NEW TECHNOLOGICAL ADVANCES: DNA, ELECTRONIC DATABASES, IMAGING RADAR

DONALD W. PARRY, DAVID V. ARNOLD,
DAVID G. LONG, AND SCOTT R. WOODWARD

Three dissimilar technological innovations have been developed at Brigham Young University (BYU) and the Foundation for Ancient Research and Mormon Studies (FARMS).[1] Each of these was developed independently of the other and each contributes in its own unique way to Dead Sea Scrolls research.[2] Scott R. Woodward, from BYU's Department of Microbiology, has led a team of experts using DNA-techniques[3] to analyze several parchment fragments of the Scrolls;[4] Donald W. Parry (Professor of Hebrew Language and Literature) has worked with a team from BYU and FARMS in the development of the Electronic Database of Dead Sea Scrolls materials;[5] and David V. Arnold and David G. Long (Department of Electrical and Computer Engineering) have developed a new and compact imaging-radar system that has archaeological applications for Qumran and its environs. This paper will set forth a brief description of each of these three innovations as they pertain to Dead Sea Scrolls research.

[1] FARMS is a nonprofit educational foundation, independent of all other organizations. Its main reasearch interests include ancient history, language, literature, culture, geography, politics and law relevant to the scriptures.

[2] A number of recent technological advances, including radiocarbon dating, multi-spectral imaging, electronic digitization of texts, computer-assisted text reconstruction, and the creation and maintenance of internet Dead Sea Scroll sites have greatly benefited researchers; see, for example, G. Bonani et al., "Radiocarbon Dating of the Dead Sea Scrolls," *ʿAtiqot* 20 (1991) 27-32; G. A. Rodley, "An Assessment of the Radiocarbon Dating of the Dead Sea Scrolls," *Radiocarbon* 35 (993) 335-38; Gregory H. Bearman, Bruce Zuckerman, Kenneth Zuckerman and J. Chiu, "Multi-spectral Imaging of Dead Sea Scrolls and Other Ancient Documents" (Paper presented at the Annual Meeting of the Society of Biblical Literature [Washington, DC], 20-23 November, 1993); Gregory H. Bearman and Sheila I. Spiro, "Archaeological Applications of Advance Imaging Techniques," *BA* 59 (1996) 56-66; idem, "Imaging Clarified," in Donald W. Parry and Eugene C. Ulrich (eds.), *The Provo International Conference on the Dead Sea Scrolls: New Texts, Reformulated Issues, and Technological Innovations*, (STDJ 30; Leiden: Brill, 1998 [forthcoming]); Neil Silberman, "Digitizing the Ancient Near East," *Archaeology* 49/5 (1996) 86-88; Armin Lange, *Computer-Aided Text-Reconstruction and Transcription—CATT-Manual* (Tübingen: Mohr-Siebeck, 1993). In addition, the Orion Center for the Study of the Dead Sea Scrolls maintains a major Internet Site called "The Orion Home Page."

[3] The well-known abbreviation "DNA" denotes deoxyribonucleic acid.

1. DNA AND THE DEAD SEA SCROLLS

A number of questions concerning the origin and production of the Dead Sea Scrolls may be addressed using DNA-analysis. Because these parchments were produced from animal skins, they may contain remnant DNA molecules. Within the last decade, new techniques in molecular biology have been developed that have made it possible to recover DNA from ancient sources. The molecular analysis of ancient DNA ("aDNA") from the Judaean Desert parchment fragments enables us to establish a genetic signature unique for each manuscript. The precision of this DNA-analysis will allow us to identify the species, population, and individual animal from which each parchment was produced.

1.1 Background

The ability to recover biomolecules, most importantly DNA, from ancient remains has opened new research that has many significant

[4] See Scott R. Woodward, Gila Kahila, Patricia Smith, Charles Greenblatt, Joe Zias and Magen Broshi, "Analysis of Parchment Fragments from the Judean Desert Using DNA Techniques," in Donald W. Parry and Stephen D. Ricks (eds.), *Current Research and Technological Developments on the Dead Sea Scrolls*, (STDJ 20; Leiden: Brill, 1996) 215-38.

[5] These include Noel B. Reynolds, professor of Political Science at BYU and president of FARMS; Steven W. Booras, electronic projects specialist at FARMS; and E. Jan Wilson, associate director of the FARMS Center for the Electronic Preservation of Ancient Religious Texts. In addition, a team of experts serve on the board of Advisors: Dr. Weston Fields, exective director of the Dead Sea Scrolls Foundation, and Professors Florentino García Martínez (Qumrân-Instituut), Dana Pike (BYU), Elisha Qimron (Ben Gurion University of the Negev), Lawrence H. Schiffman (New York University), David R. Seely (BYU), Shemaryahu Talmon (Hebrew University), Emanuel Tov (Hebrew University), and Eugene Ulrich (University of Notre Dame).

implications.[6] Access to aDNA provides the opportunity to study the genetic material of past organisms and to identify individual and population histories. Unfortunately, the DNA that has been recovered from archaeological specimens is of such a degraded nature that the usual techniques associated with DNA-fingerprinting cannot be used. However, the origin and identity of biological materials such as preserved skins or parchments may be detemined from modifications of the traditional procedures that involve the polymerase chain reaction ("PCR"), short segments of unique DNA from the mitochondria, and flanking short simple repeats from nuclear DNA.[7]

In 1984 the first reports on the retrieval of informative DNA-sequences from an extinct animal appeared,[8] followed by the cloning of DNA from the skin of an ancient Egyptian mummy[9] dated at 2,400 BP.[10] The rapid degradation of biomolecules begins immediately following death. Except in unusual circumstances, this process continues unabated until the molecules return to a native state. DNA, which occurs in large quantities in living tissue, degrades rapidly after death, and in most instances only small amounts of short DNA molecules can be recovered from dead tissue. This normally prevents recovery and analysis of DNA-sequences from ancient tissue.

However, the advent of PCR[11] in 1985 further opened the possibility of isolating DNA-sequences in extracts in which the majority of the molecules are damaged and degraded. Theoretically, a single intact copy of a target DNA-sequence, which needs only to be on the order of one hundred to two hundred base-pairs in length,

[6] Bernd Herrmann and Susanne Hummel, "Introduction," in B. Herrmann and S. Hummel (eds.), *Ancient DNA* (New York: Springer, 1994) 1-12.

[7] See Francis X. Villablanca, "Spatial and Temporal Aspects of Populations Revealed by Mitochondrial DNA," in Herrmann and Hummel (eds.), *Ancient DNA*, 31-58.

[8] See Russell Higuchi et al., "DNA Sequences from Quagga, an Extinct Member of the Horse Family," *Nature* 312 (1984) 282-84.

[9] See Svante Pääbo, "Molecular Cloning of Ancient Egyptian Mummy DNA," *Nature* 314 (1985) 644-45; Jörg T. Epplen, "Simple Repeat Loci as Tools for Genetic Identification," in Herrmann and Hummel (eds.), *Ancient DNA*, 13-30.

[10] BP ("before present") is equivalent in some scientific circles to BC or BCE.

[11] Randall K. Saiki et al., "Enzymatic Amplification of Beta-Globin Genomic Sequences and Restriction Site Analysis for Diagnosis of Sickle Cell Anemia," *Science* 230 (1985) 1350-54.

is sufficient for PCR, making it an ideal tool for aDNA studies. PCR products can be sequenced directly from a sample (which is preferable), or after cloning, making DNA-sequence comparisons an extremely useful tool for the study of kinship relationships between individuals and populations. The amplification of mitochondrial DNA ("mtDNA") from ancient bones and teeth dated from 750 to 5,450 years BP has been accomplished recently by a number of investigators.[12] In addition, aDNA has been used in the sex-identification of skeletal remains.[13] PCR has been successfully applied to the analysis of ancient mtDNA from a variety of soft tissue remains, including a 7,000-year old human brain,[14] an extinct marsupial wolf,[15] and—particularly relevant to this study—the

[12] Erika Hagelberg, B. Sykes and R. Hedges, "Ancient Bone DNA Amplified," *Nature* 342 (1989) 485; Erika Hagelberg et al., "Ancient Bone DNA: Techniques and Applications," in *Philosophical Transactions of the Royal Society of London B* 333 (1991) 339-407; Erika Hagelberg and J. B. Clegg, "Isolation and Characterization of DNA from Archaeological Bone," *Proceedings of the Royal Society of London B* 244 (1991) 45-50; S. Horai et al., "DNA Amplification from Ancient Human Skeletal Remains and Their Sequence Analysis," in *Proceedings of the Japanese Academy of Science* 65 (1989) 229-33; G. Hanni et al., "Amplification of Mitochondrial DNA Fragments from Ancient Human Teeth and Bone," *C. R. Academy of Science*, 3rd series, 310 (1990) 356-70; Susanne Hummel and Bernd Herrmann, "Y-Chromosome-Specific DNA Amplified in Ancient Human Bone," *Naturwissenschaften* 78 (1991) 266-67; D. A. Lawlor et al., "Ancient HLA Genes from 7500-year-old Archaeological Remains," *Nature* 349 (1991) 785-88; E. Beraud-Columb, J. M. Tiercy and G. Querat, "Human Beta-thalassemia Gene Detected in 7000-year-old Fossil Bones," in *Proceedings of the 3rd International Congress on Human Paleontology, Jerusalem, Israel, August 23-28, 1992* (1992) 146 (abstract); K. Thomas et al., "Spatial and Temporal Continuity of Kangaroo Rat Populations Shown by Sequencing," *Journal of Molecular Evolution* 31 (1990) 101-12; Scott R. Woodward et al., "Amplification of Nuclear DNA from Teeth and Soft Tissue," *PCR Methods and Applications* 3/4 (1994) 244-47; and Svante Pääbo, Russell G. Higuchi and Allan C. Wilson, "Ancient DNA and the Polymerase Chain Reaction," *Journal of Biological Chemistry* 264 (1989) 9709-12.

[13] Hummel and Herrmann, "Y-Chromosome-Specific DNA," 266-67; Svante Pääbo, "Ancient DNA: Extraction, Characterization, Molecular Cloning and Enzymatic Amplification," *Proceedings of the National Academy of Sciences* 83 (1989) 1939-43.

[14] See Lawlor et al., "Ancient HLA Genes," 785-88.

[15] R. H. Thomas et al., "DNA Phylogeny of the Extinct Marsupial Wolf," *Nature* 340 (1989) 465-67.

preserved museum skins of over thirty kangaroo rats.[16] Numerous reports document the successful extraction and amplification of aDNA from museum skins and field-collected specimens,[17] including both naturally-preserved (mummified) and actively-treated skins from a wide variety of organisms (especially birds and mammals).[18] Some of these skins have been subjected to the same conditions that we expect to exist in the scroll parchments, and the extraction procedures for such specimens are not substantially different from those we have used in previous studies of aDNA.

1.2 Methodology

Although there are many successful studies employing aDNA-analysis, numerous difficulties and methodological problems still arise. The PCR technology is extremely sensitive and can be easily affected by contamination from extraneous DNA material. The source of such contamination may be other personnel working in the field and laboratory or micro-organisms such as bacteria. Another problem is the presence of inhibitors of unknown origin in aDNA extracts that interfere with the PCR reaction.[19] In our laboratories, all work is routinely carried out using rooms, equipment, and reagents dedicated only to aDNA-analysis. All personnel wear masks and sterile gloves to minimize contamination, and extensive controls are routinely used in all stages of DNA-extraction and amplification. Specimens are thoroughly cleaned before sampling, and only sterile instruments that have been exposed to ultraviolet light to destroy DNA are used. Approaches have also been developed to overcome the inhibitor effect, either through dilution of the inhibitor prior to PCR[20] or via alternate purification techniques. Contamination by contemporary human DNA will not pose a serious problem to this study since it is easy to differentiate the contaminating human DNA from the animal DNA obtained from the parchments. The aDNA obtained from parchment fragments helps answer several questions:

16 K. Thomas et al., "Spatial and Temporal Continuity," 101-12.

17 R. H. Thomas et al., "DNA Phylogeny"; K. Thomas et al., "Spatial and Temporal Continuity"; M. Culver, personal communication.

18 K. Thomas et al., "Spatial and Temporal Continuity."

19 Hagelberg and Clegg, "Isolation and Characterization," 45-50; Pääbo, "Ancient DNA: Extraction."

20 Hagelberg and Clegg, "Isolation and Characterization"; Pääbo, "Ancient DNA: Extraction."

**What species of animals were used for parchment production?*

It is currently thought that most of the scrolls were written on goat- or sheepskins, but variations in texture, color, thickness, follicle number, and distribution in the surviving parchments may indicate that other skins were also used. On the basis of microscopic examination of the distribution of hair-follicles that remain in the parchment fragments, W. Ryder[21] was able to determine four different groups that may have been the possible species of origin for twenty samples of parchment from the Dead Sea area. He determined that one sample group is derived from calf, one from a fine-wooled sheep, one from a medium-wooled sheep, and one from a hairy animal that could have been either a sheep or a goat. However, identification of the exact species is not possible on the basis of microscopic examination alone.

It is easy to suppose that scrolls destined to contain religious writings were produced from ritually clean animals. According to Maimonides, "A scroll of the Law or phylacteries written on skins not expressly tanned for those purposes, is unfit for use."[22] Evidence from biblical sources and from at least one of the Judaean desert manuscripts (the Temple Scroll) shows that very strict requirements were imposed on the purity of animal skins. In particular, the skins brought into the temple or the temple city had extra requirements placed on their origin and preparation. According to Y. Yadin, these skins had to be not only pure, but "entirely holy and pure."[23] In the Temple Scroll this requirement is stressed:

> Skin, even if it was made from the hide of a clean animal, unless the animal had been sacrificed in the Temple [should not be brought to the Temple city]. Such ordinary skins are, indeed, clean for the need of all labour in other cities, but "into the city of my temple they shall not bring [them]."[24]

Some of the parchments used at Qumran may have had less strict requirements for cleanliness and purity applied to them. It was therefore possible to use skins from species of animals that were clean, but not necessarily ritually pure or used for sacrifice in the

21 W. Ryder, "Remains Derived from Skin," in *Microscopic Studies of Ancient Skins* (Oxford: Oxford University Press, 1965).

22 Maimonides, as quoted by Yigael Yadin in *The Temple Scroll* (Jerusalem: Israel Exploration Society, 1983) 1.315.

23 Yadin, *Temple Scroll*, 1.309.

24 See the previous note.

temple. These clean, but not temple- or city-worthy, animals could have included a number of animal species such as gazelle, ibex, dishon or deer. By identifying the species of animal used for the production of a specific parchment, it may be possible to postulate a hierarchy of importance for the different manuscripts. Some would have been intended for use in the temple or synagogue and other important sites within the temple city or community, while others may have had lesser religious significance.

**How many different manuscripts are represented in the collection of fragments at the Rockefeller and Israel Museums?*

Unfortunately, most of the recovered parchment material is quite fragmented, making it difficult to establish physically contiguous pieces of manuscripts. It is estimated that the many thousands of fragments can be grouped into over eight hundred different scrolls, and it would be of tremendous value to determine exactly which fragments belong together. Obtaining DNA signatures unique to each manuscript will make it possible to sort out the physical relationships of scroll fragments. Such information should prove particularly useful in sorting out the huge number of small fragments that cannot be confidently grouped on the basis of fragment shape, style of handwriting, or text, and may well provide unique insights into the subsequent interpretation of the scrolls.

**Which pieces can be grouped together as originating from the same scroll because they are from identical or related parchments?*

Because individual animals can be identified by their unique genetic signature, it is theoretically possible to identify the unique origin of each of the parchment fragments based on their genetic information. Using the techniques of aDNA-analysis, pieces belonging to the same or closely-related skins can be grouped together. This should assist both in the reconstruction of manuscripts and in the verification of assemblies that were previously already made.

**Did more than one scribe work on a single document, or did different scribes use parchment that originated from the same source for different manuscripts?*

There are examples in which two or more scribes worked on the same manuscript, as was the case with the Temple Scroll, the Thanksgiving Scroll, and several other scrolls. If more than one scribe participated in the production of a single manuscript, which

was then subsequently damaged and is today quite fragmented, the critical analysis based only on palaeography could falsely identify separate origins of what was a single text.

Because of their size, some manuscripts (i.e. the Great Isaiah Scroll, the Manual of Discipline and the Temple Scroll) are composed of parchments that were produced from a number of different animals. The Temple Scroll is written on nineteen separate sheets of parchment, each of which is thirty-seven to sixty-one centimeters in length.[25] It is probable that no more than two or four sheets were derived from the same animal. Analysis of fragments from each section of these scrolls will allow us to determine the degree of relatedness of the parchments in a single manuscript, and whether they are derived from identical or closely-related animals. This analysis can also be applied to repair patches, thus providing information about where a scroll was when it was patched.

**Is the parchment for the patch from the same herd as the original manuscript? Does the patch represent a herd from a different region, reflecting mobility of either the original scroll or the herd?*

Perhaps parchment was a trade item that was brought in from one or a number of different sources. The resulting data, revealing the level of relatedness of the parchment from a single scroll, will establish benchmarks that are valuable for the subsequent interpretation of the genetic data obtained by analysis of the aDNA from the fragments.

**Does the collection represent a library from a single locality, or is it a collection representing contributions from a wide region?*

Comparing DNA-fingerprints recovered from the parchments and those obtained from archaeological remains of animals found in ancient sites throughout Israel can determine the origins of individual parchments. In the ancient populations of domestic animals in Israel certain alleles[26] likely became fixed by inbreeding in local herds. This is especially true if a group such as that at Qumran was isolated and closed.[27] Biblical examples of the importance of sepa-

---

[25] *Temple Scroll*, 1.9-10.

[26] I.e. forms of a gene.

[27] James H. Charlesworth, *Jesus and the Dead Sea Scrolls* (New York: Doubleday, 1992), xxxiii; Emanuel Tov, "Textual Witnesses of the Bible," in idem, *Textual Criticism of the Hebrew Bible* (Minneapolis: Fortress, 1992) 102.

rating flocks and herds are reflected in Genesis 13:5–9, when Abram and Lot separate their herds to different locales, and again in 30:40, when Jacob separates his herds from those belonging to Laban.

It was apparently critical that animals for the production of skins for use in Jerusalem, the temple city, were derived from flocks and herds that were "known to their ancestors."[28] This suggests that flocks and herds were carefully observed and may have been guarded against "contaminating" crossbreeding. Such patterns of husbandry would effectively produce closed breeding-groups with predictable genetic consequences. Fixed allele patterns would establish specific markers in the population that could be used to identify and differentiate local herds. Analysis of aDNA that has been extracted from goat-bones excavated at Qumran and other archaeological sites within present-day Israel could reveal any fixed allele patterns and should be compared to the alleles found in the ancient parchments. Such an aDNA-analysis will determine if the sampled parchments were produced locally at Qumran or were collected from different locations. A test of the sensitivity of this procedure could be performed comparing genetic fingerprints from scrolls that were most likely composed at Qumran, such as the Rule of the Community (1QS), and others that were probably brought to Qumran other locations in Palestine, such as the Great Isaiah Scroll (1QIsa^a).[29] Another potential source of information about the origin of manuscripts is a comparison of DNA-sequence with "autograph" documents, several of which now appear to have been identified in the Qumran collections.[30] Since these autographs are considered to have been written by the people at Qumran, they can provide a genetic fingerprint of the parchment that was used by these individuals.

The molecular identification of parchment fragments involved a number of complex steps. We first demonstrated the ability to isolate and amplify aDNA from parchment on "modern parchment," animal skins that have been treated in a similar way to that which we believe

[28] Josephus, *Antiquities* (LCL 210; Cambridge, MA: Harvard University Press; London: Heinemann, 1966) 12 §146.

[29] Norman Golb, "The Problem of Origin and Identification of the Dead Sea Scrolls," *Proceedings of the American Philosophical Society* 124 (1980) 1-24; idem, "Who Hid the Dead Sea Scrolls?" *BA* 48 (1985) 68-82.

[30] See Golb, "The Problem of Origin," and idem, "Who Hid the Dead Sea Scrolls?"

was practiced in ancient times. To extract the DNA, the skin fragments were pulverized in liquid nitrogen, dissolved and lysed (i.e. disintegrated) in a highly chaotropic solution, and the DNA was recovered by collection on silica beads. We have extracted DNA from museum skins of rabbits and commercially-prepared deer- and sheepskins. These fragments were sequenced and shown to be specific for rabbit, deer, and sheep, respectively, and the procedures used were then repeated to obtain aDNA from the ancient parchment.

After we demonstrated that it was actually possible to obtain DNA from treated skins, the next step was to identify in modern goats—both domestic and wild—and other potential sources of parchment the appropriate DNA-sequence changes, or polymorphisms, that are capable of differentiating individuals, herds, or species. DNA was isolated from modern domestic goats, wild goats, sheep, ibex, and other animals that were possibly used for parchment-production and were then amplified using the polymerase chain reaction (PCR). From our preliminary results it is clear that unique DNA regions will be identified that will give good differentiation at both the species- and herd-levels.

1.3 The Results Obtained

We have begun to extract aDNA from small portions of parchment fragments of the Dead Sea Scrolls, to amplify biologically-active DNA using the polymerase chain reaction (PCR), to obtain DNA-sequences, and to identify unique genetic signatures of the fragments. This has shown that the process is feasible and can be used to re-establish the physical relationships of scroll fragments that may help clarify the translation and interpretation of the Scrolls.

We have extracted DNA from eleven small pieces (approximately 0.5 cm^2) of parchment from the area and time period corresponding to the Dead Sea Scroll parchments. DNA from these fragments has been successfully amplified and sequenced. The sequence of six of these fragments is most closely related to, but not identical with, that of both wild and domestic goats. It is significantly different from the human sequence, demonstrating that the parchment material was not contaminated by human DNA, neither in the handling of the parchment during collection nor during the laboratory manipulations. The number of differences between the aDNA and the contemporary goat-DNA is greater than was generally expected

because of the accumulated normal evolutionary mutations over the intervening period of two thousand years. The aDNA is probably not from the same species as the contemporary goat samples. However, fewer differences occur between the ancient sample and the modern goat than between the ancient sample and either sheep or cow. This indicates a closer relationship to an animal such as a goat, rather than a cow or sheep. We then compared the first two of the eleven fragments with sequences that we have determined for the modern ibex and gazelle. These comparisons strongly suggest that these pieces were derived from a gazelle, ibex, or similar kind of animal.

We have also examined six fragments from five different sheets of the Temple Scroll, which have all proved to be derived from goats. For these pieces, no difference exists between ancient and modern goats at this gene locus. We are currently in the process of identifying individual DNA polymorphisms in those fragments to determine the degree of relatedness of the animals that were used to produce the parchment in the scroll.

We have also been able to isolate and amplify DNA from the archaeological bones of ibex and goats that were found at Masada. In most instances, horn-cores that have been identified by species are being used as the source of DNA. This demonstrates our ability to recover from ancient animal remains the necessary genetic information that will enable us to compare Dead Sea Scroll fragments with the animals from which they were derived. Such a comparison will allow geographical localization of the parchment sources.

In conclusion, we have demonstrated the ability to recover aDNA from the parchment on which the Dead Sea Scrolls were written. We have also shown that it is possible to recover authentic sequences from this material and to use it for making comparisons with other sequences. Our early results indicate that the skins from which the first two ancient fragments were derived are not domestic or wild goats, but are most likely a wild species of gazelle or ibex. We have also determined that seven other random scroll fragments are derived from goats, six of them from the Temple Scroll. These analyses differ from the earlier classifications that were made with recourse to microscopic analyses of similar parchment fragments from the same area by Ryder.[31] We have as yet not identified any parchment made from a species of sheep.

[31] W. Ryder, "Remains Derived from Skin."

This project is the beginning of a fruitful collaboration that will continue over the next few years. We hope that the analysis of DNA from parchment fragments will add a new level of critical analysis to Dead Sea Scrolls research.

2. THE DEAD SEA SCROLLS ON CD-ROM: THE FARMS ELECTRONIC DATABASE[32]

The FARMS Electronic Database has been produced in collaboration with the Ancient Biblical Manuscript Center (AMBC), Brigham Young University (BYU),[33] the Dead Sea Scrolls Foundation, E. J. Brill, the Israel Antiquities Authority (IAA), and Oxford University Press. It contains a fully-integrated and computerized collection of transcriptional texts and digitized images (or photographic images), as well as reference materials of importance for scholarly work on the Dead Sea Scrolls—the Hebrew Bible, an English translation of the Hebrew Bible, and the Septuagint. The texts include all the transcriptions that were published in the official DJD series through 1996, the preliminary versions of transcriptions to be published in 1997 or later, and many transcriptions that have been published in non-DJD venues (e.g. the Temple Scroll and the War Scroll). 800 digitized images, which were selected from the collection held at the Ancient Biblical Manuscript Center, correspond to these transcriptions.

New, more user-friendly features have been added to the Database since its preview presentation at the Provo International Conference on the Dead Sea Scrolls (15-17 July, 1996). The search-engine used is "WordCruncher," which has recently been considerably simplified at the front-end by BYU computer specialists via the addition of a second means of searching a word or phrase. In addition, the table of contents and interface have been modified so that the display is now similar to Windows 95. Access to the menus has also been facilitated, so that users can now be guided by either beginners' or advanced menus. A new coach system is in place, which—when activated at the "Help" menu—is designed to assist all users at every stage. If the

[32] For an early description of the Database, see Donald W. Parry and Steven W. Booras, "The Dead Sea Scrolls CD-ROM Database Project," in Parry and Ricks (eds.), *Current Research and Technological Developments*, 239-50.

[33] BYU developed the search engine "Wordcruncher" in the late 1980's so that researchers could access the Scriptures and other religious texts in English.

user desires help with a particular function, he or she can simply open the Help menu and receive a brief explanation. The Database also features an automatic lexicon or thesaurus; instead of the previous multi-step process for accessing the lexicon, users now simply press a single key. For this updated Database, WordCruncher has created a substring function for the Hebrew text, especially for searches, so that if a character exists in the middle of a triconsonantal root (for example), the search-engine can still conduct a root-search.

The Database has a number of functions that enable scholars and researchers to access the scrolls in ways that are not possible through other means. In addition to its function as an exhaustive concordance (even seeking and finding every question mark in a passage!), the Database offers complex, instantaneous and comprehensive searches of the transcriptional texts.[34] The search routine allows the user to design sophisticated searches of every occurrence of words, phrases or selected forms. It also permits searching a phrase, a single word, two words separated by other words, or a single letter, as one chooses. The user can even conduct a "wildcard search," entering two or three characters from the beginning, middle or end of a word—or on one, two or three lines of text—and the search-engine seeks all occurrences of the specified characters in the selected text.

The Database user may also access the transcriptional text by using the "WordWheel," which lists every word in the Database with the number of occurrences of specific words and the total count in a given text. The WordWheel presents the words in alphabetical order in the language of the text (Hebrew, English, Greek), and text-windows are created by clicking on a word with the mouse.

The Database also conducts sophisticated Hebrew verbal root-searches, regardless of affixal attachments (such as a prefix, suffix, or infix), including prepositions, the *waw* conjunction, and pronominal suffixes. For instance, one can search for a variety of constructions where one or more of the root-letters may be missing or arranged in a different order, such as III-*he* verbs, I-*nun* verbs, I-*yod* verbs, *hithpaʿel* verbs with sibilants that have undergone metathesis, and hollow verbs.

The results of the search (called "hits") are listed almost instantaneously and may be viewed in the Reference List display, or

[34] For a description and figures of the search routine, see Parry and Booras, "Dead Sea Scrolls CD-ROM Database Project," 244-47.

within a number of windows, with one reference per window. These windows may be adjusted (i.e. enlarged or reduced) to show one or several lines of text, the entire text, or may be scrolled down so the user can see all of the hits one after another. The user then prints the results of the search, or may store and retrieve them at a later date.

Two actual examples of the search routine are as follows: a simple word search reveals that the word בית occurs 2,109 times in the Bible and 194 times in the nonbiblical texts of the Qumran Caves; and the preposition על occurs 4,552 times in the Bible and 1,131 times in the nonbiblical Qumran texts. For these simple searches, the computer screen displays their number of occurrences, the name of the text source with references, and the context in which the searched words appear. After the required search words (בית and על) had been typed in, these searches each took less than one second each to complete.

A more Complex Search

The following letters were transcribed from a small fragment belonging to 4QSam[a]:

]ה אֹ[
]ערב ונ[
]ויהו[

Although ערב is easy to locate in the Database by conducting a simple word-search, locating the reference in the books of Samuel is not as easy. After the characters ו ערב were entered "within 25 words" of ויה, the computer screen revealed a total of ten hits. But only one had all of the characters on the three lines of the small fragment, namely 1 Sam 14:24. Typing in the characters took a few seconds but WordCruncher's search-engine took less than one second to locate the ten hits. The fragment has accordingly been reconstructed as follows for the forthcoming edition in the DJD series:[35]

[	ההוא ה]יאל	[24]	1
[	ה]ערב ונ[קמתי	]	2
[	ויהו[י]	[25]	3

1 Sam 14:24-25

[35] F. M. Cross (with D. Parry), E. Ulrich, *Cave 4.XII: Samuel* (DJD 17; Oxford: Clarendon Press [forthcoming]).

The Database's approximately 900 images were scanned at 400 dpi on an Agfa Arcus II scanner. Each of these images is tagged to, and corresponds with, a particular transcriptional text. As the user reviews the transcriptions on the computer screen, he or she may click on an icon and view the corresponding digitized photographic images on the same screen. On occasion the user may also view alternate images (e.g. duplicate images taken under different conditions, with different methods and at different times). With the zooming capabilities[36] of the Database the user can examine high quality images at 500% of their actual size, often with little pixelization occurring. An example of a fragment from 4QSam^{a} (1 Sam 14:47-49) at 200% is presented on Plate 8.[37]

Beyond the advantages described in the previous paragraphs, the Database has other obvious benefits: convenience, protection of the originals, broad distribution, low cost, and the ability to manipulate the images. The Database is convenient and portable—one can carry the entire non-biblical Qumran library in the palm of one's hand and use it anywhere in the world where a computer and CD drive can be accessed. It also features high-quality digitized copies of the original scrolls and fragments, with no fear of mishandling these 2,000 year-old treasures. There is no limit to distribution of the Database (as permissions are granted), and so literally thousands of individuals may obtain a copy. Images and transcriptions may be distributed at relatively low cost to an individual or institution; and the images may be accessed through several types of commercial imaging-software (such as Adobe Photoshop). The user is thus able to cut and paste letters, words, or fragments, to enhance images via a number of techniques, to move fragments from one image to another (in the quest to identify the pieces), to flip, rotate, or manipulate images, and to carry out many other related tasks.

3. ARCHAEOLOGICAL APPLICATIONS OF IMAGING RADAR

During the past decade imaging radar has been applied to regions of potential archaeological interest.[38] For example, C. Elachi et al.[39]

[36] On the zooming capabilities and figures of the Database, cf. Parry and Booras, "Dead Sea Scrolls CD-ROM Database Project," 243-44.

[37] The Plates appear at the end of this volume.

[38] David V. Arnold and David G. Long are affiliated with the Microwave Earth Remote Sensing Laboratory, Electrical and Computer Engineering Department, Brigham Young University in Provo, Utah. Many others have assisted Arnold and Long in the development of the imaging radar, including Douglas Thompson, Thomas Karlinsey, Perry Hardin, Elaine Alger, Gayle Miner and Adam Robertson.

have shown that imaging radar can detect features buried under several meters of dry sand in the Sahara Desert, and D. Holcomb[40] describes how the subsurface capability of imaging radar can be used to provide a remote survey of the Taklamakan desert of north-western China. D. Evans et al.[41] and F. El-Baz[42] have presented more recent radar images of the Taklamakan desert, revealing features such as waterways, ancient ruins and sections of the Great Wall of China. R. Blom et al.[43] have demonstrated that radar images can help in the detection of ancient roads.[44] In September 1994, a radar-image that was taken of Angkor in Cambodia from the Space-Shuttle by the Jet Propulsion Laboratory (in Pasadena)[45] showed how features covered by heavy vegetation may be discerned.[46] These studies and others show that imaging radar has the capability of detecting surface- and subsurface-features, as well as features obscured by heavy vegetation. This capability can be of significant assistance to the archaeological community, particularly if the technology can be made more widely available.

The imaging radar discussed above is officially termed "synthetic aperture radar" (SAR), a technology that has existed for more than thirty years. SARs are usually flown aboard large aircraft or

[39] C. Elachi, L. E. Roth and G. G. Schaber, "Spaceborne Radar Subsurface Imaging in Hyperarid Regions," in *IEEE Transactions on Geoscience and Remote Sensing* 22/4 (1984) 383-87.

[40] D. W. Holcomb, "Shuttle Imaging Radar and Archaeological Survey in China's Taklamakan Desert," *JFA* 19 (1992) 129-38.

[41] D. L. Evans, E. R. Stofan, T. D. Jones and L. M. Godwin, "Earth from Sky," *Scientific American* 271/6 (1994) 70-75.

[42] See F. El-Baz, "Space Age Archaeology," *Scientific American* 277/2 (1997) 60-65.

[43] R. Blom, J. Zairins, N. Clapp and G. R. Hedges, "Space Technology and the Discovery of the Lost City of Ubar," in *Proceedings of the 1997 IEEE Aerospace Conference, 1-8 Feb. 1997, Aspen Colorado*, 19-28.

[44] These images are also found in the articles by Evans et al., "Earth from Sky," 70-75; and El-Baz, "Space Age Archaeology," 60-65.

[45] The JPL is is managed by the California Institute of Technology for NASA (the National Aeronautics and Space Administration).

[46] This image is available from the JPL website at http://www.jpl.nasa.gov.

spacecraft. Basically, SAR works by sending microwave energy-pulses towards the ground and processing the return echos, thus producing an image. Because of the complexity of SAR theory, a detailed discussion is not presented here; for further information the reader is referred to J. Curlander and R. McDonough,[47] S. Hovanessian,[48] W. Carrara et al.,[49] C. Jakowatz et al.,[50] or any of the many references contained in these works.

Even though the archaeological applications of SAR appear promising, the size, cost, and availability of SAR systems have limited their use by the archaeological community at large. In an attempt to make SAR technology more readily available and applicable to archaeology, we have developed a new compact SAR system. The Brigham Young University SAR ("YSAR") is small and inexpensive; even more important, it can be operated from a small four-to-six passenger aircraft, making the operating costs comparable to that required for optical surveys.

YSAR is flown at an altitude of 300 to 600 meters, producing images that are approximately 500 by 3,500 meters with a resolution of 1 meter. The system is operated at a microwave frequency of 2 GHz ("Gigahertz") which can allow some surface- and canopy-penetration. Many technical details related to YSAR can be provided, but for the sake of brevity we refer reders to detailed descriptions of YSAR to be found in D. Thompson et al.[51]

---

[47] J. C. Curlander and R. N. McDonough, *Synthetic Aperture Radar: Systems and Processing* (New York: Wiley, 1991).

[48] S. A. Hovanessian, *Introduction to Synthetic Array and Imaging Radars*) (Norwood, MA: Artech House, 1980).

[49] W. G. Carrara, R. S. Goodman and R. M. Majewski, *Spotlight Synthetic Aperture Radar: Signal Processing Algorithms* (Norwood, MA: Artech, 1995).

[50] C. V. Jakowatz, D. E. Wahl, P. H. Eichel, D. C. Ghiglia and P. A. Thompson, *Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach* (Boston: Kluwer Academic Publishers, 1996).

[51] D. G. Thompson, D. V. Arnold, D. G. Long, G. F. Miner and T. W. Karlinsey, "YSAR: A Compact, Low-Cost Synthetic Aperture Radar," in *Proceedings of the 1996 International Geoscience and Remote Sensing Symposium, 27-31 May 1996, Lincoln Nebraska* (1996) 1892-94. Also see D. G. Thompson, D. V. Arnold, D. G. Long, G. F. Miner, T. W. Karlinsey and A. E. Robertson, "YSAR: A Compact, Low-Cost Synthetic Aperture Radar," in *Proceedings of the 1997 International Geoscience and Remote Sensing Symposium, 27 Jul.–1 Aug. 1997, Singapore* (1997) 386-88.

In September 1996, the YSAR system was taken to Israel to collect data over several archaeological sites, which was achieved during six flights at an altitude of 300 meters. We have processed some of these data and have created SAR images of the Zippori National Forest, Tel Safi and Qumran areas. Since this project is still in its early stages, we offer here only preliminary images of these sites. More analysis is needed to fully evaluate the archaeological information in these images, but so far the results have proved encouraging.

The Zippori site sits on a large hill and contains many partially-excavated ruins, some of which are largely covered with trees and brush. A sample SAR image of the area is shown in Figure 1.[52] Many rock fences, excavations, buildings, roads, and trees can be seen throughout the image. A set of 60 cm microwave corner-reflectors which were arranged in a cross and spaced 10 meters apart are indicated by the arrow. These corner-reflectors are used to help determine the performance of the SAR system.

Tel Safi is thought to be the ancient Philistine city of Gath. A SAR image of the site appears in Figure 2. The tel spans the middle portion of the image, and an arrow is again used to indicate the locations of the corner-reflectors. As was the case in the Zippori image, many surface features that reveal human activity are evident.

Qumran is situated on a shelf between a range of cliffs and the Dead Sea. Our main purpose was not to identify the locations of possible caves, but rather to observe past global traffic patterns and human disturbance. We hope such information may be helpful in developing a regional picture of ancient life in the area surrounding Qumran. SAR images that were taken near Qumran are shown in Figures 3 and 4. Both of these show the main road along the Dead Sea, and a large orchard is evident in Figure 3. Unfortunately, the region around Qumran was difficult to image due to random aircraft motion that was caused by excessive turbulence from thermal air-currents, which resulted in blurred images. A new SAR system which is currently being developed at Brigham Young University will solve this problem for future flights. However, even with the blurring effect, different features are evident in SAR imagery than are found in optical imagery. As we carefully compare the Qumran SAR imagery with corresponding optical imagery, we hope to find important differences between the two.

---

[52] Figures 1–4 appear on Plate 15 at the end of the volume.

As is evident from results obtained over the last decade, aerial SAR surveys have the potential of providing new information to the archaeology community; our efforts have made considerable progress toward making this technology more available. We have an ongoing program aimed at improving the overall performance and availability of SAR. In this connection, we recently received a grant from NASA to design and build an interferometric SAR, a system that will operate at 10 GHz and be capable of determining surface topography as well as producing radar images. The YSAR system which has been described in this paper is being rebuilt and integrated with the newer multiple frequency system, which will be well-suited for future aerial SAR surveys. Our team will also continue to analyze the information we have collected, to collect new data, and to assess the usefulness of SAR technology for the archaeological community.

SELECT BIBLIOGRAPHY

Bearman, G. H. and S. I. Spiro. "Imaging Clarified," in Parry and Ulrich (eds.), *The Provo International Conference on the Dead Sea Scrolls* [forthcoming].

Bearman, G. H., B. Zuckerman, K. Zuckerman and J. Chiu. "Multi-spectral Imaging of Dead Sea Scrolls and Other Ancient Documents" (Paper presented at the Annual Meeting of the Society of Biblical Literature [Washington, DC], 20-23 November, 1993).

Blom, R., J. Zairins, N. Clapp and G. R. Hedges. "Space Technology and the Discovery of the Lost City of Ubar," in *Proceedings of the 1997 IEEE Aerospace Conference, 1-8 Feb. 1997, Aspen Colorado*, 19-28.

Curlander, J. C. and R. N. McDonough. *Synthetic Aperture Radar: Systems and Processing* (New York: Wiley, 1991).

El-Baz, F. "Space Age Archaeology," *Scientific American* 277/2 (1997) 60-65.

Elachi, C., L. E. Roth and G. G. Schaber. "Spaceborne Radar Subsurface Imaging in Hyperarid Regions," in *IEEE Transactions on Geoscience and Remote Sensing* 22/4 (1984) 383-87.

Evans, D. L., E. R. Stofan, T. D. Jones and L. M. Godwin. "Earth from Sky," *Scientific American* 271/6 (1994) 70-75.

Holcomb D. W. "Shuttle Imaging Radar and Archaeological Survey in China's Taklamakan Desert," *JFA* 19 (1992) 129-38.

Hovanessian, S. A. *Introduction to Synthetic Array and Imaging Radars* (Norwood, MA: Artech House, 1980).

Lange, A. *Computer-Aided Text-Reconstruction and Transcription—CATT-Manual* (Tübingen: Mohr-Siebeck, 1993).

Parry, D. W. and S. D. Ricks (eds.). *Current Research and Technological Developments on the Dead Sea Scrolls* (STDJ 20; Leiden: Brill, 1996) 215-38.

Parry, D. W. and S. W. Booras. "The Dead Sea Scrolls CD-ROM Database Project," in Parry and Ricks (eds.), *Current Research and Technological Developments*, 239-50.

Parry, D. W. and E. Ulrich (eds.). *The Provo International Conference on the Dead Sea Scrolls: New Texts, Reformulated Issues, and Technological Innovations* (STDJ 30; Leiden: Brill, 1998 [forthcoming]).

Silberman, N. "Digitizing the Ancient Near East," *Archaeology* 49/5 (1996) 86-88.

Thompson, D. G., D. V. Arnold, D. G. Long, G. F. Miner and T. W. Karlinsey. "YSAR: A Compact, Low-Cost Synthetic Aperture Radar," in *Proceedings of the 1996 International Geoscience and Remote Sensing Symposium, 27-31 May 1996, Lincoln Nebraska* (1996) 1892-94.

Thompson, D. G., D. V. Arnold, D. G. Long, G. F. Miner, T. W. Karlinsey and A. E. Robertson. "YSAR: A Compact, Low-Cost Synthetic Aperture Radar," in *Proceedings of the 1997 International Geoscience and Remote Sensing Symposium, 27 Jul.–1 Aug. 1997, Singapore* (1997) 386-88.

Woodward, Scott R. et al. "Amplification of Nuclear DNA from Teeth and Soft Tissue," *PCR Methods and Applications* 3/4 (1994) 244-47.

Woodward, S. R., G. Kahila, P. Smith, C. Greenblatt, J. Zias and M. Broshi. "Analysis of Parchment Fragments from the Judean Desert Using DNA Techniques," in Parry and Ricks (eds.), *Current Research and Technological Developments*, 215-38.

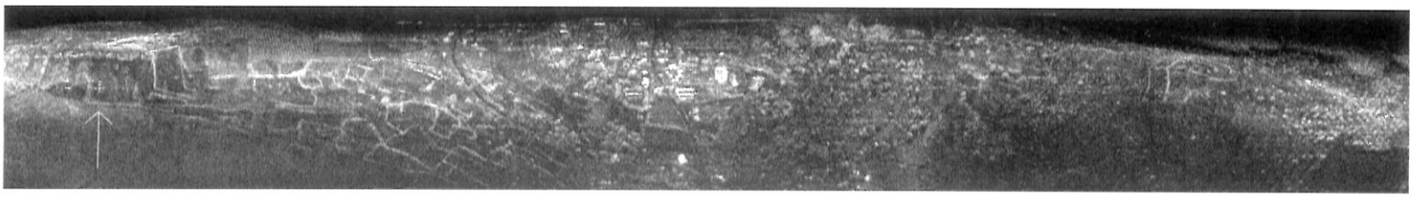

Figure 1: SAR image of ruins in the Zippori National Forest, Israel

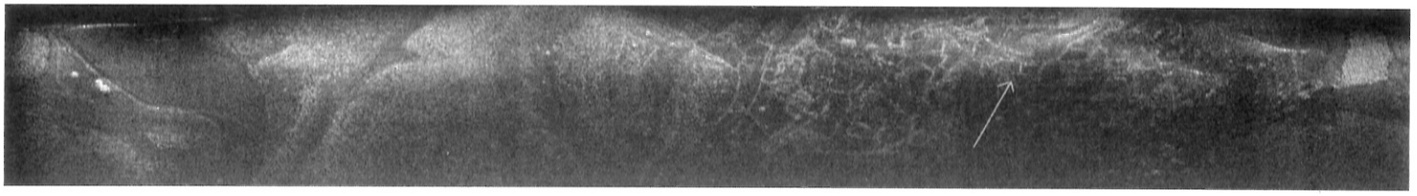

Figure 2: SAR image of ruins at Tel Safi, Israel

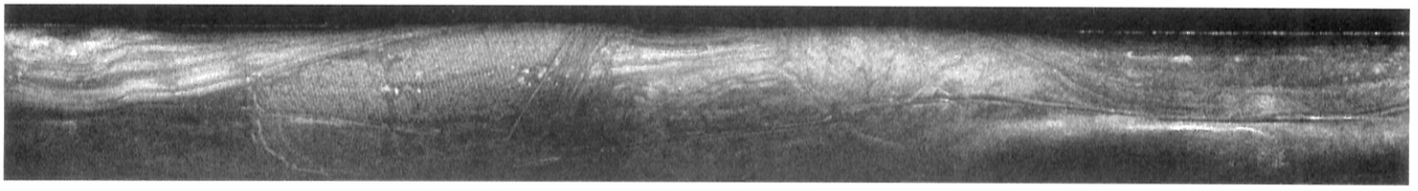

Figure 3: SAR image of the region near Qumran, Israel

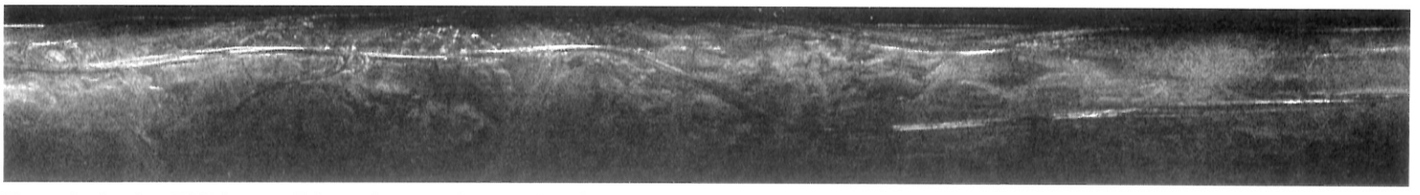

Figure 4: Another SAR image of the region near Qumran, Israel

PLATE 15: Four SAR Images of Sites in Israel