (excavation trench E) (Fig. 3).

Excavations in the Lower Town South (Operation 5) indicate that this new Tell Leilan settlement was carefully planned on previously unoccupied virgin soil. The settlement included a straight sherd-paved street that was 4.75 m wide. On each side of the street was a mudbrick wall, behind which stood domestic structures that opened only onto alleyways; a long wall perpendicular to the street probably delimited residence or property lines. A limited sample of faunal remains (total of 73) from the lowest strata of the Lower Town indicates that the inhabitants exploited almost equally pig (33%), sheep and goat (32%), and cattle (29%) during this period.

Excavations on the Tell Leilan Acropolis reveal that the simple village economy of the 29th to 27th centuries B.C. was replaced by a structured economy based on central collection and storage-and-redistribution. In an area previously occupied by small-scale domestic architecture, a block of rectangular storerooms (larger than 200 m²) was constructed. The receipt and distribution of stores was in the hands of a central administration, as reflected in 188 broken door and jar sealings of clay retrieved within the storerooms. The cylinder

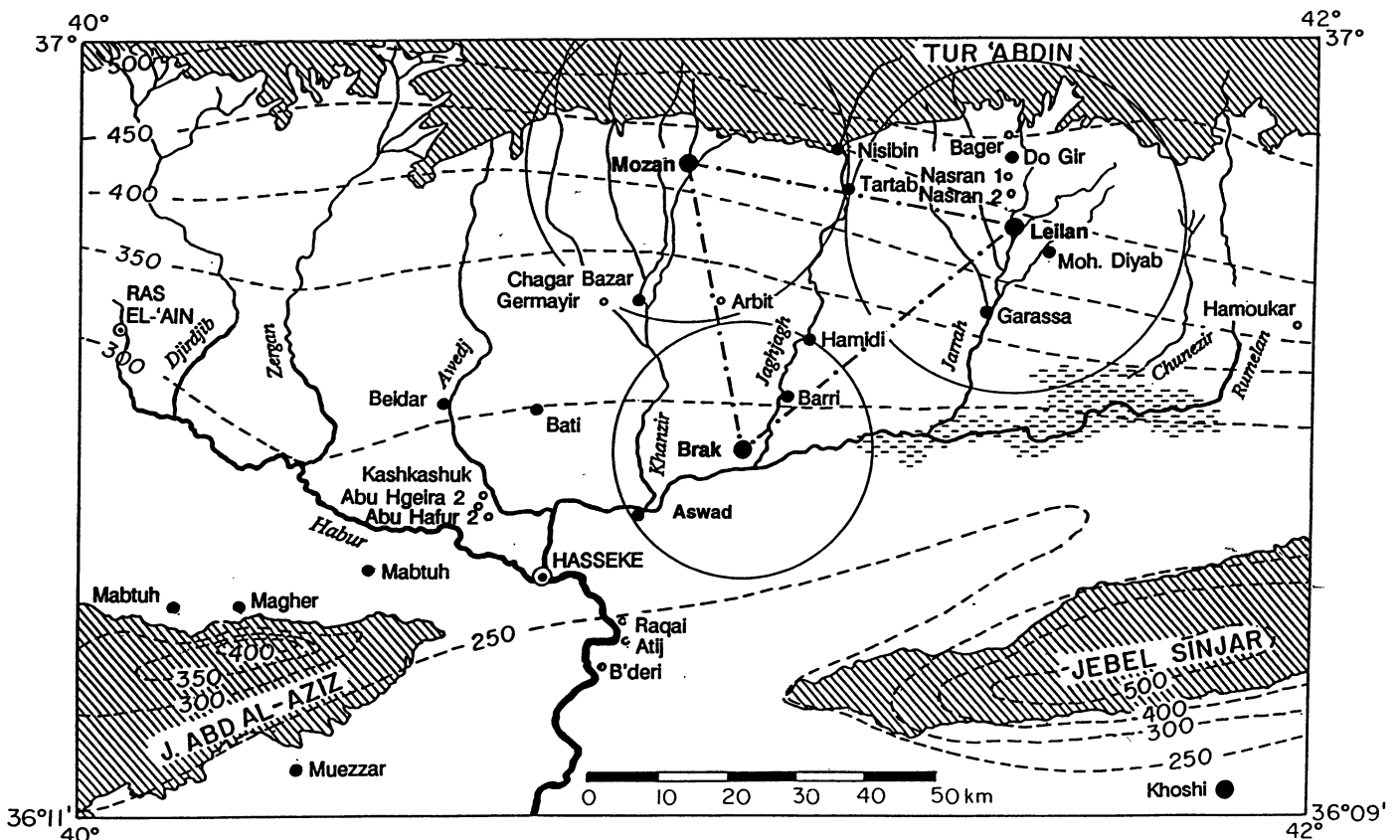


Fig. 2. Habur Plains, Northeast Syria, urban settlement system at 2600 to 2200 B.C. and sites discussed in the text. Circles indicate probable areas of agriculture and herding sustaining each city. Diagonal lines are elevation ≥ 500 m above sea level; dotted lines are modern rainfall isohyets (in millimeters). Large circles are sites of 75 to 100 hectares.

Medium circles are sites of 25 to 50 hectares. Small hollow circles are sites less than 10 hectares. Tephra deposits have been retrieved from Tell Leilan, Tell Bager, Tell Nasran 1, Tell Nasran 2, Abu Hgeira 2, and Abu Hafur 2.

seal impressions on the sealings are local Subarian-style imitations of the Early Dynastic II-IIIa iconography of banquet scenes of contemporary southern Mesopotamia (15). These suggest that northern states emulated southern administrative iconography to legitimize nascent state administrative and redistributive power (16). This north-south cultural contact followed a 300-year period of isolation from each other. The reasons for the period of isolation and the sudden reestablishment of contact remain to be determined.

Charred plant remains recovered through flotation suggest that large quantities of cereals were processed nearby in preparation for storage. The flotation samples consisted of cereal processing by-products, primarily inedible portions of the cereal head (number of samples, $n = 1867$; glume bases, glumes, and rachis segments) of barley (*Hordeum vulgare*), emmerwheat (*Triticum dicocum*), and durum wheat (*Triticum durum*), followed by the seeds of field weeds ($n = 733$), and small quantities of cereal grains ($n = 112$). This combination of materials matches the by-products of sieving and possible hand-sorting of traditional cereal processing (17). After the Tell Leilan cereals had been threshed and winnowed in the fields, they were apparently delivered to the Acropolis where they were cleaned before storage.

Climatic deterioration during this period conditioned the formation of Subarian states and the southern Mesopotamian role in this process. For at least one century before this period, regular alluviation is documented by massive sandy loam deposits that are intensively bioturbated. The presence of soils with a high moisture content at the wide active flood plain enhanced cereal production in the Tell Leilan region. During period IIIId, however, climatic conditions are marked by increased seasonality of water discharge, evident by the accumulation of coarse textured alluvial deposits that were eroded from the Tur Abdin mountains by torrential rains. More abundant pedogenic carbonates in the soil samples and changes in soil structure indicate that soil water reserves became reduced and evapotranspiration increased. The increased irregularity in Tur Abdin stream flows suggests that precipitation on the Anatolian plateau was reduced as well. The flow of the Euphrates as far south as Sumer would have declined, but it is difficult to quantify reductions (18–20). This climatic deterioration in northern Mesopotamia may be related to the rapid global aridification initiated at ~5000 B.P. (21).

The centrally administered urban economies and mixed land use strategies that developed in period IIIId may have presented adaptive advantages by facilitating max-

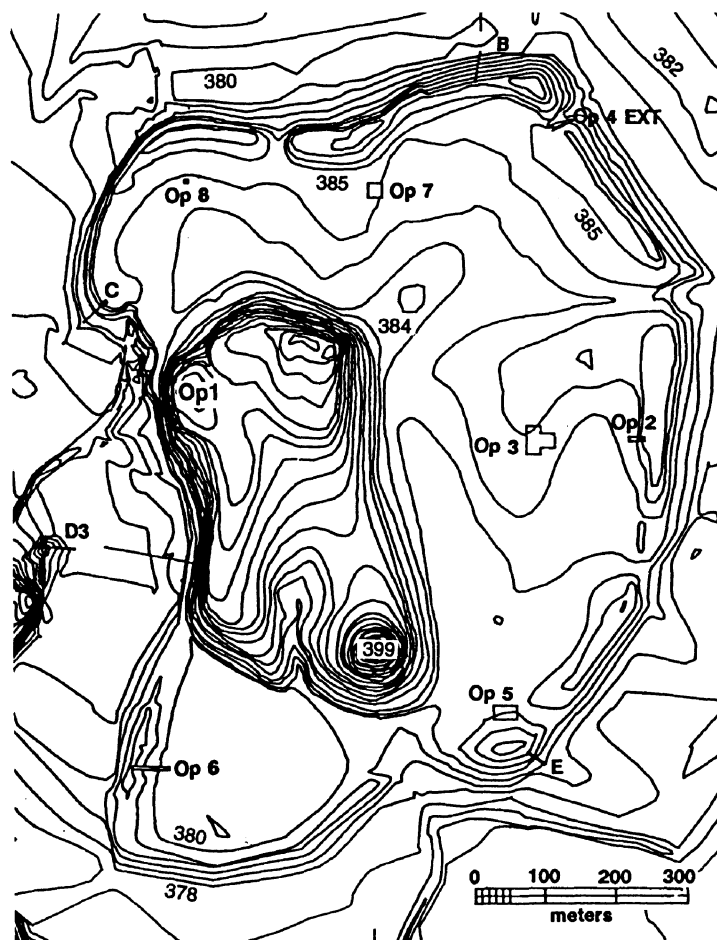


Fig. 3. Topographic map of Tell Leilan, showing areas of excavation. Contour intervals are 1 m.

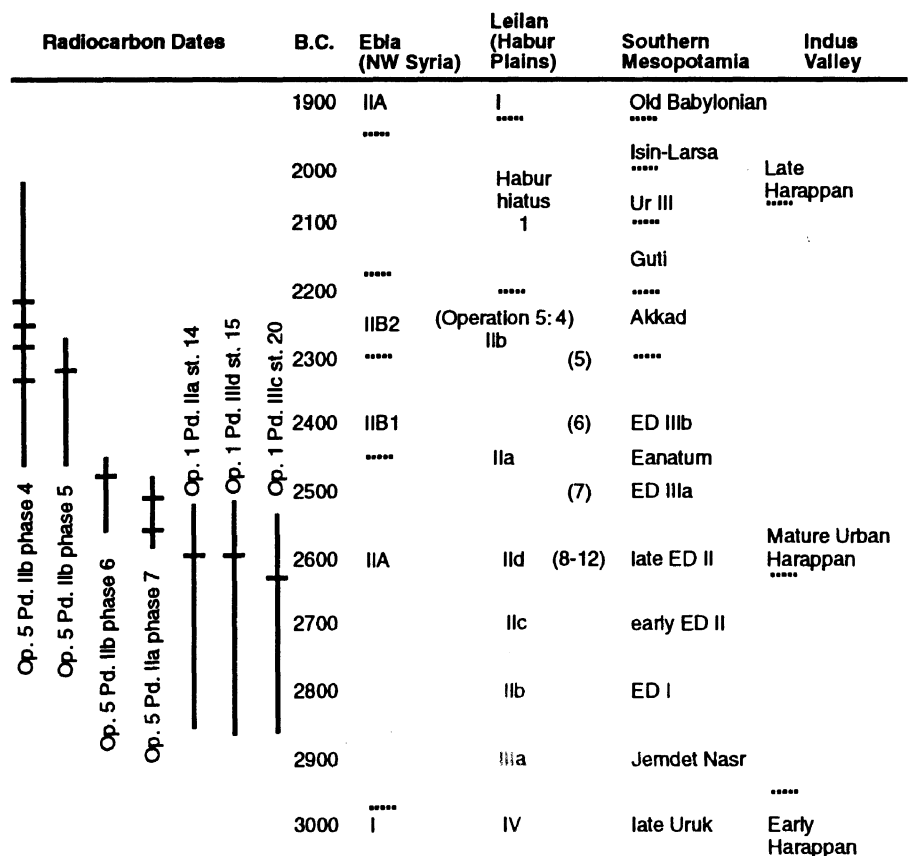


Fig. 4. Third millennium B.C. Southwest Asia chronology. Vertical lines are calibrated ranges ± 1 SD in years B.C. of Tell Leilan radiocarbon dates for periods IIIc through IIb, horizontal lines are calibrated weighted averages. Ebla occupation periods define proto- and early historic chronology for northwest Syria. Leilan ceramically defined periods are subdivided for operation 5 occupation phases. Dates for third millennium historical periods in southern Mesopotamia have an uncertainty of 120 years (67); ED, Early Dynastic. Indus Valley periods are radiocarbon-based estimates (74).

imum agricultural production under increased variability of rainfall (22). The sudden growth of Tell Leilan, Tell Mozan, and Tell Brak, each 75 to 100 hectares, transformed the Habur Plains into an urban landscape dominated by three equidistant centers with approximately equivalent territorial control extending up to 25 km around each center (Fig. 3). A three-tiered or four-tiered hierarchy of settlement optimized agroproduction and transport in the Tell Leilan region (23). These changes in settlement and political organization at Tell Leilan were part of a regionwide process of state formation and urbanization. Centers such as Tell Mozan, Tell Leilan, Tell al-Hawa, Nineveh (Ninua), and Tell Taya, developed 50 to 80 km apart, at locations where rainfall and soil fertility were most favorable.

In the south, Sumer was also transformed simultaneously by interaction with Subir. The first Sumerian palaces appeared at this time, in the late Early Dynastic II to Early Dynastic IIIa periods, in at least seven major cities. The transition from temple to secular rule marked a radical realignment of internal political structures, and was perhaps in part a response to reductions in Euphrates stream flow. The model for this transition may have derived from Sumerian contact with Subir (24).

Stage 2—Consolidation of State Power

The consolidation of a complex state administration in the cities of Subir is marked at Tell Leilan during the IIa period (~2400 to 2300 B.C.) by the construction of a 2-m-wide defensive wall around the Tell Leilan Acropolis, its storerooms, and administrative buildings, and by the appearance of numerical notations, based on circles and vertical lines, upon the rims of large cereal storage vessels (6). State organizational change in this period is also documented by retirement of fine craft incising on ceramics, which is labor-intensive, and the first appearance of mass-produced ceramics. Horse, mule, or large onager are documented in the contemporary Lower Town South street. These animals were probably used for wheel-drawn transport of the cereal harvest (25). During this period the military power of the Subarian countryside was apparently united and could have joined with forces from states in southwestern Iran (Elam) and the central Euphrates region (Mari) in attacking Sumer, which was dominated by one city, Lagash (26).

Stage 3—Imperialization

From approximately 2300 to 2200 B.C. (period IIb) southern Mesopotamia was united under the rule of Sargon of Akkad

and his dynastic successors. Akkadian rule imperialized irrigation-based agricultural production in southern Mesopotamia and expanded into adjacent rain-fed agriculture regions where production could also undergo intensification. Documents and monuments retrieved from Tell Brak indicate that the Akkadians controlled Tell Leilan and Tell Mozan through their imperial emplacement at Tell Brak (23, 27). Five features of Akkadian control have been identified at Tell Leilan during period IIb:

1) Population redistribution from sites apparently nucleated within Tell Leilan (28) seems to have been directed at removing local second-level centers and elites from the administration of production. Villages appear to have been maintained in

place to sustain imperialized production. A similar pattern of settlement during the Akkadian period is documented at Tell al-Hawa, 80 km to the east of Tell Leilan (29).

2) Plant remains recovered from floors in houses and courtyards in the Lower Town South consist primarily of weed seeds and some cereal grains, with small quantities of the inedible portions of the cereal head, and chaff. Seeds ($n = 2112$) were 9.6 to 61 times as abundant as chaff fragments ($n = 304$) in hearth, floor, oven, and courtyard contexts. Lower Town South households, therefore, received precleaned cereal stores, probably as labor ration payments in the Akkadian imperial system (30).

Table 1. Tell Leilan period IIIc-IIb radiocarbon dates and calibrated dates (years B.C.). Lower Town South (operation 5, Op5) samples are carbonized seeds retrieved from flotation. Weighted averages indicated below each group. Beta, Beta Analytic, Miami, Florida; N, Nishina Memorial, Tokyo; K, National Museum, Copenhagen; AA, University of Arizona AMS Facility, Tucson; Lab. no., laboratory number; and Op, operation. Multiple dates reflect several possible calibrations. Calibration was with CALIB 2.0 by the University of Washington.

Lab. no.	Date (years B.P. \pm 1 SD)	Years B.C.
<i>Op5, phase 4 (Leilan IIb terminal)</i>		
AA-8659	3805 \pm 75	2281
AA-8661	3610 \pm 75	2010
AA-7201	3825 \pm 65	2293
AA-7202	3885 \pm 65	2454, 2420, 2402
		2274, 2243, 2206
<i>Op5, phase 5 (Leilan IIb middle)</i>		
AA-7019	3960 \pm 80	2470
AA-7204	3780 \pm 70	2202
AA-7021	3745 \pm 60	2189, 2164, 2143
AA-7024	3915 \pm 65	2461
AA-7203	3855 \pm 65	2339
		2318
<i>Op5, phase 6 (Leilan IIb initial)</i>		
AA-7020	3935 \pm 65	2465
AA-7028	4005 \pm 65	2566, 2540, 2501
AA-7200	3905 \pm 60	2458
		2467
<i>Op5, phase 7 (Leilan IIa)</i>		
AA-7022	4020 \pm 65	2573, 2535, 2506
AA-7023	4020 \pm 60	2573, 2535, 2506
AA-7025	3940 \pm 60	2466
AA-7026	3930 \pm 60	2464
		2563, 2542, 2498
<i>Op1 str 14 (Acropolis Leilan IIa) (72)</i>		
K-5153	3870 \pm 100	2451–2356
K-5155	4070 \pm 85	2598
K-5156	4090 \pm 85	2853, 2828, 2655
K-5157	4140 \pm 85	2865–2668
		2586
<i>Op1 str 15 (Acropolis terminal Leilan IIIc) (72)</i>		
K-5154	3850 \pm 85	2334
K-5158	4060 \pm 70	2587
<i>Op1 str 20 (Acropolis Leilan IIIc) (14)</i>		
Beta-1777	4090 \pm 70	2853–2615
Beta-3099	4060 \pm 60	2587
N-3897	3970 \pm 85	2483
N-3898	4070 \pm 70	2598
		2585

3) Stacked kiln wasters from period IIb document production of standard-size 0.33-, 1- and 1.5-liter vessels. These vessels, and their nonwaster rim and base sherd equivalents only occur during this period at Tell Leilan. These observations suggest that they were used to distribute Akkadian standardized worker rations of barley and oil, which have been documented epigraphically (31).

4) A city wall was constructed for the first time. The rock-hard calcitic virgin soil was excavated to depths of 0.5 to 1.5 m, then two concentric walls of mud brick, a casemate, were set into these excavations. The inner and outer walls were 8 m wide; a middle wall, perhaps a walkway between the two, was 1 m wide. On the northern side of the city, where a natural depression and rise afforded protection, an earthen rampart was constructed by excavating a 10-m-wide by 10-m-deep ditch and then mounding the excavated virgin soil. A city wall was also constructed at Ninua (Nineveh), the regional center on the Tigris River 150 km east southeast of Tell Leilan, where a son of Sargon established Akkadian control (32).

5) As part of the Akkadian reorganization of production, and in response to the continuing reduction in water discharge and siltation that began in period IIIc, water courses were stabilized by channelization and repeated clearing. These constructions may also reflect Akkadian expertise in canal management developed in southern Mesopotamia. In trench D this water management is recorded within a 4-m sequence of repeated entrenchments into calcic virgin soil, embankments of large basalt blocks, and masses of water-borne silt and pebbles that were cleared from the channel on the western side of Tell Leilan.

Occupations during the late Akkadian period at Tell Leilan, Tell Brak, and other dry-farming sites, as well as late Akkadian period texts from dry-farming sites and sites in Sumer, document a thriving imperial economy sustaining long-distance trade and construction of monumental buildings and massive agricultural projects (33, 34). Akkadian military power bolstered distant imperial fortresses and regularly repressed local rebellions (35). The imperialism of this period created the ideology of economic, ethnic, and regional unification that legitimized all subsequent Babylonian and Assyrian imperial structures (36).

The occurrence within anthropic soils of trenches B, C, D, and E of well-structured loam with minor signs of hydric erosion, aeolian influence, and moderate biological activity indicate a climate of marked seasonal contrast similar to the present, although better developed calcic horizons suggest that temperatures were slightly warmer. Thus, for the ~100-year period of

Akkadian imperialization, politico-military control of the Habur Plains was accompanied by agricultural intensification and appropriation under conditions of gradual environmental degradation that began in period IIIc.

Stage 4—Collapse: Desertification and Desertion

At approximately 2200 B.C. the Akkadian-dominated period IIb occupations of Tell Leilan and Tell Brak were suddenly abandoned. The subsequent remnant occupation at Tell Brak was limited to one-half the area formerly occupied (37). At Tell Leilan, an occupational hiatus extending until reoccupation, historically dated at the beginning of period I (~1900 to 1728 B.C.) (38), has been documented at each sounding in the site (operations 1 to 8) (Fig. 5). Similar abandonments are evident at almost all excavated sites of this period across the Habur and Assyrian Plains, including the excavated sites of Chagar Bazar, Arbit, Germayir, Mohammed Diyab, Tell B'deri, Kaskashuk, Abu Hgeira 1, Melebiya, Tell Taya,

and Tepe Gawra (39). Surface surveys across the Habur Plains have failed to identify any ceramic assemblages for this period. Surface reconnaissance of Tell al-Hawa to the east of Tell Leilan also indicates an occupational hiatus (40). To the west, in the adjacent Balikh drainage, Tell Chuera and Jidle were abandoned, Hammam et-Turkman's occupation was reduced, site occupation in the northern Balikh drainage was reduced by 36%, and settlements along the Euphrates north of Bireçik were reduced or abandoned (41). The extant epigraphic documentation from southern Mesopotamia suggests that only remnant occupations remained at Urkish (Tell Mozan) and Ninua (Nineveh) (42). We label this abandonment period "Habur hiatus 1."

Abrupt climatic change. Habur hiatus 1 coincides with an abrupt environmental change recorded within a well-defined stratum found at Tell Leilan trench B, operation 8. Study of thin sections from this stratum reveals a rapid evolution in depositional conditions that can be divided into three phases.

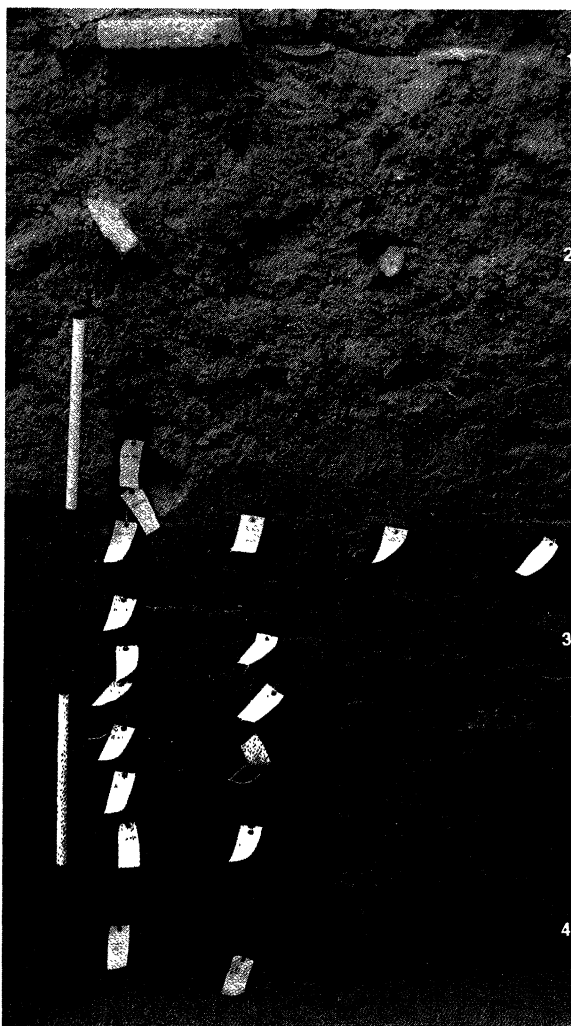


Fig. 5. Tell Leilan, operation 8 south stratigraphic section, stratigraphy and sampling. Scale is 2 m. Numbers refer to the following: 1, Leilan period I surface; 2, Habur hiatus 1; 3, Leilan period IIIc to IIb surfaces; and 4, calcic virgin soil at 2600 B.C.

The base of phase 1 is a 0.5-cm-thick layer of weakly altered fine silt-sized volcanic glass with a few potassic feldspars, phytoliths, and rounded calcitic sand-sized pellets, stratified and sealed in the last floor of period IIb in operation 8, lot 29, geology sample 203 (Fig. 5). This deposit is aeolian and was finely fragmented by human trampling on an open-air surface. Subsequently, in all three loci, the fine silt-sized volcanic glass fragments were mixed with calcitic clay loam derived from surrounding mudbrick construction collapse. This mixing occurred during the early abandonment of the site when soil moisture was sufficient to maintain earthworm activity and to alter slightly the volcanic ash, and when rainfall was high enough to disintegrate mudbrick constructions. Climatic conditions during this phase were thus broadly similar to those before the tephra fall.

Phase 2 is represented by a 20-cm-thick accumulation in each locus (for example, operation 8, lot 29, geology sample 204) of grey, well-rounded, sand-sized pellets, and loose, silt-sized, calcitic silt and abundant, very fine fragments (5 to 25 μm) of weakly weathered volcanic glass with abundant, fine silt-sized phytoliths. These sedimentary features are characteristic of both local strong wind deflation and long-distance aeolian transport. Evidence for reduced earthworm turbation of anthropic soils, scarce slaking crusts fragmented by desiccation, absence of pedogenic carbonates, and only a minor colluvial contribution, indicate simultaneous reduction of rainfall and occasional erosion at a bare soil surface by violent rainstorms. Both soil and sediment features may be evidence of the establish-

ment of marked aridity induced by intensification of wind circulation, and an apparent increase of dust veil frequency compared to present-day conditions.

Phase 3 is a clearly defined unit of rain-driven primary and secondary mudbrick wall collapse in the ditch fill of trench B (1 m of yellowish-brown compact unit), in the Lower Town South (80 cm of loose, heterogeneous, yellowish-brown to grey unit), and in operation 8 (geology samples 205 and 206; 40 cm of loose, yellowish-brown unit). Wind-blown sand-sized pellets and volcanic glass, observed within thatched-roof remains that are abundant in the fills, were trapped on the roofs during phases 1 and 2 before they collapsed. The Tell Leilan volcanic glass fragments (Fig. 6) are silt-sized (5 to 25 μm) particles and are mixed with calcitic dust. Their pale yellow color, low birefringence, and diffuse contours indicate chemical weathering induced by an increase of soil moisture during this phase. Alteration of volcanic ash by pedogenic processes under alkaline conditions is confirmed by the wide range of compositions of glass-like particles by electron microprobe analysis. Increase in earthworm activity, abundance of slaking crusts, and occurrence of pedogenic carbonates formed in situ, all mark the augmentation of soil moisture, a reestablishment of marked dry-wet seasonal contrast, a lessening of heavy rainstorms and a progressive soil stabilization.

The absence of a marked tephra layer associated with windblown dust in the deep horizons of surface soils of the Tell Leilan region is not surprising. Under present-day type climatic conditions, volcanic glass incorporated in soils weathers rapidly (43)

and windblown pellets merge into the soil fine mass (44). A well-defined stratigraphic unit similar to those of Tell Leilan hiatus phase 2 has also been observed at the uppermost part of three archaeological sites in the environs of Tell Leilan. A layer of windblown calcitic dust rich in volcanic ash and fine phytoliths seals Halaf period (~5900 B.C.) occupation layers at Tell Bager, Ubaid period (~4500 B.C.) occupation layers at Tell Nasran 2, and Uruk period (~3000 B.C.) occupation layers at Tell Nasran 1. The excellent preservation of layers of windblown dust in these specific locations can be explained by the reduced effects of post-depositional disturbance on archaeological sites in comparison to surface soils on the flood plain. Some coarse sand layers of aeolian origin consist of silt-sized volcanic glass particles and potassium feldspar phenocrysts, clearly volcanic in origin, embedded in a pale yellow, isotropic, fine-ground mass. The close morphological resemblance of these particles with the features marking Tell Leilan occupation hiatus phase 1 and the overall characteristics of the stratigraphic unit suggest that they relate to the same arid event.

The regional effects of the ~2200 B.C. arid phase are also documented by soil-stratigraphic data collected at Abu Hgeira 2 (Table 2) and Abu Hafur, 15 km northwest of Hasseke and 50 km southwest of Tell Leilan. Volcanic glass and fine sands were observed in a tephra-rich deposit at the bottom of a 3-m-deep trench excavated at the foot of Abu Hgeira 2 (Fig. 7). Stratigraphic unit I at Abu Hgeira 2 is correlated with the terminal occupation of Abu Hgeira 1 level 2, also an Akkadian period-Tell



Fig. 6 (left). Tell Leilan collapse, phase 1: operation 8, bottom of lot 29, geology sample 203. Calcitic silt rich in finely fragmented silt-sized tephra fragments, phytoliths, charcoal, and rounded, sand-sized pellets of yellowish-brown and grey calcareous soil, all of windblown origin. Accumulation of aeolian sediments lying on the upper part of last pre-hiatus occupation floor (Tell Leilan IIb) in operation 8. Length is 0.87 mm.



Fig. 7 (right). Abu Hgeira 2, layer IIa (270 to 300 cm). Moderately sorted sand including subrounded sand-sized volcanic glass particles (translucent) associated with well-rounded sand-sized pellets of calcitic silt (greyish brown) and yellowish-brown subangular, coarse sand-sized aggregates of calcitic loamy soil. This facies characterizes the initial stage of the abrupt climatic change recorded at the bottom of the Abu Hgeira 2 trench when winds of moderate intensity started to deflate soils simultaneously with the fall of volcanic ash. Length is 0.87 mm.

Leilan IIb occupation (45). The intensification of the wind subsequent to the tephra layer is clearly defined at Abu Hgeira 2 by the 1-m accumulation (soil units IIa, IIb, IIc) of fine sand-sized pellets derived from aeolian deflation of the surrounding soils. This layer accumulated in less than 500 years on the basis of chronostratigraphic correlation. A similar windblown calcitic loam with abundant silt-sized tephra particles was also observed at Abu Hafur 2 situated along the same seasonal stream as Abu Hgeira 2, 2 km farther south. The aeolian unit overlies a calcic horizon correlated with Tell Leilan period II environmental conditions and is sealed by Mitanni (~1500 B.C.) occupation levels. The similarity in the degradational sequence of late third millennium landscapes suggests that the tephra layers at Tell Leilan and Abu Hgeira 2 are products of the same eruption. The difference in size between volcanic particles observed at Tell Leilan

and Abu Hgeira 2 could be explained by differential regional dispersion coincident with strong wind turbulence.

Tephra analyses. Glass sherds from the Abu Hgeira 2 layer (sample T9-43) display a rhyodacitic composition indicating derivation from a potassium-rich calc-alkaline volcano. Their major element and trace element composition was compared to samples from the 17th-century B.C. Santorini eruption, the only ash-producing eruption known in the Mediterranean basin during the second millennium, which dispersed tephra over a large area of Asia Minor, up to regions close to the Habur Plains (46, 47). Differences in major element composition and in Th/Ta ratio rule out a Minoan origin for the Abu Hgeira 2 tephra (47) (Tables 3 and 4). Comparison with the few available trace element data from Anatolian volcanic rocks (48) suggest that Anatolian volcanoes were the source for the Habur Plains ash (Table 4). Calc-alkaline

volcanic centers, such as Nemrut and Karacilag, are situated only a few hundred kilometers from the Habur Plains. Potassic volcanic centers are also known in the Anatolian-Caucasian area, but the chronology of their activity during the Holocene is uncertain (49).

The Tell Leilan occupational hiatus and Habur hiatus 1, therefore, coincide with an episode of tephra fall, followed by an abrupt arid phase marked by intensification of wind circulation that seems to match, in duration and amplitude, a major short-term climatic change (50). The reinstallation of climatic conditions similar to those before the tephra fall preceded reestablishment of Habur Plains sedentary human occupation in the 19th century B.C.

Outside of the historical record, major volcanic eruptions have been documented by proxy dating evidence offered by tree rings and Greenland ice cores (51–53). The

Table 2. Abu Hgeira 2: pedo-sedimentary facies. Calc., calcareous; ab., abundant; com., common.

Unit	Characteristics	Environment	Correlation
Basal strata	Occupation floors, stratified cultural debris		Nuzi ware–Mitanni period ~1500 B.C.
V: 0 to 100 cm	Calc. loam, fine prismatic structure, ab. pedogenic carbonate, high biological activity	Stable soil, vegetated, reduced winds, seasonal rainfall similar to present	Early 2nd millennium B.C. ~1900 B.C.
IV: 100 to 140 cm	Calc. loam with gravel lenses, calcitic nodules	Unstable soil, surface runoff, degraded vegetation	
III: 140 to 200 cm	Calc. loam, weak prismatic structure, low biological activity, rare pedogenic carbonates, ab. crusts, ab. windblown pseudosands	Weak soil stability, heavy rains, surface runoff, reduced soil moisture, moderate winds	
IIc: 200 to 240 cm	Well-sorted, well-rounded calc. pseudosands, ab. crusts	Strong winds, saltation aeolian transport, heavy rain spells, degraded vegetation	Leilan collapse, phase 3
IIb: 240 to 270 cm	Fine pseudosands, volcanic glass, gypsum, calcitic loam, ab. sedimentary crusts	Suspension aeolian transport, horizontal winds, heavy rain spells, degraded vegetation	Leilan collapse, phase 2
IIa: 270 to 300 cm	Well-sorted, well-rounded windblown pseudosands, volcanic glass, calcitic loam, ab. sedimentary crusts	Tephra fall, saltation aeolian transport, heavy rain spells, degraded vegetation	Leilan collapse, phase 1 ~2200 B.C.
I: 300 to 370 cm	Massive calcareous loam, well-developed pedogenic carbonates, moderate biological activity, com. pseudosands, com. sedimentary crusts	Moderately stable soil, moderate winds, heavy rain spells	Leilan IIb ~2300 B.C.

Table 3. Major element composition of Minoan tephra in eastern Mediterranean cores in weight percent. For MD-90920 (35°17.53N, 28°12.46E, 1620 m depth), sample taken from 26.5 to 27.5 cm, size interval for glass sherds is 63 to 250 μm . For TRI-172-22, data from (47). Minoan* refers to glass sherds of Minoan age from marine cores (72). T9-43 refers to Abu

Hgeira 2 sample. Analyses made on individual glass sherds with a scanning electron microscope, coupled with an energy dispersive x-ray spectrometer (analyses performed at 15 kV, 0.3 nA on 20- to 50- μm^2 areas for 100 seconds). Standard deviation (2σ) in parenthesis. Total iron expressed as FeO*.

Core	N	SiO ₂	Al ₂ O ₃	K ₂ O	Na ₂ O	MgO	CaO	TiO ₂	MnO	FeO*	Cl	P	S
MD90920	14	73.33 (0.52)	13.66 (0.15)	3.42 (0.11)	4.53 (0.27)	0.26 (0.11)	1.36 (0.13)	0.34 (0.12)	0.12 (0.08)	2.06 (0.30)	0.75 (0.19)	0.03 (0.06)	0.14 (0.09)
TR172-22	10	73.02 (0.47)	13.61 (0.21)	3.37 (0.16)	4.99 (0.46)	0.12 (0.13)	1.4 (0.15)	0.3 (0.14)	0.11 (0.13)	2.13 (0.25)	0.78 (0.13)	0 (0.01)	0.17 (0.12)
Minoan*	141	72.5 (1.1)	13.7 (0.4)	3.1 (0.2)	4.9 (0.2)	0.26 (0.02)	1.3 (0.1)	0.26 (0.1)	—	1.9 (0.1)	—	—	—
T9-43	18	75.38 (0.58)	13.24 (0.32)	4.45 (0.14)	4.39 (0.31)	0.03 (0.08)	0.76 (0.11)	0.1 (0.09)	0.05 (0.06)	1.1 (0.23)	0.38 (0.09)	0.02 (0.06)	0.11 (0.14)

average global temperature signal of volcanic eruptions may, however, be undetectable for all but the largest eruptions (54), and the proxy dating is incomplete (53, 54). The ice core record has one major sulfur-rich peak, of unknown origin, at the end of the third millennium B.C. (4040 ± 10 years ago) (53). The volcanic eruption documented at Tell Leilan, however, probably occurred ~100 years earlier, may not have been a major sulfur-rich eruption, and should not necessarily correlate with a well-defined signal in the proxy record. The Anatolian tree-ring record has only one to four samples for the period 2200 to 2000 B.C., a number sufficient for the positive identification of neither a volcanic event nor abrupt climatic change. These tree ring data do, however, suggest a 200-year-long period of climatic instability culminating in reduced and irregular ring growth for the period 2055 to 2043 ± 37 B.C. (55).

The abrupt increase in aeolian deflation and aridity (from phases 1 to 2) following the tephra fall (phase 1) raises the question of the causative linkage between the two events. The climatic effects of volcanic eruptions are well documented (56). Several lines of evidence, however, suggest that the late third millennium Habur Plains climatic change may not be a direct response to volcanic activity: (i) Its duration, approximately 300 years, as estimated by the Tell Leilan radiocarbon and historic record, differs considerably from the briefer modifications of global climate induced by volcanic eruption (51). (ii) Our data suggest that atmospheric instability caused by air warming in addition to attenuated seasonality and extended aridity persisted during this period. This regional trend is apparently not consistent with the global cooling caused by atmospheric aerosol forcing, although the range of possible local effects is not yet defined (57). (iii) A dust veil persisted for several decades, long after the fall of the volcanic ash that occurred at the beginning of the event. Comparison with modern circulation patterns (58) suggests that a major modification of the climatic boundary conditions has to be invoked for explaining maintenance of air warming and strong zonal winds during phase 2 (59). A northward position of the polar jet would explain weakened cyclogenesis in Mediterranean and Near East regions. A stronger subtropical jet might also have been responsible for more intensive circulation of northerly winds synchronous with a weakened monsoon in the Indian subcontinent.

Land-Use Effects of the Abrupt Climatic Change

Phase 2 desertification, identified as increased aridity, intensified wind turbulence, and increased dust veil, is interpreted to

have significantly reduced soil moisture reserves, increased aeolian loss of soils, and reduced ground visibility. Therefore, we hypothesize that phase 2 coincides with conditions of low agricultural productivity.

During Habur hiatus 1 we estimate that the intensively surveyed Tell Leilan region suffered a net loss of ~182 hectares of built-up site area, or a displacement of between ~14,000 and ~28,000 persons within 15 km of Tell Leilan (22). Displacement of three to four times that number of persons is suggested by equivalent abandonments along Habur Plains western drainages. Synchronously, we hypothesize that the seasonally transhumant populations of the Habur Plains were also displaced as the plains were no longer the summer alternate to their winter foraging along the banks of the Euphrates (60). Comparison with archaeological data from southern Mesopotamia suggests that the desertification and desertion of the Habur Plains between ~2200 and 1900 B.C. engendered the collapse of the Akkadian empire, and the attendant displacement of Hurrian, Gutian, and Amorite populations into southern Mesopotamia.

Initially, the desertification caused the abandonment or reduction of northern settlements such as Tell Leilan, Tell Brak, and Mohammed Diyab, on the Habur plains, and the collapse of the Akkadian economy that was dependent in part upon imperialized agriculture throughout the rain-fed lands adjacent to southern Mesopotamia (61). The abandonment displaced the sedentary Hurrian-speakers of Subir (62). Gutians, perhaps from the Diyarbakr plains adjacent to the Habur Plains, were also displaced by this abrupt climatic change, and eventually seized control of the collapsed imperial core (63). Amorite populations, formerly seasonally transhumant, moved down the Euphrates and Tigris banks, and forced the succeeding Ur III dynasty to construct the Repeller of the Amorites wall (64). These populations, however, continued to immigrate into southern villages (65) at the same time that southern irrigation agriculture was suffering from reduced flow of the Euphrates (66, 67). While the Ur III dynasts were able to extend some political control as far north as Assur, they did not reestablish control over the Habur and Assyrian plains (68) because these regions were not efficiently productive for southern imperialism during this period.

The abrupt climate change that generated Habur hiatus 1 and the associated Akkadian-Guti-Ur III collapse are synchronous with climate change and collapse phenomena documented in the Aegean, Egypt, Palestine, and the Indus (69). The reoccupation of the Habur Plains in the 19th century B.C. and the sudden emergence of centralized Amorite control of the plains under Shamshi-Adad at Tell Leilan was

evidently facilitated by the amelioration of climatic conditions documented by the phase 3 soil-stratigraphic data at Tell Leilan and the subsequent return of Amorite, sed-

Table 4. Concentrations of trace elements in a Minoan ash layer from a marine core, a sample from Abu Hgeira 2 and comparison with trace element ratios in volcanic rocks from Turkey. For marine core MD-90920, samples consisted of 80 mg of purified glass sherds. Sample 1 was from a depth of 26.5 to 27.5 cm; sample 2 was from a depth of 32 to 33 cm. Glass sherds are from the 63- to 125- μ m size fraction. The T9-43 sample consisted of 50 mg of purified glass sherds from the 80- to 150- μ m size fraction. Neutron activation was carried out by activation analysis: irradiation with an epithermal neutron flux of 10^{14} cm² s⁻¹ for 12 hours in Cd tubes or 60 minutes in quartz tubes. Experiments were performed at the Centre d'Etudes Nucléaires of Saclay, France; samples were counted using a 80-cm³ Ge detector. BEN and GSN rock standards were from the CRPG (Nancy, France). Ta*: the new adopted value for this element in GSN is 2.578 ppm. Analytical precision is ±10% for Ag, Sr, Zr, Cr, Ni, and ±5% for other elements. For comparison, we present data from eastern Anatolia lavas having a subduction signature (73); 16 analyses from Ararat district yielded a Th/Ta ratio of 8.53 and 27 analyses from the Kars plateau yielded a Th/Ta ratio of 10.2. When Ta data were not available, they have been calculated from the equation Ta = (Nb/16). Units expressed in parts per million except for Ag and Au, which are in parts per billion. Th/Ta, La/Eu, and Eu/Yb ratios calculated from average data of marine core MD-90920 samples 1 and 2.

Element	MD-90920		T9-43
	1	2	
U	5.39	5.26	7.06
Th	16.72	17.09	24.5
Zr	301	302	139
Hf	7.87	7.73	3.94
Ta	0.937	0.944	2.27
Ba	493	503	399
Sr	101	102	221
Cs	2.68	2.70	7.1
Rb	94.0	94.1	155
Sb	0.30	0.3	0.8
Cr	8	9	13
Co	3.3	5.7	1.7
Ni	1.8	2.3	8.6
Sc	7.7	7.8	2
La	26.5	26.6	28
Ce	53.7	53.5	53.6
Nd			3.96
Sm	4.82	4.72	3.1
Eu	0.91	0.92	0.38
Tb	0.785	0.791	0.4
Yb	4.49	4.53	2.57
Lu			0.45
As	2.49	2.95	
Mo	2.79	2.86	
Br	12.6	12.4	
Ag	80	120	
Au	3.7	5.5	
Th/Ta	17.9		10.8
La/Eu	29.1		73.7
Eu/Yb	0.20		0.15

entary and seasonally transhumant exploitation of the Habur Plains (70).

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Antisense Oligonucleotides as Therapeutic Agents—Is the Bullet Really Magical?

C. A. Stein and Y.-C. Cheng

Because of the specificity of Watson-Crick base pairing, attempts are now being made to use oligodeoxynucleotides (oligos) in the therapy of human disease. However, for a successful outcome, the oligo must meet at least six criteria: (i) the oligos can be synthesized easily and in bulk; (ii) the oligos must be stable *in vivo*; (iii) the oligos must be able to enter the target cell; (iv) the oligos must be retained by the target cell; (v) the oligos must be able to interact with their cellular targets; and (vi) the oligos should not interact in a non-sequence-specific manner with other macromolecules. Phosphorothioate oligos are examples of oligos that are being considered for clinical therapeutic trials and meet some, but not all, of these criteria. The potential use of phosphorothioate oligos as inhibitors of viral replication is highlighted.

It is the idea of specificity that provides the underlying allure of oligodeoxynucleotide technology (Fig. 1). Standard cytotoxic chemotherapy for conditions such as neoplastic disease is fraught with systemic toxicity. The ratio of the toxic dose to the therapeutic dose is relatively low, which reflects the large number of cellular targets affected by the chemotherapeutic agent and the agent's inability to distinguish between normal and diseased cells. In theory, this problem can be solved by taking advantage of the specificity conferred by Watson-Crick base pair formation, if an appropriate target can be identified. For example, an oligo of more than 15 to 17 nucleotides in length would have a unique sequence relative to the entire human genome. In principle, a suitable oligo should be able to interfere, in a

sequence-specific manner, with processes such as the translation of mRNA into protein (1). If the synthesis of that protein is a requirement for cell growth or, alternatively, for intracellular viral replication, then these processes would be slowed by the antisense agent. Furthermore, the property of complementarity may also be used to inhibit other physiologic processes in addition to mRNA translation; for example, oligos targeted to donor-acceptor sites for splicing pre-mRNA inhibit human immunodeficiency virus-type 1 (HIV-1) replication (2). In addition, oligos complementary to genomic DNA can interact with it, by means of Hoogsteen base pairing in the major groove, to form a triple-helical structure. Investigators have inhibited transcription in tissue culture by inducing triple helix formation, and several examples are given below.

Phase I clinical trials of oligos, designed to evaluate the toxicity of these compounds in cancer patients, have already com-

menced. A phosphorothioate (PS) oligo complementary to the p53 mRNA has been administered to a patient with chemotherapy-refractory acute myelogenous leukemia (3). Another trial that has been proposed [for a methylphosphonate (MP) oligo] is a phase I-II trial in patients with chronic myelogenous leukemia. The trial design calls for patients to receive transplants of autologous oligo-purged marrow (4) after they receive standard chemotherapy and radiotherapy.

Requirements for the Therapeutic Use of Oligos

The use of antisense oligos as therapeutic agents presupposes that six criteria can be satisfied.

The oligos can be synthesized easily and in bulk. The development of phosphoramidite chemistry by Caruthers and co-workers and its elaboration into an automated technology (5) have greatly enhanced the ease with which oligos are synthesized and consequently their availability. Methods for large-scale oligo synthesis are being commercially pursued (6). Although the cost has been dramatically reduced, the final cost to the consumer of a "treatment" with oligo has not been determined.

The oligos must be stable in vivo. This precludes the use of phosphodiester (PO) oligos as therapeutics because serum and intracellular nucleases (both endo- and exonucleases) will degrade them (7). For the past decade, significant effort has been expended by synthetic chemists to develop nuclease-resistant oligos. Perhaps the greatest successes in doing so have been achieved with the PS (8) and MP oligos (9), which can be synthesized with relative ease.

The oligos must be able to enter the target cell. The ability of oligos to penetrate the cell membrane and the mechanism of entrance are critical considerations in devel-

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