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A Knowledge-based Design for Geologic Learning Systems

by

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CONTENTS

ILLUSTRATIONS

INTRODUCTION

This paper describes an interactive computer learning system which demonstrates the potential of using a knowledge-based design approach in the teaching of geologic concepts. By presenting such a methodology, the authors hope to encourage the use of such artificial intelligence (AI) tools in other applications within the geology. The specific knowledge-based system implemented in this paper is designed to provide geologic students with a better understanding of the complex processes involved in making interpretations of geologic data.

The ability to interpret geochemical data is a crucial skill for the research geologist. This skill is usually acquired by the slow process of interpretation/feedback cycles in which the individual develops a set of heuristics used to approach each subsequent problem. A learning system which can provide a more rapid development of these interpretive skills could be very beneficial to the geologic student. A learning curve acceleration could result from providing the student with a "window" in which to view in part the intuitive processes of more advanced experts in the field.

Learning systems for such problems normally consist of three main components (Barr and Feigenbaum, 1982). First is the tutoring strategy or how the system presents the material to the student. The second system component is the the problem solving expertise which includes the knowledge to be presented to the student. The third component is the student model which indicates what the student does and does not know. The expertise component can represent the subject matter knowledge in several manners. Production rules provide one method for constructing modular representations of skills and problem-solving knowledge.

Rule-based systems are ideal tools for teaching interpretive skills because a rule-based approach can easily integrate the geologic data and geologic models. Such a learning system not only incorporates the geologic rules but can also explicitly represent the reasoning strategies of the experts in such a knowledge-based structure. Also, because production rules can be represented in a knowledge-based design, the student can be exposed to only the specific knowledge areas required by the current problem. Sometimes, because of possible limitations on the system size, the student may be introduced to only a "technician" level expertise. However, by rapidly acquiring these basic interpretive skills, a individual could more quickly develop a true expertise in a specific field.

System Description

GEOLEARN is the knowledge-based system which interacts with the student during the tutorial. The system, written in the LISP language, consists of a knowledge base which incorporates the specific geologic models, and a knowledge interpreter or

inference engine which manipulates the knowledge base and the user data. The knowledge base is a network representation of the domain knowledge encoded in binary structures (figure 1). This tree structure, which consists of a query with a left-hand YES branch and a right-hand NO branch, is easily implemented because the principal data structure in LISP is the binary tree.

The hierarchial structure design of the GEOLEARN knowledge interpreter is presented in figure 2. After selection of the appropriate knowledge base, the interpreter obtains general background information, such as data suite name and rock type, and then proceeds to the interpretive stage. The knowledge interpreter, using information about the knowledge base structure, can query the user for specific information, search the appropriate network structure, and index to the data interpretation. The student responses control the tree parsing action of the interpreter through the knowledge base. Because the knowledge interpreter can reconstruct the knowledge network at any point, the user can return to any previous query, re-evaluate it, and continue with a different mode of reasoning. Responses to interpretive questions are stored in the queue and summarized prior to interpretation.

Although the system currently does not accommodate judgemental knowledge with numerical thresholds, this omission is less significant because the system does have the ability to re-evaluate queries. Numerical thresholds can be used, however, in measuring the overall "strength of belief" in the final interpretation. The data scatter of a geochemical data suite may be measured by a specific data scatter parameter. This parameter is represented as an object property of the data suite under evaluation. The final interpretation can then be presented in light of the actual scatter of the data. Because parameters differ from one subject to another, the data scatter functions are maintained in the knowledge base.

System Requirements

GEOLEARN is written in XLISP version 1.4 (Betz, 1985) and has been implemented on the IBM PC and compatibles which utilize the MS-DOS 2.1 operating system. Hardware requirements include 256K memory, one floppy disk drive, and an 80 character display. These GEOLEARN features allow the system to operate on many commonly used microcomputer systems.

XLISP 1.4 is an experimental object-oriented language which is a subset of LISP and most closely follows the Common LISP dialect. This programming language is ideally suited for dealing with complex information problems and queries of arbitrary difficulty because of its expression-oriented nature and the dynamic storage allocation feature. The highly interactive environment and recursive ability of LISP also enhance the learning mode presented by the GEOLEARN system. For a more

detailed discussion of LISP and XLISP the reader is refered to the references cited.

Problem-solving Expertise

The GEOLEARN system can be implemented using any knowledge base which conforms to the design structure described (see Appendix B). To demonstrate the GEOLEARN system, the knowledge base CONCORDIA was constructed from a specific domain. By selecting this knowledge base the student is introduced to the basic concepts involved in the interpretation of U-Pb concordia data. The concordia diagram is a graphic representation tool for presenting U-Pb isotopic data. Information derived from the concordia diagram must be interfaced with known geologic constraints to formulate reasonable conclusions. Several geologic models have been developed to help explain various data configurations on the concordia diagram. The CONCORDIA knowledge base incorporates accepted geologic models and basic expertise used by a geochronologist to interpret U-Pb data on a concordia plot.

The major emphasis of a tutorial using CONCORDIA is to demonstrate to the student the importance of incorporating geologic constraints in the interpretation of isotope data. GEOLEARN allows the user to explore the CONCORDIA knowledge network. As mentioned, a user can backtrack to any query, re-evaluate it and proceed with a different mode of reasoning. This feature allows the student to determine the effect on the final interpretation when reconsidering an interpretive question.

Student Model for the CONCORDIA Tutorial

The CONCORDIA tutorial is directed towards the student with a good basic background in geology or the geologist specializing in a field other than geochronology who has completed basic readings on U-Pb dating. Interacting with the system requires an understanding of the important terms and concepts involved in U-Pb dating of minerals. The user should be very familiar with the structure of the concordia diagram. For a brief review of this specific knowledge domain the user is referred to the text by Jager and Hunziker listed in the references.

The integration of mineralogic, geochemical, and problem specific geologic knowledge is crucial to the interpretation of concordia data. Therefore, the user should be familiar with the geochemistry of the elements, characteristics of commonly analyzed minerals, and effects of geologic processses on the U-Pb system. The interpretation of discordant systems based on these knowledge areas is the most crucial step in U-Pb dating process. The GEOLEARN system can actively demonstrate to the user how these areas might be integrated during the interpretive process.

Running the GEOLEARN System

To initiate a learning session with the GEOLEARN system, the tutorial disk must be in the default drive and you must enter "geolearn". After initial loading of the GEOLEARN and the CONCORDIA knowledge base, instructions will be presented and, if requested, references for the knowledge base will be displayed also. Next, you will be queried for general sample information followed by specific interpretive questions. During this interaction with the system an appropriate knowledge network is selected, model matching occurs, and the data is interpreted. All queries can be answered by a "y" for YES or "n" for NO unless otherwise stated. During the interpretive questioning stage (after selection of the rock type) you may also respond with "p" for PREVIOUS which will allow you to bactrack to any previous interpretive query the system has presented. Appendix A presents a sample learning session with the system.

The system can be exited at any point by ctrl-G followed by the return key (this puts you in XLISP). To return to the system at various points you must type "(help)" and the return key and the GEOLEARN system will respond. Also, a ctrl-Z followed by the return key will quit the break loop and return the user to the next lower level. Using the ctrl-C followed by the return key will cause the user to exit the program. XLISP does have limitations of which you should be aware. All input must be in lowercase and cannot include " . " . Also, XLISP cannot evaluate real numbers and therefore all numeric data must be in integer form.

GEOLEARN Features

The learning system presented by this paper offers several desirable features for the educational environment. The system is interactive and allows students to easily explore the knowledge base. Accessibility is also an important consideration. For this reason GEOLEARN was written in a public domain LISP which requires minimal computer hardware. Due to the widespread availibility of personal computers the system can be utilized by many students.

Several other design considerations are demonstrated by GEOLEARN. One objective of GEOLEARN is to minimize the time spent learning how to interact with the system so that the student spends more time learning from interacting with the system. Therefore, the system provides a clear presentation of possible actions, and an easy and memorable selection of choices. Should problems arise during interaction with the system, an online help mode is available. Input errors are handled by repeating the query so that the user can correct the input before any action is taken. The system demonstrates a consistent presentation format and use of the screen, desirable features in an educational environment.

In its current form, GEOLEARN utilizes a tutorial strategy in which the questioning pattern presented to the student is designed to encourage him to reason about what he knows and modify his current interpretive patterns. The GEOLEARN learning system puts the student in a learn-by-doing environment in which activity is the important element. Users are free to experiment and browse through the system without worrying about a right or wrong response. However, such a teacherless system has some disadvantages over a more direct tutorial approach. A system with a more developed tutoring component can adapt to considerable variation in the student model and modify its actions as the student becomes more knowledgeable. However, the modular design of GEOLEARN could easily allow development of a tutorial module which could present specific examples, direct the student towards "correct" answers, and provide more detailed explanations for its actions.

CONCLUSION

The GEOLEARN learning system was developed using some of the current knowledge engineering tools now available. The knowledge-base design of GEOLEARN allows for a flexible and expandable system. Because the domain knowledge is explicitly represented, the knowledge base can be easily modified or enlarged. The development of other knowledge bases in different subject areas could be easily integrated into GEOLEARN and would allow the student to select various areas of interest for tutorials sessions.

The selection and development of a geologic knowledge base can present some problems. The area of study must be somewhat limited in scope, but large enough to challenge the student. Also, geologists may vary considerably in their interpretive approaches and conclusions. In the case of CONCORDIA we tried to integrate only textbook level and commonly accepted geologic rules and models to avoid such disparities. Also, a system used in a tutorial mode risks development of a student population with a very homogeneous approach. By limiting the knowledge base, the student is given a good domain backround but must develop creative approaches to the more complex problems.

The development of GEOLEARN also demonstrates the current passage of knowledge engineering tools from the software research laboratories to the general scientific community. The increasing availability of sophisticated software and the increasing power of microcomputers have made these tools available for paraprofessionals desiring to view the knowledge structure in their own domains. While the computational potential of computers has readily been recognized by geologists, advances in recent years present the geologist with the possibility of using computers for symbolic manipulation as well. The ability to capture and utilize knowledge is cited as a key resource for the solving of complex scientific problems. Knowledge-based systems can help geologists multiply their expertise by storing and manipulating their domain knowledge. Such systems can assist in

the solving of problems with multiple solution paths and/or for which there is no known algorithm, and in the discovery of previously unknown algorithms. The development of knowledge-based systems, whether for tutorial or expert systems, offer geologists the opportunity to explore and develop a better understanding of their own knowledge domain.

Acknowledgements

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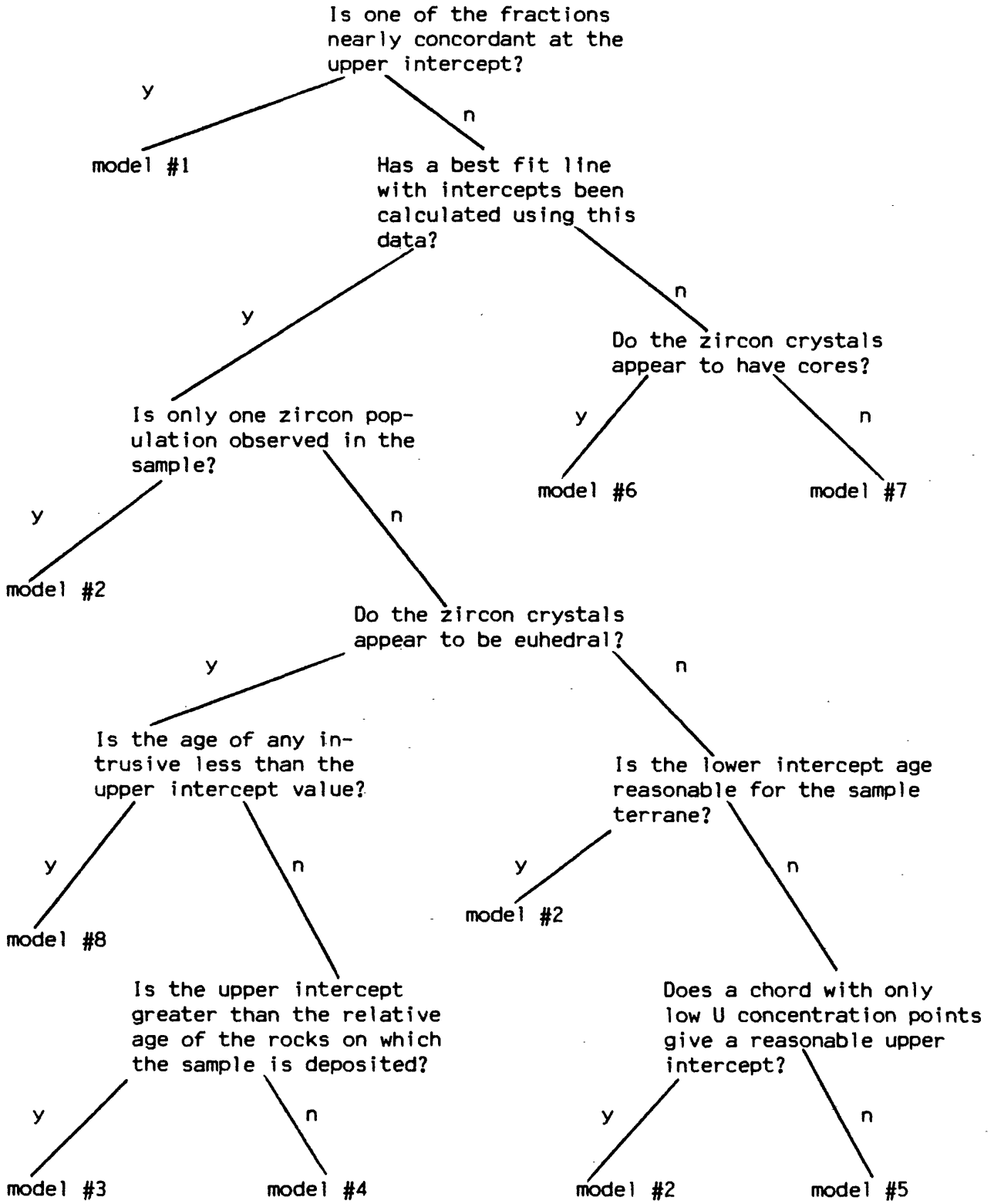
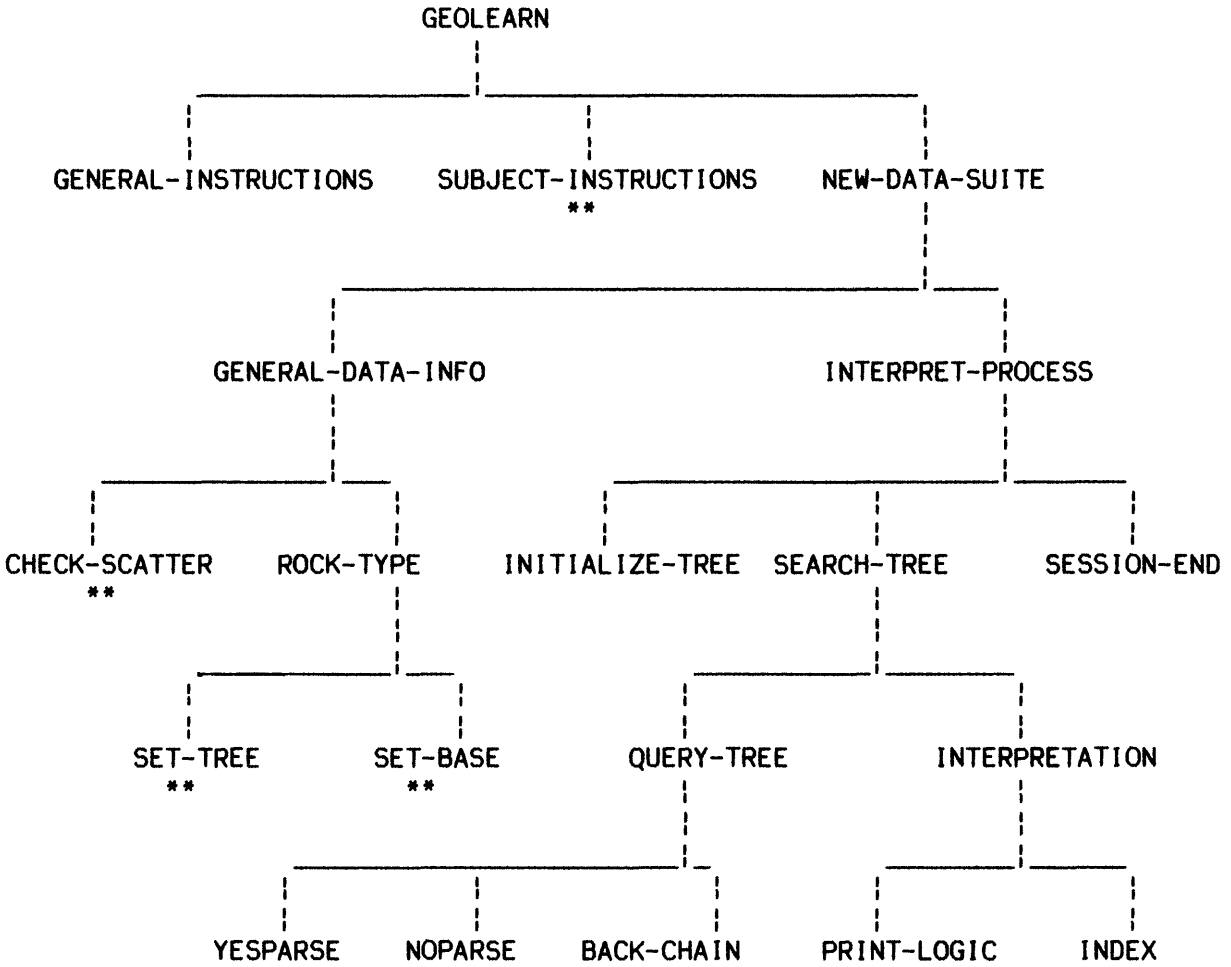
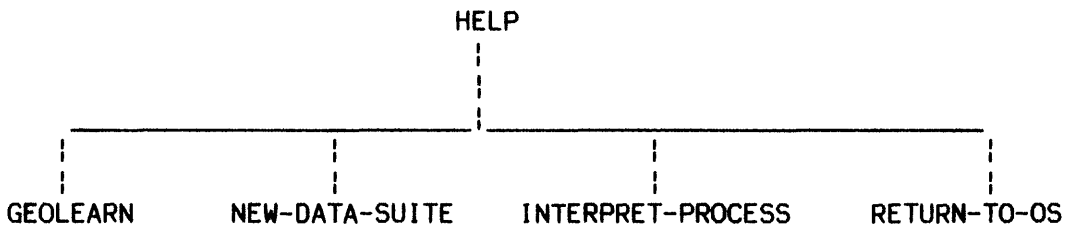


FIGURE 1. - Sedimentary Tree Structure



To access from cntrl-G :



** = accesses knowledge base at this point.

FIGURE 2. - Hierarchial Structure Chart for the knowledge interpreter.

APPENDIX A - Tutorial Session Listing (interpretive section)

```
What is the name of the data suite you wish to discuss?
(please be sure to include an alphanumeric and do not use spaces)
>sal459
Does the data suite have a percent probability of fit value?
>y
What is the percent probability of fit?
>25
Is the sample rock type igneous, metamorphic, or sedimentary
 (i, m, or s)?
>s
Is one of the fractions nearly concordant at the upper intercept?
>n
Has a best fit line with intercepts been calculated using this data?
>y
Is only one zircon population observed in this sample?
>n
Do the zircon crystals appear to be euhedral?
>n
Is the lower intercept age reasonable for the sample terrane?
>n
Does a chord with only low U points give a reasonable upper intercept?
>p
Is the lower intercept age reasonable for the sample terrane?
>p
Do the zircon crystals appear to be euhedral?
>y
Is the age of any intrusive less than the upper intercept value?
>n
Is the upper intercept greater than the relative age of the rocks
on which the sample is deposited?
>n



Here is a summary of our interpretive questioning session:


Is one of the fractions nearly concordant at the upper intercept? - n
Has a best fit line with intercepts been calculated using this data? - y
Is only one zircon population observed in the sample? - n
Do the zircon crystals appear to be euhedral? - y
Is the age of any intrusive rock less than the upper intercept value? - n

Is the upper intercept greater than the relative age of the rocks
 on which the sample is deposited? - n
-------------------------------------------------------------------
Based on your responses during our discussion of
data suite sal459 my interpretation is:

Because the age of sedimentation is less than or equal to the
age of the rock on which the sample is deposited, the upper
intercept is the age of provenance.
```

```
Limited confidence should be placed on this interpretation
due to the presence of some data scatter.  (probability = 25)
-------------------------------------------------------------------

Do you wish to re-evaluate the Previous question
 or Continue with your session? (p or c)
>
```

APPENDIX B. - Listing of the source code.

```
;          GEOLEARN SYSTEM



;          GEOINFER.LSP file

;This is the knowledge interpreter file
;  which passes through the binary tree in both
;  a forward and backward chaining manner.  Data
;  is elicited from the user when required and is
;  integrated with the knowledge from the knowledge
;  base to reach the appropriate interpretation
;  of the geochemical data suite.



(defun readall (x)
   (setq input (read x))
   (if (null input) (princ "file read")
     (readall x)) )

(defun geolearn ()
   (general-instructions)
   (subject-instructions)
   (new-data-suite) )

(defun new-data-suite ()
    (general-data-info)
    (interpret-process))

(defun interpret-process()
     (terpri)
     (initialize-tree)
     (search-tree)
     (session-end)
     (terpri) )

(defun general-instructions ()
     (mapcar printline '(
      "   Hello.  Before we begin our discussion today I would like"
      "to explain a few details to you.  I will be asking you a series"
      "of questions to gain a better understanding of your specific"
      "interests.  Most questions can be answered by a 'y' for YES or 'n'"
      "for NO unless indicated otherwise.  If during interpretive ques-"
      "tioning you wish to return to a previous query for re-evaluation"
      "just type 'p' for PREVIOUS question.  You may continue to re-"
      "spond with a 'p' to each query so that you can re-evaluate"
      "questions I have asked you.  "
      "   A few more points I would like to mention.  All query responses"
      "must be in lowercase letters.  If you would like a printed record"
      "of our discussion just type the shift-PrtSc command when you feel"
      "we have made some interesting points.  "
      "  "
```

```
      "IMPORTANT:  If at any point we seem to be having trouble com-"
      "municating just enter-  "
      "                        Ctrl-G         (this stops all dialogue)"
      "  "
      "                        (help)         (for some assistance)"
      "  "
      "We should be able to continue our discussion."))
      (terpri)
      (mapcar printline '( "Please respond with yes ('y') and the return key"
        "when you are ready to begin."))
      (terpri)
      (setq begin (read))
      (if (eql 'y begin) (terpri) (general-instructions))
      (line-spaces 10) )

(defun search-tree ()
      (if (null tree) (setq tree master-tree))
      (query-tree)
      (interpretation)
      (setq paths-used (cdr paths-used))
      (setq tree (car paths-used))
      (setq answers (cdr answers))
      (setq query-path (cdr query-path))
      (query '("Do you wish to re-evaluate the Previous question"
        " or Continue with your session ? (p or c)"))
      (if (eql 'p response) (search-tree)) (terpri) )

(defun session-end ()
      (query "Do you wish to evaluate a new data suite?")
      (if (eql 'n response) (return-to-OS))
      (if (eql 'y response) (new-data-suite)
         (session-end)) )

(defun general-data-info ()
    (line-spaces 10)
    (princ "What is the name of the data suite you wish to discuss ?")
    (terpri)
 (princ "(please be sure to include an alphanumeric and do not use spaces)")
    (terpri)
    (setq name (read))
    (check-scatter)
    (rock-type))


(defun initialize-tree ()
  (setq tree master-tree)
  (setq answers nil)
  (setq query-path nil)
  (terpri) )

(defun query-tree ()
     (if (null answers) (setq tree master-tree))
     (if (null answers) (setq paths-used master-tree))
     (query (car tree))
     (if (eql 'y response) (yesparse))
```

```
     (if (eql 'n response) (noparse))
      (if (eql 'p response) (back-chain)
         (setq paths-used (cons tree paths-used)))
    (setq value (car tree))
    (if (numberp value) (terpri)
      (query-tree)) )

(defun yesparse ()
     (setq query-path (cons (car tree) query-path))
     (setq tree (car (cdr tree)))
     (setq answers (cons 'y answers)) )

(defun noparse ()
     (setq query-path (cons (car tree) query-path))
     (setq tree (car (cdr (cdr tree))))
     (setq answers (cons 'n answers)) )

(defun back-chain ()
   (setq answers (cdr answers))
   (setq query-path (cdr query-path))
   (setq tree (car (cdr paths-used)))
   (setq paths-used (cdr paths-used))
   (terpri) )

(defun query (lst)
 (if (atom lst) (princ lst) (mapcar printline lst))
    (terpri)
    (setq response (read)) )

(defun interpretation ()
  (line-spaces 8)
  (princ "Here is a summary of our interpretive questioning session:")
  (setq temp-answers (reverse answers))
  (setq temp-query-path (reverse query-path))
  (terpri)
  (terpri)
  (print-logic temp-answers temp-query-path)
  (princ "-----------------------------------------------------------------")
  (terpri)
  (princ "Based on your responses during our discussion of ")
  (terpri)
  (princ "data suite ")
  (princ name)
  (princ " my interpretation is: ")
  (terpri)
  (index value master-base)
  (mapcar printline (get name 'scatter-limit))
  (if (eql 'y scatter-value-yn) (print-scatter
           scatter-value scatter-value-name))
  (terpri)
  (princ "-----------------------------------------------------------------"))

(defun print-scatter (x y)
   (princ " (" )
   (prinl y)
```

```
   (princ " = " )
   (prinl x)
   (princ " ) " ))

(defun index  (n lst)
  (setq n (- n 1))
  (mapcar printline (cdr (nth n lst)))
  (terpri) )

(defun print-logic (a lst)
  (prog (x)
  loop
   (setq x (car lst))
   (if (null (cdr x)) (princ (car x)) (mapcar printline x))
   (princ "  - ")
   (setq lst (cdr lst))
   (print (car a))
   (setq a (cdr a))
   (if (null a) (princ "  ") (go loop))) )

(defun return-to-OS ()
  (terpri)
  (setq response nil)
  (query '("Would like to return to the operating system?"))
  (if (eql 'y response) (terpri) (geolearn))
  (princ "I enjoyed our discussion today. Please come again.")
  (line-spaces 10)
(exit) )

(defun line-spaces (x)
  (prog (cnt)
   (setq cnt x)
loop
   (terpri)
   (setq cnt (- cnt 1))
   (if (/= 0 cnt) (go loop)) ))

(defun printline (lst)
  (terpri)
  (princ lst) )

(defun load-geobase ()
  (terpri)
  (load "geobase")
  (setq file (openi "geobase.lsp"))
  (readall file)
  (close file)
  (terpri)
  (terpri) )

;For geochemical interpretations in which the sample rock type
;  is an important constraint, the following functions can be
;  used.  These functions are operate on a knowledge base which
;  is divided into three distinct query trees.
;  If only one query tree is desired, the above function can be
```

```
;  used and the knowledged base designed accordingly.

(defun rock-type ()
 (line-spaces 4)
 (query '("Is the sample rock type igneous, metamorphic, or sedimentary"
          "(i,m, or s)?"))
 (rr 'set-tree response)
 (rr 'set-base response)
 (if (null master-tree) (error-response))
 (terpri)
 (terpri) )


(setq Rock (Class 'new))
(Rock 'ivars '(trees bases))
(Rock 'answer 'isnew '()
    '((setq trees nil)
      (setq bases nil)
      self))
(Rock 'answer 'add '(response treex basex)
    '((setq trees
       (cons (cons response treex) trees))
     (setq bases
       (cons (cons response basex) bases)) ))

(setq rr (Rock 'new))
(rr 'add 'i 'igtree 'igbase)
(rr 'add 's 'sedtree 'sedbase)
(rr 'add 'm 'metatree 'metabase)


(Rock 'answer 'set-tree '(response &aux entry)
  '((cond ((setq entry (assoc response trees))
    (setq entry (cdr entry)))
    (t nil))
    (setq master-tree (eval entry))))

(Rock 'answer 'set-base '(response &aux entry)
  '((cond ((setq entry (assoc response bases))
    (setq entry (cdr entry)))
    (t nil))
    (setq master-base (eval entry))))

(defun error-response ()
(mapcar printline '(" I'm sorry-  we are having a problem in communicating."
      "  Your response must be one of the three rock types."))
   (rock-type) )

;This help function allows the user to re-enter the system
;  at various points.

(defun help ()
   (set-ups)
   (terpri)
   (mapcar printline '(
```

```
"I am assuming that you have abruptly ended our discussion"
"because of some difficulty in communications.  Have all"
"your responses been lower case letters?  If so there could"
"be a some misunderstanding or an error in my system."
"You may continue our discussion at various points by typing"
"one of the following words:  "
"  "
"              run      -To review the instructions and completely"
"                           restart the discussion."
"  "
"              new      -To begin discussion of a new data suite."
"  "
"              redo     -To re-interpret the current data suite of interest."
"  "
"              quit     -To exit to your operating system."
"   "
"  Please enter your selected option.") )
(terpri)
(terpri)
 (setq input (read))
 (eval (eval input))  )


(defun set-ups ()
(setq run '(geolearn))
(setq new '(new-data-suite))
(setq redo '(interpret-process))
(setq quit '(return-to-OS)) )
```

GEOBASE.LSP file

```
;This is the CONCORDIA knowledge base file.
;  The file consists of three LISP lists which represent
;  the binary query tree for each of the tree rock types.
;  The end nodes of each tree index to a specific inter-
;  pretation which is found in the appropriate database
;  list.



(defun subject-instructions ()
     (mapcar printline '(
      "    Today we are concerned with the interpretation of U-Pb data"
      "which is graphically represented by the concordia diagram.  I'm"
      "assuming you are very familiar with the concept.  If not, a re-"
      "view of the subject is given in 'Lectures in Isotope Geology' by"
      "Gebauer and Grunenfelder (1979) and I highly recommend that you"
      "read this first.  "
      "    The major objective of our discussion today is to demonstrate"
      "to you the importance of incorporating geologic constraints during"
      "the interpretation of isotope data.  I will attempt to present"
      "to you one possible interpretive strategy for a wide variety of"
      "concordia problems.  Also, I will be using the terms data suite "
      "and sample somewhat interchangeably.  In order to first under-"
      "stand the basic geologic constraints, our discussion would be"
      "simplified if you concern yourself with isotope data derived "
      "from one sample or a few very similiar samples."
      "    If you are interested in some of the backround references for"
      "more expanded discussions of some of the concepts we cover, I"
      "would be glad to list several references for you."
      "  "
      "    Please type 'r' to view the references or 'y' to continue."))
     (terpri)
     (setq cont (read))
     (if (eql 'r cont) (load-references)
         (if (eql 'y cont) (terpri) (subject-instructions)))
     (line-spaces 10) )

(defun load-references ()
   (load "georef")
   (setq filer (openi "georef.lsp"))
   (readall filer)
   (close filer)
   (terpri)
   (concordia-references)  )

;This section is concerned with the scatter of the data on
;  the concordia diagram.

(defun check-scatter ()
   (setq scatter-value-name 'probability )
   (line-spaces 4)
   (princ
```

```
"Does the data suite have a percent probability of fit value?")
   (terpri)
   (setq scatter-value-yn (read))
   (setf (symbol-plist name) 'scatter-limit)
   (if (eql 'y scatter-value-yn) (set-prob-fit)
     (if (eql 'n scatter-value-yn) (setf (get name 'scatter-limit) level0)
       (check-scatter)))
   (terpri) )

(setq levelx '("Because your plot has only two data points, I cannot"
               "comment on the certainty of my interpretation."))

(setq level0 '("I cannot comment on the certainty of this interpretation"
               "due to lack of information about data scatter."))

(setq level1 '("This interpretation is made with a high degree of"
               "confidence due to the small amount of data scatter."))

(setq level2 '("Limited confidence should be placed on this interpretation"
     "due to the presence of some data scatter."))

(setq level3 '("Very little confidence can be placed in this interpretation"
      "due to the high degree of data scatter."))

(defun set-prob-fit ()
 (line-spaces 3)
   (query
'("What is the percent probability of fit value?"
   "(Please round your number up to the nearest integer value.)" ))
 (setq scatter-value response)
 (if (numberp scatter-value) (terpri) (input-error))
 (if (< 100 scatter-value) (input-error))
 (if (= 100 scatter-value) (setf (get name 'scatter-limit) levelx)
   (if (>= scatter-value 70) (setf (get name 'scatter-limit) level1)
      (if (< 20 scatter-value) (setf (get name 'scatter-limit) level2)
          (setf (get name 'scatter-limit) level3))))
   (terpri))

(defun input-error ()
  (terpri)
  (mapcar printline '(
     "Please re-enter your value for the percent probability fit."
     "(value must be a number between and including 0 and 100)"))
  (set-prob-fit)
  (terpri))


;The query trees:

;This is the binary query tree for igneous rocks.

(setq igtree '(
("Is one of the fractions nearly concordant at the upper intercept?")
(1)
(("Has a best fit line with intercepts been calculated using this data?")
```

```
  (("Is the lower intercept a negative value?")
    (6)
    (("Is the lower intercept zero Ma. (within std.dev.)?")
      (("Is there an abraded zircon fraction?")
       (("Did abrasion increase the Pb/Pb age significantly?")
          (7)
          (2))
        (2))
     (("Are there other known constraining geologic events?")
      (("Is the last known geologic event less than the age of the"
        " lower intercept?")
        (3)
 (("Is the age of the last known geologic event greater than the"
    "lower intercept?")
            (("Do the data points plot near the upper intercept"
               "(upper third of the discordia)?")
              (3)
              (("Do the data points plot near the lower intercept"
                "(lower third of the discordia)?")
                (12)
(("Do other rocks in the terrane of this sample contain inheritance?")
  (("Is there an abraded zircon?")
   (("Does the abraded fraction plot on the discordia?")
      (12)
      (8))
    (12))
  (9) )))
(("Are there other igneous rocks in the terrane of this sample with"
  " the same upper intercept age?")
  (3)
  (("Did you analyze a monazite from this rock?")
    (("Is the Pb/Pb age of the monazite the lower intercept age?")
      (4)
     (("Is the Pb/Pb age of the monazite the upper intercept age?")
        (3)
      (("Is the Pb/Pb age of the monazite less than the lower intercept age?")
          (5)
          (3) )))
  (10) ))))
(("Was a monazite analyzed from this sample rock?")
  (("Is the age of the monazite the lower intercept age?")
    (4)
   (("Is the age of the monazite the upper intercept age?")
      (3)
      (("Is the age of the monazite less than the value of the"
        " lower intercept?")
        (5)
        (3) )))
  (10) ))))
(11) )))
;
;
;This is the igneous interpretive database.
;
(setq igbase '(
```

```
 (1 "The upper intercept is the age of crystallization.")
 (2 "The upper intercept is the age of crystallization and"
    "the lower intercept indicates a modern lead loss.")
 (3 "The upper intercept is the age of crystallization and"
    "the lower intercept is due to a later event lead loss.")
 (4 "The lower intercept is the age of crystallization of the zircons."
    "The upper intercept may be the age of inheritance.  The monazite age"
    "may represent cooling through the monazite cooling temperature.")
 (5 "The lower intercept may be age of crystallization and"
    "the zircons may contain inheritance.")
 (6 "These zircons contain inheritance and have undergone at"
    "least two stages of lead loss.  The upper intercept is"
    "the minimum age of crystallization.")
 (7 "Probably all fractions contain some inheritance and "
   "therefore, the upper intercept may be the age of crystallization."
    "The Pb/Pb age of the abraded fraction is the minimum age of"
    "inheritance." )
 (8 "The upper intercept from non-abraded points is the minimum age"
    "of the sample.  The lower intercept Yorkfitted with the"
    "abraded points may be the real geologic age.")
 (9 "Two possibilities exist.  Inheritance may be present but"
    "not well supported by data.  Second, no inheritance is present"
    "and therefore the geologic constraints are invalid due to"
    "undeciphered juxtaposition of terranes.")
 (10 "The sample age may the be upper or lower intercept. You must consider"
     "other geologic constraints before interpreting the data.")
 (11 "The oldest Pb-Pb age is the minimum age of inheritance and"
     "the youngest Pb-Pb age is the minimum age of crystallization.")
 (12 "The lower intercept is the age of crystallization and the"
     "upper intercept may be the age of inheritance.") ))

;This list represents the binary query tree for
;concordia analysis of sedimentary samples.
;
(setq sedtree '(
("Is one of the fractions nearly concordant at the upper intercept?")
(1)
(("Has a best fit line with intercepts been calculated using this data?")
  (("Is only one zircon population observed in the sample?")
   (2)
    (("Do the zircon crystals appear to be euhedral?")
(("Is the age of any intrusive rock less than the upper intercept value?")
       (8)
 (("Is the upper intercept greater than the relative age of the rocks"
    " on which sample is deposited?")
          (3)
         (4)))
 (("Is the lower intercept age reasonable for the sample terrane?")
        (2)
 (("Does a chord with only low U points give a reasonable upper intercept?")
          (2)
          (5)))))
  (("Do the zircon crystals appear to have cores?")
    (6)
    (7)) )))
```

```
;
;This is the indexed database for sedimentary interpretations.
;
(setq sedbase '(
  (1 "The upper intercept is the age of provenance.")
  (2 "The upper intercept is the age of provenance and the"
     "lower intercept is later event Pb loss.")
  (3 "The upper intercept maybe the age of sedimentation.")
  (4 "Because the age of sedimentation is less than or equal to the"
     "age of the rock on which the sample is deposited, the upper"
     "intercept is the age of provenance.")
  (5 "The lead-lead age of the oldest point is the minimum age of"
     "provenance (suggest a Yorkfit through the oldest point plus"
     "a known lead loss event for the possible age of provenance)."
     "Multiple lead loss events occurred after zircons were found"
     "in the provenance.")
  (6 "The lead-lead age of each fraction is the minimum age of each"
     "provenance.")
  (7 "This sedimentary rock contains material that is at least as"
     "old as the oldest Pb-Pb age plotted.")
  (8 "The upper intercept is the age of sedimentation.") ))


;This list represents the binary query tree for
;metamorphic type samples
;
(setq metatree '(
("Is the sample a metaigneous type rock?")
(("Is the sample a low grade metamorphic rock?")
  (("Has a best fit line with intercepts been calculated using this data?")
    (("Is the lower intercept through zero Ma. (within std.dev.)?")
      (("Do the zircon crystals have a fairly low uranium content?")
        (1)
        (2))
      (("Are the data points mostly in the upper third of the discordia?")
        (2)
       (("Are the data points mostly in the lower third of the discordia?")
          (3)
          (5) )))
    (4))
  (("Has a best fit line with intercepts been calculated using this data?")
    (("Is the sample a granulite grade metamorphic rock?")
      (("Is the lower intercept through zero Ma. (within std.dev.)?")
        (6)
        (("Does the lower intercept give an age greater than"
            " zero Ma. (within std.dev.)?")
("Are the ages of any lower grade metamorphic rocks greater than "
  "the lower intercept age of this sample?")
           (6)
("Are ages of any lower grade metamorphic rocks less than"
  "the lower intercept age of this sample?")
    (("Do the data points plot mostly in the upper third of the discordia?")
               (7)
("Do the data points plot mostly in the lower third of the discordia?")
                 (8)
```

```
                (9) ))
            (10) ))
        (11) ))
      (("Are the zircons reabsorbed (physically damaged?)")
        (13)
        (14) ))
  (12) ))
(("Is the sample rock a metasedimentary type?")
  (("Is the sample a low grade metamorphic rock?")
    (("Can a line be fit to the data points?")
      (("Does the lower intercept give a negative value?")
        (16)
        (("Is the lower intercept through zero Ma. (within std.dev.)?")
          (17)
          (18) ))
      (15) )
    (("Has a best fit line with intercepts been calculated using this data?")
      (("Is there a concordant fraction at the upper intercept?")
        (("Are the zircon crystals euhedral grains?")
          (7)
          (17) )
        (("Do the data points plot very near the upper intercept?")
          (19)
          (("Is the lower intercept a non-negative value?")
            (("Are the zircon crystals euhedral grains?")
              (7)
              (17) )
            (16) )))
      (20) ))
 (("Invalid response - the sample must be metaigneous or metasedimentary."
     "Please re-evaluate your responses ('p')."))))

;
;
;This is the metamorphic interpretive database.
;
(setq metabase '(
 (1 "The upper intercept is the age of the protolith.")
 (2 "The upper intercept is the age of intrusion and the"
    "lower intercept is the age of metamorphism.")
 (3 "The upper intercept is the age of inheritance and the"
    "lower intercept is the age of crystallization."
    "No metamorphic effect is observed.")
 (4 "The youngest Pb-Pb age is the maximum age of the last"
    "metamorphic event.")
 (5 "The upper intercept is probably age of intrusion and the"
    "lower intercept is probably the age of metamorphism."
    "Geologic constraints need to be determined.")
 (6 "The upper intercept is the age of granulite facies"
    "metamorphism.")
 (7 "The upper intercept is the age of metamorphism.")
 (8 "The lower intercept may be the age of granulite facies"
    "metamorphism.")
 (9 "The upper or lower intercept could be the age of"
    "metamorphism.")
```

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(10 "The lower intercept is the age of metamorphism and later"
    "events have brought the sample rocks to the present erosional"
    "surface.")
(11 "The oldest Pb-Pb age is the minimum age of metamorphism and"
    "multiple lead loss events have occured.")
(12 "Data suggests that the oldest Pb-Pb age is the minimum age"
    "of metamorphism.")
(13 "The zircons may be xenocrystic. If the lower intercept is zero"
    "Ma., then the upper intecept may be the age of metamorphism."
    "If the lower intercept is greater than zero Ma., then the upper"
    "intercept may be the age of the protolith and the lower intercept"
    "may be the age of metamorphism.")
(14 "The zircons are probably metamorphic. If the lower intercept"
  "is at zero Ma., then the upper intercept may be the age of metamorphism."
 "If the lower intercept is greater than zero Ma., then the upper intercept"
    "may be the age of protolith and the lower intercept may be the age of"
    "metamorphism.")
(15 "The oldest Pb-Pb age is the minimum age of the provenance and the"
    "youngest Pb-Pb age is the maximum age of the last premodern Pb"
    "loss event.")
(16 "A minimum three-stage lead loss model is indicated.")
(17 "The upper intercept is the age of provenance.")
(18 "The upper intercept is the age of provenance and the lower intercept"
    "is the age of metamorphism.")
(19 "The upper intercept is close to some real geologic event.")
(20 "The oldest Pb-Pb age is the minimum age of the provenance.")  ))
```

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;                    GEOREF.LSP file


(defun concordia-references ()
     (line-spaces 4)
     (mapcar printline '(
"References for interpreting U-Pb data on concordia diagrams: "
"   "
"For a general review of U-Pb dating-"
"    "
"Gebauer, D. and Grenenfelder, M., 1979, U-Th-Pb dating of Minerals:"
"     in Jager, E. and Hunziker, J.C. (eds.), Lectures in Isotope"
"     Geology, Springer-Verlag, New York, p.105-131."
"  "
"Single and multiple episodic lead loss-"
"  "
"Krogh, T.E., McNutt, R.H., and Davis, G.L., 1982, Two high"
"     precision U-Pb sircon ages for the Sudbury Nickel Irruptive:"
"     Can. Jour. Earth Sci., v.19, p.723-728."
"   "
"Allegre, C.J., Albarede, F., Grunenfelder, M., and Koppel, V.,"
"     1974, 238U/206Pb-235U/207Pb-232Th-208Pb zircon geochronology"
"     in Alpine and non-Alpine environment: Contrib. Mineral."
"     Petrol., v.43, p.163-194."
" "
"Please type any key to continue."))
   (line-spaces 1)
   (setq con (read))

   (mapcar printline '(
"Dating of metamorphic rocks-"
""
"Peterman, Z.E., Goldich, S.S., Hedge, C.E., and Yardley, D.H.,"
"     1972, Geochronology of the Rainy Lake Region, Minnesota-"
"     Ontario: Mem. Geol. Soc. Amer. Rew. 135, p.193-215."
"  "
"Lancelot, J., Vitrac, A., and Allegre, C.J., 1976, Uranium and lead"
"     isotopic dating with grain by grain zircon analysis; a study"
"     of complex geological history with a single rock: Earth"
"     Planet. Sci. Lett., v.29, p. 357-366."
"  "
"Please type any key to continue."))
   (line-spaces 8)
   (setq con (read))

   (mapcar printline '(
"Dating of sedimentary rocks-"
"  "
"Gaudette, H.E., Vitrac-Michard, A., and Allegre, C.J., 1981,"
"     North American Precambrian history recorded in a single"
"     sample; high resolution U-Pb systematics of the Potsdam"
"     Sandstone detrital zircons, New York State: Earth Planet."
"     Sci. Lett., v.54, p.248-260."
"  "
"Inheritance-"
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"   "
"Aleinikoff, J.N., Dusel-Bacon, C., Foster, H.L. and Futa, K.,"
"      1981, Proterozoic zircon from augen gneiss, Yulem-Tanana"
"      Upland, east-central Alaska: Geology, v.9, p.469-473."
"  "
"Abrasion-"
"  "
"Goldich, S.S., and Fischer, L.B., 1986, Air-abrasion experiments"
"      in U-Pb dating of zircon: Chemical Geology (Isotope Geoscience"
"      section), v.58, p.195-215."
" "
"Please type any key to continue."))
   (line-spaces 1)
   (setq con (read))

   (mapcar printline '(
"Dating of monazite, sphene and other minerals-"
"  "
"Tilton, G.R., and Grunenfelder,M., 1968, Sphene; U-Pb ages:"
"      Science, v.159, p.1458-1461."
"  "
"Ludwig, K.R., and Stuckless, J.S., 1978, U-Pb isotope systematics"
"      and apparent ages of zircons and other minerals in Precambrian"
"      granitic rocks, Granite Mountains, Wyoming: Contri. Mineral. "
"      Petrol., v.65, p.243-254."
"  "
"Koppel, V., and Grunenfelder, M., 1978, The significance of monazite"
"      U-Pb ages; Examples from the Lepontine area of the Swiss Alps:"
"      Short papers of the 4th Int'l. Conf., Geochron., Cosmochron.,"
"      Isot. Geo., Zartman, R.E. (ed), USGS open file report 78-701,"
"      p.226-227."
"Please type any key to continue."))
   (terpri)
   (setq con (read))
   (line-spaces 10)   )
```