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An Example Expert System for the Interpretation of Depositional Environments

by

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ABSTRACT

Expert Systems can be applied to the interpretation of sedimentary depositional environments by comparing the distinguishing features of the environments to the characteristics of a core or an outcrop. An example Expert System has been constructed which determines whether an outcrop or a core under consideration is consistent with shelf sands deposition. This rule-based system was constructed using the Knowledge Acquisition System developed by SRI International and is easily used. This example system indicates that Expert Systems for determining depositional environments are useful for teaching as well as consulting. These Expert Systems will increase the availability and applicability of sedimentological classifications. As educational tools, these systems demonstrate the progressive logic of an expert in solving a problem, as well as providing ready access to reference material.

INTRODUCTION

Expert Systems are a result of applied research in Artificial Intelligence. They have been used to predict the location of mineral deposits (Duda, Hart, Konolige, Reboh, 1979), diagnose diseases (Shortliffe, 1975), and to perform many other functions requiring expertise. Both the factual and heuristic knowledge of an expert is incorporated into an Expert System. Factual knowledge is found in textbooks; heuristic knowledge is the intuitive or "rules-of-thumb" understanding that is gained from years of specialized work.

The Expert System described here was constructed on a VAX-780[1] using the Knowledge Acquisition System (KAS) developed by Stanford Research Institute. In the Expert System knowledge is represented as an inference network (Figure 1). In the inference network, pieces of evidence are combined to form other pieces of evidence and, subsequently, to form hypotheses. Evidence can be assembled through logical combinations (and, or, not), through plausible inference, and through contexts. An example of a logical combination is shown in figure 1: if a piece of evidence E_1 and a piece of evidence E_2 are true, then evidence E_3 is true. Plausible inference is of the type

A piece of evidence E suggests a hypothesis H with strength S.

A piece of evidence E can be highly or only slightly suggestive of the hypothesis H. Contexts (depicted by the dashed line between E_2 and E_4) indicate that E_4 will be asked about only if E_2 is present or if the certainty associated with E_2 is in the appropriate range. Contexts make the system

[1] Use of trade names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

more effective and more pleasant for the user. For example, if E_2 represents the presence of burrows in a sedimentary sequence and E_4 indicates that the amount of burrowing decreases upward in the sequence, E_2 is a context for E_4. It is logical to ask whether burrowing decreases upward only if burrowing has been confirmed in the sequence.

This system uses a backward chaining control strategy for determining which questions the user is asked. This means that the system works backward from a hypothesis it is considering to obtain the pieces of evidence which pertain to the hypothesis. The set of questions asked by the system varies from interaction to interaction. Answers to earlier questions determine the character of later questions. An example of this is the use of contexts, as described previously. The system also uses certainty factors to represent belief in pieces of evidence, prior probabilities for each piece of evidence or hypothesis, and an inference mechanism based mainly on Bayesian probability theory (Reboh, 1981).

DISCUSSION

The example Expert System described here determines if a particular outcrop or core indicates the depositional environment of a marine shelf sand. The system uses sedimentational sequences and structures and other information to determine the certainty that strata were deposited on a marine shelf. This system is an example of what can be done using Artificial Intelligence techniques to predict depositional environments from outcrop or core observations. The computer file containing the various nodes and connections of the inference network for this example system is in Appendix A.

Appendix B contains a sample interaction with the example expert system for shelf sands. The system asks the user to provide numerical certainties for characteristics of the outcrop or core. Certainty factors vary from -5 to 5, -5 indicating absolute certainty that the characteristic is not present, 5 indicating absolute certainty that it is present, 0 indicating no information about the characteristic, and intermediate values indicating some certainty (positive or negative).

Two other capabilities of the system are the "why" and "?". If the user asks "why" a certain question is being asked, the system indicates why that answer is important in determining whether the outcrop or core under consideration represents a shelf sand. If the user responds with a "?", the system rephrases the question, usually at a more basic level. The file containing the information for these functions is shown in Appendix C.

When the system has accumulated enough information, it provides an overall certainty that the outcrop or core reflects a shelf sand deposit. It also indicates which pieces of evidence were important in reaching the conclusion and provides the reasoning used in deriving the certainty.

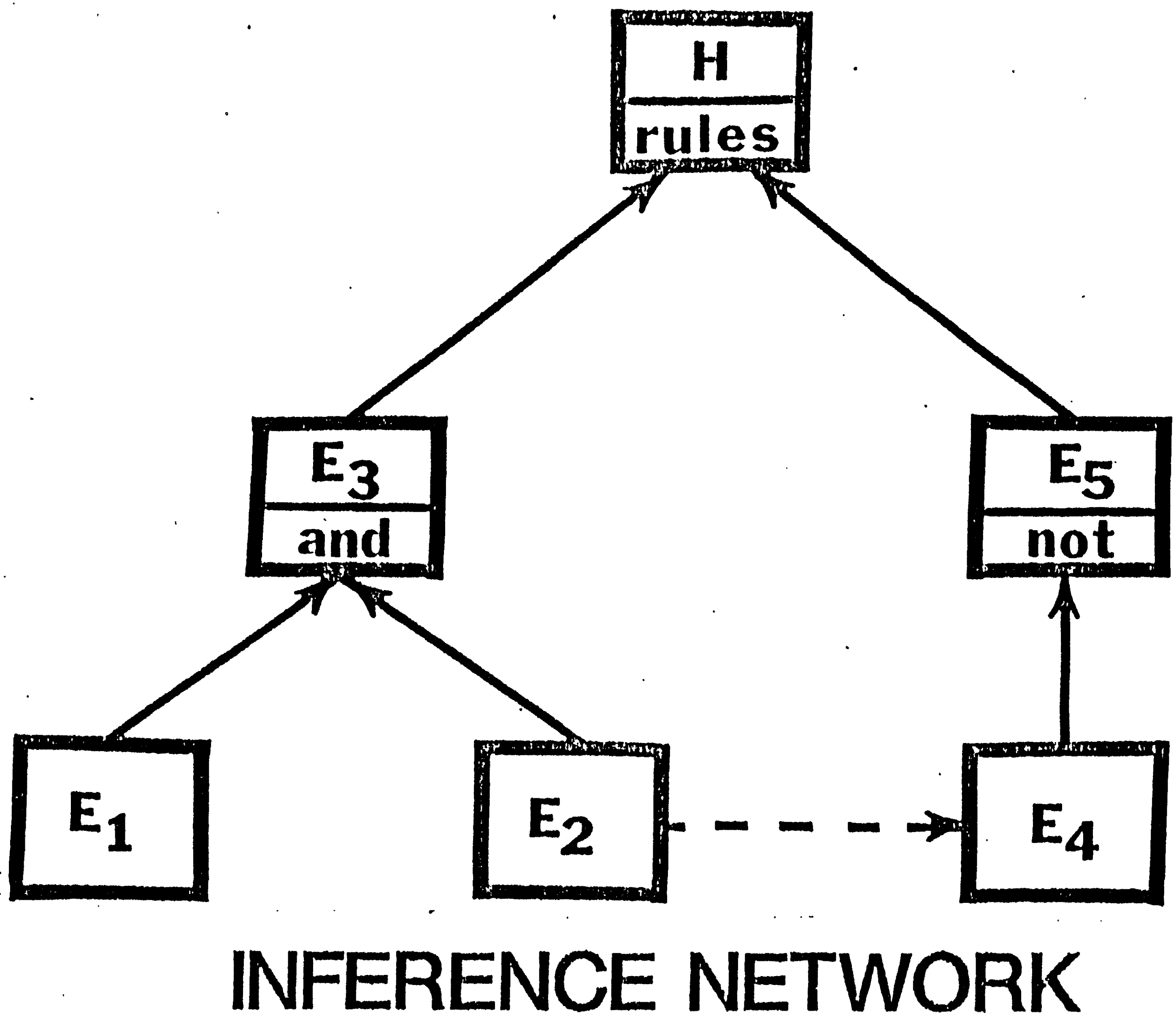

Figure 1.--Inference network. Pieces of evidence (E_i) are combined to form other pieces of evidence and, subsequently, a hypothesis (H) by using logical relations (and, or, not), contexts (depicted by the dashed arrow), and plausible inference (rules, each with an associated strength β).

CONCLUSIONS

This example system was constructed to show the feasibility and usefulness of Expert Systems in predicting depositional environments. The availability of expertise in interpreting depositional environments allows the construction of such systems. A very useful characteristic of these systems is the separation of the inference or control mechanism from the knowledge base. This separation allows quicker and easier modification of the Expert System than if the two were intertwined.

Systems such as this example are useful for consulting and teaching. They are not intended to replace the sedimentologist, but rather to make his or her knowledge more available to the working geologist. Since references can be added easily and the why functions are present, these systems can provide rapid and easy access to reference material for any depositional environment, as well as access to an expert's procedure for identifying environments of deposition.

ACKNOWLEDGMENTS

D. L. Gautier and E. A. Merewether offered many helpful suggestions during the development of this example Expert System. R. B. McCammon taught a course on KAS and Prospector, which made learning to use KAS much easier, and he answered many questions about on the software.

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Duda, R. O., Hart, P. E., Konolige, K., and Reboh, R., 1979, A computer-based consultant for mineral exploration: SRI International final report on project 6415, 185 p.

Reboh, R., 1981, Knowledge engineering techniques and tools in the prospector environment: SRI International Technical Note 243, 149 p.

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Appendix A

Listing of the computer file containing information about the spaces (or nodes; see figure 1) of the inference network for the shelf sands example Expert System. For each space, its text description and information about its relation to other spaces is given.

```
model SHELF

   topspace SHELF


-------------------------------------------------------
space      BED
    text   description
/*   THE LOWER PART OF THE SEQUENCE IS FLAT-BEDDED,
   CROSS BEDS AND/OR RIPPLES ARE ABOVE, AND THE UPPERMOST
   PART OF THE SEQUENCE IS FLAT-BEDDED*/
    inference
           prior 0.1
    control askable
           context of    OBSC   interval -5.0 2.5

-------------------------------------------------------
space      BIO
    text   description
/*   BURROWING IS PRESENT AND THE AMOUNT DECREASES UPWARD
   IN THE SEQUENCE*/
    inference
           prior 0.1
           logical definition   AND DECU PRES
    control unaskable
           context of    SEQ

-------------------------------------------------------
space      BOROBSC
    text   description
/*   AS YOU MOVE UP THE SEQUENCE THE BEDDING CHANGES FROM FLAT TO
   CROSS-BEDDED AND /OR RIPPLED AND THEN TO FLAT AT THE
   UPPERMOST PART OF THE SEQUENCE OR THE BEDDING IS OBSCURED
   BY BURROWING*/
    inference
           prior 0.1
           logical definition   OR OBSC BED
    control unaskable
           context of    SEQ

-------------------------------------------------------
space      DECU
    text   description
/* THE AMOUNT OF BURROWING DECREASES UPWARD IN THE SEQUENCE*/
    inference
           prior 0.1
    control askable
           context of    PRES

-------------------------------------------------------
space      FOSS
    text   description
```

```
/*    THERE ARE SOME MACRO OR MICROFOSSILS INDICATING OPEN
    MARINE CONDITIONS*/
    inference
           prior 0.1
    control askable

------------------------------------------------------
space      LOC
    text   description
/* THE LOCATION IS THAT OF A SUBMARINE SHELF */
    inference
           prior 0.1
           logical definition   AND SHORE PAR
    control unaskable
           context of    SEQ

------------------------------------------------------
space      MTOP
    text   description
/*   NONMARINE ROCKS OVERLIE THE SEQUENCE OR DID OVERLIE
   THE SEQUENCE AND WERE ERODED */
    inference
           prior 0.5
           logical definition   OR NMAR NMERODE
    control unaskable

------------------------------------------------------
space      NMAR
    text   description
/*   NONMARINE ROCKS OVERLIE THE SEQUENCE*/
    inference
           prior 0.5
    control askable

------------------------------------------------------
space      NMERODE
    text   description
/*  NONMARINE ROCKS DID OVERLIE THE SEQUENCE AND
  HAVE BEEN ERODED */
    inference
           prior 0.5
    control askable

------------------------------------------------------
space      OBSC
    text   description
/* BEDDING IS OBSCURED BY BIOTURBATION*/
    inference
           prior 0.1
    control askable
           context of    BIO

------------------------------------------------------
space      PAR
    text   description
/*  THE SEQUENCE REPRESENTS AN ELONGATE SAND BODY THAT
  WAS DEPOSITED WITHIN 30 DEGREES OF PARALLEL TO THE
  SHORELINE */
    inference
           prior 0.1
    control askable
```

```
-----------------------------------------------
space       PRES
    text    description
/* BURROWING IS PRESENT*/
    inference
            prior 0.1
    control askable

-----------------------------------------------
space       SAND
    text    description
/*  SANDSTONE (POSSIBLY INTERCALATED WITH SHALE) IS
    ABOVE THE SHALE AND SILTSTONE IN THE SEQUENCE*/
    inference
            prior 0.1
    control askable

-----------------------------------------------
space       SEQ
    text    description
/* THE SEQUENCE IS COARSENING UPWARD AND CONSISTS OF
   SHALE, SILTSTONE, SANDSTONE AND IS NOT OVERLAIN BY
   ROCKS OF NONMARINE ORIGIN*/
    inference
            prior 0.1
            logical definition   AND SHALE SILT SAND TOP
    control unaskable

-----------------------------------------------
space       SHALE
    text    description
/* THERE IS SHALE IN THE LOWER PART OF THE SEQUENCE*/
    inference
            prior 0.1
    control askable

-----------------------------------------------
space       SHELF
    text    description
/* THE OUTCROP INDICATES A SHELF SAND DEPOSITIONAL MODEL*/
    inference
            prior 0.2
            rules      antecedents  BIO      LS  2.0
                                             LN 0.1
                                    SEQ      LS  6.0
                                             LN 1.000000E-05
                                    LOC      LS  2.0
                                             LN 1.000000E-02
                                    BOROBSC  LS  2.0
                                             LN 0.1
                                    FOSS     LS  2.0
                                             LN 0.1

    control unaskable

-----------------------------------------------
space       SHORE
    text    description
/* THE SHORELINE WAS MANY MILES AWAY AT TIME OF DEPOSITION*/
    inference
```

```
          prior 0.1
    control askable

-------------------------------------------------------
space       SILT
    text    description
/* SILTSTONE (POSSIBLY INTERCALATED WITH SHALE) IS DIRECTLY
   ABOVE THE SHALE IN THE SEQUENCE*/
    inference
          prior 0.1
    control askable

-------------------------------------------------------
space       TOP
    text    description
/* NONMARINE ROCKS DO NOT OVERLIE THE SEQUENCE*/
    inference
          prior 0.5
          logical definition    NOT MTOP
    control unaskable


STOP
```

Appendix B

Sample interaction with the shelf sands example Expert System.

```
1 -- To what degree do you believe that THERE IS
     SHALE IN THE LOWER PART OF THE SEQUENCE  ? 4

2 -- To what degree do you believe that SILTSTONE
     (POSSIBLY INTERCALATED WITH SHALE) IS DIRECTLY
     ABOVE THE SHALE IN THE SEQUENCE  ? 4

3 -- To what degree do you believe that SANDSTONE
     (POSSIBLY INTERCALATED WITH SHALE) IS ABOVE
     THE SHALE AND SILTSTONE IN THE SEQUENCE  ? 4

4 -- To what degree do you believe that NONMARINE
     ROCKS OVERLIE THE SEQUENCE  ? -4

5 -- To what degree do you believe that NONMARINE
     ROCKS DID OVERLIE THE SEQUENCE AND HAVE BEEN
     ERODED   ? -5

6 -- To what degree do you believe that THE SHORELINE
     WAS MANY MILES AWAY AT TIME OF DEPOSITION  ? 3

7 -- To what degree do you believe that THE SEQUENCE
     REPRESENTS AN ELONGATE SAND BODY THAT WAS
     DEPOSITED WITHIN 30 DEGREES OF PARALLEL TO THE
     SHORELINE  ? 3

8 -- To what degree do you believe that THERE ARE
     SOME MACRO OR MICROFOSSILS INDICATING OPEN
     MARINE CONDITIONS  ? 0

9 -- To what degree do you believe that BURROWING
     IS PRESENT  ? 4

10 -- To what degree do you believe that THE AMOUNT OF
     BURROWING DECREASES UPWARD IN THE SEQUENCE  ? WHY

   BIOTURBATION DECREASING UPWARD INDICATES
     1.)DEGREE OF REWORKING BY STORM EVENTS IS INCREASING
     UPWARD 2.)RATE OF SEDIMENTATION IS INCREASING UPWARD.
     BOTH OF THESE ARE CONSISTENT WITH SHELF SAND DEPOSITS.

10 -- To what degree do you believe that THE AMOUNT
      OF BURROWING DECREASES UPWARD IN THE SEQUENCE  ? 4

11 -- To what degree do you believe that BEDDING IS
      OBSCURED BY BIOTURBATION  ? ?

  BIOTURBATION OBSCURING THE BEDDING MEANS THAT THERE IS
     SO MUCH BURROWING THAT THE BED TYPES CANNOT BE DISCERNED.

To what degree do you believe that BEDDING IS OBSCURED BY
BIOTURBATION  ? WHY
```

SUCH BIOTURBATION IS COMMON IN SHELF SANDS. IF
BIOTURBATION DOESN'T OBSCURE THE BEDDING, THE BEDDING
TYPES WILL BE EXAMINED FOR CONSISTENCY WITH A SHELF SANDS
MODEL.

11 -- To what degree do you believe that BEDDING IS OBSCURED
BY BIOTURBATION ? -1

12 -- To what degree do you believe that THE LOWER PART OF
THE SEQUENCE IS FLAT-BEDDED, CROSS BEDS AND/OR RIPPLES
ARE ABOVE, AND THE UPPERMOST PART OF THE SEQUENCE IS
FLAT-BEDDED ? 3

I have nothing more to ask about this hypothesis.

I suspect that THE OUTCROP INDICATES A SHELF SAND DEPOSITIONAL
MODEL (certainty 3.89142).

There are several favorable factors; in order of importance:
1) THE SEQUENCE IS COARSENING UPWARD AND CONSISTS OF
SHALE, SILTSTONE, SANDSTONE AND IS NOT OVERLAIN BY
ROCKS OF NONMARINE ORIGIN (certainty 4.0)
2) BURROWING IS PRESENT AND THE AMOUNT DECREASES UPWARD
IN THE SEQUENCE (certainty 4.0)
3) THE LOCATION IS THAT OF A SUBMARINE SHELF (certainty 3.0)
4) AS YOU MOVE UP THE SEQUENCE THE BEDDING CHANGES FROM FLAT TO
CROSS-BEDDED AND /OR RIPPLED AND THEN TO FLAT AT THE
UPPERMOST PART OF THE SEQUENCE OR THE BEDDING IS OBSCURED
BY BURROWING (certainty 3.0)

There is one uncertain factor whose score may be subject to change:
5) You were unsure whether THERE ARE SOME MACRO OR
MICROFOSSILS INDICATING OPEN MARINE CONDITIONS
(certainty 0.000000E+00)

For which of the above do you wish to see additional information?
(Type ? for available options) 1

On a scale from -5 to 5, my certainty that
1: THE SEQUENCE IS COARSENING UPWARD AND CONSISTS OF
SHALE, SILTSTONE, SANDSTONE AND IS NOT OVERLAIN BY
ROCKS OF NONMARINE ORIGIN is now 4.0.

There are several favorable factors; in order of importance:
1: 1) NONMARINE ROCKS DO NOT OVERLIE THE SEQUENCE
(certainty 4.0)
1: 2) You were sure that THERE IS SHALE IN THE LOWER
PART OF THE SEQUENCE (certainty 4.0) ** limiting factor **
1: 3) You were sure that SILTSTONE (POSSIBLY INTERCALATED
WITH SHALE) IS DIRECTLY ABOVE THE SHALE IN THE
SEQUENCE (certainty 4.0) ** limiting factor **
1: 4) You were sure that SANDSTONE (POSSIBLY INTERCALATED
WITH SHALE) IS ABOVE THE SHALE AND SILTSTONE IN
THE SEQUENCE (certainty 4.0) ** limiting factor **

For which of the above do you wish to see additional
information? NONE

Do you wish to see additional information about THE OUTCROP INDICATES A SHELF SAND DEPOSITIONAL MODEL ?   NO

Appendix C

Listing of the computer file containing information for the spaces in the shelf sands example Expert System for the "why" and "?" functions.

```
MODEL SHELF

SPACE BED
PROPS APPEND-DESC-TEXT T
WHY /*   IN A SHELF SAND DEPOSIT CURRENT ENERGY INCREASES
     UPWARD AND THEN DECREASES AT THE UPPERMOST PART
     AS WOULD BE INDICATED BY THESE TYPES OF BEDDING.  */

SPACE DECU
PROPS APPEND-DESC-TEXT T
WHY /*   BIOTURBATION DECREASING UPWARD INDICATES
     1.)DEGREE OF REWORKING BY STORM EVENTS IS INCREASING
     UPWARD 2.)RATE OF SEDIMENTATION IS INCREASING UPWARD.
     BOTH OF THESE ARE CONSISTENT WITH SHELF SAND DEPOSITS.   */

SPACE FOSS
PROPS APPEND-DESC-TEXT T
WHY /*   SOME FOSSIL GROUPS ARE RESTRICTED TO MARINE
     ENVIRONMENTS AND  MARINE CONDITIONS ARE NEEDED FOR A
     SHELF SAND DEPOSIT. */

SPACE NMAR
PROPS APPEND-DESC-TEXT T
WHY /*   NONMARINE ROCKS OVERLYING THE SEQUENCE IS NOT
     CONSISTENT WITH A SHELF SAND MODEL.  */

SPACE NMERODE
PROPS APPEND-DESC-TEXT T
? /*  IF A UNIT HAS BEEN ERODED, AN EROSIONAL SURFACE
     MAY BE PRESENT.  ALSO, THERE MAY BE MISSING
     BIOSTRATIGRAPHIC ZONES DIRECTLY ABOVE THE SEQUENCE.*/
WHY /*  NONMARINE ROCKS OVERLYING THE SEQUENCE BEFORE BEING
     ERODED IS NOT CONSISTENT WITH THE DEPOSIT BEING A
     SHELF SAND. */

SPACE OBSC
PROPS APPEND-DESC-TEXT T
? /*  BIOTURBATION OBSCURING THE BEDDING MEANS THAT THERE IS
     SO MUCH BURROWING THAT THE BED TYPES CANNOT BE DISCERNED.  */
WHY /*  SUCH BIOTURBATION IS COMMON IN SHELF SANDS.  IF
     BIOTURBATION DOESN'T OBSCURE THE BEDDING, THE BEDDING
     TYPES WILL BE EXAMINED FOR CONSISTENCY WITH A SHELF SANDS
     MODEL. */

SPACE PAR
PROPS APPEND-DESC-TEXT T
WHY /*  MANY MODERN SHELF SAND BODIES TREND PARALLEL TO
     SHORE AND THIS IS A COMMON CHARACTERISTIC OF SHELF
     SAND DEPOSITS. */

SPACE PRES
```

```
PROPS APPEND-DESC-TEXT T
WHY /* THE REWORKING OF SEDIMENT BY ORGANISMS (BURROWING)
     INDICATES 1.)PROBABLE MARINE 2.)LOW ENOUGH ENERGY THAT
     THE SEDIMENT COULD BE INHABITED 3.)SEDIMENT INPUT
     THAT WAS SLOW ENOUGH TO ALLOW REWORKING BY ORGANISMS.
     ALL OF THESE ARE CONSISTENT WITH SHELF DEPOSITION.   */

SPACE SAND
PROPS APPEND-DESC-TEXT T
WHY /*   SANDS INDICATE ENERGIES HIGH ENOUGH TO ENTRAIN
     SAND-SIZED DEBRIS AND WANING STORM ENERGY CAUSING SAND
     DEPOSITION. THESE WOULD BE EXPECTED IN THIS PART OF
     THE SHELF SEQUENCE.  */

SPACE SHALE
PROPS APPEND-DESC-TEXT T
WHY /*  MUDSTONE OR SILTY SHALE INDICATES LOW ENERGY DEPOSITION
     OFTEN REPRESENTING LONG QUIESCENT PERIODS AS WOULD BE
     EXPECTED IN THE LOWER PART OF THE SHELF SAND DEPOSIT.  */

SPACE SHORE
PROPS APPEND-DESC-TEXT T
WHY /* THIS IS CONSISTENT WITH SHELF DEPOSIIION.  */

SPACE SILT
PROPS APPEND-DESC-TEXT T
WHY /*  SILTSTONE INDICATES SLIGHTLY GREATER CURRENT VELOCITIES
     THAN DOES SHALE, BUT STILL REPRESENTS GENERALLY QUIESCENT
     CONDITIONS AS WOULD BE EXPECTED AT THIS POINT IN SHELF SAND
     DEPOSITION. */


STOP
```