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# COMPUTER-ASSISTED TERRAIN AND GEOLOGIC FEATURE INTERPRETATION FROM AERIAL AND SATELLITE IMAGERY

Final Technical Report

by

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In all earlier efforts in constructing prototype expert terrain-related systems, knowledge related to the physiographic region of a site and to the spatial pattern of related landforms were not explicitly represented and used. In this research we have identified, named, described, organized and related detailed, "book-level" knowledge pertaining to physiographic regions (provinces and sections), physiographic features, topographic forms and landforms. Collected, systematized, and defined landform, geomorphologic, topographic, and physiographic indicators. We have developed an object-oriented model for the factual and structural representation of these terrain features. We have also developed a rule-base for representing the strategic knowledge needed for inferring these features from their own indicators. We have provided for the representation of multiple terrain objects at a given interpretive scenario and for bidirectional reasoning for the identification of terrain features depending on the goals of the interpretation at a given time. Eleven scenaria of photointerpretation problem solving were described. They compose three contexts: landform, physiographic and spatial. The presented case studies concern typical terrain of the Basin and Range Province of Southwest USA (Great Basin and Sonoran Desert). The conceptual scheme was formalized and implemented in a knowledge-base resulting in the Terrain Analysis eXpert (TAX-4-5) system which assists step by step the user in the eleven problem solving scenaria.

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# PREFACE

This report - entitled "Computer-Assisted Terrain and Geologic Feature Interpretation From Aerial and Satellite Imagery"- is the result of an investigation entitled "Steps Towards Terrain Knowledge Acquisition" which was conducted for the U.S. Army Topographic Engineering Center (TEC), 2592 Leaf Road, Fort Belvoir, VA 22060-5546, through the European Research Office of the U.S. Army, under Contract No: N68171-94-C-9115.

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Technical Representative of the European Research Office, London, UK was Mr. Jerry C. Comati, Chief Environmental Sciences Branch.

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# 1. Introduction and Aim

## 1.1. Terrain Analysis and Landform Interpretation

*Terrain analysis* is the systematic study of image elements relating to the nature, origin, morphologic history and composition of distinct units called landforms (Way 1978, Leighty 1973, Lillesand and Kiefer 1979, Mintzer 1983, Mintzer and Messmore 1984). *Landforms* are natural terrain units, usually of the third relief order, which when developed under similar conditions of climate, weathering, and erosion exhibit a distinct and predictable range of visual and physical characteristics. The entity of landform is fundamental in representing and organizing topographic and geomorphic information through the pattern-element approach to terrain analysis. The *landform-pattern element approach* is based on the following premise: any two terrain surfaces derived from the same soil and bedrock, or created by a similar process, occupying the same relative position, and existing under the same climatic conditions exhibit similar physical and visual features on aerial images, called *pattern elements*. The elements examined include topographic form, drainage pattern, gully characteristics, soil tone variation and texture, land use, vegetation, and special features. An analysis of the meanings of some of these generic topographic-terms has been published by Rinker and Corl (1984), Hoffman (1985) and Hoffman and Pike (1993).

Terrain analysts use the pattern elements, as well as maps and bibliographic information, to identify landforms, their parent material, and their engineering characteristics and significance. The landform is inferred from the pattern-elements of the site and then the parent material is inferred by its association with the landform. The discipline was developed by terrain analysts who used image analysis as a source for terrain information for operations planning and construction projects (Way 1978, Lillesand and Kiefer 1979, Mintzer and Messmore 1984).

## 1.2. Need for Computational Models for Landform Interpretation

Terrain analysis can be time consuming, labor intensive and costly. Its skills are a product of lengthy and expensive training. Therefore, it could help to at least partially automate this process by developing computer-assisted interactive systems (Leighty 1973, Argialas 1995). Such systems could improve training by introducing students to the decisions made by experts and by improving the quality and reliability of interpretation. At the same time they provide a research vehicle to explore and test the landform-related knowledge.

Landform interpretation is still an art without a formal theory (Leighty 1973, Hoffman 1987, Argialas and Harlow 1990, Argialas and Mintzer 1992). Knowledge, available in books, is descriptive and fuzzy. For example, Mintzer and Messmore (1984) describe as following the landform interpretation process. Problem solving in this approach commences with the analyst formulating hypotheses about the landforms likely to occur in the study area, by drawing upon his experience and auxiliary information specific to the region. Then the analyst searches the aerial image, to find a match between the expected pattern elements of one of the hypothesized landforms - as those are found in texts and guides - and the observed characteristics. The analyst continues this procedure, until all the pattern elements are examined. If there is a significant match between the expected and observed pattern elements, the identity of the landform of the site is established. Otherwise, the next landform in the hypothesis list is investigated for a match.

A procedural framework for problem solving is missing: books do not elaborate on the strategies needed to guide a novice to the process required for landform identification. On the other hand, trained and skilled experts routinely perform landform interpretation. Implicit terrain-related knowledge, somehow enables the expert to directly perceive or indirectly infer landforms from aerial images. Expertise is not documented in textbooks and manuals and hence it is not clear, explicit and unambiguous. It can not be easily taught, expanded, preserved, transferred, replicated, and criticized.

There is, therefore, a need to methodically study the terrain-analysis reasoning process and, to better understand this process, develop a systematic framework for the recognition of landforms from aerial images (Leighty 1973 and 1979, Hoffman 1985, Argialas and Narasimhan 1988a and 1988b, Edwards 1988).

Knowledge-based expert systems offer the promise for the representation of data and reasoning in many fields including image interpretation. First, we briefly review the knowledge-based expert system approach and then we review the knowledge based landform interpretation.

## 1.3. Knowledge-Based Expert Systems

*Knowledge-based expert-systems* (KBES) are a field of artificial intelligence that addresses complex, domain specific, problem solving that requires unique expertise (Hayes-Roth et al. 1983, Harmon and King 1985, Jackson 1986). Their performance depends critically on facts and heuristics used by experts. Their success is largely determined by the effective computer representation of domain knowledge.

*Production rule-based systems* are the most widely used scheme for knowledge representation. *Factual knowledge* is represented as object-attribute-value triples or frames. *Strategic knowledge* is represented as sets of *rules*, of the form IF ["condition statements"] THEN ["action statements"], that will be checked against a collection of problem *facts* to infer new facts. When a problem satisfies or matches the IF part of a rule, the action specified by the THEN part of the rule is performed. The execution of a set of rules, commonly called *rule-chaining*, results in a new set of facts which is added to the existing list, which trigger other rules. In such a system rules can operate in forward or backward chaining. *Forward chaining* matches rules against facts to establish new facts. In *backward chaining*, the system starts with what it wants to prove and tries to establish the facts it needs to prove it.

*Frames*, another knowledge-representation scheme, are structural models for representing stereotyped objects or situations (Minsky 1975). A *class frame* is a collection of all information that describes a class of objects. An *object* or *instance frame* is a collection of all information that describes an individual of a class frame. Each frame has *slots* that contain properties and relations about classes and objects. The slots specify, through an associated set of rules or procedures, what is known about an object and how can be acquired. *Inexact reasoning procedures* have been developed to complement the knowledge representation and inferencing mechanisms of rule and frame based systems in case where facts, rules and, consequently, conclusions are uncertain or inexact. These techniques represent *uncertainties* in facts, combination of facts, rules of inferencing, and facts supported independently by several rules (Harmon and King 1985, Jackson 1986).

## 1.4. Knowledge Engineering Environment Feature

There are many languages and tools for building expert systems. In our earlier efforts (Table 1) we have used OPS5, Intelligence Compiler, and the Knowledge Engineering Environment (Argialas 1995).

The Knowledge Engineering Environment used was in this effort was the NEXPERT OBJECT (by Neuron Data), recently called SMART ELEMENTS. NEXPERT OBJECT's ability to support both a reasoning system and a powerful, object-oriented representation makes it a very powerful hybrid system for representing terrain related reasoning. The following paragraphs describe briefly both aspects of the hybrid system (Neuron Data 1993a,b,c,d).

<u>Class and Subclass Definition</u>

Descriptive information is expressed in class-member relationships stored in the knowledge base. Functionally, classes act as a template that define the characteristics its members must possess. Classes can include sub-classes if additional levels are needed to define unique characteristics.

<u>Class members (Instances, or Objects) Definition</u>

The members of a class are its objects and are typically referred to as "instances of a class." One can cause objects to obtain their characteristics dynamically from a particular class through a mechanism called inheritance.

<u>Class and Object Property Definition</u>

The characteristics of an object are its properties. Properties can have one of six data types, including boolean, integer, float, string, date, time, or special (for objects that do not have declared properties). A particular property when associated with an object is called a slot. A slot in the knowledge base is a variable written as ObjName. PropName (read as "object name dot property name") that has some value.

Class-subclass hierarchies and Property Inheritance Definition

Classes, objects, and properties are the structures of representation. Classes can store information relevant to all their objects. The objects, when necessary, will inherit this information. This mechanism is called inheritance. The illustrations in the following use circles to represent the classes and triangles to represent the objects.

Object-Subobject or Whole-Part Hierarchy Definition

Objects can include sub-objects if additional levels are needed to define unique characteristics such as whole-part hierarchies.

Rule structure and rule evaluation

To represent reasoning it is necessary to use situation-action statements that are stored in the knowledge base as rules. A rule is a chunk of knowledge representing a situation, usually an interpretation scenario, and its immediate consequences. The format of a rule is expressed as:

if situations then hypothesis and do actions

The "if" is followed by a set of situation (conditions), the "then" by a hypothesis or goal which becomes true when the conditions are met, and the "do" by a set of actions to be undertaken as a result of a positive evaluation of the rule. Therefore, a rule has three parts. The first part, comprised of one more If-clauses, gives verifiable conditions/evidences that must apply if the second part, comprised of a hypothesis (conclusion), and the third part, comprised of one more do-clauses, are to be triggered by the inference engine. The "if" and "do" parts of a rule may contain actions the system initiates.

Single rule evaluation (backward and forward)

The building-block of the most complex reasoning path is a single rule. All expert system tools process a single rule at a time. Rules can be structured to perform backward or forward chaining or both along reasoning paths. In backward chaining, a rule can be used to verify a condition in another rule. In forward chaining, a rule can trigger the activation or the evaluation of other rules. Some expert system tools provide mechanisms for only forward or only backward chaining, others provide for both, and yet others provide for the use of the same rule in a forward or backward chaining mode. In the last case, rule evaluation is bi-directional, that is the system can either prove the hypothesis (goal-driven) or draw conclusions from the conditions (data-driven). This is the case with Nexpert Object.

Assuming that the value of a slot involved in one of the rule's conditions is known, by an action of a user volunteering (giving) the value of that property, the rule, as a chunk of knowledge, will become relevant and the system can use this rule to try to prove or disprove the hypothesis and make further inferences. This procedure of starting with data to evaluate rule conditions is called forward chaining.

## 1.5. Building Knowledge-Based Expert Systems

Knowledge acquisition involves development of the following five interdependent and overlapping typical tasks for building the Terrain Analysis eXpert system prototypes (Argialas 1995): (1) Identification, (2) Conceptualization and representation, (3) Formalization, (4) Implementation, and (5) Testing and evaluation. These are the steps followed in this research effort.

## 1.6. Knowledge-Based Landform Interpretation: Past Approaches

For the past ten years, scientists working toward knowledge-based landform interpretation have developed various approaches and have implemented expert system prototypes for terrain analysis (Leighty 1973, Mark 1976, Leighty 1979, Rinker and Corl 1984, Argialas and Narasimhan 1988a and 1988b, Edwards 1988, Mintzer 1988, Argialas 1989, Narasimhan and Argialas 1989, Argialas 1995). The approach by Argialas and his associates has used different methods of knowledge representation such as rules, frames, Bayesian reasoning under uncertainty, and fuzzy descriptors to address terrain knowledge-representation through the landform-pattern element approach and to construct prototype expert-systems for inferring the landform of a site from user observations of pattern elements (Table 1).

The expert-system approach to terrain-analysis problem-solving was first implemented in a rule-based production system language involving inexact reasoning (Argialas and Narasimhan 1988a and 1988b). Subsequent work added such knowledge-representation formalisms as frames (Argialas 1989) and fuzzy sets (Narasimhan and Argialas 1989). The systems described were termed Terrain Analysis eXperts (TAX-1, 2, 3).

In TAX-1 *factual knowledge* described the landforms in relation to their pattern elements and the physiographic sections in relation to their expected landforms (Table 2, Table 3). *Strategic knowledge* (problem-solving decisions) were represented by inexact production rules through a Bayesian formalism. Based on user response for the query of the physiographic section of the site, the system constructed a set of candidate landforms of the site and estimated their *a priori* probabilities. TAX then chose the landforms in this candidate list, one by one, and attempted to establish each one of them, by matching the user-supplied pattern-elements of the site with those expected for each landform. A typical consultation script is listed in.Table 4.

A second prototype, the Terrain Analysis Expert-2 (TAX-2) system (Argialas 1989) was designed in the Intelligence Compiler, a frame and rule based expert-system tool (Intelligence Ware 1986). TAX-2 (Table 1) demonstrates the representation and reasoning capabilities of frames, backward and forward chaining rules, and inexact reasoning for the landform interpretation. A third prototype (Table 1), the Terrain Analysis Expert-3 (TAX-3) system was designed so that to represent the vagueness and imprecision that is inherent in the qualitative descriptions of terrain terms by fuzzy sets (Narasimhan and Argialas 1989). *Fuzzy set* approaches provide a way for dealing with vague linguistic descriptions such as "gentle relief", and "partly dendritic, partly rectangular drainage pattern".

The identification of TAX-4 was described in Argialas and Miliaresis (1996) and it pertained to naming, describing and organizing detailed, "book-level" knowledge pertaining to physiographic regions (provinces and sections), in particular, the Basin and Range Province (Great Basin and Sonoran Desert) of Southwest USA (Table 1).

Table 1. Comparative features of five terrain analysis expert-system prototypes (TAX-1, 2, 3, 4, 5).

| **Name of prototype⇨**<br>**Feature of prototype⇩** | **TAX-1** | **TAX-2** | **TAX-3** | **TAX-4-5** |
|---|---|---|---|---|
| Landform Interpretation model | Landform pattern elements | Landform pattern elements | Landform pattern elements | Extended Landform pattern elements |
| Physiographic information model | Trough a priori odds | Trough a priori odds | Trough a priori odds | Trough a knowledge-base involving physiographic indicators |
| Spatial Reasoning Model | NA | NA | NA | Trough a knowledge-base involving a variety of spatial indicators and reasoning paths |
| Object representation | Object-attribute-value | Frames | Frames, objects | Frames, objects |
| Inference | Production rules | Rules | Rules, demons | Object and Rule-based |
| Inexact reasoning | Bayesian | Bayesian | Fuzzy sets | Knowledge-based |
| Rule chaining | Forward | Backward and forward | Backward and forward | Backward and Forward |
| Reasoning direction | Forward mainly | Forward mainly | Forward mainly | Backward and Forward |
| Expert system tool | OPS5 | INTELLIGENT COMPILER | KEE | NEXPERT OBJECT<br>SMART ELEMENTS |

Table 2. Probabilities of occurrence of three landforms in the physiographic section Cumberland Plateau as used in the TAX-1-2-3 expert systems

| Physiographic Section | Landform type | Probability of occurrence |
|---|---|---|
| Cumberland Plateau | Humid sandstone | 0.45 |
| Cumberland Plateau | Humid shale | 0.45 |
| Cumberland Plateau | Humid limestone | 0.10 |

## 1.7. Knowledge-Based Landform Interpretation: Limitations of Past Approaches

Terrain knowledge acquisition and representation involved development of the following five interdependent and overlapping typical tasks for building the Terrain Analysis eXpert system prototypes: (1) Identification, (2) Conceptualization and representation, (3) Formalization, (4) Implementation, and (5) Testing and evaluation. The TAX-1-2-3 prototypes shared the same identification stage, while they differed in the other stages. For this reason, in the following we describe the limitations of the identification stage of the earlier TAX-1,2,3 systems.

Identification pertains to data, hypothesis, goals, and reasoning tasks of TAX. The identification step of TAX 1, 2, 3 (Argialas and Narasimhan 1988a and 1988b, Argialas 1989, Argialas 1996) was characterized as following:

- The class of problems the expert system was expected to solve was the inference of the landform type of a site, assuming that one landform type was present on the site. The user was asked first to select the physiographic region of the site, and then he/she was guided to provide the pattern elements of the site (Table 4).

- The conceptual scheme for the recognition of the landforms was the landform pattern-element approach. The hypotheses were the landforms and the evidences or data used for inference were the pattern-elements of a site. The association between physiographic sections and their expected landform types were described with the use of probabilities expressing the occurrence of each landform in the corresponding physiographic section (Table 2).

- Six landform types were chosen to focus the knowledge-representation process, the humid and arid forms of sandstone, shale and limestone. Six to ten pattern elements were collected for each landform. The landforms considered for the knowledge-representation process were those that are common to the Cumberland Plateau section, e.g., sandstone, shale, limestone. This domain knowledge was composed of facts collected from (1) books (Way 1978, Lillesand and Kiefer 1979), (2) reports (Mintzer and Messmore 1984), (3) the experience of the authors, and (4) an interview with an expert terrain analyst.

TAX-1, 2, 3 have assumed the same, rather simple, conceptual framework characterizing landforms through their pattern elements: the landform-pattern element framework. The landform-pattern element framework was based on the photographic interpretation charts found in terrain analysis books and guides (Way 1978, Lillesand and Kiefer 1979, Mintzer 1983, Mintzer and Messmore 1984). The photographic interpretation charts contain the significant summaries of the pattern element values of each landform. This conceptual framework was an appropriate approach to start with and develop our first prototypes. The traditional pattern elements, however, only hint at what the expert perceives. Therefore, the use of pattern elements as the means for identifying the landform is a "zero order approximation" to how experts work during landform identification and as such it is limited. It has contributed to the first-generation prototype expert-systems for terrain analysis. To build the next generation of systems, which could successfully handle additional aspects of problem solving, it is necessary to create new conceptualization schemes to more explicitly represent additional aspects of landform identification problem solving.

Furthermore, while TAX-1, 2, 3 have demonstrated the use of *a priori* physiographic information for focusing the search for the identification of the landform of the site, the expert analyst would better take into account the physiographic context, the regional context, the geomorphic process context and other contexts to arrive at an interpretation of a landform. With such "deeper knowledge" taken into account, the landform expert systems would be able to reason much beyond the pattern elements alone. Therefore there is a need to study such additional landform-contexts.

In TAX-1, 2, 3, the landform of a site was identified on the basis of it's pattern elements alone with no account taken of its position in the landscape (site) and of how the neighboring landforms were labeled (association). Also, knowledge of an already identified landform of a given site was not used to assist in the interpretation of its neighboring landforms.

Yet, in any site, especially in those belonging to the same physiographic region, adjacent landforms are related or associated because many times there are expectations about the neighbors of each landform type and also because a landform generally occurs over a physiographic region that contains many geomorphologically similar landforms. For example in the Basin & Range physiographic province, if a particular site represents an alluvial fan landform, it is likely that its neighboring sites, except those upslope of it, will be either alluvial fan, bajada, pediment, valley fill, perhaps even playa, flood plain, or sand dunes. This knowledge of spatial neighborhood associations is a rich source of information that has not been exploited in the earlier approaches although we may safely assume that photointerpreters have developed and used such expertise.

Table 3. Probabilities of occurrence of each pattern element value (evidence) in each of three landforms (hypotheses) provided by an expert interpreter and used in the TAX-1 expert system.

| Pattern element | Pattern element value (Evidence) | P (Evidence/Hypothesis) Conditional probability of each evidence given the hypothesis of | | |
|---|---|---|---|---|
| | | Humid Sandstone | Humid Shale | Humid Limestone |
| Topography | Steep slopes | 0.6 | 0.15 | 0.5 |
| | Medium slopes | 0.2 | 0.7 | 0.25 |
| | Flat-undulating | 0.2 | 0.15 | 0.25 |
| Drainage pattern | Dendritic | 0.6 | 0.8 | 0.1 |
| | Rectangular | 0.2 | 0.1 | 0.0 |
| | Angular | 0.2 | 0.1 | 0.1 |
| | Internal | 0.0 | 0.0 | 0.8 |
| Drainage texture | Coarse | 0.6 | 0.1 | 0.1 |
| | Medium | 0.3 | 0.3 | 0.0 |
| | Fine | 0.1 | 0.6 | 0.0 |
| Soil tone | Light | 0.7 | 0.2 | 0.3 |
| | Medium | 0.2 | 0.6 | 0.5 |
| | Dark | 0.1 | 0.2 | 0.2 |
| Landuse-valleys | Cultivated | 0.3 | 0.7 | 0.8 |
| | Forested | 0.5 | 0.1 | 0.1 |
| | Urban | 0.2 | 0.2 | 0.1 |
| Landuse-slopes | Cultivated | 0.1 | 0.1 | 0.7 |
| | Forested | 0.9 | 0.8 | 0.2 |
| | Urban | 0.0 | 0.1 | 0.1 |

Table 4. A typical consultation script generated with the terrain analysis expert system TAX-1. Underscored and boldfaced numbers indicate the user's certainty, between -3 and 3, for the presence of the specific pattern-element value in the study area.

Please provide the following information about the site.
To which Physiographic-section does the site belong?
Cumberland-plateau
Is the "gully-amount" of the site "none" ? **-3**
Is the "gully-amount" of the site "few" ? **1**
Is the "gully-type" of the site "v-shaped" ? **3**
Is the "landuse-valleys" of the site "cultivated" ? **-1**
Is the "landuse-valleys" of the site "forested" ? **3**
Is the "landuse-slopes" of the site "cultivated" ? **-3**
Is the "landuse-slopes" of the site "forested" ? **3**
Is the "soil-tone" of the site "medium" ? **1**
Is the "soil-tone" of the site "light" ? **0**
Is the "soil-tone" of the site "dark" ? **0**
Is the "drainage-texture" of the site "coarse" ? **3**
Is the "drainage-type" of the site "internal" ? **-2**
Is the "drainage-type" of the site "angular" ? **2**
Is the "topography" of the site "steep-slopes" ? **3**
Is the "gully-amount" of the site "many" ? **-2**
The site appears to be "sandstone-humid"
The certainty associated with this result is "0.99"

# 2. Methodology (Knowledge Base Design)

## 2.1. Identification and Conceptualization of Terrain Features and Reasoning Strategies in TAX-4-5

### 2.1.1. Problem Solving Scenaria in Terrain Analysis

The above stated concerns have urge us in pursuing the present research effort so that to develop new identification, conceptualization and representation schemes which could help us build smarter terrain analysis expert systems.

Knowledge conceptualization or epistemological analysis and representation aim at uncovering the key concepts of the domain and the relationships between them and at conceiving a formal description of knowledge in terms of the primitive concepts and conceptual relations. In particular involves characterization of the different kinds of data, the flow of information and the underlying structural properties of the conceptual knowledge, in terms of causal, spatial, part-whole relationships, taxonomic relations, knowledge sources, structuring relations, strategies and so on. The result is a formal typology of relevant concepts. The first and practical stage to the epistemological analysis includes naming. describing, relating, and organizing of the entities of the domain.

In this effort it has been developed a **new conceptual scheme** which was **formalized through and implemented in objects and rules** so that to provide representation of eleven interpretation scenaria:

1. Extended Landform-Pattern Element Reasoning (Rules which pertain to the interpretation of landforms from an expanded set of pattern elements),
2. Landform-Geomorphic Indicator Reasoning (Landform-Geomorphic Indicator Reasoning: Rules which pertain to the interpretation of landforms from their geomorphologic indicators),
3. Topographic Form Reasoning,
4. Physiographic Feature Reasoning,
5. Physiographic Region (Provinces and Sections) Reasoning,
6. Landform-To-Topographic Form Reasoning,
7. Topographic Form-To-Physiographic Feature Reasoning,
8. Physiographic Feature-To-Physiographic Region Reasoning,
9. Landform Spatial Context: landform identification by spatial association,
10. Landform Spatial Context: landform identification verification by spatial association, and
11. Landform Spatial Context: Landform Hypotheses-Formulation by Spatial Association

The above eleven aspects of interpretation scenaria are grouped here under three general classes of photointerpretation problem solving:

A. **Landform context**, to include interpretation scenaria 1, and 2

B. **Physiographic context**, to include interpretation scenaria 3, 4, 5, 6, 7, 8, and

C. **Spatial** or **regional context**, to include interpretation scenaria 9, 10, and 11.

The new schemes as designed and demonstrated are called TAX-4 and TAX-5. TAX-4 is concerned mainly with physiographic context, while TAX-5 is mainly concerned with regional context.

The class of problems TAX-4 has addressed included **physiographic context reasoning** in addition to our previous schemes. It is evident that the expert in deciding the landform of a site is studying first, among other things, the physiography of a region and performs what we call here physiographic analysis and reasoning so that to create reasonable hypotheses of the possible landforms of the site. On the other hand if the expert has already identified a landform, the expert is in a position to create physiographic region hypotheses and consequently to be guided to interpret additional landforms. We call this type of bidirectional reasoning *physiographic context reasoning*. Physiographic context reasoning is an informal task at present since it is not described explicitly in a formal manner in books and guides. In the following sections we develop a formal conceptual framework for the representation of physiographic context reasoning and formalize and implement it in a prototype expert system. Emphasis is placed in the definition of the subproblems and subtasks trough domain-dependent concepts, hypotheses and data.

In TAX-5 we consider the importance of spatial knowledge and examine the benefit of taking it into account, while performing landform interpretation. The underlying idea of the **landform spatial knowledge**, proposed here, is that geomorphologic processes controlling the development of a specific landform also determine the kind of landforms developed in it's neighborhood or they are associated with the geomorphic processes of the neighboring landforms. Therefore. the identification of one landform may lead to suggestions (indirect evidences) regarding the interpretations of the neighboring landforms by spatial association. Furthermore, the spatial position of a landform in the landscape is largely dependent on the geomorphic processes that have created that landform in that particular position in the landscape. Therefore, the location of a feature in the landscape can be used to generate landform hypotheses for that feature. In summary, both the expected **site** (location) of a landform in the landscape and its spatial **association** with other landforms can be formalized and used in a knowledge-based consultation system to assist users in identifying landforms. This is also important given the significance of site and association as basic photointerpretation elements. We call this type of reasoning spatial or **regional context reasoning**.

### 2.1.2. Terrain Analysis Knowledge Sources

To practically demonstrate the developed conceptual scheme we will give examples reflecting the landforms of the physiographic region of the Basin and Range Province of Southwest USA, in particular, those found on the piedmont plain, e.g., alluvial fans, pediments, bahadas and on the basin floor, e.g., playas, valley fills.

In the following we briefly describe the relevant physiographic and geomorphologic knowledge that was identified and used for the presented conceptual scheme. The relevant knowledge was acquired and compiled by a **trial and error effort** from examples and cases studies found in engineering, physiographic, and geomorphologic books and reports:

- mainly from Fenneman (1931, 1938), Lobeck (1932), Hammond (1954), Lueder (1959), Hunt (1973, 1975), Peterson (1981), Mintzer and Messmore (1984), Rinker and Corl (1984), Short and Blair (1986), Pandey (1987), McGeary and Plummer (1994), and Ritter et al. (1995), and

- furthermore from Hamplin and Howard (1995), Helms (1986), an d Thomson and Turk (1993).

This research aimed to explicitly represent the necessary concepts, entities, and recognition elements for the physiographic and spatial context reasoning. The compiled concepts, terrain entities, and recognition elements concerning the geomorphologic processes that have created each landform or physiographic region were implicitly, and not explicitly, embedded in the bibliographic sources. Clearly, the step by step strategic reasoning required to effectively articulate and use the physiographic and spatial knowledge for image interpretation and terrain analysis **is missing** from the literature and it was conceptualized by a **trial-and-error effort**.

### 2.1.3. Physiographic Regions (Provinces and Sections)

Geologists and geographers have subdivided the United States into areas called **physiographic provinces**, each of which has characteristic landforms. In the conterminous USA more than 80 such subdivisions are recognized, but for simplification they have been grouped together into 25 major provinces (Figure 1). This classification of landforms has been further simplified by grouping the provinces into six large regions. The six regions are (1) the Central Stable Region, (2) the Appalachian Highland Region, (3) the Ozark Region, (4) the Cordillera Mountain Region, (5) the Great Plains Region, and (6) the Atlantic Coastal Plain Region.

The Cordillera Mountain Region is a wide mountainous belt that stretches from Central America northward to Alaska composed of a series of ranges. It occupies the Western third of the United States. One of its provinces, the **Basin and Range Province** is centered principally on the State of Nevada but extending across the Southern parts of Arizona and New Mexico, located west & south of Colorado Plateaus (Figure 2). It is a large area, one tenth of USA, occupied mostly by wide desert plains, generally almost level, interrupted by great, largely dissected, north trending, roughly parallel mountain ranges formed by a series of tilted fault blocks (Figure 3). The typical block mountain has an escarpment on the faulted side and a long, comparatively gentle slope away from the fault. The differences in slope on the two sides are significant. Climatically is characterized by want of sufficient runoff to reach to sea or to forward its load of detritus. The Province of Basin and Range is further subdivided to five sections of unequal size and of different erosion cycles such as the Great Basin (youthful erosion stage) and Sonoran Desert (maturity erosion stage) (Fenneman 1931 and 1938). We describe the two of them below (Figure 2, Figure 3).

1. The **Great Basin section** is a large part of the Basin and Range province, in its northern half and mainly in Arizona & New Mexico. It is known as the Great Basin section because its drainage waters do not reach the sea but evaporate in saline lakes on the plains between the mountain ranges (Figure 2, Figure 3). Such basins are by no means universal. Much of the area has slopes on which water might run directly to the sea but it is too arid to supply continuous flow. Considerable areas have no run-off at all. The space taken by the mountains is about the half of the total.
2. The **Sonoran Desert section** is south of and much lower in altitude from the Great Basin (Figure 2, Figure 3). Mountain ranges are smaller and perhaps older, occupying perhaps the 1/5 of the space. Moreover large areas are without concave basins of internal drainage and the section belongs to the maturity erosion stage.

### 2.1.4. Physiographic Features or Parts

For the physiographic context reasoning, we have named and identified the following three **physiographic features** or **parts** of the Basin and Range province and its sections:

1. The **highlands** (mountain ranges and mountains),
2. The **major desert valleys** formed by erosiononal excavation (canyons, arroyos etc.), and
3. The **intermontane basins** which are broad structural depressions created through alluvial filling rather than by erosional excavation and thus they are much wider than stream valleys of equal relief that are cut by erosion. The term intermontane is used in structural sense only and refers the structural depression regardless of its surface drainage type which might be centripetal/internal (bolsons) or external (semi-bolsons).

Subsequently, we have identified the following two **specializations of intermontane basins**.

1. The **bolson** represents a special stage in valley filling in which the fans and bahadas fill the entire border of the valley, causing all the drainage to be centripetal. In very advanced stages of bolson-type filling, the area may be essentially a true filled valley.
2. The **semibolson** is deeply filled with alluvium from the surrounding mountains in such extent that alluvium is spilled over a bedrock divide to an adjacent drainage basin, resulting to external drainage. Thus, other once closed bolsons have been opened to external drainage by headward eroding streams, where valleys are undergoing destruction (Lueder 1959) that have cut through bedrock or alluvial divides (Peterson, 1981). Some of them are transversed by perennial desert streams fed from mountain sources (an arid floodplain might be evident), others have only the topographic possibility for external drainage but seldom do under the arid climate.

### 2.1.5. Topographic Forms

We have identified two distinct **topographic forms** of an intermontane basin: the piedmont plain and the basin floor. The **piedmont plain** is a gross topographic form, forming a gently sloping surface parallel to mountain front and surrounding the mountain belts. It includes all of the noticeably sloping land from the bounding mountain front down to the nearly level basin floor. The slope is 8-15% near the mountain front and 1% where it merges with the basin floor, but includes short erosional slopes as steep as 30% where it is dissected. It can be thought of as comprised of landforms that are roughly parallel to the mountain front. It consists of depositional (alluvial fans, bahadas) and partly erosional landforms (pediment) (Figure 4). The steep upper boundary between the mountain front and the relatively gentle piedmont slope is called piedmont angle. The **basin floor** is the continuous and gently curved or essentially horizontal surface of a basin. The basin floor of undrained type basins is usually consisting of valley fill and playa landforms (Figure 4).

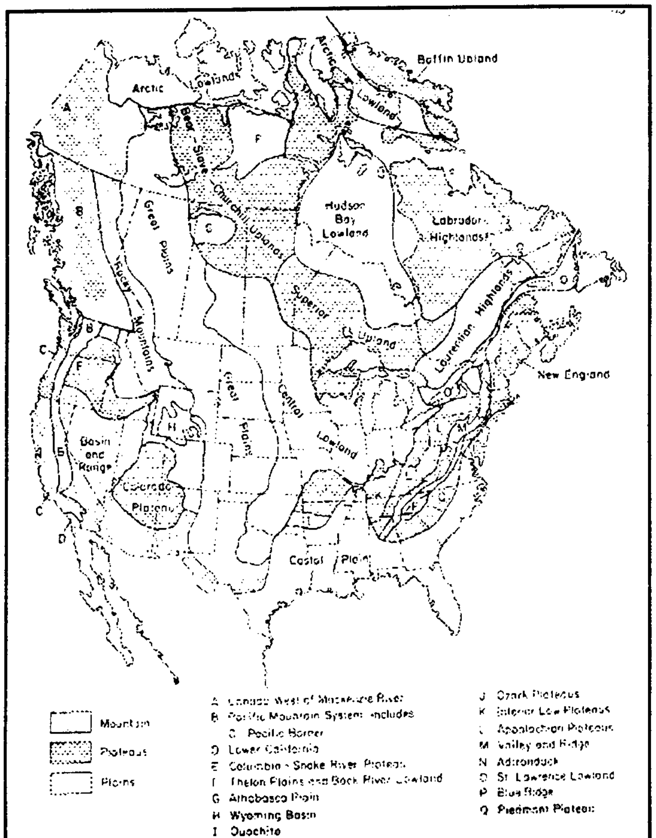


Figure 1. Physiographic Provinces of USA.

Figure 2. Geographic location of the Basin and Range Province and the Great Basin and Sonoran Desert sections.

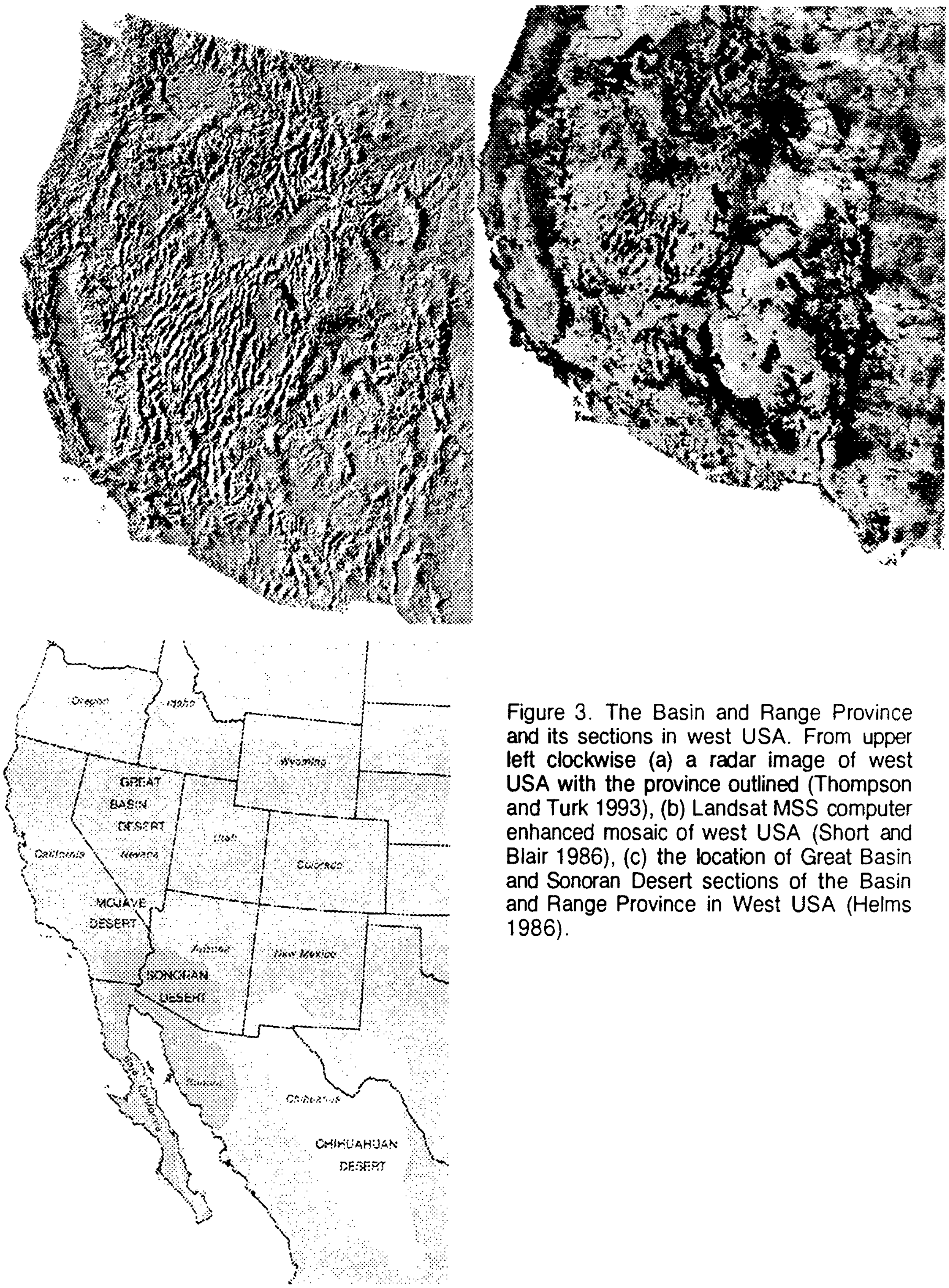
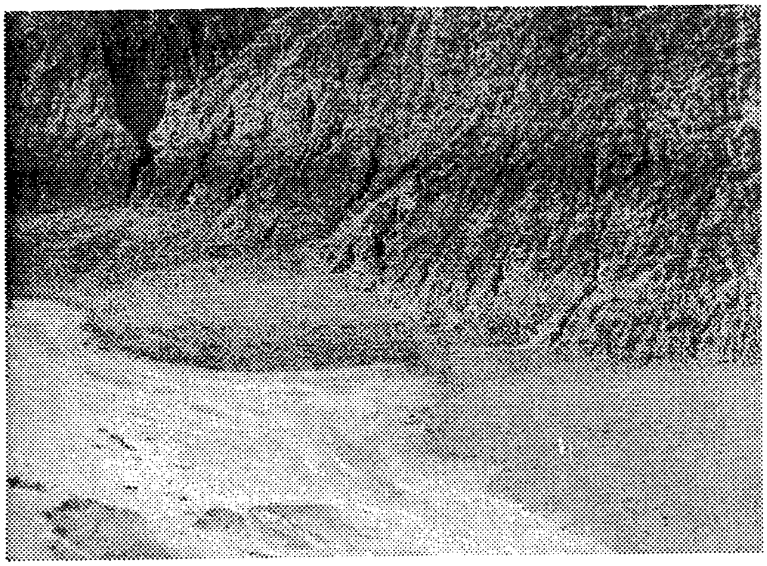
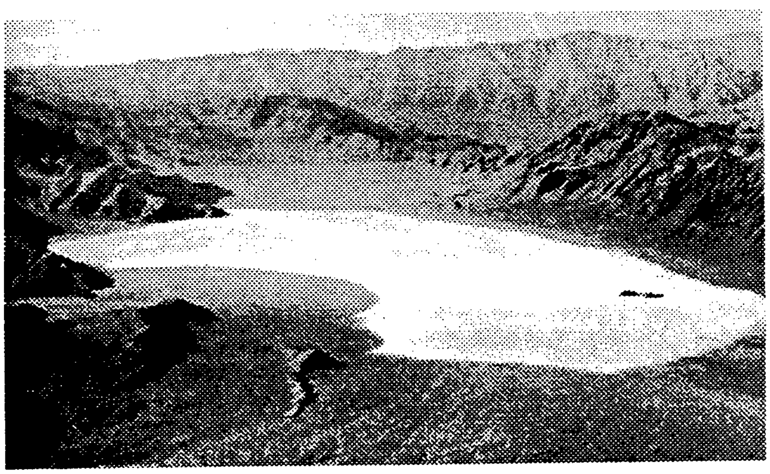



Figure 3. The Basin and Range Province and its sections in west USA. From upper left clockwise (a) a radar image of west USA with the province outlined (Thompson and Turk 1993), (b) Landsat MSS computer enhanced mosaic of west USA (Short and Blair 1986), (c) the location of Great Basin and Sonoran Desert sections of the Basin and Range Province in West USA (Helms 1986).



(a)



(b)

Figure 4. In (a) a playa is adjacent to an alluvial fan (in the downslope direction with respect to the alluvial fan). In this case study, the two adjacent landforms belong to different topographic forms: the alluvial fan belongs to a piedmont slope and the playa to a basin floor (McGeary and Plummer, 1994). In (b) a playa is deposited in the lower central part of a closed undrained basin surrounded by mountains or mountain ranges. In this case, the playa is adjacent to or surrounded by the valley fill (consisting of alluvial deposits transferred from highlands) and thus both landforms are parts of the same topographic form (basin floor) (Ritter et al 1995).

## 2.2. Formalization of Terrain Features and Reasoning Strategies and Implementation of the TAX-4-5 Knowledge Base

Knowledge formalization entails into mapping of the designed key concepts and strategies into the formal representation of a certain expert system tool. Implementation entails into programming these formal representations within an expert system tool which in this case was Nexpert Object.

Based on the earlier identified terrain features (physiographic regions, physiographic features, topographic forms, and landforms) we have focused on the following key elements for the knowledge engineering process:

1. **Identified, named, described and organized** detailed, "book-level" knowledge pertaining to physiographic regions (provinces and sections), physiographic features, topographic forms, and landforms.

2. Developed an object-oriented model for the **structural representation** of the relevant terrain knowledge.

3. Developed a rule-base for representing the **inferential** and **strategic knowledge** needed for inferring the designed terrain features from their own indicators.

4. Provided mechanisms for representation of **multiple terrain objects** at a given interpretive scenario,

5. Provided for both **forward and backward (bidirectional) reasoning** for the identification of terrain features depending on the goals of the interpretation at a given time.

We now present a formal framework for the representation of structural, strategic and inferential knowledge (landform, physiographic and regional):

- For the **structural knowledge representation** we assume an **object-oriented representation** structure that uses frames as classes, subclasses, objects, subobjects, and slot frames as properties of objects.

- For the **strategic knowledge representation** we assume a **rule based inference engine**.

These **representations** are available in Nexpert Object and our representation will be based on this expert system tool which was very briefly described earlier in the section "Knowledge Engineering Environment Feature" (Neuron Data 1993a,b,c,d).

In the following section "Terrain Feature Structural Representation", the emphasis is on clarifying **what is represented**: the object organization of the knowledge base including its dynamic objects. In the section "Inferential and Strategic Terrain Knowledge Representation" emphasis is on **how each dynamic object is inferred (interpreted)**.

In the following paragraphs we introduce and describe a case study for an interpretation scenario to be used in almost all the examples and figures that demonstrate the capabilities of the TAX-4-5 expert system prototype.

- **The case study is focusing** on typical terrain of the Basin and Range Province of Southwest USA, including the Great Basin and Sonoran Desert sections, the physiographic features of bolsons and semibolsons, the topographic forms of piedmont plain and basin floor, and the typical landforms of alluvial fans, pediments, bahadas, playas, and valley fills. (Figure 5).

- The Death Valley region from the Basin and Range Province sets up the environment of the case study (Figure 6) and in particular the segment shown in the Landsat scene shown in Figure 7. Selected terrain objects which have been interpreted with the assistance of the TAX-4 and TAX-5 expert systems have been marked on this Landsat scene (Figure 7).

- The block diagram of Figure 8 shows a different view of the identified terrain features.

- Figure 9 illustrates each identified terrain instance and the whole-part relationship to other terrain instances.
- Table 5 shows the class-subclass and whole-part relationships between these terrain features.
- Appendixes 1-4 contain transcripts of interaction of the user with the expert system prototypes TAX-4-5 that demonstrate the step by step consultation process for some of the capabilities of the implemented landform, physiographic, and spatial reasoning.

In this case study (Figure 7, Figure 8, Figure 9, Table 5):

- the Physiographic Province dynamic instance is that of the Basin and Range USA - identified here as PH_1.
- the identified physiographic feature dynamic instance PF_1 is a kind of an Intermontane Basin of Bolson type and it was part of the Physiographic Province Basin and Range.
- Three dynamic instances of topographic forms were identified,
    - TF_1 and TF_3 are kinds of piedmont plains (developed along the mountain ranges between which the Intermontane Basin is enclosed) and
    - TF_2 is a kind of Basin Floor (lying between the topographic forms TF_1 and TF_3).
- Six landform dynamic instances were identified:
    - LF_1 and LF_2 are kinds of alluvial fans belonging to topographic form TF_1,
    - LF_3 is a kind of pediment belonging to topographic form TF_1
    - LF_4 is a kind of playa and LF_5 is a kind of valley fill, both of them are parts of TF_2, and
    - LF_6 is a bahada belonging to topographic form TF-3.

A word of caution. Structural and inferential knowledge are acquired and formalized in parallel. However, for the purpose of presentation one is forced to present them separately and sequentially: usually by preceding the structural to the inferential knowledge. This separate and sequential presentation of two intimately connected processes leeds to some problems in the flow of written presentation. Thus, while the structural organization of knowledge is presented before the inferential aspects of reasoning, a great number of figures that present the structural organization of knowledge contain not only static terrain classes and subclasses but dynamically interpreted terrain features (**dynamic instances** of landforms, topographic forms, physiographic parts, and physiographic regions) which, however, are generated during reasoning and thus they demand an explanation in terms of reasoning methods. The reasoning methods however are presented in the following sections. Thus, some of the figures presented in the section "Terrain Feature Structural Representation", will be fully explained in the section "Inferential and Strategic Terrain Knowledge Representation".

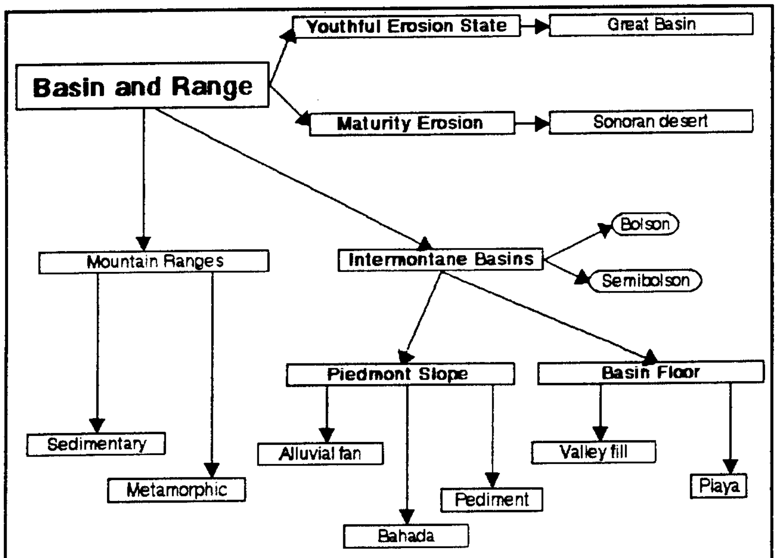



Figure 5. Major entities of the Basin and Range Concept.

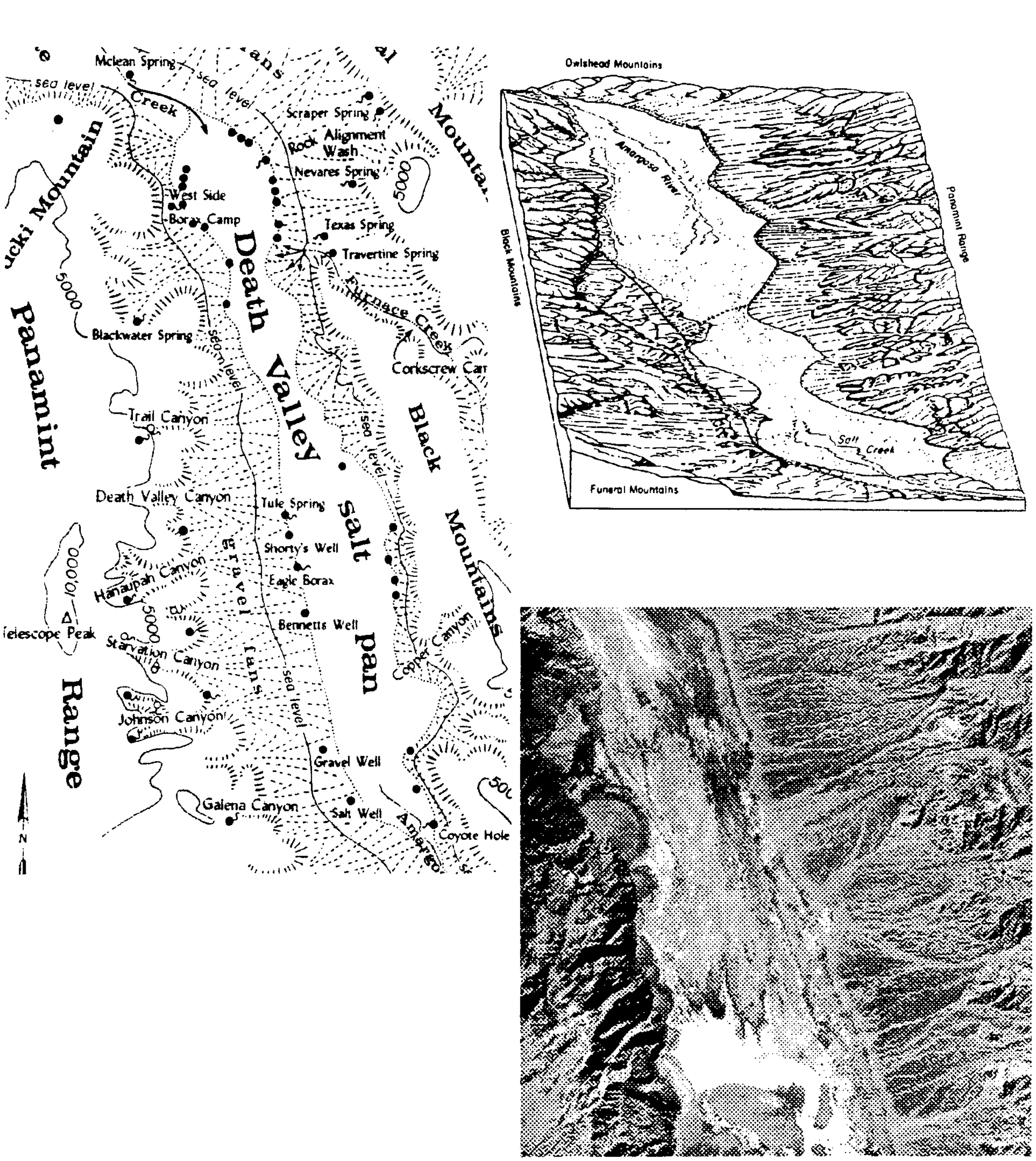



Figure 6. Death Valley. Clockwise from top left are: (a) a map of Death Valley by Hunt (1975), (b) a block diagram of same by Hunt (1973), and (c) a satellite image of same by Earth Satellite Corporation (Hamblin and Howard 1995). North is pointing upwards in the map, while it points south in the other two figures. Death Valley, California, is typical of the valleys in the Basin and Range Province which are mainly undrained (bolsons), having structural/tectonic origin (Intermontane Basin) and developed, usually, between two parallel mountain ranges (in Death Valley's case the two ranges are the Panamint Range and the Black Mountains). The main landforms present, as we see them in the block diagram (b) and in the satellite image (c) are extensive gravel fans sloping from the mountains to the plain and a salt-crusted, dry lake bed (playa) that forms the valley floor. In (a) we observe the relative spatial position of alluvial fans & bahadas (gravel fans) with respect to canyons.

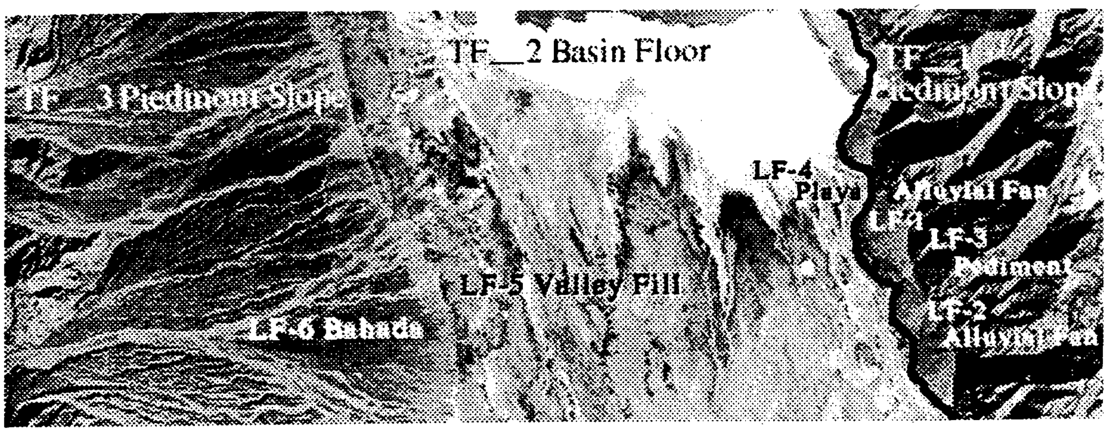



Figure 7. Landsat image depicting a part of the Death Valley basin (Hamblin & Howard, 1995, page 167, Courtesy of EOSAT) and marked with the terrain features identified during the photointerpretation session with the expert system TAX-4-5: the Death Valley was identified as physiographic feature PF_1 contained in the physiographic region of the Basin and Range PH_1, the landform instances LF_1 (Alluvial Fan), LF_2 (Alluvial Fan), LF_3 (pediment), LF_4 (playa), LF_5 (Valley Fill) and LF_6 (bahada), the topographic form instances TF_1 and TF_3 (piedmont plains) and TF_2 (basin floor). These terrain features are also explained in Table 5 and shown in the block diagram of Figure 8 and in the diagram of Figure 9. These features are used throughout the discussions in the text and the Appendixes 1-4.

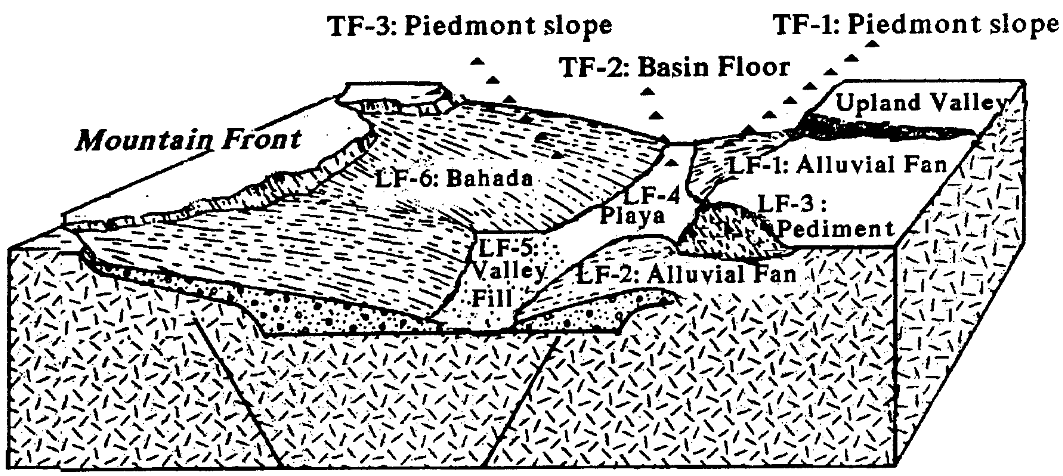



Figure 8. The location of a landform in the landscape and the spatial associations between adjacent landforms are usually shown in block diagrams. This block diagram shows an intermontane basin similar to that of Figure 7 with the associated landforms and topographic forms (piedmont plains and basin floor). The landform instances LF_1 (Alluvial Fan), LF_2 (Alluvial Fan), LF_3 (pediment), LF_4 (playa), LF_5 (Valley Fill) and LF_6 (bahada) and the topographic form instances TF_1 and TF_3 (piedmont plains) and TF_2 (basin floor) correspond to the terrain features identified during the photointerpretation session with the expert system TAX-4-5. These terrain features are also explained in Table 5 and shown in Figure 9. These features are used throughout the discussions in the text.

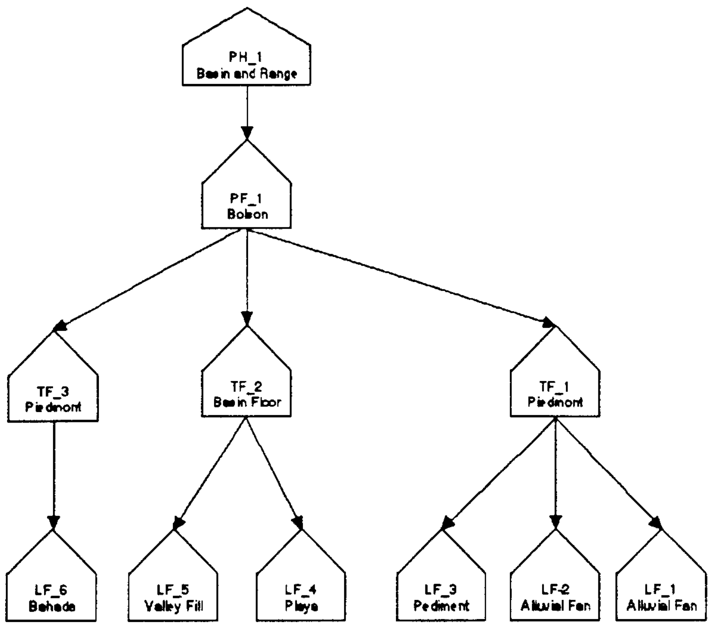



Figure 9. This diagram shows the various terrain instances identified during a typical example of the use of the TAX-4 and TAX-5 systems. Terrain instances include six landform instances (LF_1 to LF_6), three topographic forms (TF_1, TF_2, TF_3), one physiographic feature or part (PF_1) which is an intermontane basin, and one physiographic region (PH_1) which is a kind of Basin and Range. These terrain features are also outlined on the Landsat image used during the interpretation session (Figure 7) as well as on the block diagram displayed on Figure 8. They are also explained in Table 5. These features are used throughout the discussions in the text.

Table 5. Terrain class - instance and whole-part relationships specific to the case study. These terrain features are also marked on the Landsat image used during the interpretation session (Figure 7) as well as on the block diagram displayed on Figure 8 and in the diagram of Figure 9. These features are used throughout the discussions in the text and the Appendices.

| Landform Instances (LF_x) | PE | GM | SR | Topographic Form Instance | Physiographic Feature Instance | Physiographic Province Instance |
|---|---|---|---|---|---|---|
| LF_1 = Alluvial fan | y | y | y | TF-1 (Piedmont slope) | PF_1 (Intermontane Basin of Bolson type) | PH_1 Basin and Range |
| LF_2 = Alluvial fan | y | y | | | | |
| LF_3 = Pediment | | y | | | | |
| LF_4 = Playa | y | | | TF-2 (Basin Floor) | | |
| LF_5 = Valley fill | y | | | | | |
| LF_6 = Bahada | y | | | TF-3 (Piedmont slope) | | |

## 2.3. Terrain Feature Structural Representation

For the factual and structural representation of terrain features we developed a **multilevel object-oriented representation structure** that uses frames as classes, subclasses, objects, subobjects, and slots as properties (Figure 10, Figure 11). Structural knowledge representation develops terrain feature classes, objects, subclasses and structuring relations needed for all three general interpretation contexts we have introduced:

1. Landform context,

2. Physiographic context, and

3. Spatial context.

In Figure 10, and Figure 11, each horizontal plain (A to D) indicates some of the important class-subclass and class-instance structural relations of the terrain features. From plain to plain, it is indicated the whole-part or object-subject structural relations between the terrain features (E, F, G). This figure does not contain all the developed structural relations. Additional relations are shown in the examples of the knowledge-base that are used through the next sections.

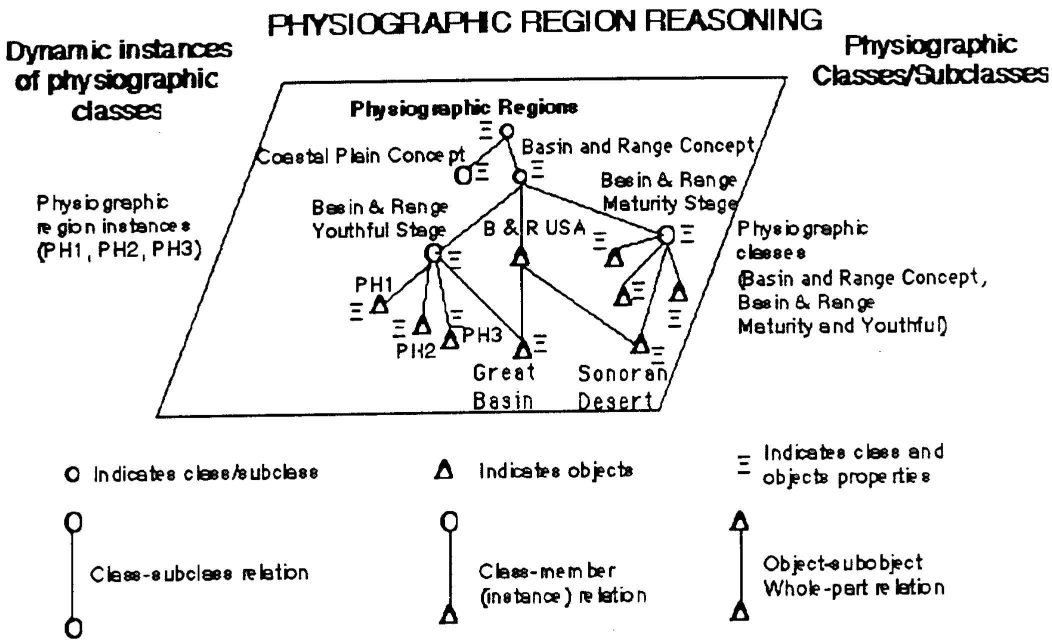



Figure 10. An object-oriented conceptual scheme for physiographic-region reasoning in TAX-4.

### 2.3.1. Terrain Feature Classes

First, we need to name and describe the terrain feature of our domain. In the object-oriented paradigm this description takes place by defining terrain classes as follows (Figure 10, Figure 11).

**Landforms** are identified as in the landform-pattern element approach used in our earlier expert system prototypes (Argialas and Narasimhan 1988, Argialas 1995). Landforms correspond to second order relief forms.

The landform class (Landform Top) is the root under which are linked the subclasses containing various aspects of landforms: landform pattern elements (LF_PE), landform geomorphic indicators (LF_GM), landform spatial reasoning indicators (LF_SR), landform engineering property indicators (LF_Engineering), landform suitability indicators (LF_Suitability), landform military suitability indicators (LF_Military), etc. (Figure 12). The class of landforms contains the subclasses of alluvial fans, pediments, bahadas, playas, valley fills, etc.

Furthermore, we have compiled a geomorphic class-subclass organization to describe the geomorphology of each landform (LF_GM) and another class to describe the spatial relations of landforms (LF_SR). From the geomorphologic point of view, landforms are classified into Initial (the result of the activity of endogenic forces) and Sequential (the result of exogenic forces). The Sequential landforms are subdivided to Erosional and Depositional. The Initial landforms are subdivided into volcanic, tectonic and plutonic landforms (Figure 13). The Depositional subclass is subdivided into various subclasses among them are the Fluviolacustrine and Fluvial subclasses. The subclasses of Valley Fill, Alluvial Fan and Bahada are kinds of Fluvial landforms. On the contrary, Playa, although it is a depositional landform, it is a kind of fluviolacustrine landform.

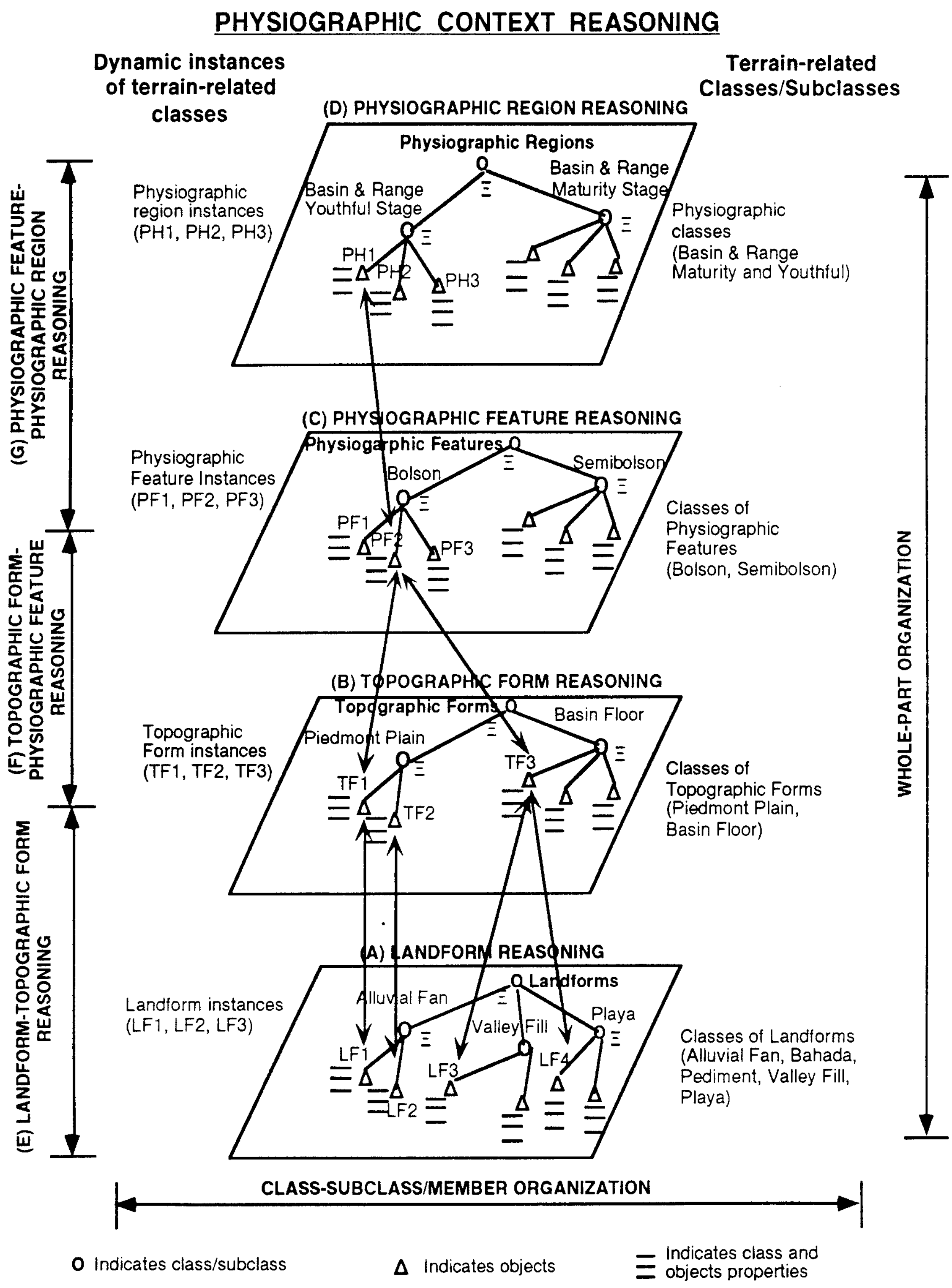



Figure 11. An object-oriented conceptual scheme for landform, physiographic and spatial reasoning in TAX-4 and TAX-5.

**Topographic forms**, like basin floors and piedmont plains, are relief forms of the second order which have minimal geomorphologic meaning. A topographic form is a relief form to which landforms might be assigned and it is determined according to its overall topographic shape, its relative position with other terrain features and its geographical scale (Figure 15, Figure 16). The class of topographic forms contains the subclasses of piedmont plain and basin floor (Figure 11, Figure 16).

**Physiographic features** or **parts**, like bolsons (drained structural basins), semibolsons (undrained structural basins), highlands, lowlands, are again relief forms of the second order which have a significant degree of geomorphologic meaning (Figure 11, Figure 16). The Physiographic Part (or Feature) class has, among other classes, the subclass of Intermontane Basin with two subclasses: the Bolson and Semibolson (Figure 16).

**Physiographic regions** are defined here as both physiographic provinces and sections according to the traditional USA physiographic approach (Figure 10, Figure 11, Figure 17).

The term **physiographic region**, in our conceptual scheme, encompasses both the physiographic provinces and the sections according to the traditional USA physiographic approach (Fenneman 1931 and 1938). In our study of the USA physiographic provinces and sections, we have recognized that behind each particular USA province or section was hidden a **physiographic concept** defined by specific geomorphologic criteria and indicators. Furthermore, in our search for a scheme to represent all the basin and range type of terrain, we were compelled to define the class "Basin and Range concept" and to let each of these terrain units to be subclasses of this class. Thus, since a class, in our object-oriented design framework, acts as a template that defines the properties of its members, we exercised care so that to define for each physiographic province (e.g., the Basin and Range USA) an equivalent concept-class so that each specific instance of the concept-class, e.g., the Basin and Range (USA), to be considered an object belonging to that class. The same design was followed for the sections of the Basin and Range, e.g., Great Basin and Sonoran Desert. We have recognized that these sections, actually correspond to **different stages of erosion**: the first is in the **youthful erosion stage** and the second is in the **maturity erosion stage**. Therefore, we have developed the corresponding classes of the youthful and maturity stages of the superclass of Basin and Range concept-class. These classes and subclasses are shown as little circles on the plain of physiographic regions of Figure 10 and Figure 11.

Figure 17 shows the physiographic provinces hierarchy. The root superclass name is Physiographic Provinces and has as subclasses all the provinces. The subclass Basin and Range is linked to this superclass. The Basin and Range Youthful Stage and Basin and Range Maturity Stage are subclasses of the Basin and Range class.

### 2.3.2. Terrain Feature Properties (indicators)

Each terrain class was defined by a set of properties which define the class. These properties are shown with the symbol $\Xi$ in Figure 10 and Figure 11.

The properties of all the earlier defined terrain feature classes are determined so that to reflect the **distinguishing characteristics** of each class and therefore they are also used for inferring instances of that class. Hence, they are termed **terrain feature indicators** as well.

The identification and selection of **terrain feature indicators** and their values (properties) was done in a bottom-up approach by a study of geomorphologic and physiographic books and reports. The identification of the properties was done according to the processes and the topographic descriptions of the various geomorphologic and topographic features described in such books. As an example, in the chapter of Basin and Range, in the Sonoran Desert Section under the title of "Basins" we noted and underlined the following statements in a paragraph (Fenneman 1931 and 1938):

> While the area occupied by mountains is smaller in this section than in the Great Basin, the extent of rock platforms, bare of detritus or only thinly covered is correspondingly large. It is estimated that 1/5 is covered by mountains, 2/5 by rock platforms and the remaining 2/5 by deposits of detritus.

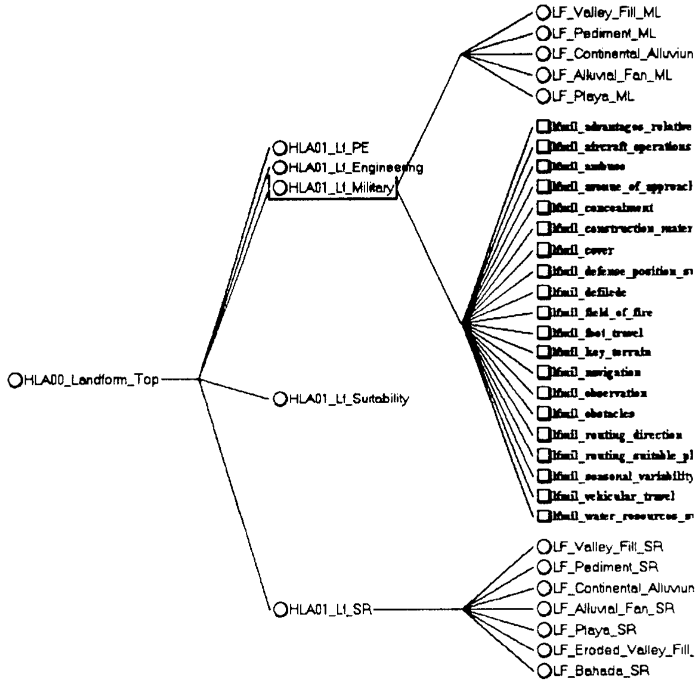



Figure 12. The landform class-subclass hierarchy. The landform class (Landform Top) is the root under which are linked the subclasses containing various aspects of landforms: landform pattern elements (LF_PE), spatial reasoning indicators (LF_SR), engineering property indicators (LF_Engineering), suitability indicators (LF_Suitability), military suitability indicators (LF_Military), etc. There are also shown a number of military indicators of landforms.

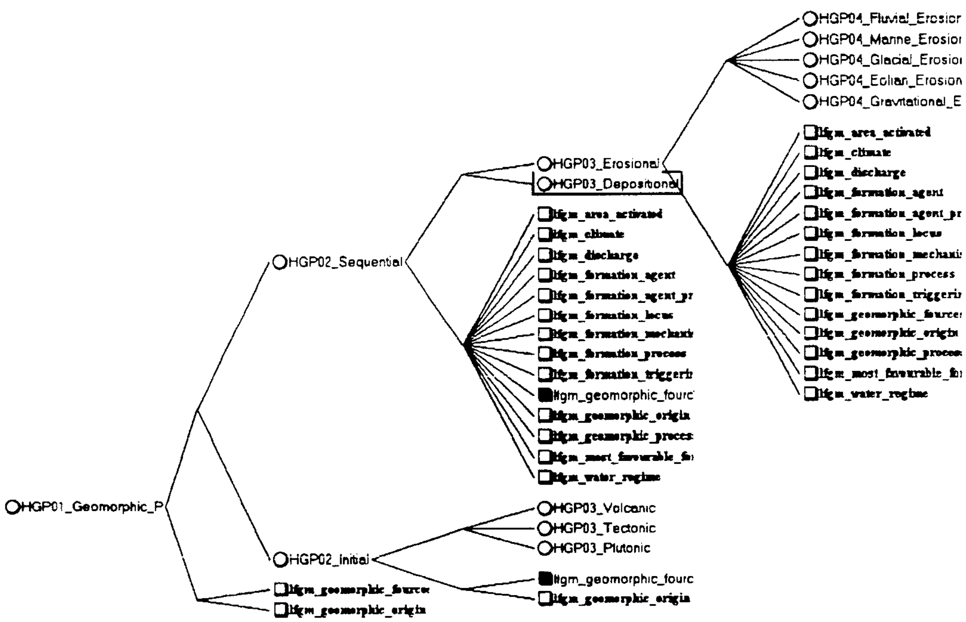



Figure 13. The top part of the geomorphic class-subclass hierarchy. Landforms are classified into Initial (the result of the activity of endogenic forces) and Sequential (the result of exogenic forces). The Sequential landforms are subdivided to Erosional and Depositional. The Initial landforms are subdivided into volcanic, tectonic and plutonic landforms. It is also shown the property inheritance from the parent classes (Sequential) to the subclasses (Erosional).

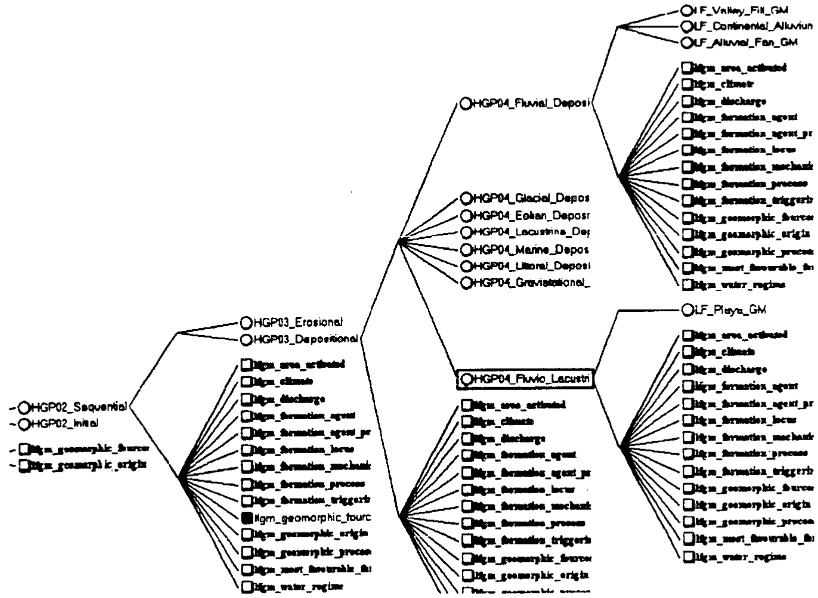



Figure 14. A part of the Geomorphic class-subclass Hierarchy. The class of Sequential landforms is subdivided into the Erosional and Depositional subclasses. The Depositional subclass is subdivided into various subclasses among them are the Fluviolacustrine and Fluvial subclasses. The subclasses of Valley Fill, Alluvial Fan and Bahada are kinds of Fluvial landforms. On the contrary, Playa, although it is a depositional landform, it is a kind of fluviolacustrine landform. It is also shown the property inheritance from the parent classes to the subclasses (Sequential--->Depositional--->Fluviolacustrine, etc.).

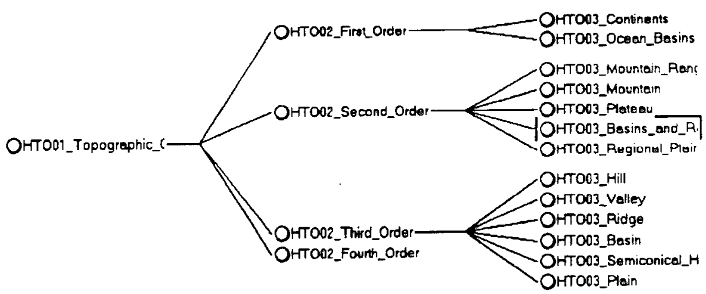



Figure 15. Topographic hierarchy

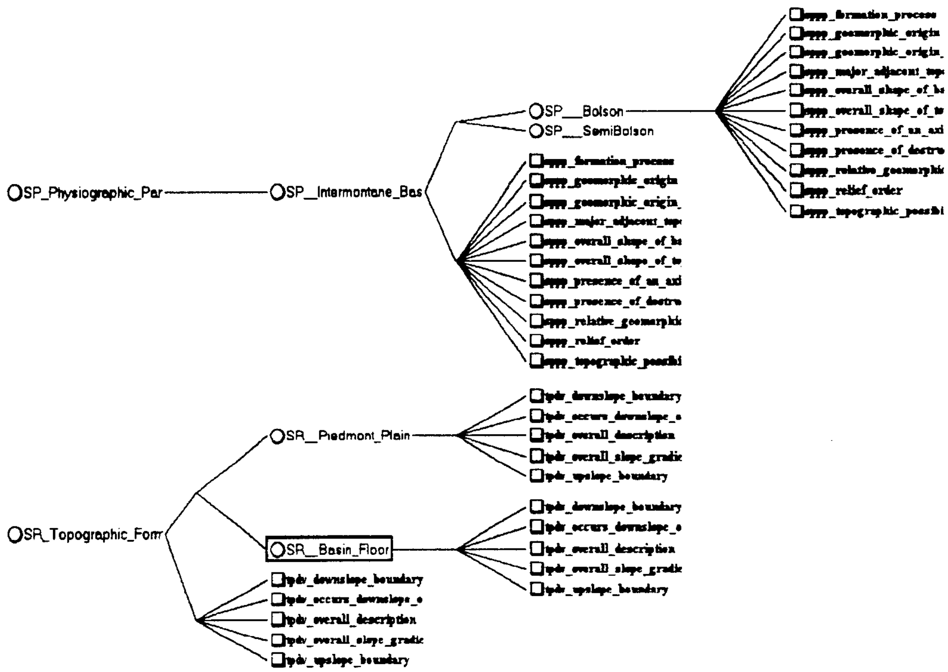



Figure 16. The Physiographic Part (or Feature) class-subclass hierarchy (top) and the Topographic Form class-subclass hierarchy (bottom). The Physiographic Part (or Feature) class contains, among other classes, the subclass of Intermontane Basin with two subclasses: the Bolson and Semibolson. The Topographic Form class has two subclasses the Piedmont Plain and the Basin Floor. It is also shown the property inheritance from the parent classes to the subclasses.

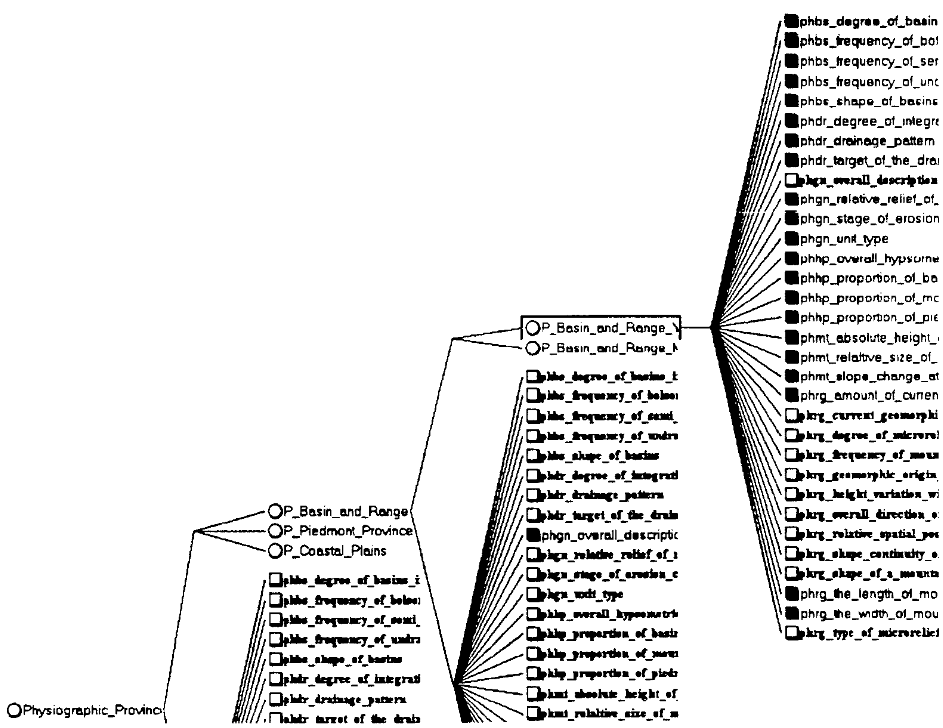



Figure 17. The conceptual physiographic provinces hierarchy. The root superclass name is Physiographic Provinces and has as subclasses all the provinces. The subclass Basin and Range is linked to this superclass. The Basin and Range Youthful Stage and Basin and Range Maturity Stage are subclasses of the Basin and Range class. It is also shown the property inheritance from the parent classes to the subclasses.

Based on these statements, we have designed the following property for the Sonoran Desert Section subclass:

proportion_of_Mountain_Ranges_versus_Piedmont_Plains_versus_Basins= 20% / 40% / 40%

**Landforms** (LF_PE) are described by visual pattern elements. However, in this effort, we have compiled an extended set of pattern elements than those usually employed in terrain analysis (Argialas and Narasimhan 1988, Argialas 1995). Table 6 lists the extended set of landform pattern elements and the landform subclasses. This extended set of landform pattern elements can be used as a whole or in part for the identification of each landform as this is explained in the section "Extended Landform-Pattern Element Reasoning" in the following.

We have also compiled a set of geomorphic process indicators to describe the **geomorphology of each landform** (LF_GM). For each geomorphologic class, e.g., Initial, Sequential, Erosional, Depositional, volcanic, tectonic, plutonic, Fluviolacustrine, Fluvial, Valley Fill, Alluvial Fan, Bahada, Playa, and valley fill we have designed a set of indicators to distinguish it from the other classes (Table 7).

**Topographic forms** were described by a set of topographic form indicators which are used for their identification (Table 8, Table 9, Table 10). Similarly, **physiographic feature indicators** were compiled to describe and distinguish the classes of intermontane basins, highlands, etc., as well as the subclasses of bolsons and semibolsons (Table 11, Table 12, Table 13, Table 14).

**Physiographic region indicators** were compiled so that to describe physiographic regions and distinguish their subclasses, including the Basin and Range, Coastal Plains, Basin and Range Youthful Stage, Basin and Range Maturity Stage, etc. (Table 15, Table 16, Table 17).

Most or the properties used for formulating the **landform spatial knowledge** were expressing spatial associations between landforms and between landforms and topographic forms, such as: upslope to given landform, downslope to given landform, surrounded by given landform, surrounds the given landform, adjacent to given landform in a direction transverse to slope vector, adjacent to given landform (in a plain surface), and "no spatial relationship can be defined". Figure 18 to Figure 21 show spatial terrain feature attributes diagrammatically.

Table 6. The Landform-Pattern Elements superclass with its seven subclasses and their characteristic properties.

```
(@CLASS=     HLA01_Lf_PE
      (@SUBCLASSES=
             LF_Valley_Fill_PE
             LF_Pediment_PE
             LF_Continental_Alluvium_PE
             LF_Alluvial_Fan_PE
             LF_Playa_PE
             LF_Eroded_Valley_Fill_PE
             LF_Bahada_PE
      )
      (@PROPERTIES=
             boundary_type
             boundary_type_downslope
             boundary_type_upslope
             drainage_pattern
             drainage_texture
             gullies_frequency
             gullies_shape
             landuse_landcover_overall
             microscale_indicators
             microtopography
             phototone
             phototone_texture
             phototone_uniformity
             planimetric_2d_shape
             ridge_lines
             size_absolute_area
             size_length
             size_radial_extent
             size_relative_area
```

```
                size_surface_height
                size_thickness
                size_width
                slope_average_gradient
                slope_gradient_range
                slope_spatial_direction_of_average_change
                soil_tone
                soil_tone_sharpness
                surface_axial_profile
                surface_curvature
                surface_highest_point
                surface_lowest_point
                surface_shape_axial_symmetry
                surface_topographic_3d_shape
                vegetation_density
                vegetation_spatial_distribution
                vegetation_type
                vegetation_uniformity
        )
)
```

Table 7. The Fluvial Deposition superclass with its three Landform-Geomorphology subclasses and their characteristic properties.

```
(@CLASS=        HGP04_Fluvial_Deposition
        (@SUBCLASSES=
                LF_Valley_Fill_GM
                LF_Continental_Alluvium_GM
                LF_Alluvial_Fan_GM
        )
        (@PROPERTIES=
                area_activated
                climate
                discharge
                formation_agent
                formation_agent_process
                formation_locus
                formation_mechanism
                formation_process
                formation_triggering_process
                geomorphic_fources
                geomorphic_origin
                geomorphic_process
                most_favourable_forming_geographic_conditions
                water_regime
        )
)
```

Table 8. The Topographic Form superclass with its two subclasses (Piedmont Plain and Basin Floor) and their characteristic properties.

```
(@CLASS=        SR_Topographic_Form
        (@SUBCLASSES=
                SR__Piedmont_Plain
                SR__Basin_Floor
        )
        (@PROPERTIES=
                downslope_boundary
                occurs_downslope_of
                overall_description
                overall_slope_gradient
                upslope_boundary
        )
)
```

Table 9. Piedmont_plain Indicators and their values

| | |
|---|---|
| tpdv_occurs_downslope_of | "mountain front", "mountain range", "mountain belt" |
| tpdv_overall_slope_gradient | "gentle" |
| tpdv_upslope_boundary | "abrupt change of slope", "piedmont junction angle" |
| tpdv_downslope_boundary | "a plain" |
| tpdv_overall_description | "sloping land from the bounding mountain front to level basin lowland" |

Table 10. Basin_Floor Indicators and their values

| | |
|---|---|
| tpdvl_occurs_downslope_of | "a gently sloping plain" |
| tpdvl_overall_slope_gradient | "flat" |
| tpdvl_upslope_boundary | "piedmont plain" |
| tpdvl_downslope_boundary | "at the lowest relative elevation" |
| tpdvl_overall_description | "a large area of nearly level land" |

Table 11. The Intermontane Basin superclass with its two subclasses (Bolson and Semibolson) and their characteristic properties.

```
(@CLASS=     SP__Intermontane_Basin
        (@SUBCLASSES=
                SP___Bolson
                SP___SemiBolson
        )
        (@PROPERTIES=
                formation_process
                geomorphic_origin
                geomorphic_origin_of_the_erosion_products
                major_adjacent_topographic_feature
                overall_shape_of_basin
                overall_shape_of_topographic_form
                presence_of_an_axial_stream
                presence_of_destructive_erosion
                relative_geomorphic_size
                relief_order
                topographic_possibility_of_external_drainage
        )
)
```

Table 12. Intermontane basin indicators and their values

| | |
|---|---|
| overall_shape_of_topographic_form | "depression" |
| geomorphic_origin | "structural" |
| relative_geomorphic_size | "gross topographic form", "broad depression", "much wider than erosional stream valleys" |
| relief_order | "second" |
| formation_process | alluvial filling" |
| major_adjacent_topographic_feature | "surrounded by mountains/mountain ranges" |
| geomorhpic_origin_of_the_erosion_products | "surrounded mountains" |

Table 13. Bolson indicators and their values

| | |
|---|---|
| phbl_presence_of_an_axial_stream | "none" |
| phbl_overall_shape_of_basin | "concave", "flat" |
| phbl_drainage_pattern | "centripetal" |
| phbl_presence_of_destructive_erosion | "no" |
| phbl_possibility_of_external_drainage | "no" |

Table 14. Semi bolson indicators and their values

| | |
|---|---|
| phbl_presence_of_an_axial_stream | "yes" |
| phbl_overall_shape_of_basin | "flat" |
| phbl_presence_of_destructive_erosion | "yes" |
| phbl_possibility_of_external_drainage | "yes" |

Table 15. The Basin and Range Province superclass with its two subclasses (Basin and Range Youthful Stage, Basin and Range Maturity Stage) and their characteristic properties.

```
(@CLASS=     P_Basin_and_Range
        (@SUBCLASSES=
                P_Basin_and_Range_Youthful_Stage
                P_Basin_and_Range_Maturity_Stage
```

```
    )
    (@PROPERTIES=
            degree_of_basins_integration
            frequency_of_bolsons
            frequency_of_semi_bolsons
            frequency_of_undrained_basins
            shape_of_basins
            degree_of_integration_of_drainage_pattern
            drainage_pattern
            target_of_the_drainage_network
            overall_description
            relative_relief_of_region
            stage_of_erosion_cycle
            unit_type
            overall_hypsometric_distribution_within_the_section
            proportion_of_basins_within_the_section
            proportion_of_mountain_ranges_within_the_section
            proportion_of_piedmont_plains_within_the_section
            absolute_height_of_mountains
            relaltive_size_of_mountains
            slope_change_at_piedmont_angle
            amount_of_current_tectonic_evidences_in_mountain_ranges
            current_geomorphic_process_of_mountain_ranges
            degree_of_microrelief_dissection_in_mounntain_ranges
            frequency_of_mountain_ranges
            geomorphic_origin_of_mountain_ranges
            height_variation_within_mountain_ranges
            overall_direction_of_mountain_ranges
            relative_spatial_position_of_mountain_ranges
            shape_continuity_of_mountain_ranges
            shape_of_a_mountain_range
            the_length_of_mountain_ranges
            the_width_of_mountain_ranges
            type_of_microrelief_dissection_in_mountain_ranges
    )
)
```

Table 16. Basin and Range-Maturity_Erosion_Stage Indicators and their values (partial)

| | |
|---|---|
| relative_relief_of_region | "low" |
| relaltive_size_of_mountains | "small" |
| slope_change_at_piedmont_angle | "not abrupt" |
| shape_of_basins | "rather plain than concave" |
| overall_hypsometric_distribution_within_the_se ction | "more than 1/2 of the surface is below 2000 ft" |
| proportion_of_Mountain_Ranges_versus_Pied mont_Plains_versus_Basins | "20% : 40% : 40%" |
| amount_of_observed_tectonic_evidences_in_m ountain_ranges | "low (the minority has a fault origin)" |
| degree_of_basin_integration | "high" |
| stage_of_erosion_cycle | "maturity (advanced,late)" |
| frequency_of_bolsons | "low (less prelevant)" |
| frequency_of_semi_bolsons | "high (more prelevant)" |
| degree_of_integration_of_drainage_pattern | "high" |
| outlet_of_the_drainage_network | "usually to another drainage basin" |

Table 17. Basin and Range Youthful_Erosion_Stage and their values (partial)

| | |
|---|---|
| relative_relief_of_region | "high" |
| proportion_of_Mountain_Ranges_versus_Piedmont_Pl ains_versus_Basin | "50% : 0% : 50%" |
| relaltive_size_of_mountains | "large" |
| slope_change_at_piedmont_angle | "rather abrupt" |
| absolute_height_of_mountains | "3000-5000 ft above their base", "7000-10000 ft above sea level" |
| overall_hypsometric_distribution_within_the_section | "more than 1/2 of the surface is 3000 ft above sea level" |
| drainage_pattern | "centripetal", "internal" |
| stage_of_erosion_cycle | "youthful (beginning, moderate)" |
| the_width_of_mountain_ranges | "6 to 15 miles commonly" |
| the_length_of_mountain_ranges | "50 to 70 miles commonly" |

| | |
|---|---|
| amount_of_observed_tectonic_evidences_in_mountain _ranges | "great (the majority has fault origin)" |
| degree_of_basin_integration | "little (independence of drainage basins)" |
| frequency_of_bolsons | "high (more prelevant)" |
| frequency_of_semi_bolsons | "low (less prelevant)" |
| shape_of_basins | "predominatly concave than plain" |
| frequency_of_undrained_basins | "high" |
| outlet_of_the_drainage_network | "playa", "sink" |

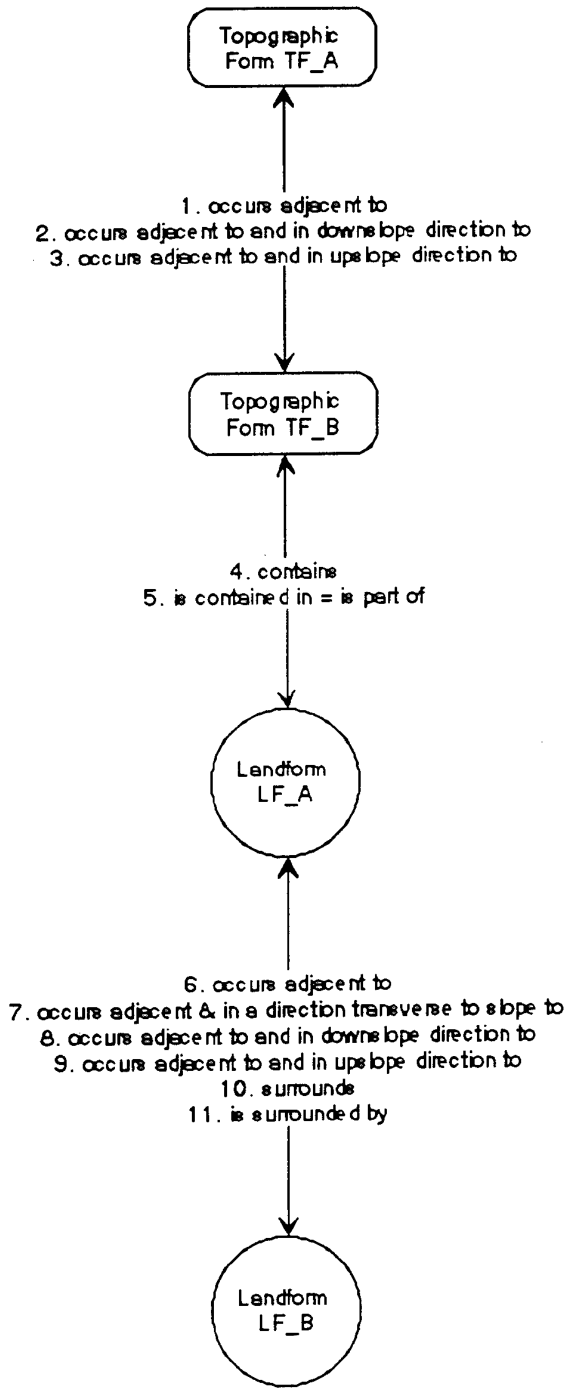



Figure 18. Spatial relations between landforms and topographic forms.

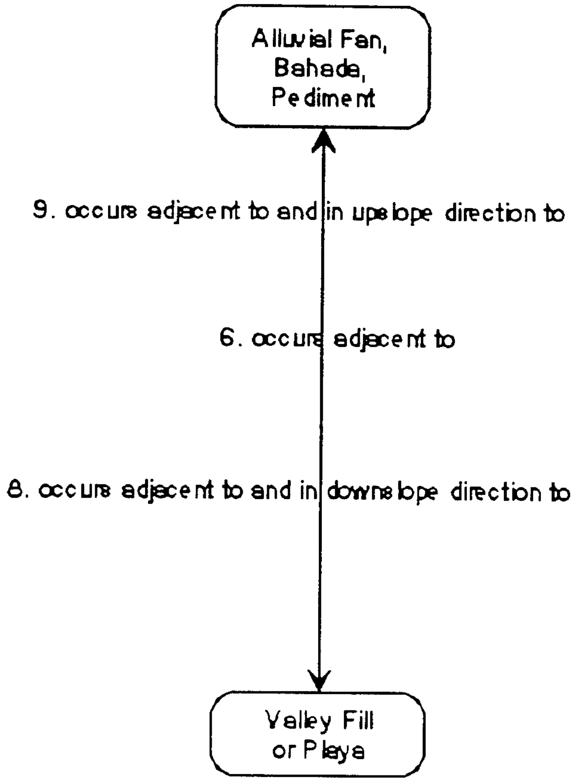



Figure 19. Spatial relations between significant landforms of the Basin and Range Province: in particular between the landforms of the piedmont slope and those of the basin floor.

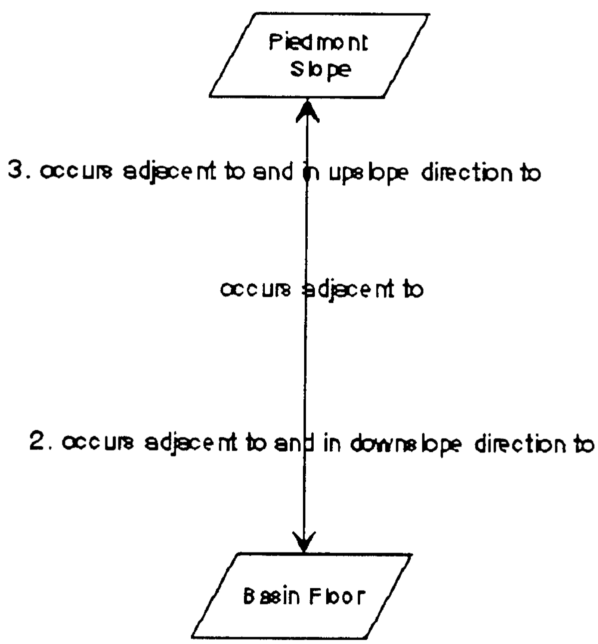
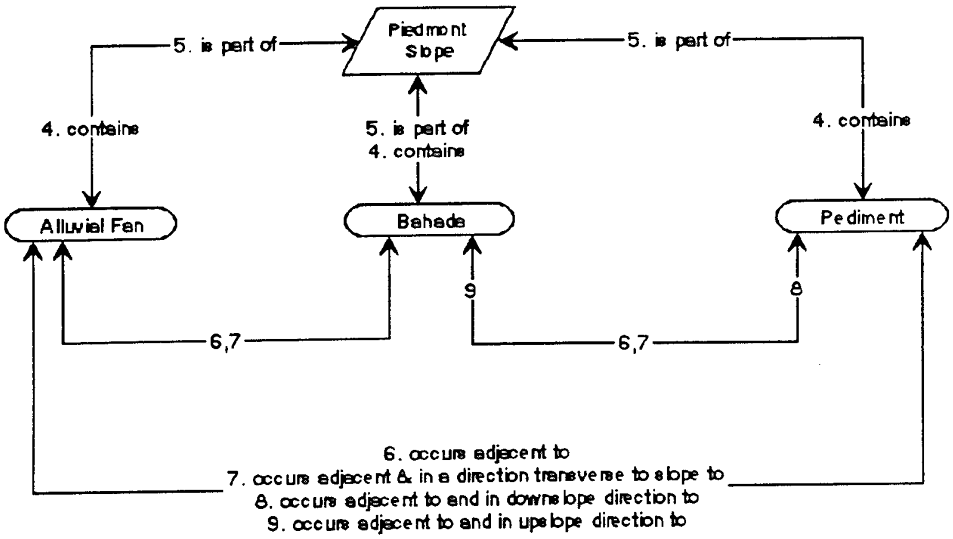



Figure 20. Spatial relations betweeen the piedmont slope and the basin floor.



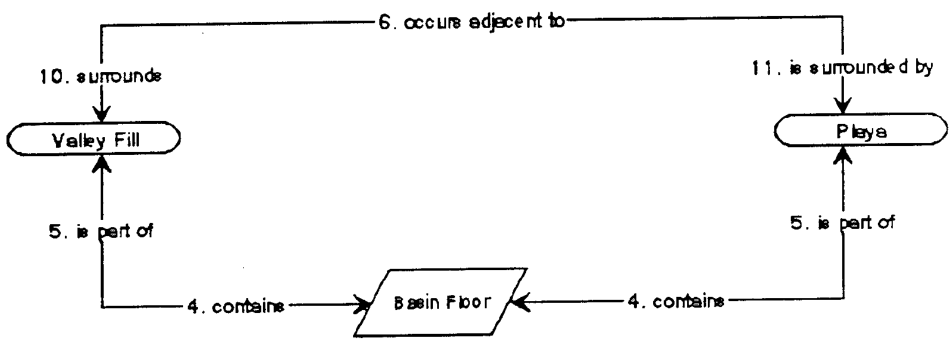




Figure 21. Spatial relations between significant landforms of the Basin and Range Province. The top figure refers to the piedmont slope and the bottom to the basin floor.

### 2.3.3. Terrain Feature Instances (Objects)

While terrain classes are useful in representing a concept as a whole, it is necessary to define individual (static or dynamic) object instances of each class or subclass so that to use them for symbols as we interpret features of each class on an image. The members of a class are its objects and are typically referred to as "instances of a class." They express a class-instance relationship. Some of these instances are dynamic objects generated during our reasoning and inferencing, e.g., they do not exist beforehand. We defined **class instances** for each terrain class.

The dynamic instances of a class are made for representing the features interpreted for a site. For example, when a new interpretation is a made of an alluvial fan landform, then that landform is made to be an instance, designated as LF1, of the class of alluvial fan landforms. If a second alluvial fan landform is being recognized then it takes the designation LF2 and it is considered an instance of the same class. If a valley fill is recognized then it is designated as LF3, and it is considered a member of the class of valley fills. If a playa is recognized then it is designated as LF4, and it is considered a member of the class of playas.

Thus we consider:

- landform instances termed LF1, LF2, LF3, etc., belonging to the various classes of landforms (Figure 22 to Figure 33),
- topographic form instances such as TF1, TF2, TF3, etc. belonging to the topographic form class (Figure 27 to Figure 33),
- physiographic feature instances termed PF1, PF2, PF3, etc., belonging to the class of physiographic features (Figure 27 to Figure 33), and
- physiographic region instances such as PH1, PH2, PH3, etc. belonging to the physiographic class-concept (Figure 30 to Figure 33).

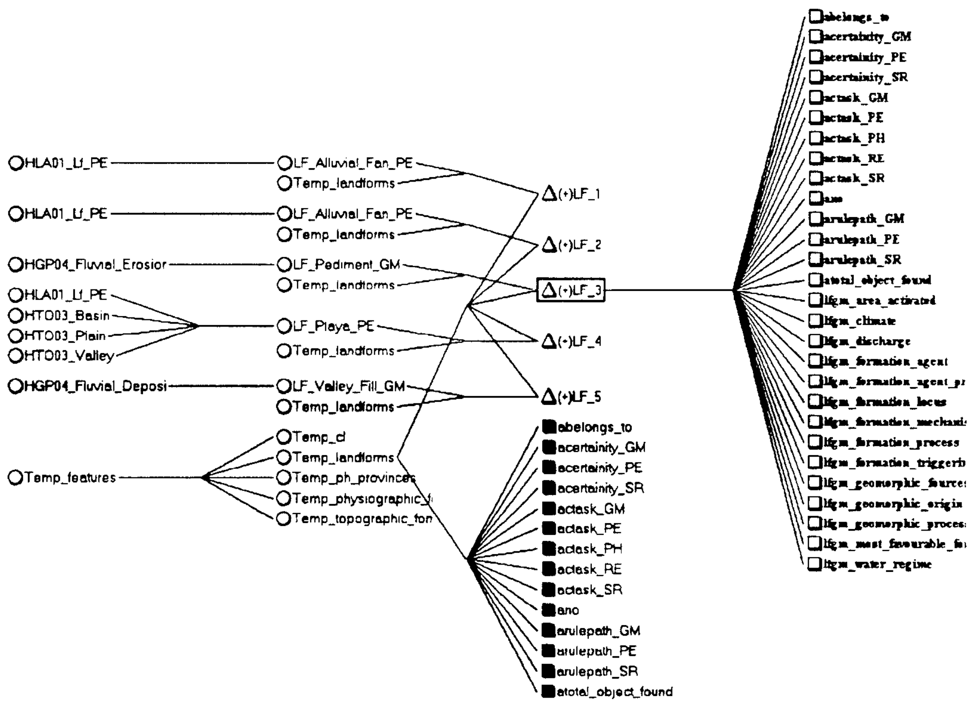



Figure 22. The identified landform instances LF_1 to LF_5 and their relationship to their parent landform classes. The instance LF_6 has not been as yet determined at this point of expert system consultation and thus it is not shown. It is also shown the property inheritance from the parent classes to the subclasses. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

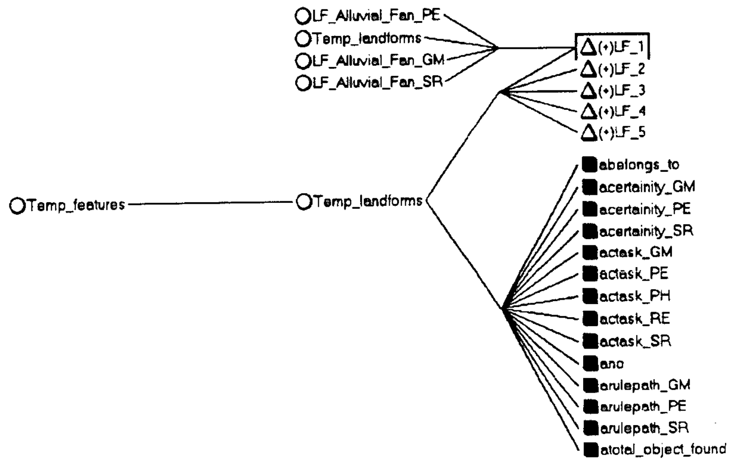



Figure 23. The landform instance LF_1 has further being refined from geomorphological pattern elements and regional pattern elements and thus it appears linked to the classes of Alluvial_Fan_GM (geomorphologic) and Alluvial_Fan_SR (regional). It should be noted that in Figure 22, instance LF_1 was determined only from pattern elements and thus it appeared linked only to the classes of Alluvial_Fan_PE. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

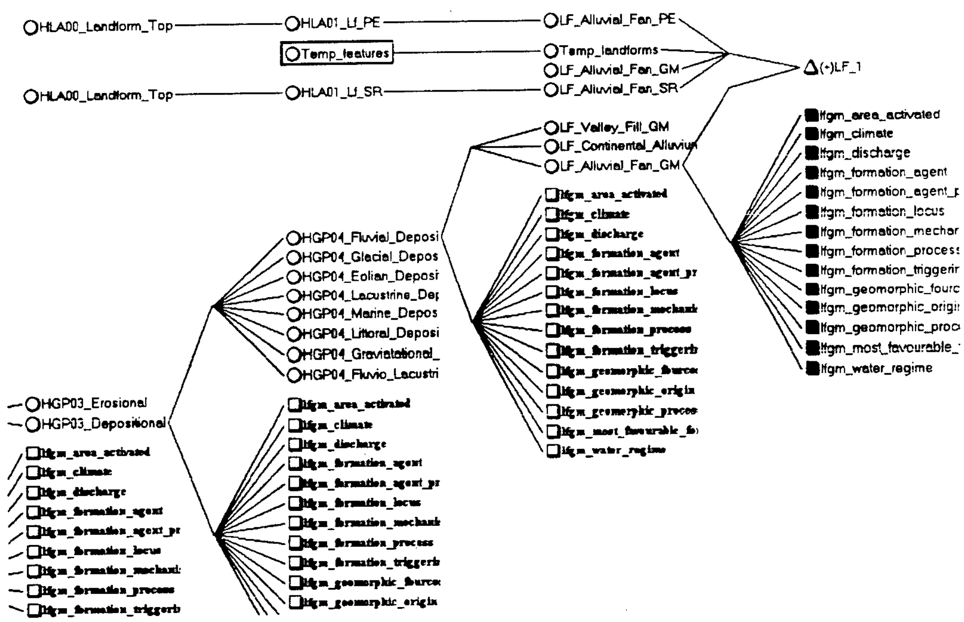



Figure 24. This hierarchy presents mainly the geomorphological parent classes of landform instance LF_1. Observe that landform LF_1 has been identified as being a kind of Depositional landform, more specifically a kind of Fluvial Depositional landform, and even more specifically it's geomorphology resembles the geomorphology of an alluvial fan (Alluvial_Fan_GM). It is also shown the property inheritance from the parent classes to the subclasses. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

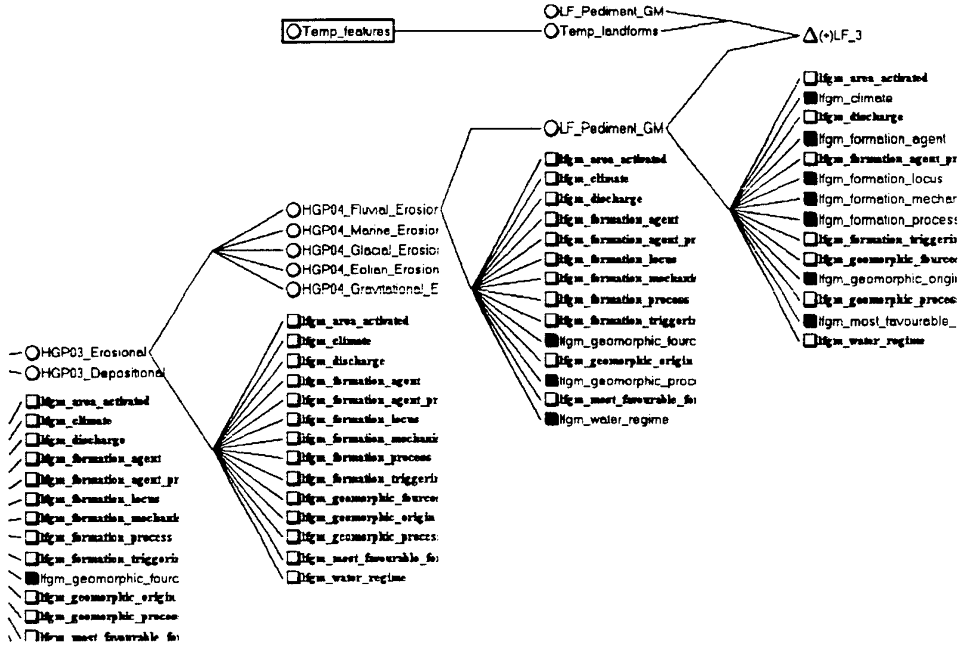



Figure 25. This hierarchy presents mainly the geomorphological parent classes of landform instance LF_3. Observe that landform LF_3 has been identified as being a kind of Erosional landform, more specifically a kind of Fluvial Erosional landform, and even more specifically it's geomorphology resembles the geomorphology of a pediment (Pediment_GM). It is also shown the property inheritance from the parent classes to the subclasses. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

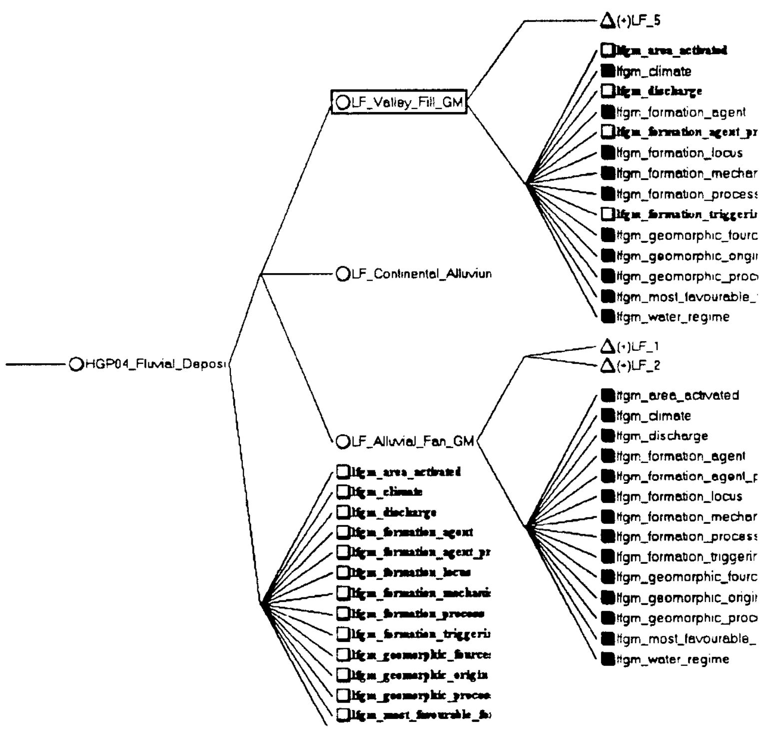



Figure 26. This hierarchy of geomorphologic classes shows that landform instances LF_5, LF_1 and LF_2 have been recognized to be kinds of Fluvial Depositional landforms. Furthermore, LF_5 was recognized as having the geomorphology of a valley fill and LF_1, LF_2 resembled the geomorphology of alluvial fans. It is also shown the property inheritance from the parent classes to the subclasses. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

### 2.3.4. Terrain Feature Class-subclass Hierarchies and Property Inheritance

Objects and subclasses can **obtain their properties dynamically** from a particular class through a mechanism called **inheritance**. Through the class-subclass or class-instance hierarchy these **properties are inherited down each hierarchy** so that to be shared by all the members and instances of each class.

Therefore, we organized the designed classes into **class-subclass hierarchies** thus creating the **class-subclass terrain organization** (Figure 10, Figure 11). Classes included sub-classes so that additional levels of detail were described only in the subclasses. Describing classes through subclasses gave access to a hierarchical representation of concepts and objects. Thus, for example, we defined for the class of topographic forms, the subclasses of piedmont plain and basin floor and for the class of landforms the subclasses of alluvial fan, playa, etc. These classes and subclasses are shown as little circles on the various plain of reasoning (Figure 10, Figure 11).

The major class-subclass relations in TAX-4-5 are:

- the class of landforms, with subclasses the alluvial fans, pediments, playas, valley fills, etc.
- the class of topographic forms with subclasses the piedmont plains, the basin floors, etc.,
- the class of physiographic features with subclasses the bolson semibolson, etc., and
- the class of physiographic regions with subclasses the Basin and Range Province, and its maturity and youthful stages.

The above class-subclass relations and property inheritance are shown on the four plains of Figure 11, on the object network displays of Nexpert Object (Figure 12 to Figure 17) and in the TAX-4-5 program segments (Table 6 to Table 15).

### 2.3.5. Terrain Feature Whole-part Hierarchies

Objects can include sub-objects if additional levels of detail are needed to define unique characteristics. We have defined an object-subobject or whole-part hierarchy thus defining the **whole-part terrain organization** (Figure 11).

In particular, we partition (Figure 27 to Figure 33):

- a physiographic region (being a province or section) to its component physiographic features,
- a physiographic feature to its component topographic forms, and
- a topographic form to its component landforms.

Each landform belongs to a specific topographic form which in our case could be either a **piedmont slope** (alluvial fan, bahada, pediment) or a **basin floor** (playa, valley fill). The Piedmont slope and basin floor belong to an Intermontane Basin of bolson or semibolson type. The Intermontane Basin belongs to a Physiographic context of Basin and Range type and more specifically on one that is either at the Youthful (Great Basin) or at the mature erosion stage (Sonoran Desert).

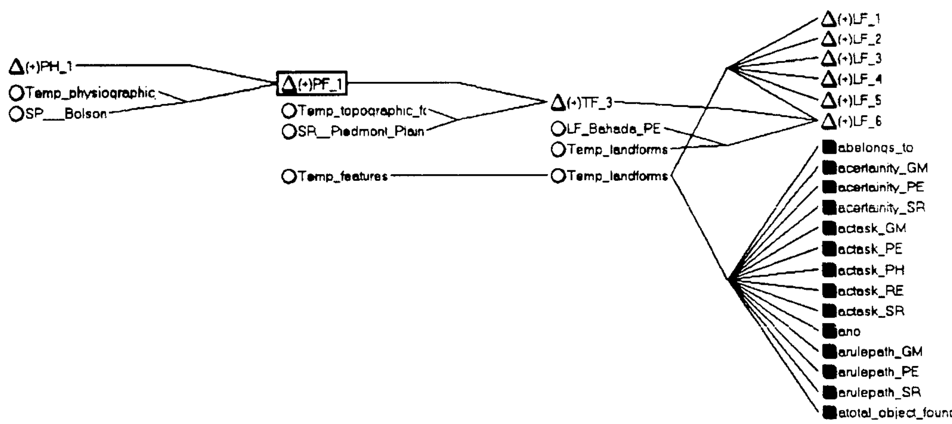



Figure 27. Landform instance LF_6 has been identified as Bahada from Pattern Elements and therefore it is linked to the class LF_Bahada_PE. LF_6 has been recognized and assigned as a part of the topographic form TF_3. TF_3 has been identified as a piedmont plain, and therefore it is linked to the class SR_Piedmont_Plain. TF_3 is a part of the physiographic feature PF_1. PF_1 has been identified as an Intermontane Basin of Bolson type. PF_1 has been recognized and assigned as a part of the physiographic province instance PH_1 which is a kind of Basin and Range physiographic region. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

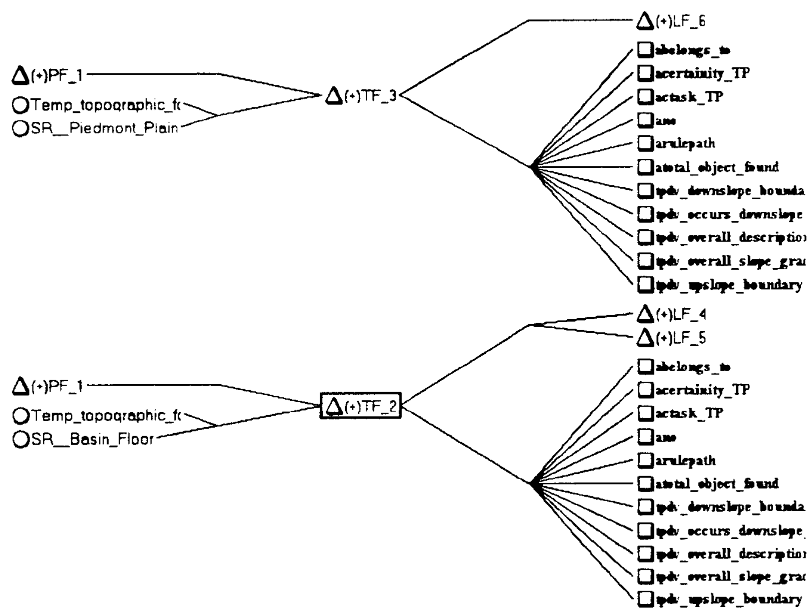



Figure 28. Landform instance LF_6 has been recognized and has been assigned as a part of the topographic form instance TF_3 which is a kind of piedmont plain and landform instances LF_4, and LF_5 have been recognized and have been assigned as parts of the topographic form instance TF_2 which is a kind of basin floor. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

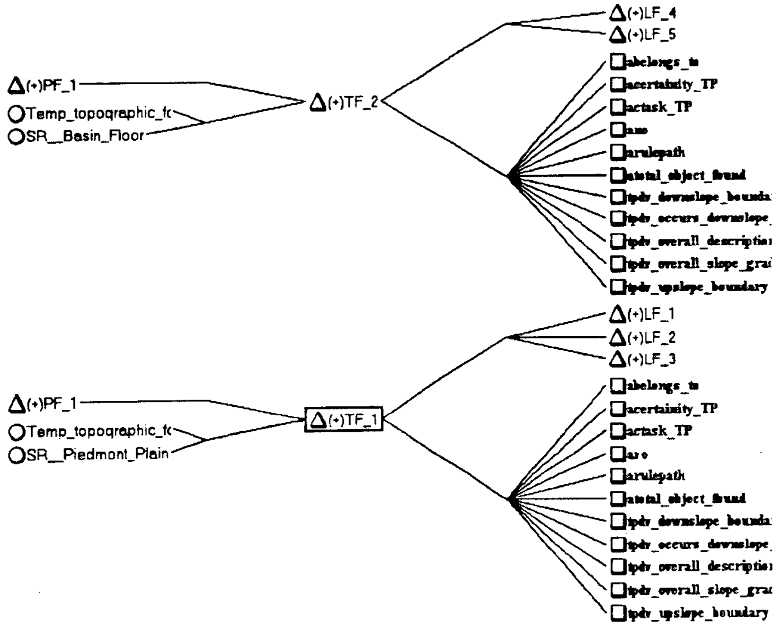



Figure 29. Landform instances LF_1, LF_2, LF_3 have been recognized and assigned as parts of the topographic form instance TF_1 which has been interpreted as being a kind of piedmont plain and landform instances LF_4 and LF_5 have been recognized and have been assigned as parts of the topographic form instance TF_2 which has been interpreted as being a kind of basin floor. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

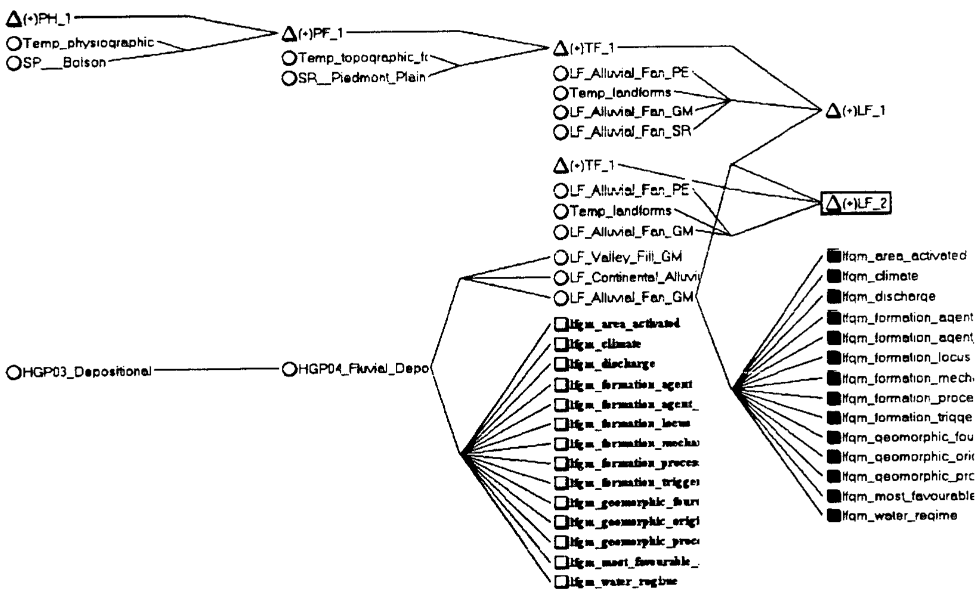



Figure 30. Landform instances LF_1 and LF_2 are kinds of alluvial fan, and as such they are shown to be kinds of fluvial deposition landforms. It is also shown the part-of hierarchy assigning landform instance LF_1 to topographic form instance TF_1, topographic form instance TF_1 to physiographic feature instance PF_1, and physiographic feature instance PF_1 to Physiographic region instance PH_1. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

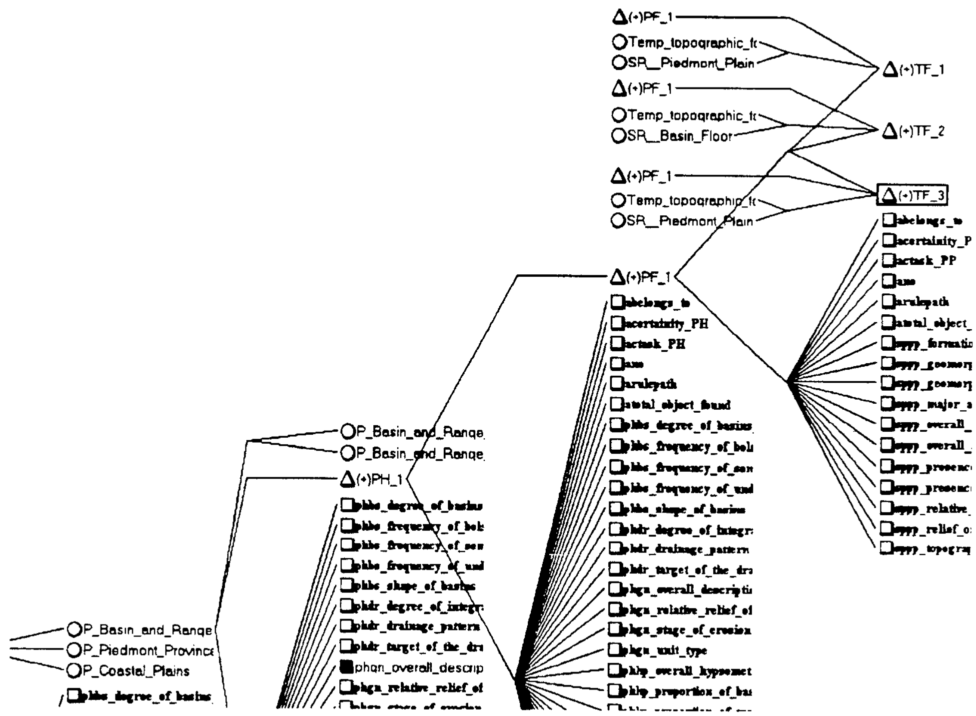



Figure 31. This hierarchy shows identified part-of relationships between the topographic form instances TF_1, TF_2, and TF_3 to the physiographic feature instance PF_1 and the part-of relationship of instance PF_1 to the physiographic region instance PH_1. At the very left of the tree we see that the physiographic region instance PH_1 is a kind of the Basin and Range physiographic province. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

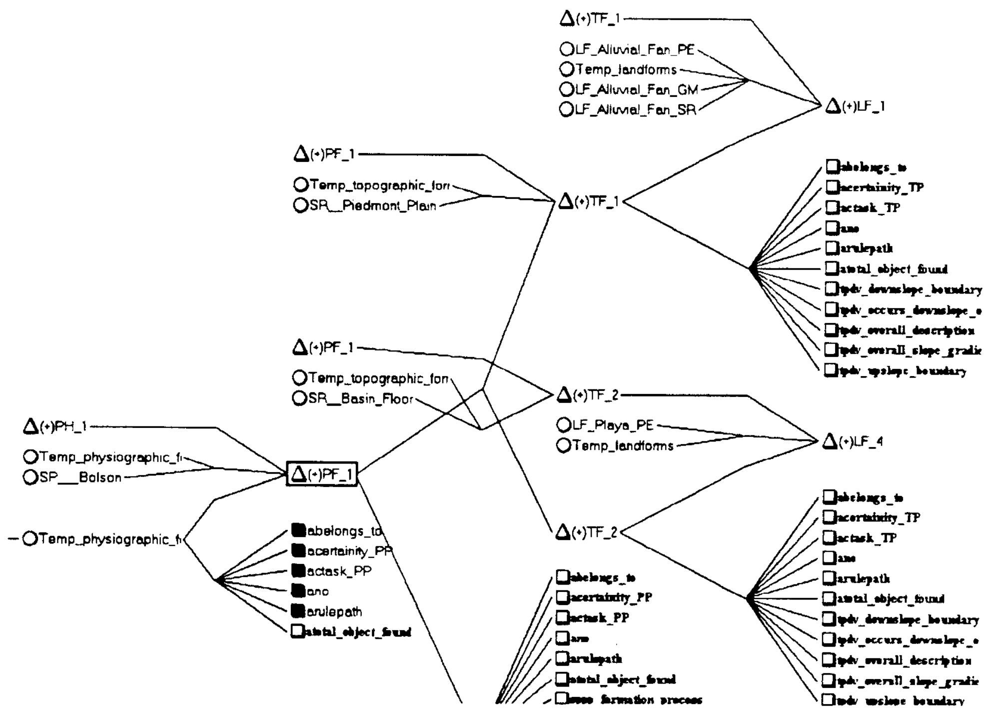



Figure 32. This diagram shows identified part-of relationships, e.g., landform instance LF_1 is part of topographic form instance TF_1. Landform instance LF_4 is part of topographic form instance TF_2. Topographic form instances TF_1 and TF_2 are parts of physiographic feature instance PF_1, and physiographic feature instance PF_1 is part of physiographic region instance PH_1. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

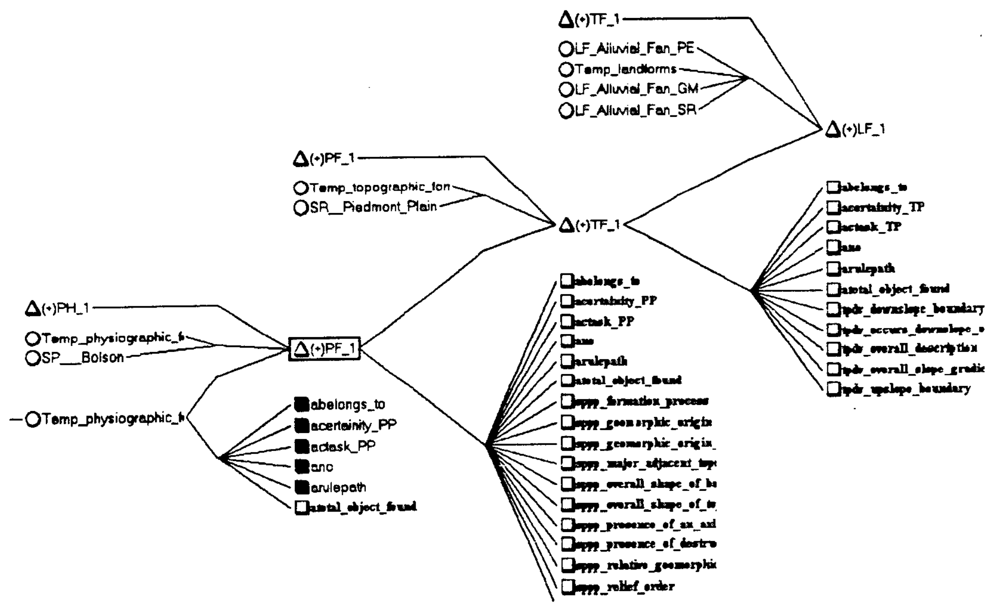



Figure 33. This diagram shows that landform instance LF_1 is part of topographic form instance TF_1. Topographic form instance TF_1 is part of physiographic feature instance PF_1. Physiographic feature instance PF_1 is part of physiographic region instance PH_1. The kind-of (class-subclass) relationships of each instance are also shown. See also Figure 7, Figure 8, Figure 9, Table 5, and Appendixes 1-4.

## 2.4. Inferential and Strategic Terrain Knowledge Representation

Having defined in the earlier section the classes, subclasses, objects, component objects, and instances of our terrain features (physiographic regions, topographic forms, physiographic features, and landforms) we can use them to describe the strategic and inferential knowledge to be used for reasoning and problem solving.

We have developed a **rule-based model** for the representation of strategic and inferential domain knowledge.

Inferential and strategic knowledge representation will address evidence accumulation, hypotheses formulation, and rule structuring needed for the three general **interpretation contexts** we have developed:

1. Landform context (1,2),
2. Physiographic context (3,4,5,6,7,8), and
3. Spatial context (9,10,11).

The three general interpretation contexts are further subdivided into the following **eleven problem solving interpretation scenaria** based on the earlier developed identification stage:

1. Extended Landform-Pattern Element Reasoning (Rules which pertain to the interpretation of landforms from an extended set of pattern elements.) (Plain A)
2. Landform-Geomorphic Indicator Reasoning (Landform-Geomorphic Indicator Reasoning: Rules which pertain to the interpretation of landforms from their geomorphologic indicators) (Plain A)
3. Topographic Form Reasoning (Inference of a topographic form from its own set of indicators) (Plain B)
4. Physiographic Feature Reasoning (Inference of a physiographic feature by its own indicators) (Plain C)
5. Physiographic Region Reasoning (Inference of the physiographic region (province, section) of a site by using physiographic site indicators) (Plain D)
6. Landform-To-Topographic Form Reasoning (E)
7. Topographic Form-To-Physiographic Feature Reasoning (F)
8. Physiographic Feature-To-Physiographic Region Reasoning (G)

9. Landform Spatial Context: landform identification by spatial association (H)
10.Landform Spatial Context: landform identification verification by spatial association (I)
11.Landform Spatial Context: Landform Hypotheses-Formulation by Spatial Association (J)

The first **five problem solving interpretation scenaria** (1 to 5) are taking place on the four horizontal plains A-D of Figure 11 and they are concerned with the identification of an instance of each of the earlier defined classes from its own indicators (physiographic regions, topographic forms, physiographic features, and landforms). These plains also indicate the **class-subclass** or **class-instance organization** of the terrain objects.

The next **three** problem solving interpretation scenaria (6 to 8) are taking place on the vertical direction E-F-G in Figure 11. They indicate the **whole-part organization** of terrain related objects and they are concerned with the evaluation of:

- a higher-level object of the whole-part hierarchy based on the existence of one or more lower level-object, or

- a lower level object of the whole-part hierarchy based on the existence of a higher level-object.

It concerns, in particular, the reasoning across the whole-part hierarchy (E to G). It takes place by using rules relating each physiographic region to its component physiographic features, each physiographic feature to its component topographic forms, and each topographic form to its component landforms.

The last **three** problem solving interpretation scenaria (9,10,11) are shown in Figure 34 and Figure 35 as H, I and J. They indicate the **landform spatial knowledge** which was conceptualized to be composed of three distinct aspects (Figure 4):

(H) landform identification by spatial association, implying that a landform LF_i can be identified by its own spatial indicators, e.g., by its position in the landscape and its spatial relations with key terrain features,

(I) landform verification by spatial association, implying that after the user has identified two landforms LF_i and LF_j, the system will prompt for verification of their spatial relation, and

(J) landform hypotheses-formulation by spatial association, implying that after the user has identified one landform LF_i, additional landform candidate hypotheses (LF_j) for the sites adjacent to a previously identified landform would be suggested for further investigation.

All classes of reasoning described briefly above are further explained in the following sections.

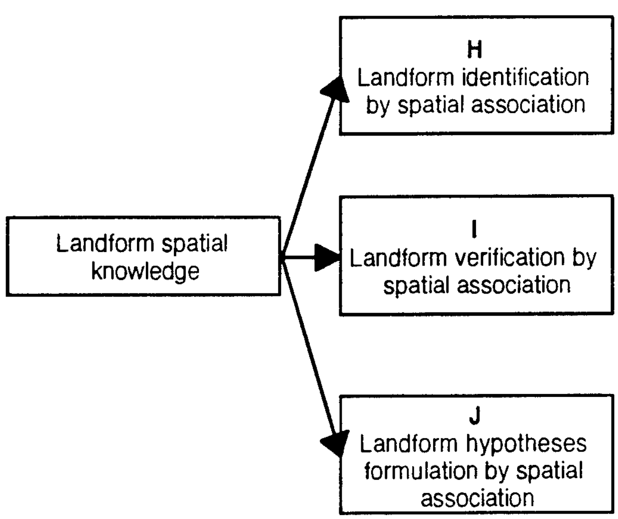



Figure 34. Landform spatial knowledge has at least three alternative meanings (H, I, J). See also Figure 35.

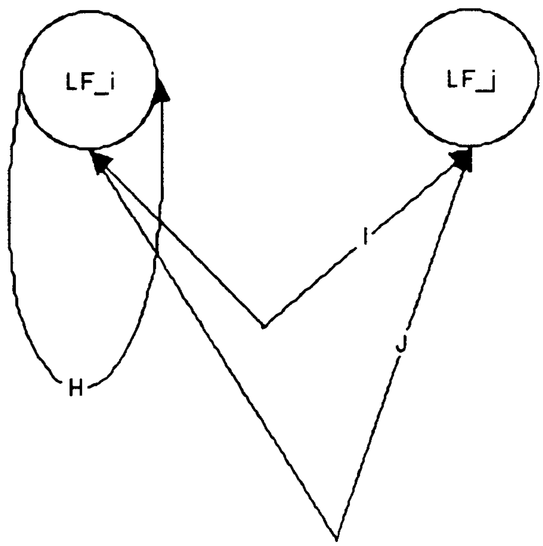



Figure 35. The strategic landform spatial knowledge was conceptualized to be composed of three distinct aspects: (H) landform identification by spatial association, implies that a landform LF_i can be identified by its spatial indicators, (I) landform verification by spatial association, implies that after the user has identified two landforms LF_i and LF_j, the system will prompt for verification of their spatial relation, and (J) landform hypotheses-formulation by spatial association, implies that after the user has identified one landform LF_i, it will suggest some additional landforms (LF_j) for further investigation.

### 2.4.1. Extended Landform-Pattern Element Reasoning

The Extended Landform-Pattern Element Reasoning includes rules which pertain to the interpretation of landforms from their pattern elements as these were developed in the section "Terrain Feature Properties (indicators)". This reasoning is taken place on the landform reasoning plain (Plain A, Figure 11). These rules may be activated in a **backward mode** when the user wishes to suggest a possible landform hypothesis to be investigated or in a **forward mode** when the user, having no idea about the presence of a certain landform hypothesis, wishes to be prompted and to provide pattern element values of a site which may eventually lead to a landform hypothesis. The landforms of the Basin and Range that are at present included in this conceptual scheme are: alluvial fan, bajada, pediment, playa, and valley fill. One of the partial rules that infers an alluvial fan is shown in Table 18. In contrast to the alluvial fan, Table 19 shows a partial rule for inferring a playa type of landform and Table 20 shows a partial rule for inferring a valley fill kind of landform.

Since it may be difficult for all users to answer the queries of complex landform identification rules, we have designed multiple rules for each landform, each having a **variable number of premises**. Thus the landform rules were ranked according to their difficulty and different weights were given to each rule to reflect the certainty of the outcome hypothesis for a given landform. Figure 36 shows a view of the rule network displaying one of the partial rules for the hypothesis of alluvial fan to have fired, while another rule has failed. Figure 37 shows that the Hypothesis of Alluvial Fan from Pattern Elements is consisting of three partial rules (ALFAN_PE_1, ALFAN_PE_2, ALFAN_PE_3) and is referenced in many other rules.

Table 18. RULE ALFAN_PE_3: One of the multiple rules used for alluvial fan identification from the extended set of pattern elements.

**If** lfpe_drainage_pattern is precisely equal to "dichotomic"
  And lfpe_planimetric_2d_shape is precisely equal to "fan shaped"
  And lfpe_slope_average_gradient is precisely equal to "2 to 3 degrees", "gently sloping"
  And lfpe_slope_spatial_direction_of_average_change is precisely equal to "decreases downslope towards the outer fringle", "gradually flatten to the landform lower extremity"
  And lfpe_surface_curvature is precisely equal to "concave radially & convex transversely"
  And lfpe_surface_highest_point is precisely equal to "upslope near the apex", "upslope near the valley mouth"

And lfpe_surface_lowest_point is precisely equal to "downslope near the outer fringle"
And lfpe_size_surface_height is precisely equal to "low"
And lfpe_gullies_frequency is precisely equal to "none", "many longitutinal gullies", "typically gullies are not found outside the drainage patterns"
And lfpe_phototone is precisely equal to "light gray", "light to medium tones"
And lfpe_phototone_texture is precisely equal to "uniform", "interlaced"
And lfpe_vegetation_density is precisely equal to "sparse", "none"
And lfpe_vegetation_spatial_distribution is precisely equal to "readily development near the outer fringle and along drainage channels"
And lfpe_landuse_landcover_overall is precisely equal to "natural_cover", "barren", "cultivated in porous materials having ground water"
And lfpe_boundary_type is precisely equal to "distinct"
And lfpe_boundary_type_upslope is precisely equal to "a valley mouth and the mountain front"
**Then** LFHPE_Alluvial_Fan is confirmed.

Table 19. RULE PLAYA_PE_1: One of the multiple rules used for playa identification from the extended set of pattern elements.

**If** lfpe_drainage_pattern is precisely equal to "none"
And lfpe_planimetric_2d_shape is precisely equal to "variable","elongated along structural axis in tectonic basins"
And lfpe_surface_topographic_3d_shape is precisely equal to "plain"
And lfpe_slope_average_gradient is precisely equal to "0"
And lfpe_size_absolute_area is precisely equal to "varies from few sq.m to 9.000 sq.km"
And lfpe_microtopography is precisely equal to "humocky relief of 1 to 2 meters"
And lfpe_microscale_indicators is precisely equal to "desiccation cracks","polygon pans","beach ridges"
And lfpe_gullies_frequency is precisely equal to "none"
And lfpe_ridge_lines is precisely equal to "beach ridges"
And lfpe_phototone is precisely equal to "white","darker if covered by a shallow water sheet"
And lfpe_phototone_texture is precisely equal to "scrabbled"
And lfpe_phototone_uniformity is precisely equal to "gridded patterns if cultivated","uniform","irregular tones indicating alkali & moisture differences"
And lfpe_vegetation_density is precisely equal to "llitle","none","devoid vegetation cover"
And lfpe_vegetation_spatial_distribution is precisely equal to "a vegetation ring surrrounding landform"
And lfpe_vegetation_type is precisely equal to "shrubs,reeds,grasses"
And lfpe_landuse_landcover_overall is precisely equal to "barren","cultivated"
And lfpe_boundary_type is precisely equal to "occasionally fuzzy","occasionally distinct","a vegetation ring surrounding landform"
**Then** LFHPE_Playa is confirmed.

Table 20. RULE valley_fill_PE_1: One of the multiple rules used for valley fill identification from the extended set of pattern elements.

**If** lfpe_drainage_pattern is precisely equal to "parallel"
And lfpe_drainage_texture is precisely equal to "somewhat many inactive streams"
And lfpe_planimetric_2d_shape is precisely equal to "plain"
And lfpe_microtopography is precisely equal to " few rocks outcroping in the valley","inselbergs"
And lfpe_gullies_frequency is precisely equal to "none","typically none are found outside the braided drainage pattern"
And lfpe_slope_average_gradient is precisely equal to "gently sloping"
And lfpe_slope_spatial_direction_of_average_change is precisely equal to "gently sloping away from the highlands"
And lfpe_surface_topographic_3d_shape is precisely equal to "plain"
And lfpe_boundary_type is precisely equal to "gradual fuzzy"
And lfpe_phototone is precisely equal to "light gray","medium to very light gray"
And lfpe_phototone_texture is precisely equal to "uniform","uniform with numerous black dots (vegetation) following the drainage pattern"
And lfpe_vegetation_density is precisely equal to "sparse"
And lfpe_vegetation_spatial_distribution is precisely equal to "uniform"
And lfpe_vegetation_type is precisely equal to "shrubs,reeds,grasses","none","cultivated"
And lfpe_landuse_landcover_overall is precisely equal to "natural_cover","cultivated"
**Then** LFHPE_Valley_Fill is confirmed.

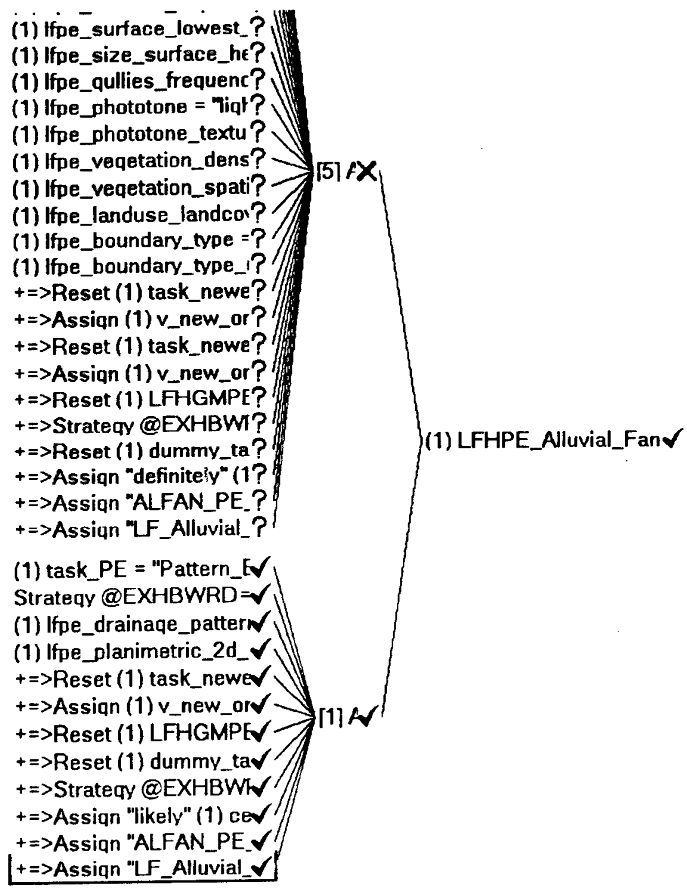



Figure 36. Rule network created during the consulatation of TAX-4-5 showing one of the partial rules for the hypothesis of alluvial fan that has fired, while another rule has failed.

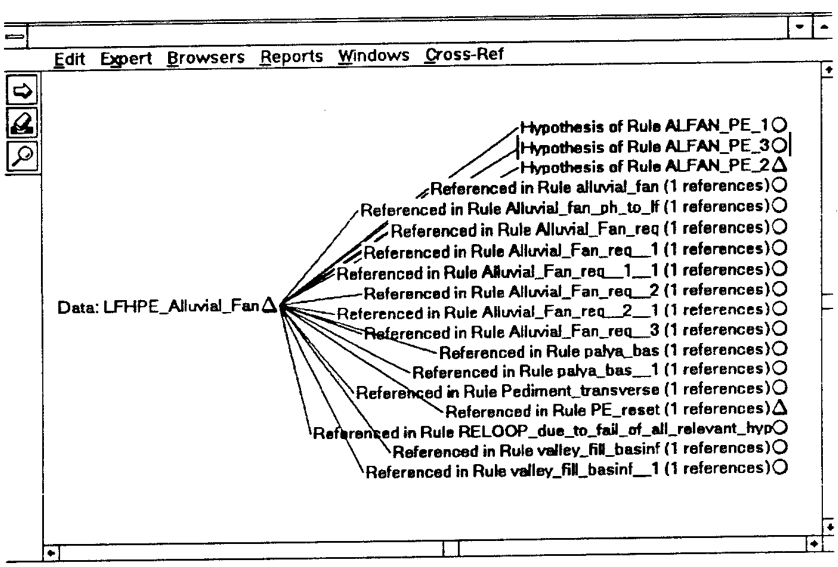



Figure 37. We see that the Hypothesis of Alluvial Fan (identified from Pattern Elements) is consisting of three partial rules (ALFAN_PE_1, ALFAN_PE_2, ALFAN_PE_3). It is also referenced into various others rules. For example: physiographic context identification from Landform, Suggestion of spatially associated landforms etc.

### 2.4.2. Landform-Geomorphic Indicator Reasoning

The Landform-Geomorphic Indicator Reasoning includes rules which pertain to the interpretation of landforms from their geomorphologic indicators as these were developed in the section "Terrain Feature Properties (indicators)". These rules may be activated in a backward mode when the user wishes to suggest a possible landform hypothesis to be investigated or in a forward mode when the user, having no idea about the presence of a certain landform geomorphic hypothesis, wishes to provide **geomorphic indicators** of a site which may eventually lead to a landform hypothesis. The Landform-Geomorphic Indicator Reasoning is implicitly embedded in plain A of Figure 11. Table 21 displays the alluvial fan rule based on geomorphologic indicators, Table 22 displays the pediment rule based on geomorphologic indicators, Table 23 displays the playa rule based on geomorphologic indicators, and ?Table 24 displays the valley fill rule based on geomorphologic indicators. Figure 38 shows the rule network displaying one of the partial rules which has fired for the hypothesis of alluvial fan based on geomorphic indicators.

Table 21. RULE Alluvial_Fan_from_GM: One of the multiple rules used for alluvial fan identification from geomorphologic indicators

**If** lfgm_climate is precisely equal to "arid", "semi-arid"
  And lfgm_geomorphic_forces is precisely equal to "exogenic"
  And lfgm_geomorphic_origin is precisely equal to "sequential"
  And lfgm_geomorphic_process is precisely equal to "deposition"
  And lfgm_formation_process is precisely equal to "fluvial deposition"
  And lfgm_formation_agent is precisely equal to "loaded stream"
  And lfgm_formation_agent_process is precisely equal to "braided stream"
  And lfgm_most_favourable_forming_geographic_conditions is precisely equal to "semiarid regions with elongate mountain ranges subject to episodic heavy precipitation"
  And lfgm_formation_triggering_process is precisely equal to "heavy rain", "snow melt"
  And lfgm_formation_mechanism is precisely equal to "abrupt change of stream velocity & gradient"
  And lfgm_formation_locus is precisely equal to "at the emergence of a steep valley into a relatively flat surface"
  And lfgm_water_regime is precisely equal to "ephemeral", "intermittient"
  And lfgm_discharge is precisely equal to "flashy"
  And lfgm_area_activated is precisely equal to "10 to 50%"
**Then** LFHGM_Alluvial_Fan is confirmed.

Table 22. RULE Pediment_from_GM: One of the multiple rules used for pediment identification from geomorphologic indicators

**If** lfgm_climate is precisely equal to "arid","semi-arid"
  And lfgm_geomorphic_fources is precisely equal to "exogenic"
  And lfgm_geomorphic_origin is precisely equal to "sequential"
  And lfgm_geomorphic_process is precisely equal to "erosion"
  And lfgm_formation_process is precisely equal to "fluvial erosion"
  And lfgm_formation_agent is precisely equal to "sheetfloods","lateral erosion by streams"
  And lfgm_most_favourable_forming_geographic_conditions is precisely equal to "arid regions with gently sloping plains surronding the montain ranges"
  And lfgm_formation_mechanism is precisely equal to "erosional flow"
  And lfgm_formation_locus is precisely equal to "gently sloping plain in piedmont plains"
  And lfgm_water_regime is precisely equal to "ephemeral"
**Then** LFHGM_Pediment is confirmed.

Table 23. RULE Playa_from_GM: One of the multiple rules used for playa identification from geomorphologic indicators

**If** lfgm_climate is precisely equal to "arid","semi-arid"
  And lfgm_geomorphic_fources is precisely equal to "exogenic"
  And lfgm_geomorphic_origin is precisely equal to "sequential"
  And lfgm_geomorphic_process is precisely equal to "deposition"
  And lfgm_formation_process is precisely equal to "fluviolacustrine deposition"
  And lfgm_formation_agent is precisely equal to "runoff accumulation,subsurface seepage water,wind"
  And lfgm_most_favourable_forming_geographic_conditions is precisely equal to "closed depression in arid regions and episodic flows"
  And lfgm_formation_mechanism is precisely equal to "episodic_flows_in_closed_drainage_basin"
  And lfgm_formation_locus is precisely equal to "internal_basin","closed_depression","tectonic_lowland","baselevel_plains"
  And lfgm_water_regime is precisely equal to "ephemeral"
**Then** LFHGM_Playa is confirmed.

Table 24. RULE Valley_Fill_from_GM: One of the multiple rules used for valley fill identification from geomorphologic indicators

**If** lfgm_climate is precisely equal to "arid","semi-arid"
And lfgm_geomorphic_fources is precisely equal to "exogenic"
And lfgm_geomorphic_origin is precisely equal to "sequential"
And lfgm_geomorphic_process is precisely equal to "deposition"
And lfgm_formation_process is precisely equal to "fluvial deposition"
And lfgm_formation_agent is precisely equal to "loaded streams"
And lfgm_most_favourable_forming_geographic_conditions is precisely equal to "closed basins in which loaded streams end during severe storms"
And lfgm_formation_mechanism is precisely equal to "streams_deposition_of_vast_amounts_of_alluvial_deposits_during_episodic_flows"
And lfgm_formation_locus is precisely equal to "flat valley bottoms"
And lfgm_water_regime is precisely equal to "ephemeral"
**Then** LFHGM_Valley_Fill is confirmed.

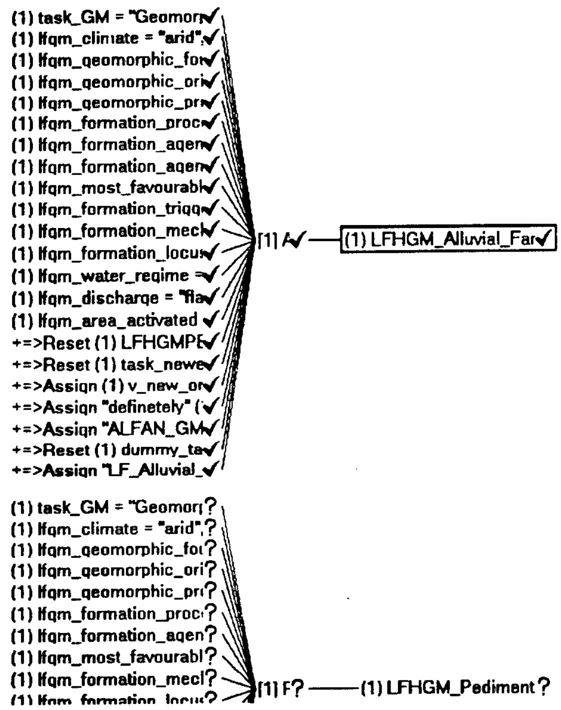



Figure 38. Rule network created during the consulatation of TAX-4-5 showing one of the partial rules for the hypothesis of alluvial fan based on geomorphic indicators that has fired.

### 2.4.3. Topographic Form Reasoning

Regarding the topographic form reasoning (plain B in Figure 11), rules were developed which pertain to the interpretation of topographic forms (piedmont plains and basin floors) from the topographic form indicators as these were developed in the section "Terrain Feature Properties (indicators)".. Two rules follow that infer the piedmont plain and basin floor (Table 25, Table 26). Figure 39 displays the rule network displaying one of the rules for establishing a topographic form.

Table 25. RULE D_piedmont_plain: One of the multiple rules used for piedmont plain identification from its own indicators

**If** tpdvl_occurs_downslope_of is precisely equal to "mountain front", "mountain range", "mountain belt"
And tpdvl_overall_slope_gradient is precisely equal to "gentle"
And tpdvl_upslope_boundary is precisely equal to "abrupt change of slope", "piedmont junction angle"
And tpdvl_downslope_boundary is precisely equal to "a plain"
And tpdvl_overall_description is precisely equal to "sloping land from the bounding mountain front to level basin lowland"
**Then** swTopographic_Form is confirmed.
And "Piedmont Plain" is assigned to what_is_the_Topographic_Form

Table 26. RULE D_Basin_Floor: One of the multiple rules used for basin floor identification from its own indicators

| | |
|---|---|
| **If** | tpdvl_occurs_downslope_of is precisely equal to "a gently sloping plain" |
| | And tpdvl_overall_slope_gradient is precisely equal to "flat" |
| | And tpdvl_upslope_boundary is precisely equal to "piedmont plain" |
| | And tpdvl_downslope_boundary is precisely equal to "at the lowest relative elevation" |
| | And tpdvl_overall_description is precisely equal to "a large area of nearly level land" |
| **Then** | swTopographic_Form is confirmed. |
| | And "Basin Floor" is assigned to what_is_the_Topographic_Form |

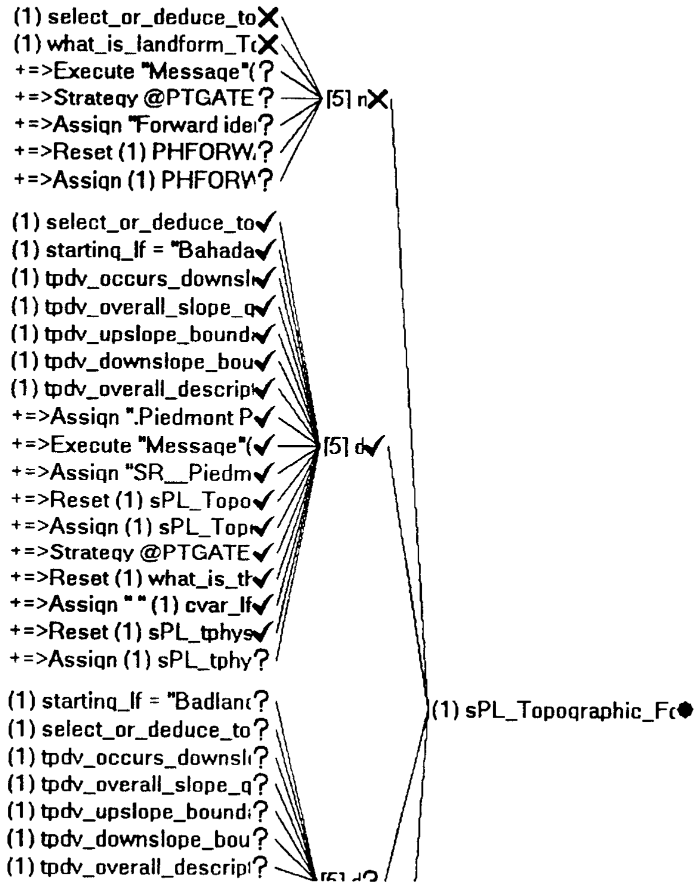


Figure 39. Rule network created during the consulatation of TAX-4-5 showing one of the multiple rules for establishing a topographic form.

### 2.4.4. Physiographic Feature Reasoning

For the physiographic feature reasoning (C in Figure 11), rules were developed which pertain to the interpretation of physiographic features (intermontane basins, bolsons and semibolsons) from their physiographic feature indicators as these were developed in the section "Terrain Feature Properties (indicators)".

This module of physiographic feature rules, first attempts to establish the hypotheses of a physiographic feature, such as an intermontane basin, a highland, etc., and then it attempts to refine this hypothesis to one of its kinds, such as bolson, or semi-bolson. Table 27 shows the rule used for establishing an intermontane basin.

Table 27. RULE D_Intermontane_basins_physiographic_feature: One of the multiple rules used for intermontane basin identification from its own indicators

| | |
|---|---|
| **If** | sppl_overall_shape_of_topographic_form is precisely equal to "depression" |
| | And sppl_geomorphic_origin is precisely equal to "structural" |

And sppl_relative_geomorphic_size is precisely equal to "gross topographic form", "broad depression", "much wider than erosional stream valleys"
And sppl_relief_order is precisely equal to "second"
And sppl_formation_process is precisely equal to "alluvial filling"
And sppl_major_adjacent_topographic_feature is precisely equal to "surrounded by mountains/mountain ranges"
And sppl_geomorhpic_origin_of_the_erosion_products is precisely equal to "surrounded mountains"
**Then** swPhysiographic_xparts is confirmed.
And "Intermontane Basin" is assigned to what2_is_the_major_physiographic_part

Assuming that an intermontane basin has been established, the user is prompted to either specify or deduce the physiographic feature subclass of an intermontane basin. If the user can suggest a physiographic feature subclass the proper rules will determine if the given physiographic feature is appropriate for the Intermontane basin. For the case of the intermontane basin it should be specified if it is either a bolson (a topographically closed basin of internal drainage leading usually to a playa) or a semi-bolson (having an axial stream across its floor).

If the user can not suggest a physiographic feature subclass and instead the user wishes to infer by deduction the type of physiographic feature subclass then the proper rules of bolson and semibolson are called to query the user and to perform the sought inference (Plain C in Figure 11). Two rules that infer the bolson and semibolson are indicated in Table 28 and Table **29**. Figure 40 shows the rule network structure displaying one of the physiographic rules that has fired.

Table 28. RULE D_Bolson: One of the multiple rules used for bolson identification from its own indicators

**If** phbll_presence_of_an_axial_stream is precisely equal to "none"
And phbll_overall_shape_of_basin is precisely equal to "concave", "flat"
And phbll_drainage_pattern is precisely equal to "centripetal"
And phbll_presence_of_destructive_erosion is precisely equal to "no"
And phbll_possibility_of_external_drainage is precisely equal to "no"
**Then** swPhysiographic_xparts_bolson_semibolson is confirmed.
And "Bolson" is assigned to what_is_the_type_of_Intermontane_basin

Table 29. RULE D_Semi_bolson: One of the multiple rules used for semibolson identification from its own indicators

**If** phbll_presence_of_an_axial_stream is precisely equal to "yes"
And phbll_overall_shape_of_basin is precisely equal to "flat"
And phbll_presence_of_destructive_erosion is precisely equal to "yes"
And phbll_topographic_possibility_of_external_drainage is precisely equal to "yes"
**Then** swPhysiographic_xparts_bolson_semibolson is confirmed.
And "SemiBolson" is assigned to what_is_the_type_of_Intermontane_basin

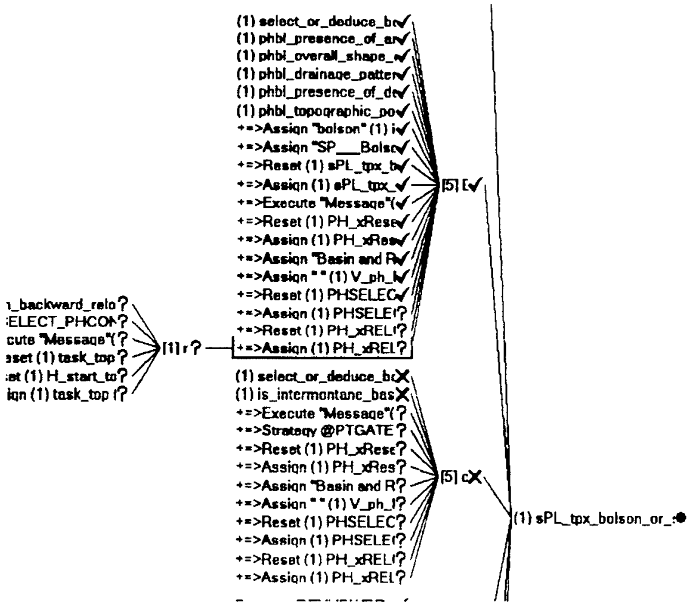



Figure 40. Rule network structure displaying one of the physiographic feature rules that has fired and another that has failed.

### 2.4.5. Physiographic Region Reasoning (Provinces and Sections)

The Physiographic Region Reasoning (Provinces and Sections) is shown in plain D of Figure 11. Rules were developed which pertain to the interpretation of physiographic regions (provinces and sections) from their physiographic indicators as these were developed in the section "Terrain Feature Properties (indicators)". It should be emphasized that the approach developed aims at inferring the **geomorphologic concept** hidden behind a province or a section so that the methodology is applicable to all basin and range landscapes of the world, not only to the USA Basin and Range Province. Thus the present approach is expected to be easily extended to all relevant physiographic regions. Figure 41 portrays a Landsat image segment containing the Death Valley and surrounding mountain ranges which compose a significant physiographic feature (part) of the Basin and Range Province.

Since it may be difficult for the users to answer all the queries of complex physiographic rules, we have designed **multiple rules** for each physiographic region, each having a variable number of premises. Thus the physiographic region rules were ranked according to their difficulty and different weights were given to each rule to reflect the certainty of the outcome hypothesis for a given physiographic region. The following three tables (Table 30, Table 31, Table 32) list three **alternative rules** for the Hypothesis of Basin and Range Concept containing progressively increased number of evidences (indicators). It is observed that the three rules result in different **certainties** in support of the Basin and Range Hypothesis. The rule with the highest number of fulfilled premises results in the highest certainty for this hypothesis.

Besides the rules for inferring a physiographic concept at the level of a province, rules were developed, following a method of **conceptual refinement**, which refined the concept of the province to that of a physiographic section (concept) of that province. In the case of the Basin and Range concept, the refinement rules inferred the concept of a youthful or mature erosion stage which corresponded to the USA Great Basin and Sonoran Desert sections. Both of the rules follow (Table 33, Table 34). A segment of the Rule network created during the consultation of TAX-4-5 showing alternative rules leading to the hypothesis of Basin and Range Concept is displayed in Figure 42.

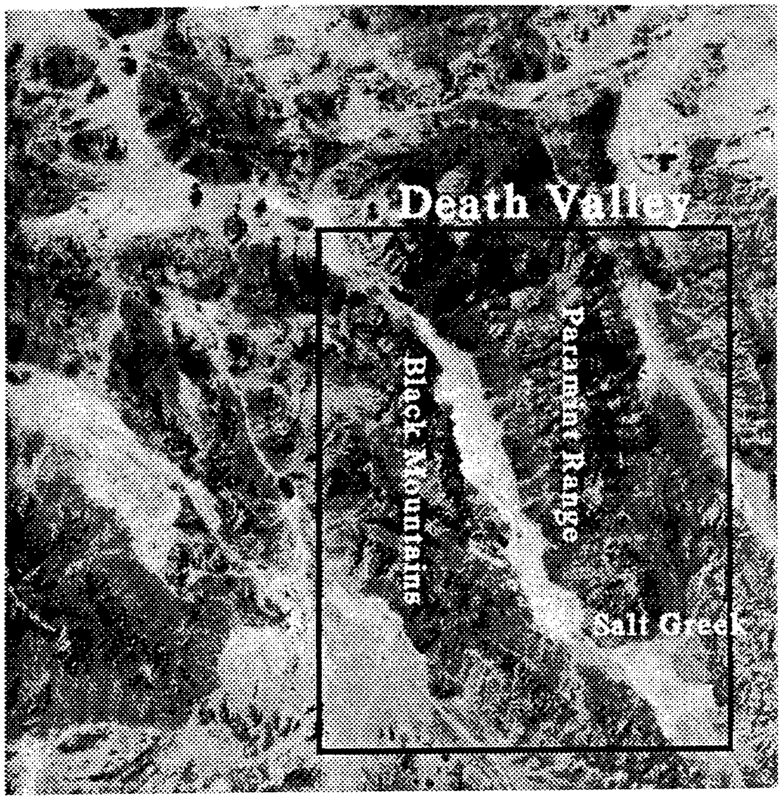



Figure 41. The Death Valley and surrounding mountain ranges compose a significant physiographic feature (part) of the Basin and Range Province.

Table 30. Basin-and_Range_partial_rule_1: One of the multiple rules used for the Basin and Range Concept identification from its own indicators (low certainty).

| | |
|---|---|
| **IF** | |
| frequency_of_mountain_ranges is | "high" |
| presence_of_desert_basins is | "high" |
| overall_description is | "basin ranges intervening desert planes" |
| **Then** HYPOTHESIS Basin_and_Range is true with certainty=low | |

Table 31. Basin-and_Range_partial_rule_2: One of the multiple rules used for the Basin and Range Concept identification from its own indicators (medium certainty).

| | |
|---|---|
| **IF** | |
| frequency_of_mountain_ranges | is "high" |
| presence_of_desert_basins | is "high" |
| shape_of_a_mountain_range | is "asymmetric" |
| relative_spatial_position_of_mountain_ranges | is "rather straight" |
| overall_direction_of_mountain_ranges | is "roughly parallel" |
| overall_description | is "basin ranges intervening desert planes" |
| **Then** HYPOTHESIS Basin_and_Range is true with certainty=medium | |

Table 32. RULE Ph_Basins_Range_all_rule: One of the multiple rules used for the Basin and Range Concept identification from its own indicators (definite certainty).

**If** phrg_frequency_of_mountain_ranges is precisely equal to "high"
And phrg_presence_of_desert_basins is precisely equal to "high"
And phrg_shape_of_a_mountain_range is precisely equal to "assymetric"
And phrg_relative_spatial_position_of_mountain_ranges is precisely equal to "rather straight"
And phrg_overall_direction_of_mountain_ranges is precisely equal to "roughly parallel"
And phgn_overall_description is precisely equal to "basin ranges intervening desert planes"
And phrg_height_variation_within_mountain_ranges is precisely equal to "little (no great & sudden)"
And phrg_shape_continuity_of_mountain_ranges is precisely equal to "rather great (fairly continous)"
And phrg_type_of_microrelief_dissection_in_mountain_ranges is precisely equal to "notched & segmented"
And phrg_geomorphic_origin_of_mountain_ranges is precisely equal to "tectonic (eroded tilted faulted blocks)"
And phrg_current_geomorphic_process_of_mountain_ranges is precisely equal to "erosion and deposition"
**Then** PH_Basin_and_Range is confirmed.
And "definetely" is assigned to certainty

Table 33. RULE Basin and Range_Maturity_Erosion_Stage: One of the multiple rules used for the Basin and Range Mature Erosion Concept identification from its own indicators (definite certainty).

**If** phgn_relative_relief_of_region is precisely equal to "low"
And phmt_relaltive_size_of_mountains is precisely equal to "small"
And phmt_slope_change_at_piedmont_angle is precisely equal to "not abrupt"
And phbs_shape_of_basins is precisely equal to "rather plain than concave"
And phhp_overall_hypsometric_distribution_within_the_section is precisely equal to "more than 1/2 of the surface is below 2000 ft"
And phhp_proportion_of_Mountain_Ranges_versus_Piedmont_Plains_versus_Basins is precisely equal to "20% : 40% : 40%"
And phrg_amount_of_observed_tectonic_evidences_in_mountain_ranges is precisely equal to "low (the minority has a fault origin)"
And phbs_degree_of_basins_integration is precisely equal to "high (dependence of drainage basins)"
And phgn_stage_of_erosion_cycle is precisely equal to "maturity (advanced,late)"
And phbs_frequency_of_bolsons is precisely equal to "low (less prelevant)"
And phbs_frequency_of_semi_bolsons is precisely equal to "high (more prelevant)"
And phdr_degree_of_integration_of_drainage_pattern is precisely equal to "high"
And phdr_outlet_of_the_drainage_network is precisely equal to "usually to another drainage basin"
**Then** PH_Basin_and_Range_refinement is confirmed.
And "definetely" is assigned to certainty

Table 34. RULE Basin_and_Range_Youthful_Erosion_Stage: One of the multiple rules used for the Basin and Range Youthful Erosion Concept identification from its own indicators (definite certainty).

**If** phgn_relative_relief_of_region is precisely equal to "high"
And phhp_proportion_of_Mountain_Ranges_versus_Piedmont_Plains_versus_Basins is precisely equal to "50% : 0% : 50%"
And phmt_relaltive_size_of_mountains is precisely equal to "large"
And phmt_slope_change_at_piedmont_angle is precisely equal to "rather abrupt"
And phmt_absolute_height_of_mountains is precisely equal to "3000-5000 ft above their base", "7000-10000 ft above sea level"
And phhp_overall_hypsometric_distribution_within_the_section is precisely equal to "more than 1/2 of the surface is 3000 ft above sea level"
And phdr_drainage_pattern is precisely equal to "centripetal", "internal"
And phdr_degree_of_integration_of_drainage_pattern is precisely equal to "low (independence of drainage basins)"
And phgn_stage_of_erosion_cycle is precisely equal to "youthful (beginning, moderate)"
And phrg_the_width_of_mountain_ranges is precisely equal to "6 to 15 miles commonly"
And phrg_the_length_of_mountain_ranges is precisely equal to "50 to 70 miles commonly"
And phrg_amount_of_observed_tectonic_evidences_in_mountain_ranges is precisely equal to "great (the majority has fault origin)"
And phbs_degree_of_basins_integration is precisely equal to "little (independence of drainage basins)"
And phbs_frequency_of_bolsons is precisely equal to "high (more prelevant)"
And phbs_frequency_of_semi_bolsons is precisely equal to "low (less prelevant)"
And phbs_shape_of_basins is precisely equal to "predominatly concave than plain"
And phbs_frequency_of_undrained_basins is precisely equal to "high"
And phdr_outlet_of_the_drainage_network is precisely equal to "playa", "sink"
**Then** PH_Basin_and_Range_refinement is confirmed.
And "definetely" is assigned to certainty

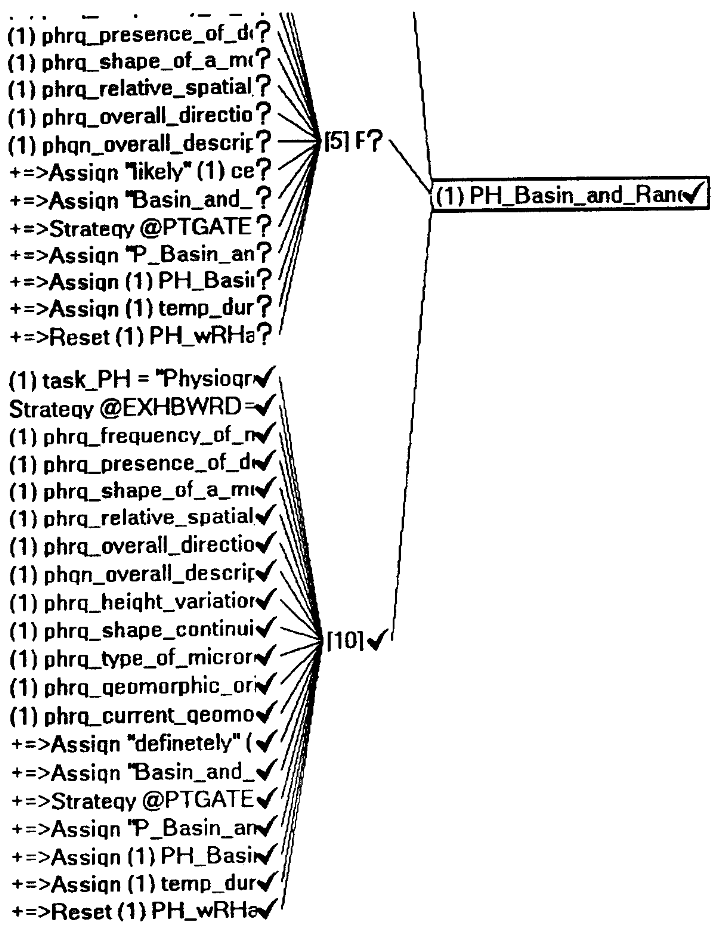



Figure 42. A segment of the rule network created during the consulatation of TAX-4-5 showing alternative rules leading to the hypothesis of Basin and Range Concept.

### 2.4.6. Landform-To-Topographic Form Reasoning

Landform to topographic form reasoning (E in Figure 11). Let's assume that a landform LF-i has been established and its type is known. The user is prompted now to either specify or deduce the topographic form to which the identified landform (LF-i) belongs to.

If the user can suggest a topographic form that contains the identified landform, then the landform to topographic form rules will determine if the given topographic form is appropriate for the interpreted landform. The following alternatives are stored in the knowledge base:

- Alluvial fan, bahada & pediment are landforms belonging to the topographic form of piedmont plain.
- Playa and valley fill belong to the topographic form of Basin Floor.

If the user can not suggest a topographic form that contains the identified landform, then no suggestion can be made for the physiographic context. The search in the whole-part hierarchy will be continued by looking to establish a physiographic context based on physiographic indicators alone by forward physiographic reasoning (with no use of topographic form and physiographic feature reasoning).

If the user wishes to infer the type of topographic form, then the rules of piedmont plain and basin floor, given in an earlier section, are called to query the user for the values of these topographic forms so that to perform the sought inference (Plain B in Figure 11).

### 2.4.7. Topographic Form-To-Physiographic Feature Reasoning

Topographic Form-To-Physiographic Feature Reasoning (F in Figure 11). Let's assume that a topographic form TF-i has been established and its type is known. The user is prompted now to either specify or deduce the Physiographic Feature to which the identified topographic form TF-i belongs to.

If the user can suggest a Physiographic Feature that contains the identified topographic form, then the Topographic Form-To-Physiographic Feature rules will determine if the given Physiographic Feature is appropriate for the interpreted topographic form. The following alternatives are stored in the knowledge base:

- Piedmont plain and Basin Floor are topographic forms of an intermontane basin.

If the user can not suggest a Physiographic Feature that contains the identified topographic form, then no suggestion can be made for the physiographic context. The search in the whole-part hierarchy will be continued by looking to establish a physiographic context based on physiographic indicators alone by forward physiographic reasoning (with no use of topographic forms and physiographic features reasoning).

If the user wishes to infer the type of Physiographic Feature then the rules of Piedmont plain and Basin Floor, given in an earlier section, are called to query the user for the values of these Physiographic Features so that to perform the sought inference (Plain C in Figure 11).

### 2.4.8. Physiographic Feature-To-Physiographic Region Reasoning

Physiographic Feature-To-Physiographic Region Reasoning (G in Figure 11). Lets assume that a physiographic feature PH_i has been established and its type was either bolson or a semibolson. The user is prompted now to either specify or deduce the Physiographic region concept to which the identified physiographic feature PH-i belongs to.

If the user can suggest a physiographic region that contains the identified physiographic feature, then the Physiographic Feature-To-Physiographic Region rules will determine if the given physiographic region is appropriate for the identified physiographic region.

If a bolson is selected then the most probable physiographic context is that of the Basin and Range (mountain ranges intervening desert plains). However, bolsons are most frequently evident in the youthful erosion stage. The most common characteristics of that stage are the equal amount between mountain ranges and basins, the independence of drainage basins, and the great amount of closed basins with playas and relict landforms. Alluvial fans are greater in size and more frequent in the youthful stage because there is a greater amount of mountains and greater catchment areas than in the maturity erosion stage. The physiographic context of Basin and Range will be suggested backwardly. The user is suggested to look rather for an instance of the youthful erosion stage.

If a semibolson is selected then the most probable physiographic context is that of Basin and Range. However, semibolsons are most frequently evident in a maturity erosion stage. The most common characteristics of that stage are the great amount of basins and pediments in comparison to mountain ranges, the dependence of drainage basins, and the great amount of opened basins. Alluvial fans, playas and relict landforms are less frequent in the maturity than in the youthful erosion stage. The physiographic context of Basin and Range will be suggested backwardly. The user is suggested to look rather for an instance of the maturity erosion stage.

### 2.4.9. Spatial Context: landform identification by spatial association

The **landform identification by spatial association** was developed in order to identify a landform by using its relevant spatial indicators (pattern elements). The spatial indicators are four types, each of them describing a specific kind of spatial associations (Figure 4):

- *Altitude associations*

  They express relationships of altitude between adjacent landforms, such as "higher than", or "downslope of".

- *Planimetric associations*

  They express relationships of adjacency between landforms having common border, being either side by side, or next to each other, or facing in the same direction, such as, occurs adjacent to, occurs adjacent to in a downslope direction, occurs adjacent to in upslope direction, occurs adjacent to in a direction transverse to slope

- *Enclosure Relationships*

  They express relationships like is-surrounded-by (enclosing on all sides) or occurs-around (on all sides) or occurs-within, contains, is contained in, etc.

- *Boundary Type Relationships*

  They determine the boundary sharpness type (distinct, fuzzy, occasionally fuzzy, occasionally distinct) and the kind (a vegetation ring, an outer fringe surrounding landform in the downslope direction), etc.

The set of spatial indicators currently used in the knowledge base was given in the section "Class and Object Property Definition" and in figures (Figure 18 to Figure 21).

For example, the rule for the identification of an alluvial fan by spatial association is listed in Table 35, while a rule network segment displaying the rules of alluvial fan and continental alluvium is shown in Figure 43.

Table 35. RULE ALFAN_SR: One of the multiple rules used for the alluvial fan identification from its spatial indicators

```
If lfsr_contained_in is precisely equal to "piedmont plains"
   And lfsr_occurs_at is precisely equal to "at the emergence of a steep valley to a relatively flat surface"
   And lfsr_occurs_in_front_of is precisely equal to "a valley mouth"
   And lfsr_occurs_adjacent_to is precisely equal to "pediment, bahada, valley fill, playa"
   And lfsr_downslope_boundary is precisely equal to "a fan shaped outline/vegetation fringe"
   And lfsr_contains_in is precisely equal to "boulders & cobbles near the apex"
Then LFHSR_Alluvial_Fan  is confirmed.
```

### 2.4.10. Spatial Context: landform verification by spatial association

The **landform identification-verification by spatial association** was developed so that to test if two or more landforms, identified by the pattern element approach, were satisfying the required regional spatial constraints as these are determined by geomorphologic and physiographic considerations (Figure 4). These constraints were specified according to the type of adjacency and the type of spatial direction. Figure 18 to Figure 21 described the possible acceptable spatial relationships evident between the various landforms occurring on the topographic forms of piedmont plain and basin floor of an Intermontane Basin of the Basin & Ranges Province. A typical rule that uses one of these relationships is listed in Table 36.

Table 36. RULE Allluvial_Fan_and_Pediment: One of the multiple rules used for the alluvial fan - pediment identification-verification by spatial association

```
If Initial_landform_1 is precisely equal to "Alluvial Fan"
   And Initial_landform_2 is precisely equal to "Pediment"
Then twwr__spatial_adjacency_of_two_lf   is confirmed.
   And Execute "Message"(@WAIT=TRUE;@STRING="@TEXT=The landforms given : @V(Initial_landform_1)
         and @V(Initial_landform_2) could be adjacent.,@OK";)
```

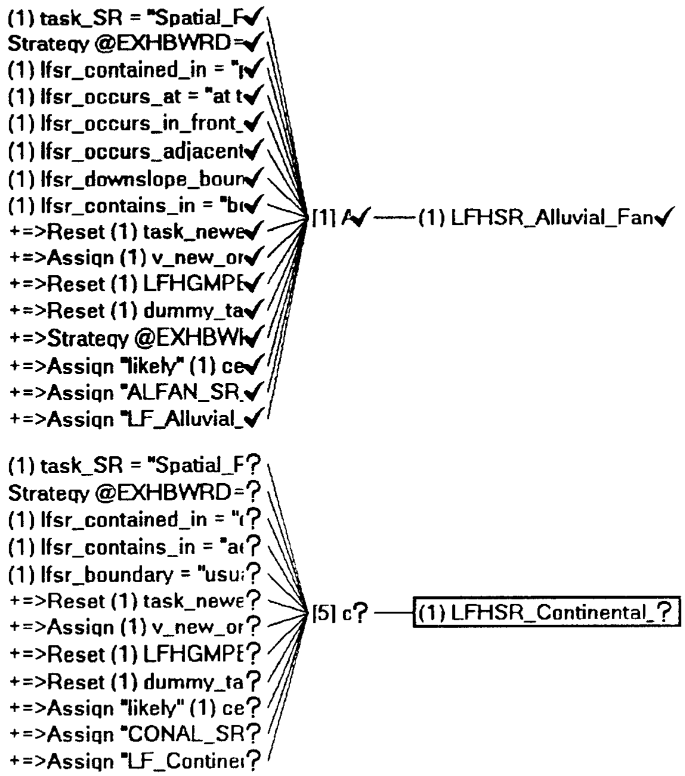



Figure 43. Rule network segment displaying the rules of alluvial fan and continental alluvium concerning landform identification by spatial association.

### 2.4.11. Spatial Context: Landform Hypotheses-Formulation by Spatial Association

The **landform hypotheses-formulation by spatial association**, was developed so that once a landform was identified by pattern elements, the landform spatial knowledge suggested a small set of candidate landform hypotheses to be investigated by the user as being the most promising neighboring landforms according to geomorphologic constraints. This candidate set included landforms which might be theoretically adjacent to the previously identified landform according to geomorphologic principles of form and process (Figure 4). The suggested landform hypotheses must be verified by performing backward reasoning on these landform hypotheses using the pattern element approach. When the photointerpretation session is completed, each identified site landform is provided with a set of spatial boundary relationships determining it's adjacent neighboring landforms.

The implementation of this inference strategy is as following (Figure 44). Once a landform was been identified by an other approach (pattern elements or geomorphologic indicators), the system requests from the user the type of topographic form on which the identified landform is located. If the topographic form is known to the user then the user will be guided for the identification of additional expected landforms on the specified topographic form according to a user-specified spatial constraint (direction, relationship, condition) binding the identified and the unknown landforms. If such a constraint can not be determined by the user then the system suggests for further evaluation all adjacent landforms independently of spatial direction. Figure 44 shows the derived flowchart for the Landform Hypotheses-Formulation by Spatial Association reasoning.

As an example, let's assume that the user wishes to initiate the **landform hypotheses-formulation**. assuming that an alluvial fan landform has been already identified by an other approach (pattern elements, or geomorphologic indicators). Alluvial fans might be developed on the piedmont slope (a gently sloping surface surrounding a mountain front) at the emergence of a steep valley to a relatively flat surface. With respect to the landform alluvial fan the following spatial conditions need to be considered in order to describe its adjacency to other landforms:

1. in a direction upslope to the alluvial fan,

2. in a direction downslope to the alluvial fan, and

3. adjacent to the alluvial fan in a direction transverse to the slope vector.

Given the above spatial relationships, the four rules indicated in Table 37, Table 38, Table 39, and Table 40 were developed to generate new landform hypotheses. Figure 45 shows the derived flowchart for the Landform Hypotheses-Formulation by Spatial Association reasoning when the initially known landform is an alluvial fan.

Figure 46 to Figure 49 and Figure 54 show examples of rules (from the rule network) for Landform Hypotheses Formulation when the initially known landform is an alluvial fan identified on a piedmont slope and under a variety of spatial constraints.

Figure 50 to Figure 51 show examples of rules (from the rule network) for Landform Hypotheses Formulation when the initially known landform is a pediment identified on a piedmont slope and under a variety of spatial constraints.

Figure 52 to Figure 53 show examples of rules (from the rule network) for Landform Hypotheses Formulation when the initially known landform is a playa identified on a basin floor and under a variety of spatial constraints.

Table 37. Spatially associated landforms to an alluvial fan on a piedmont slope in the downslope direction: RULE 1

**If**
- the given landform is an ALLUVIAL FAN, and
- the given landform belongs to a topographic form of PIEDMONT SLOPE, and
- the unknown landform is adjacent to the ALLUVIAL FAN in the DOWNSLOPE DIRECTION,

**then** the unknown landform could be that of a PLAYA, a VALLEY FILL or a PEDIMENT.

Table 38. Spatially associated landforms to an alluvial fan on a piedmont slope in a direction transverse to the slope vector: RULE 2

**If**
- the given landform is an ALLUVIAL FAN, and
- the given landform belongs to a topographic form of PIEDMONT SLOPE, and
- the unknown landform is adjacent to given landform in a DIRECTION TRANSVERSE TO THE SLOPE VECTOR

**then** the unknown landform could be that of another ALLUVIAL FAN, a BAHADA or a PEDIMENT.

Table 39. Spatially associated landforms to an alluvial fan on a piedmont slope in an upslope direction: RULE 3

**If**
- the given landform is an ALLUVIAL FAN, and
- the given landform belongs to a topographic form of PIEDMONT SLOPE, and
- the unknown landform is adjacent to given landform in an UPSLOPE DIRECTION

**then** the unknown landform could be that of a PEDIMENT (It is currently assumed that only landforms of the piedmont plain are examined).

Table 40. Spatially associated landforms to an alluvial fan on a piedmont slope independent of direction: RULE 4

**If**
- the given landform is an ALLUVIAL FAN, and
- the given landform belongs to a topographic form of PIEDMONT SLOPE, and
- no spatial direction of adjacency can be defined by the user,

**then** the unknown landform could be that of another ALLUVIAL FAN, a PEDIMENT, a BAHADA, a PLAYA, or a VALLEY FILL.

Landform Hypotheses Formulation by Spatial Association

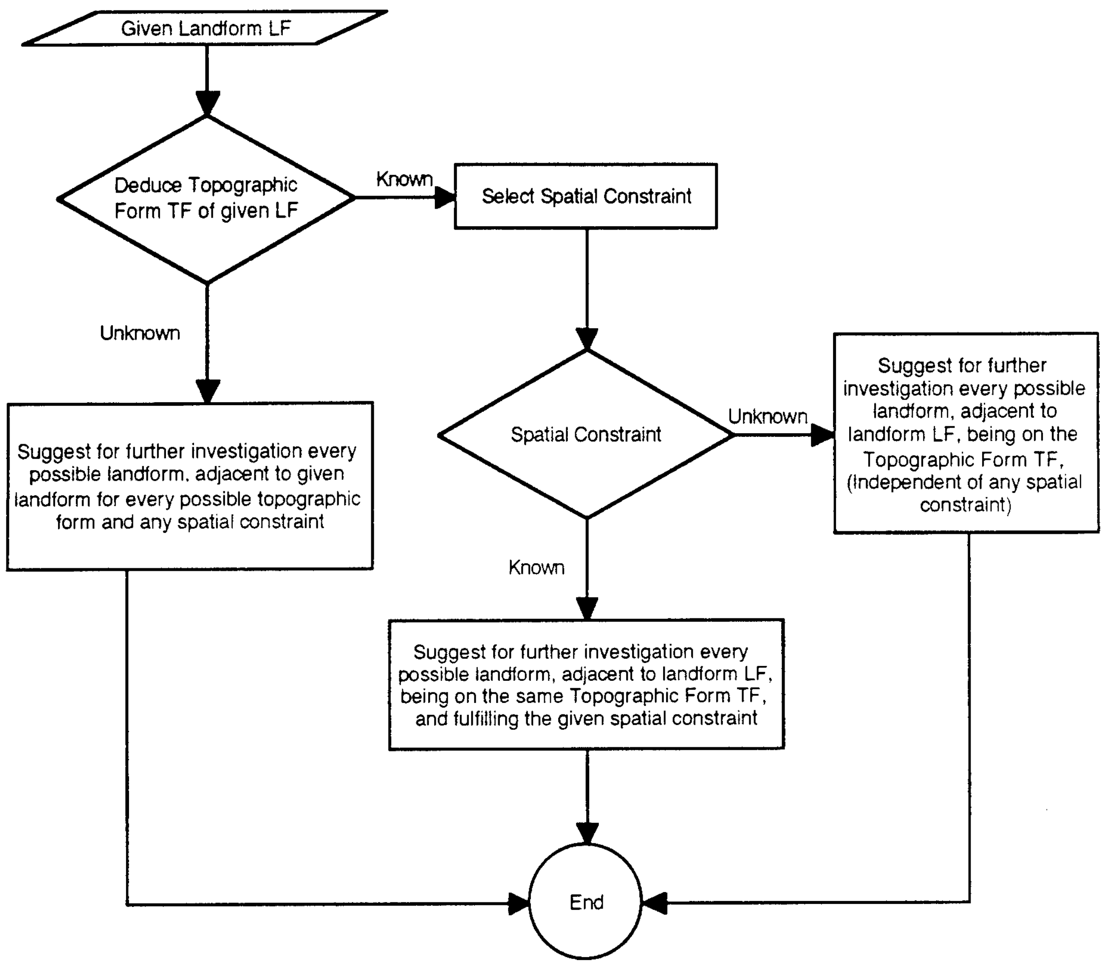



Figure 44. Landform Hypotheses Formulation by Spatial Association

## Landform Hypotheses Formulation by Spatial Association: Example: Alluvial Fan

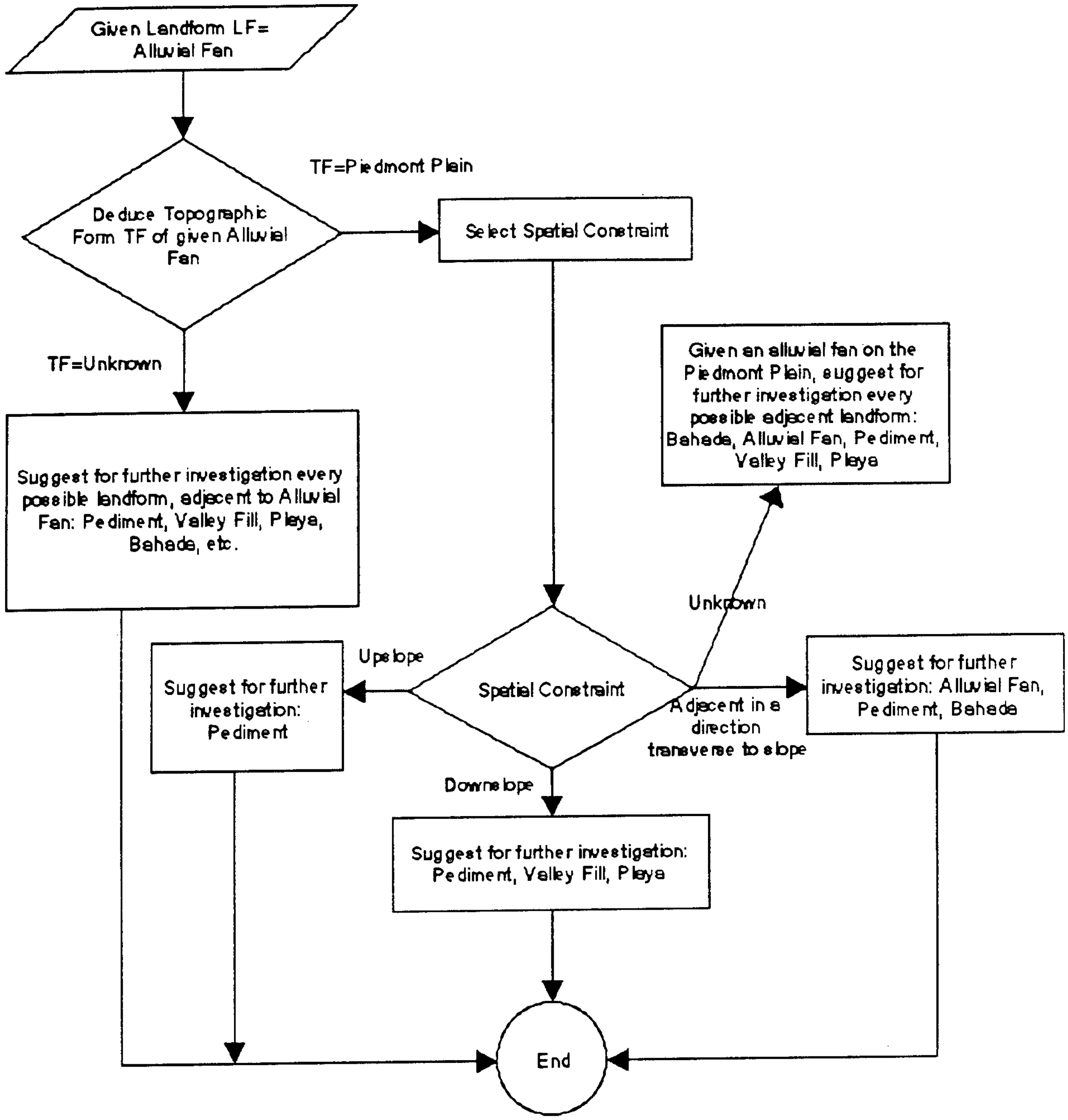



Figure 45. Landform hypotheses formulation by spatial association to an alluvial fan (in the context of a piedmont plain in the Basin and Range Province)

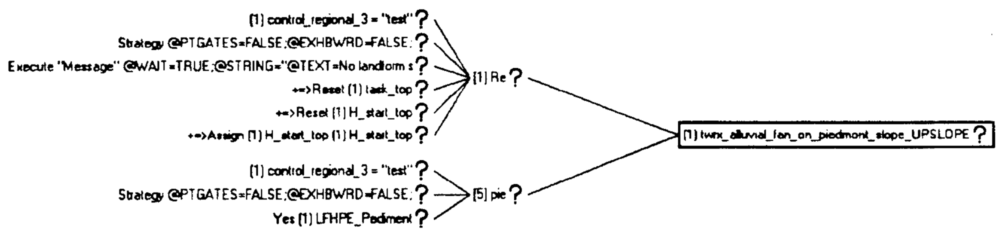



Figure 46. Example of rules for Landform Hypotheses Formulation by Spatial Association: A pediment is suggested [right hand side action: Yes (1) LFHPE_Pediment] in the upslope direction of an alluvial fan, identified on a piedmont slope.

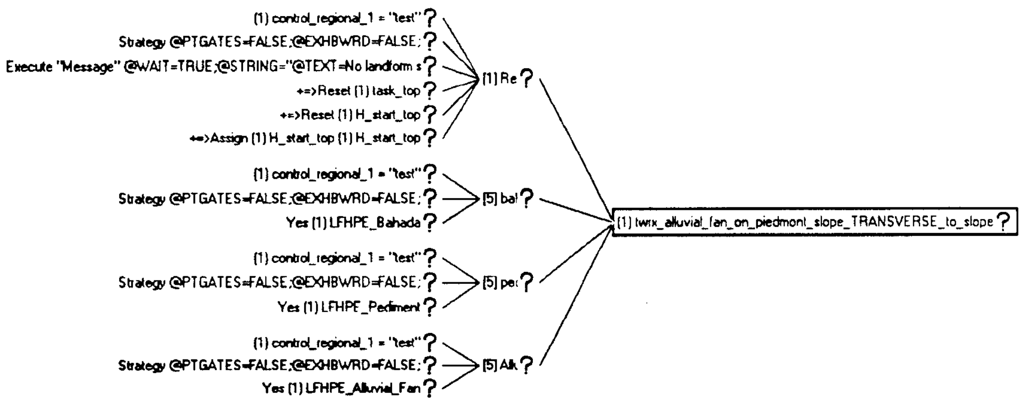



Figure 47. Example of rules for Landform Hypotheses Formulation by Spatial Association: A pediment, a bahada, and an alluvial fan are suggested to be adjacent to an alluvial fan in a direction transverse to slope on a piedmont slope.

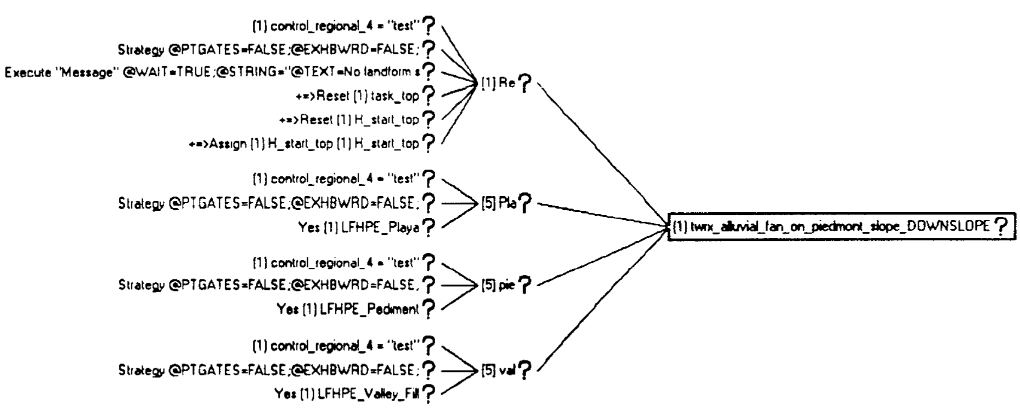



Figure 48. Example of rules for Landform Hypotheses Formulation by Spatial Association: A pediment, a playa, and a valley fill are suggested to be adjacent to an alluvial fan in a downslope direction on the piedmont slope.

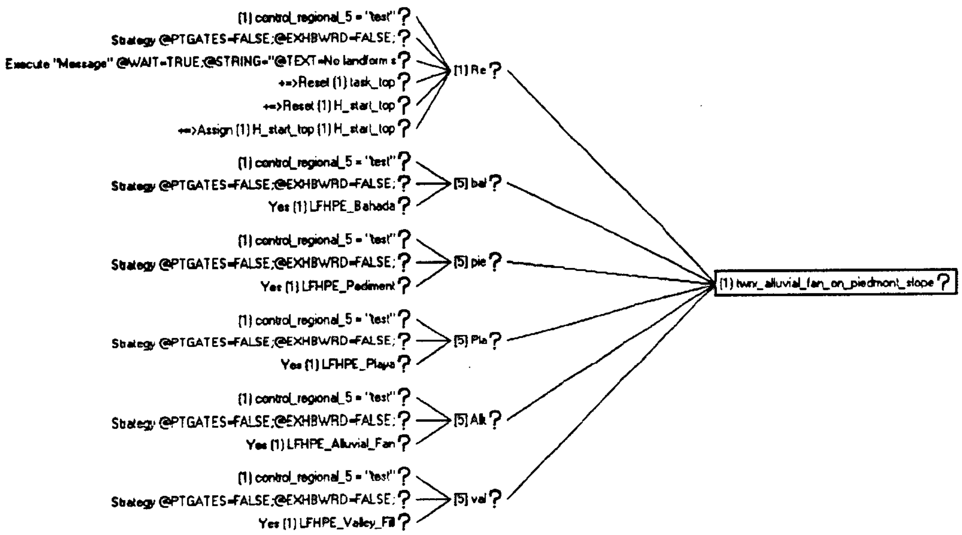



Figure 49. Example of rules for Landform Hypotheses Formulation by Spatial Association: A pediment, a bahada, a playa, an alluvial fan and a valley fill are suggested to be adjacent to an alluvial fan on a piedmont slope when no spatial direction was provided by the user.

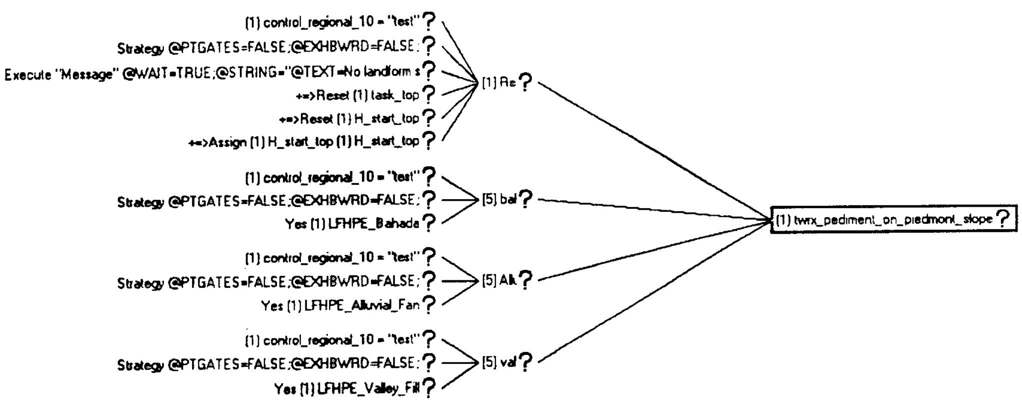



Figure 50. Example of rules for Landform Hypotheses Formulation by Spatial Association: A valley fill, a bahada, and an alluvial fan are suggested to be adjacent to a pediment on a piedmont slope when no spatial direction was provided by the user.

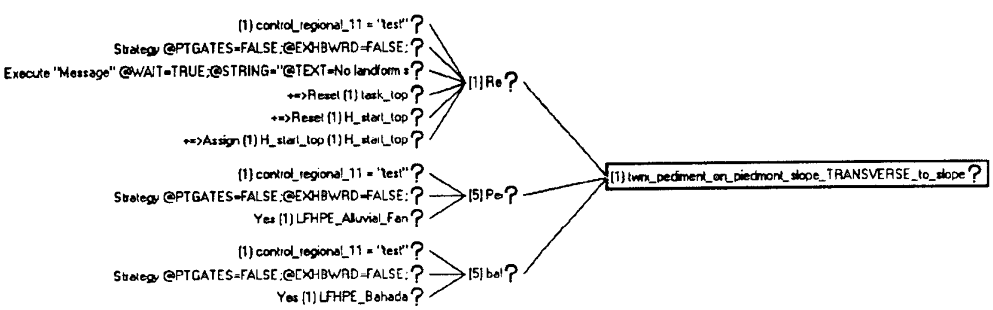



Figure 51. Example of rules for Landform Hypotheses Formulation by Spatial Association: A bahada, and an alluvial fan are suggested to be adjacent to a pediment on a piedmont slope in a direction transverse to slope.

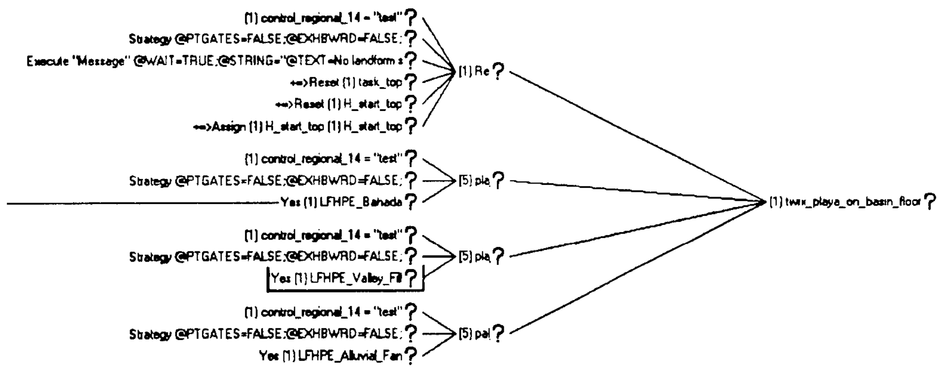


Figure 52. Example of rules for Landform Hypotheses Formulation by Spatial Association: A bahada, a valley fill and an alluvial fan are suggested to be adjacent to a playa on basin floor.

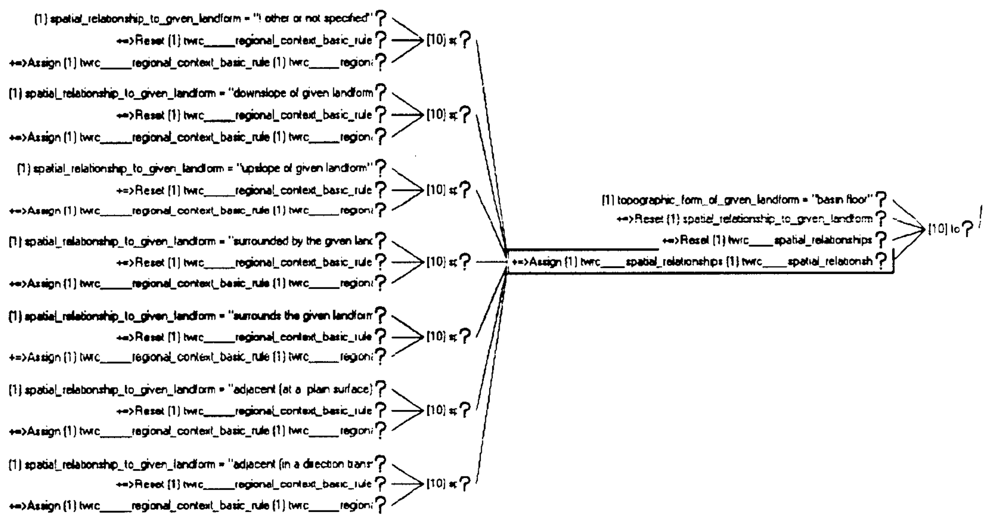


Figure 53. Example of rules for Landform Hypotheses Formulation by Spatial Association: The possible spatial directions (adjacent to, surrounded by, upslope of a given landform, etc.) which are taking into account during the inference of a new landform from an existing landform identified on a basin floor.

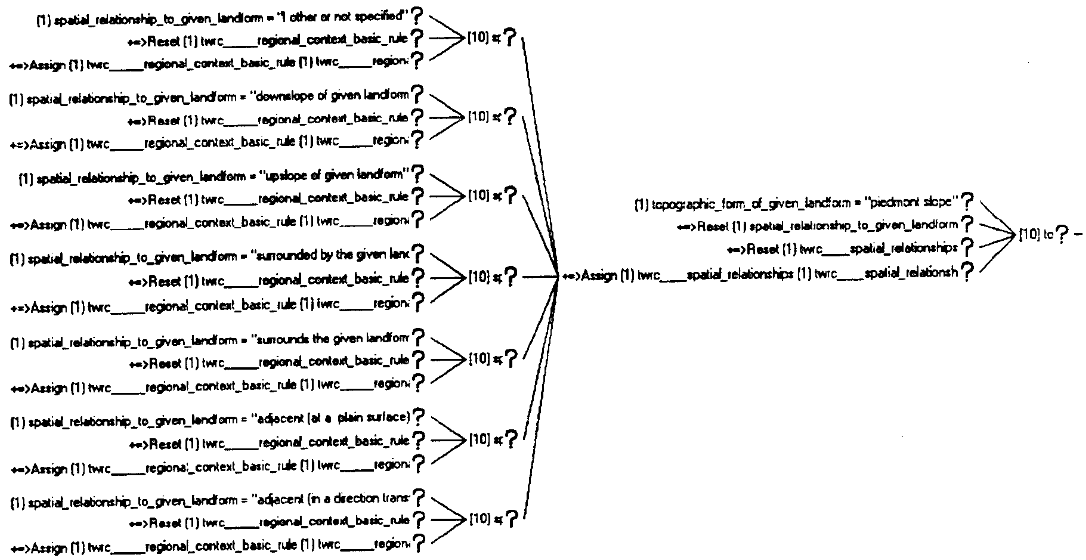



Figure 54. Example of rules for Landform Hypotheses Formulation by Spatial Association: The possible spatial directions (adjacent to, surrounded by, upslope of a given landform, etc.) which are taking into account during the inference of a landform from an existing landform identified on a piedmont slope.

## 3. Conclusions and Prospect

The major contribution of this study was the formalization of physiographic and spatial context for the interpretation of terrain and geologic features from aerial and satellite imagery. In all earlier efforts in constructing prototype expert terrain-related systems, knowledge related to the physiographic region of a site and to the spatial pattern of related landforms were not explicitly represented and used. In this research we have identified, named, described, organized and related detailed, "book-level" knowledge pertaining to physiographic regions (provinces and sections), physiographic features, topographic forms and landforms. Collected, systematized, and defined landform, geomorphologic, topographic, and physiographic indicators. We have developed an object-oriented model for the factual and structural representation of these terrain features. We have also developed a rule-base for representing the strategic knowledge needed for inferring these features from their own indicators. We have provided for the representation of multiple terrain objects at a given interpretive scenario and for bidirectional reasoning for the identification of terrain features depending on the goals of the interpretation at a given time. Eleven scenaria of photointerpretation problem solving were described. They compose three contexts: landform, physiographic and spatial. The presented case studies concern typical terrain of the Basin and Range Province of Southwest USA (Great Basin and Sonoran Desert). The conceptual scheme was formalized and implemented in a knowledge-base resulting in the Terrain Analysis eXpert (TAX-4-5) system which assists step by step the user in the eleven problem solving scenaria.

We have developed the identification, conceptualization, representation and formalization of landform, physiographic and spatial knowledge, relying mostly on book-level knowledge because the first step in knowledge acquisition requires the formulation of a conceptual framework of shallow and deep knowledge, which usually is found in books and reports. Our present-level knowledge falls into the category of "zeroth to first order approximation of physiographic knowledge". We have made an extra effort in capturing a number of "intermediate-level concepts" which are perhaps the most important tools available for organizing knowledge bases, both conceptually and computationally. Going too much to the books and reports may have lead us to the incorporation of knowledge that is either not a part of practical reasoning or that has exceptions that the expert has had to discover and work around. It is therefore necessary, in future efforts, to acquire the "second to third order level of knowledge" from experts. Our feeling is that the expert's knowledge will be more of the heuristic type, e.g., exceptions and corrections of the "zeroth order of knowledge".

The identification of terrain-related objects, their organization. and their relations is the hardest part of conceptualization. Identification of the conceptual structure involves both discovery and invention of the key abstractions and mechanisms that form the vocabulary of our terrain analysis problem and it will come with very hard work.

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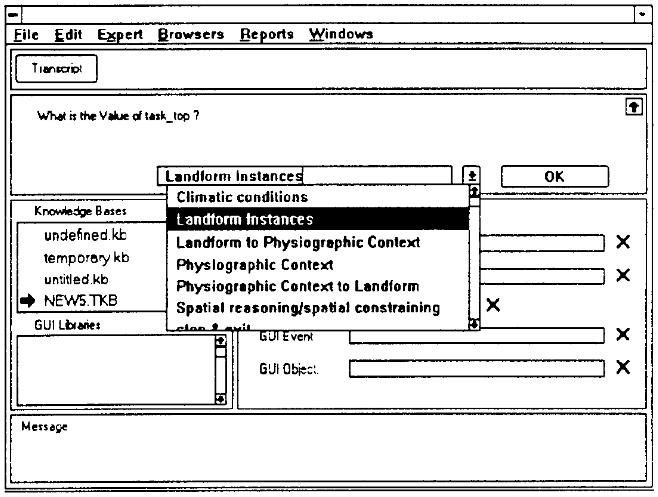
## 1. APPENDIX 1

These appendices are organized so that to present selected examples of runs of the system TAX-4-5. Each of the four appendices lists first all the captions of the figures and then the figures.

In this Appendices in the captions, we have marked with
plain text to show the selections by the user which are strategic in nature
• Bullets to show the selections by the user of various terrain indicators
⇒ Such a pointer to indicate the responses of the system
♦ Big Bullets to indicate object or rule network graphs which we have invoked to show certain aspects of object and rule based programming.

| CASE STUDY: A new landform is identified in forward direction from pattern elements. Then, the existing landform is refined in backward direction from geomorphic and spatial reasoning indicators. | |
|---|---|
| **No** | **Description / Caption** |
| 1. | From the main menu select as the top task «Landform Instances» |
| 2. | Select to Identify landform from «Pattern Elements» |
| 3. | Select Forward Landform Identification |
| 4. | Select Identify «new» landform |
| 5. | • Select value for Drainage Pattern |
| 6. | • Select value for Drainage Texture |
| 7. | • Select value for Planimetric 2d-shape |
| 8. | • Select value for Topographic 3d-shape |
| 9. | • Select value for Surface shape axial symmetry |
| 10. | • Select value for Surface axial profile |
| 11. | • Select value for Slope average gradient |
| 12. | • Select value for Slope gradient range |
| 13. | • Select value for Spatial direction of slope average change |
| 14. | • Select value for Surface curvature |
| 15. | • Select value for Surface highest point |
| 16. | • Select value for Surface lowest point |
| 17. | • Select value for Surface height |
| 18. | • Select value for area relative size |
| 19. | • Select value for Gullies frequency |
| 20. | • Select value for Phototone |
| 21. | • Select value for Phototone texture |
| 22. | ⇒ Verification of a new **Alluvial Fan based on Pattern Elements** |
| 23. | Select Show Landform Instances |
| 24. | ⇒ **LF_1= Alluvial fan, pe=ok**, gm=?, sr=? |
| 25. | ♦ Object Network showing the creation of the newly identified landform instance LF_1 which was assigned to the class Temp Landforms where from inherited all the landform attributes and to class Alluvial_Fan_PE since it was interpreted as such. |
| 26. | ♦ Rule Network showing two (partial) rules for the hypothesis of Alluvial_Fan on of which has been fired |
| 27. | From the main menu select «**Landform Instances**» |
| 28. | SELECT Identify landform form «**Geomorphic Process**» |
| 29. | Select **Backward** Landform Identification |
| 30. | Select Identify an **existing** landform |
| 31. | Specify **landform instance** (LF_x, where x=1) |
| 32. | • Select value for Climate |
| 33. | • Select value for Geomorphic forces |

| | |
|---|---|
| 34. | • Select value for Geomorphic origin |
| 35. | • Select value for Geomorphic process |
| 36. | • Select value for Formation process |
| 37. | • Select value for Formation agent |
| 38. | • Select value for Formation agent process |
| 39. | • Select value for Most favorable forming geographic conditions |
| 40. | • Select value for Formation triggering process |
| 41. | • Select value for Formation mechanism |
| 42. | • Select value for Formation locus |
| 43. | • Select value for Water Regime |
| 44. | • Select value for Discharge |
| 45. | ⇒ Verification of an existing Alluvial Fan based on Geomorphic Indicators |
| 46. | ♦ Object Network showing the landform instance LF_1 which was assigned to the class Temp Landforms where from inherited all the landform attributes and to the classes Alluvial_Fan_PE and Alluvial_Fan_GM since it was interpreted by both the pattern elements approach (earlier) and the geomorphic process indicators (at this stage). |
| 47. | ♦ Rule Network showing the rule for the hypothesis of Alluvial_Fan_GM (based on geomorphologic process indicators) which has been fired. The rule of pediment has lead into a false Pediment hypothesis. |
| 48. | Select Show Landform Instances |
| 49. | ⇒ **LF_1= Alluvial fan, pe=ok, gm=ok**, sr=? |
| 50. | Select to identify this landform form «Spatial Reasoning» at the top menu |
| 51. | Select to identify an **existing** landform |
| 52. | Specify **landform instance** (LF_x, where x=1) |
| 53. | • Select value for landform is contained in |
| 54. | • Select value for landform occurs at |
| 55. | • Select value for landform occurs in front of |
| 56. | • Select value for landform occurs adjacent to |
| 57. | • Select value for landform downslope boundary |
| 58. | • Select value for landform contains |
| 59. | ⇒ Verification of an **existing Alluvial Fan based on spatial reasoning** |
| 60. | Select Landform Instances |
| 61. | Select Show instances |
| 62. | ⇒ **LF_1= Alluvial fan, pe=ok, gm=ok, sr=ok** |
| 63. | ♦ Object Network showing the landform instance LF_1 which was assigned to the class Temp Landforms where from inherited all the landform attributes and to the classes Alluvial_Fan_PE, Alluvial_Fan_GM, and Alluvial_Fan_SR since it was interpreted by both the pattern elements and the geomorphic process indicators approach (earlier) and the spatial reasoning indicators (at this stage). |
| 64. | ♦ Rule Network showing the rule for the hypothesis of Alluvial_Fan_SR (based on spatial reasoning indicators) which has been fired. The rule of continental alluvium has lead into a false hypothesis. |

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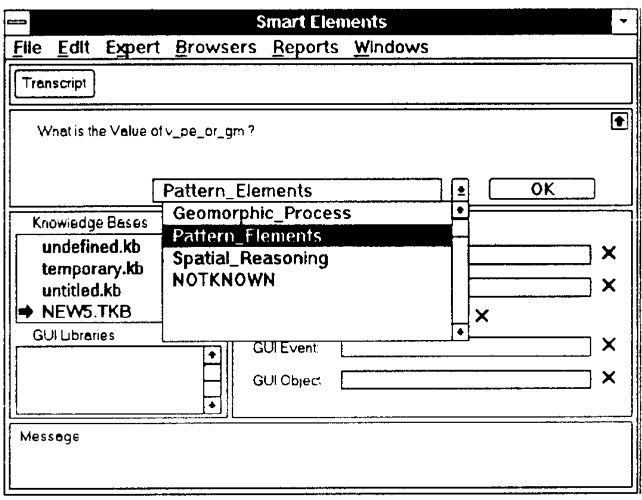


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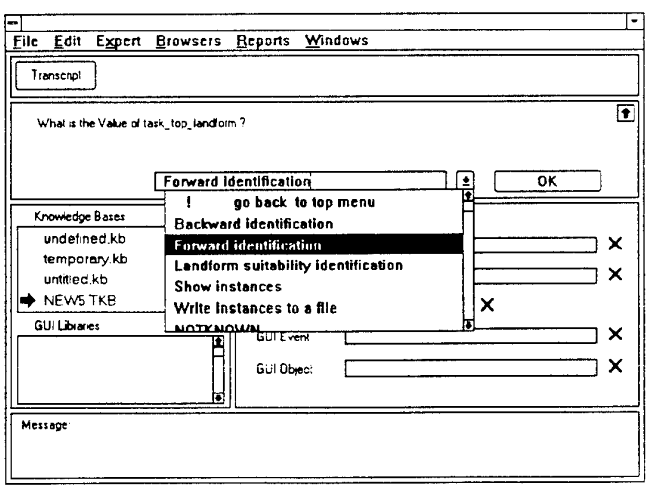


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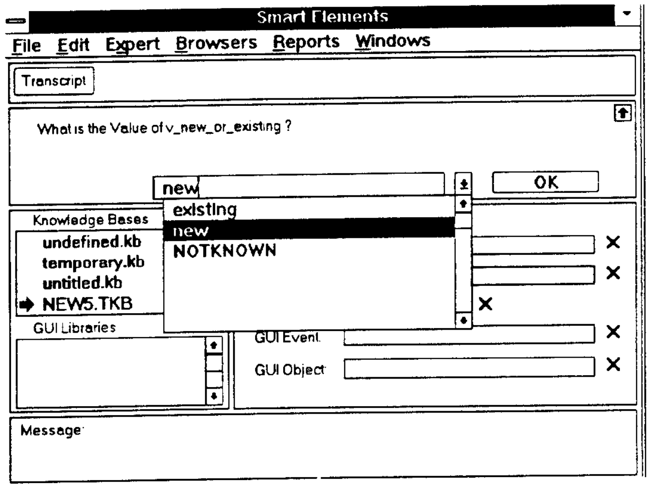


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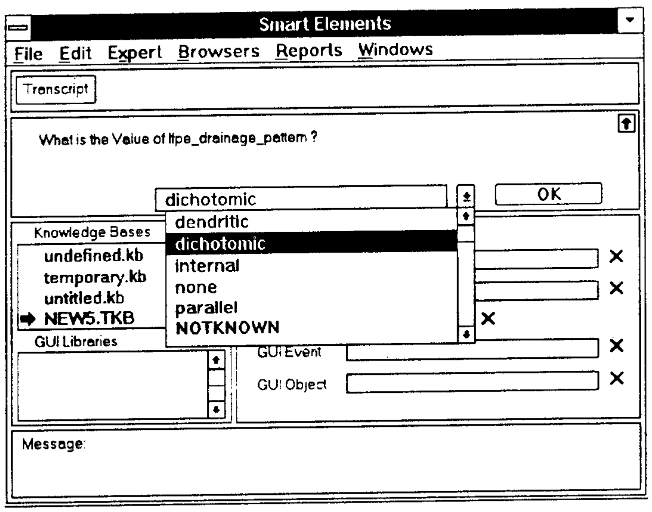


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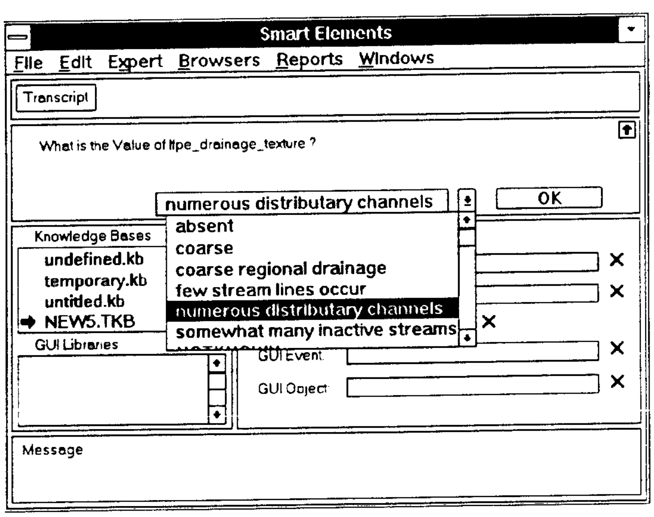


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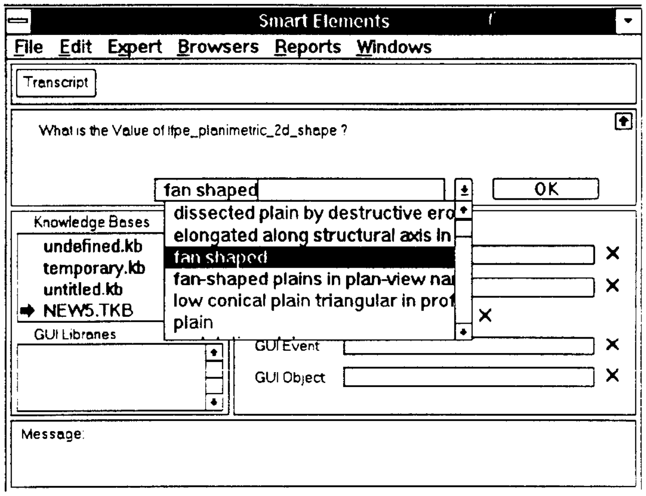


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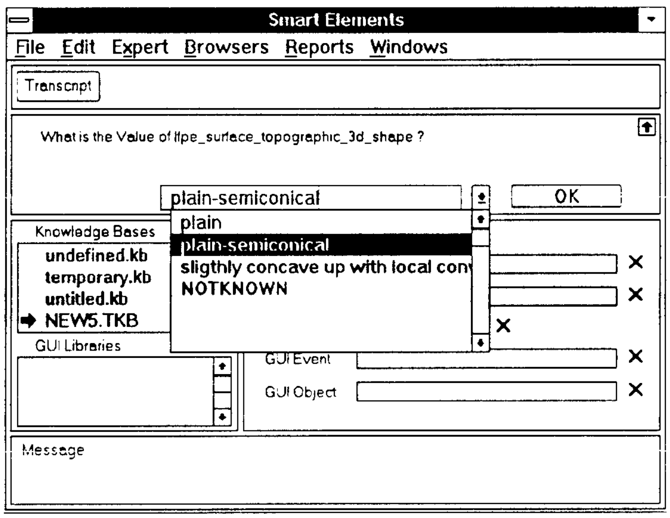


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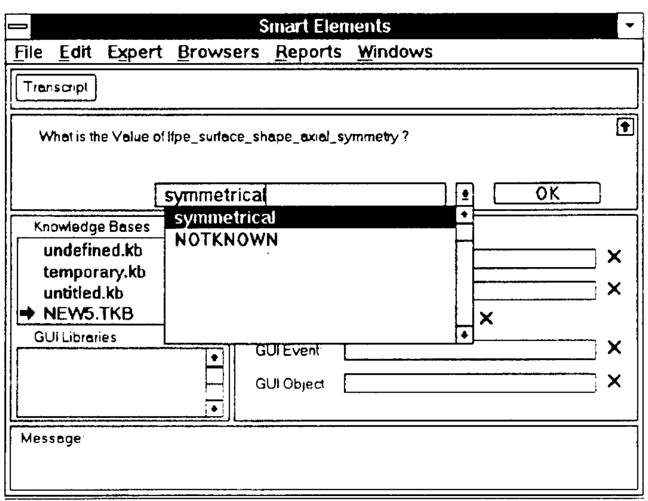


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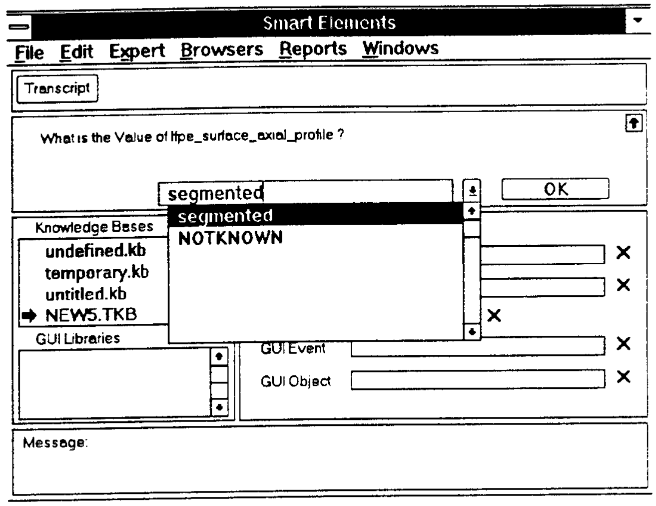


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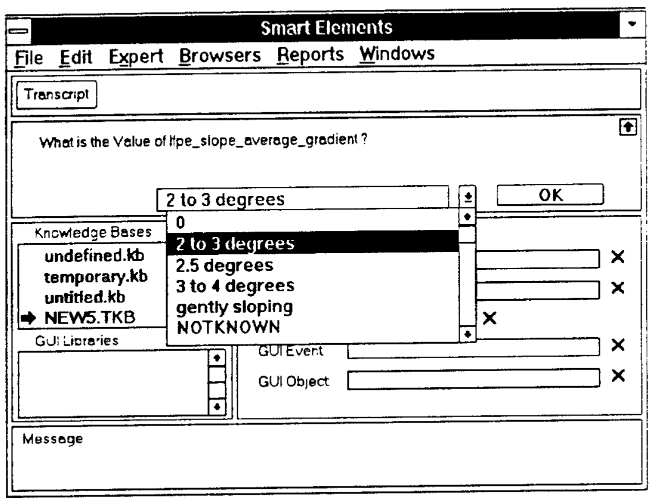


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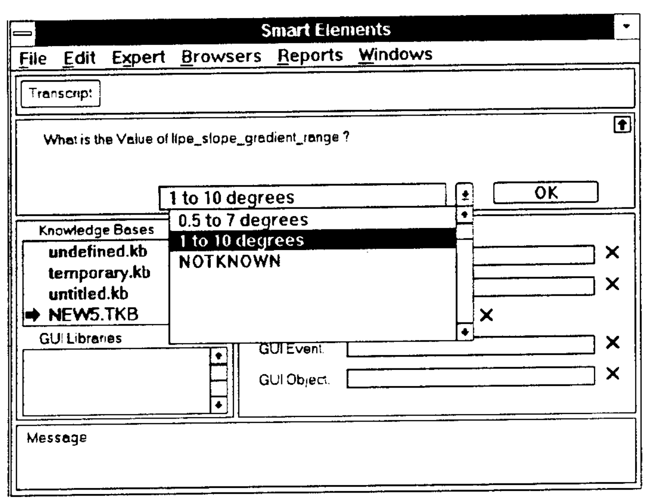


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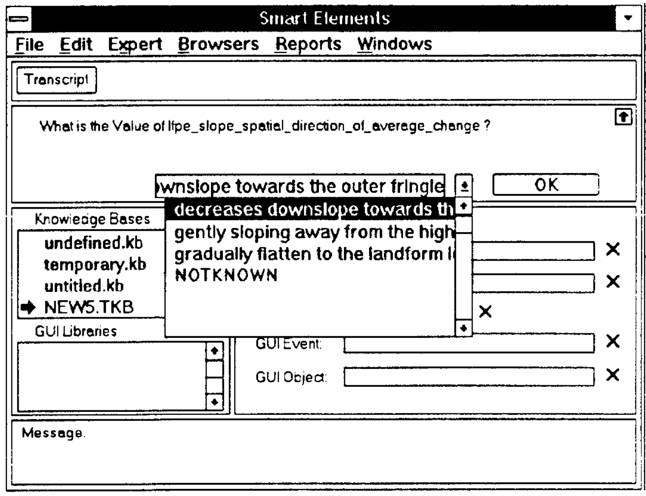


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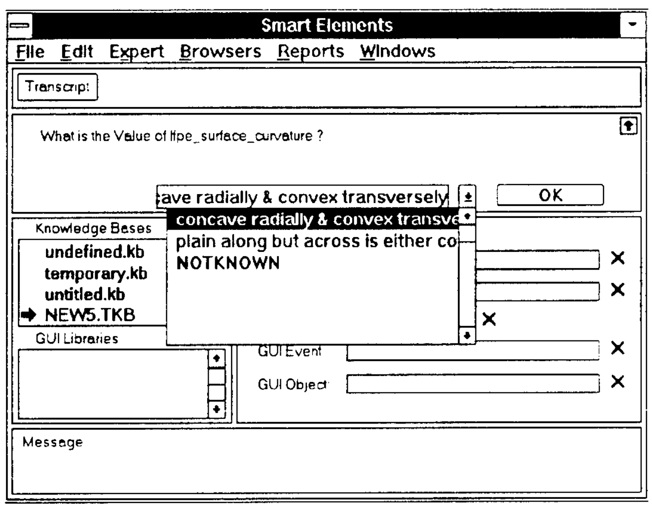


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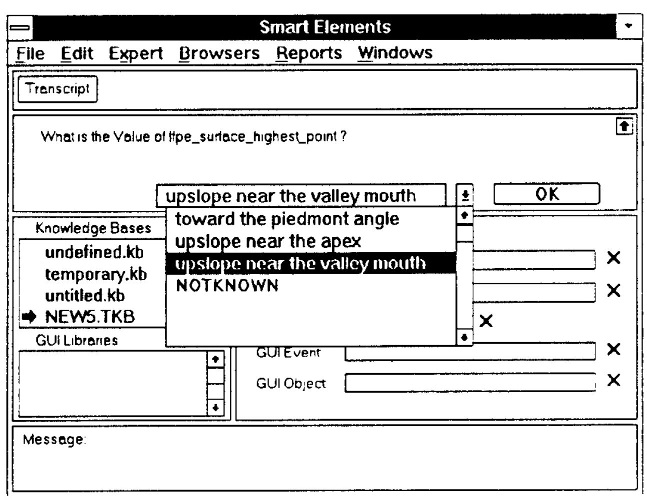


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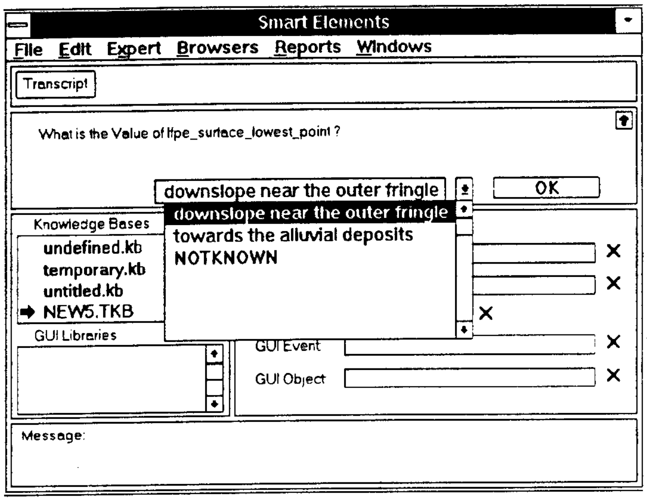


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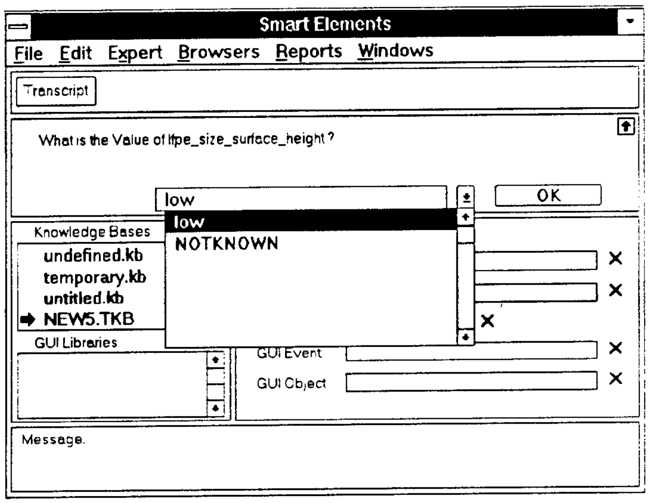


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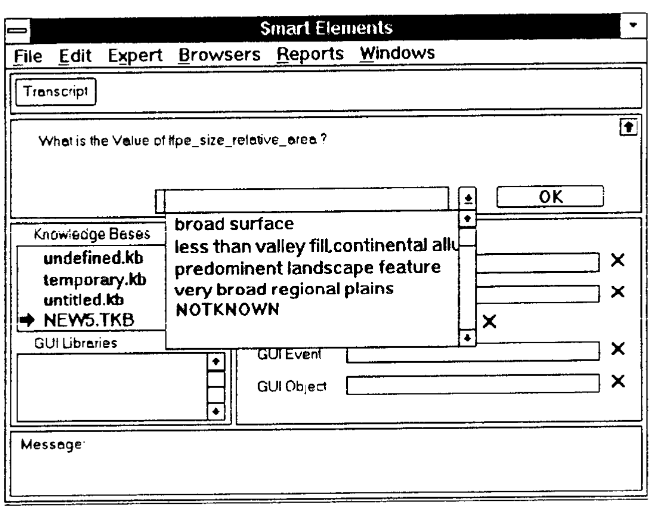


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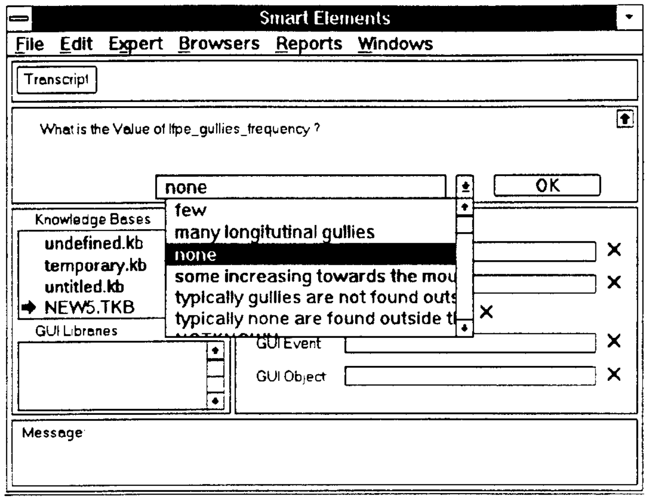


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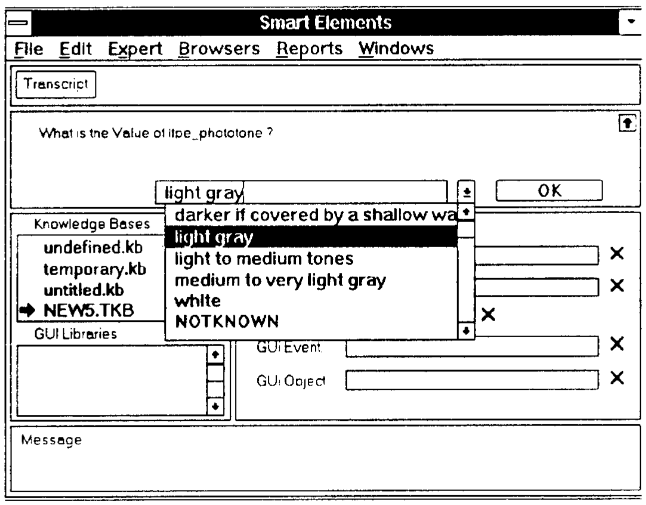


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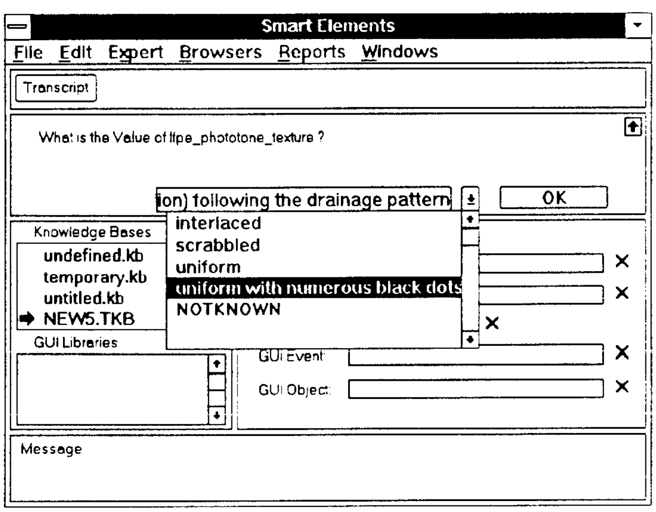


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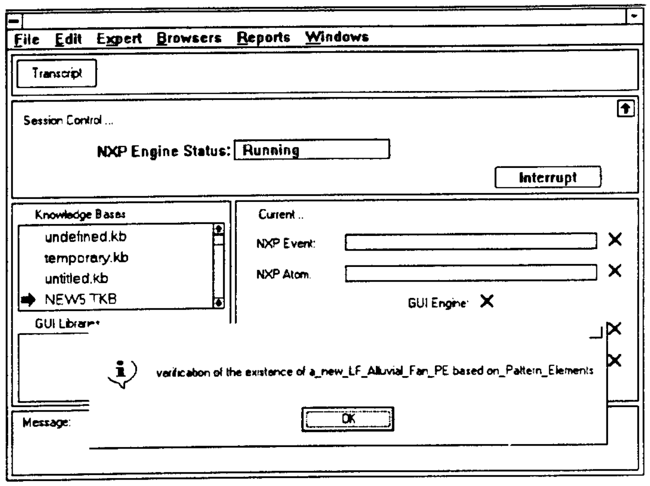


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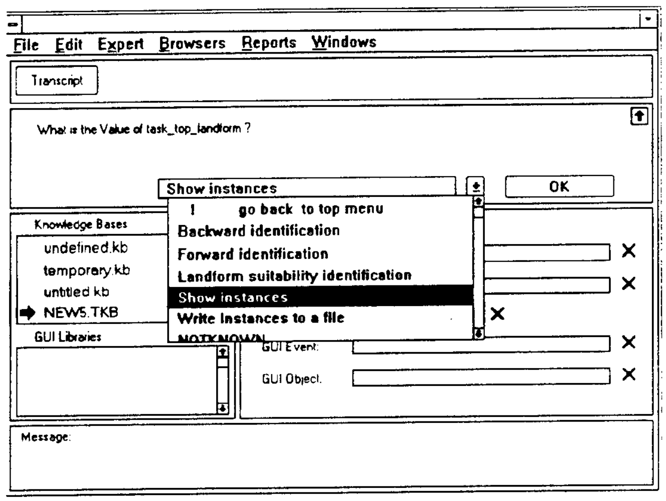


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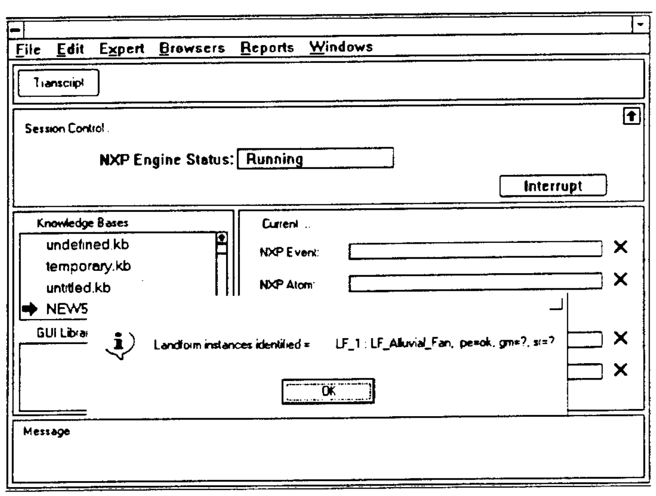


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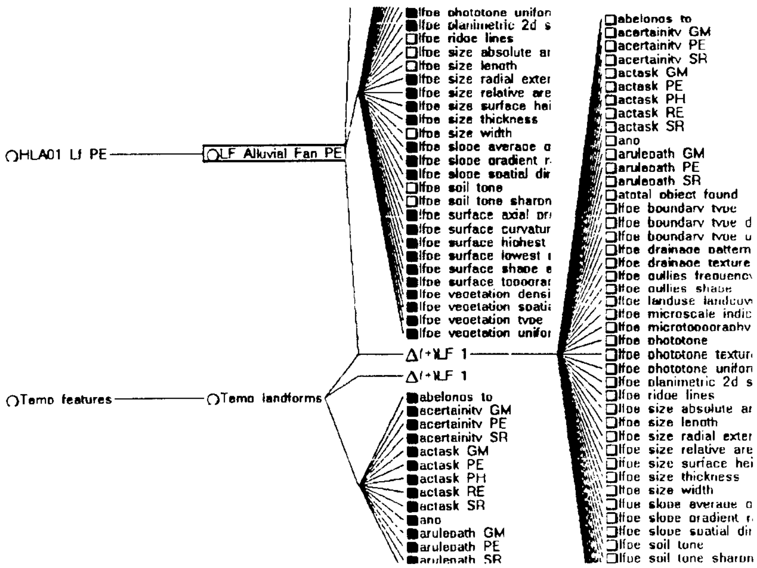


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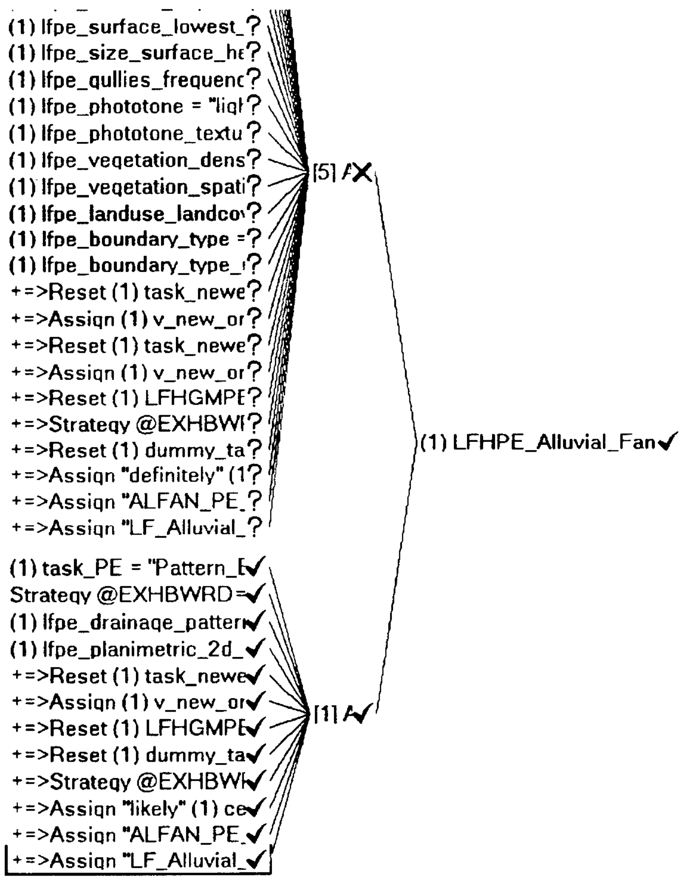


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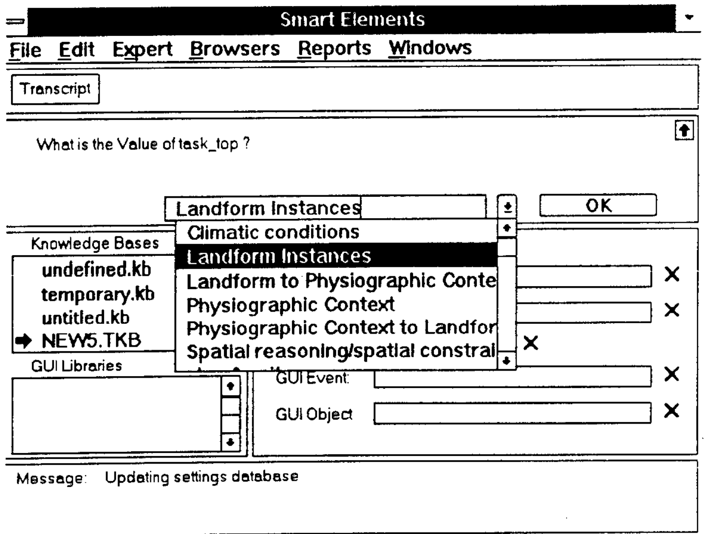


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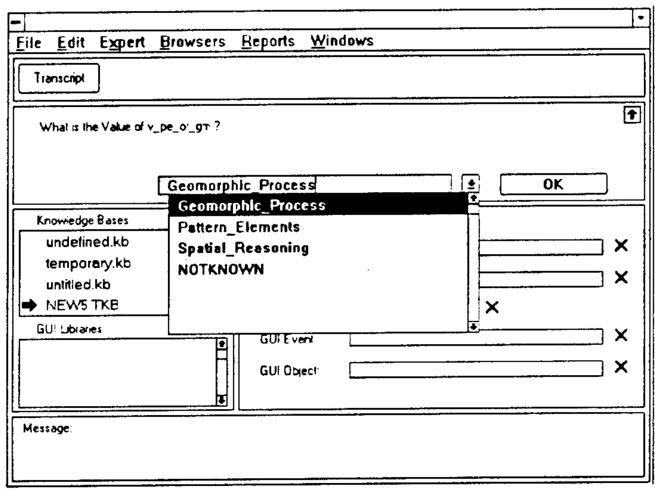


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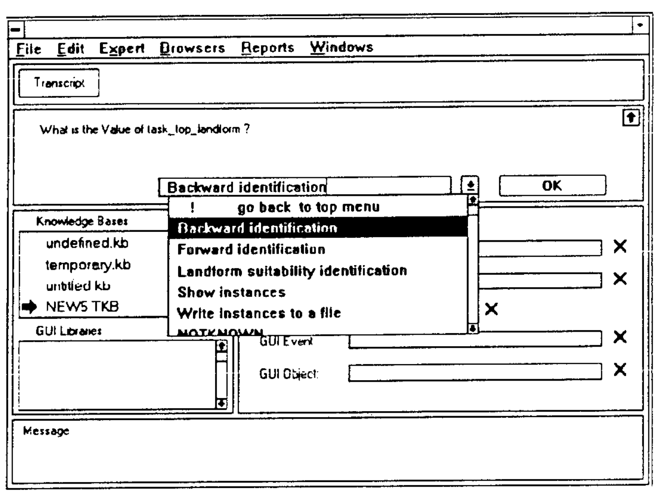


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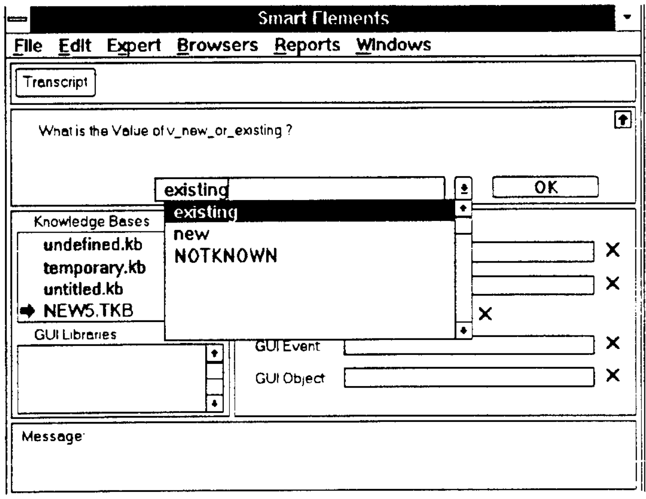


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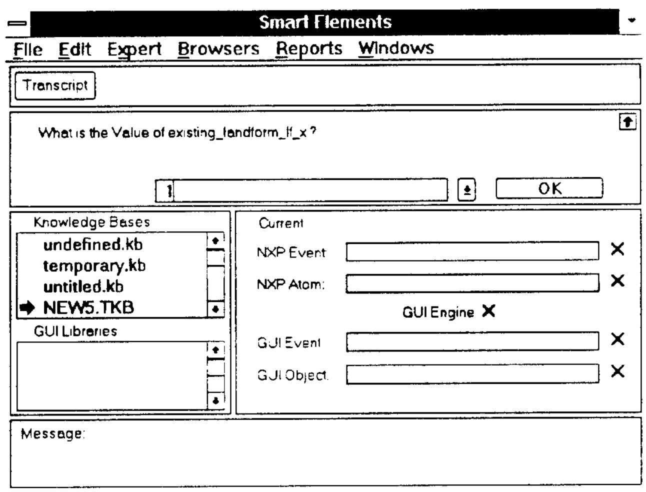


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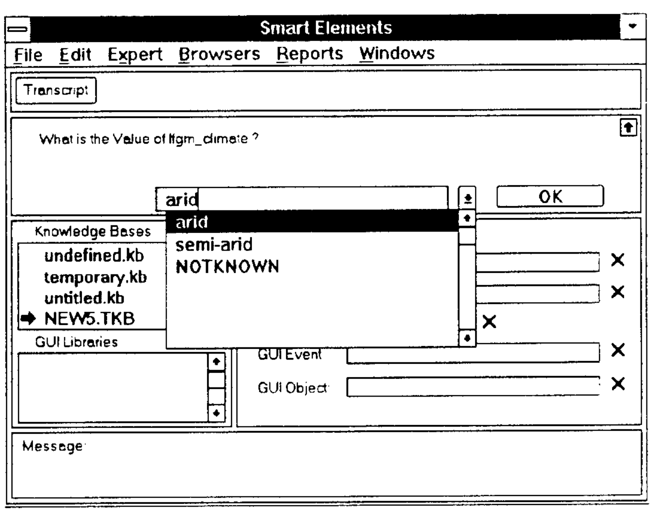


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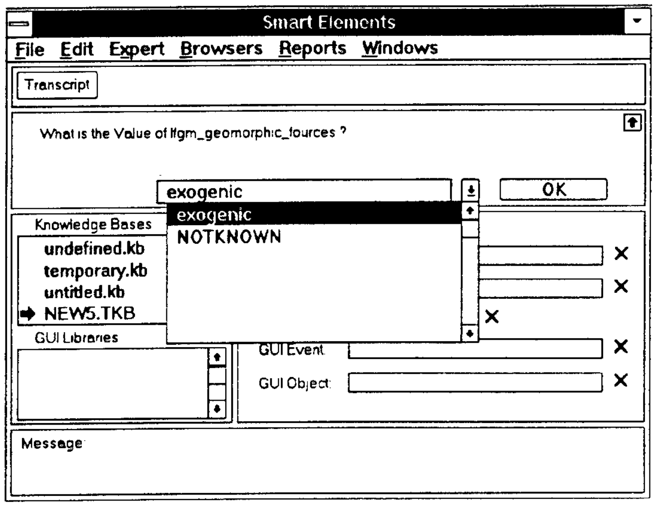


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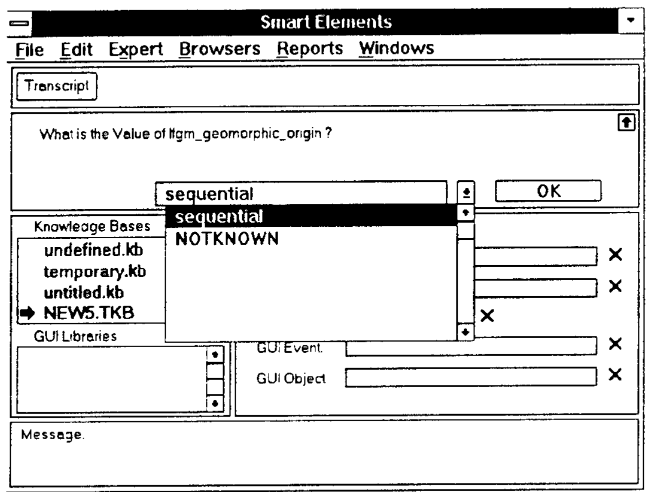


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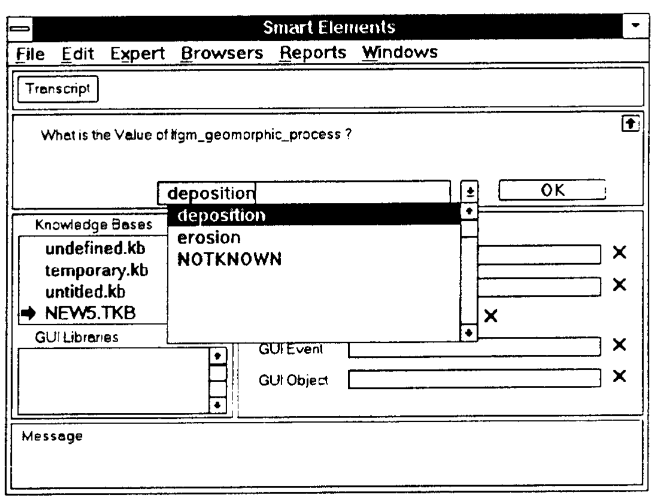


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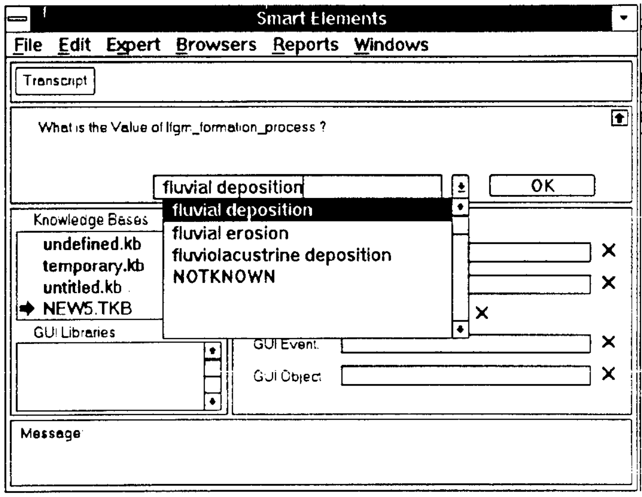


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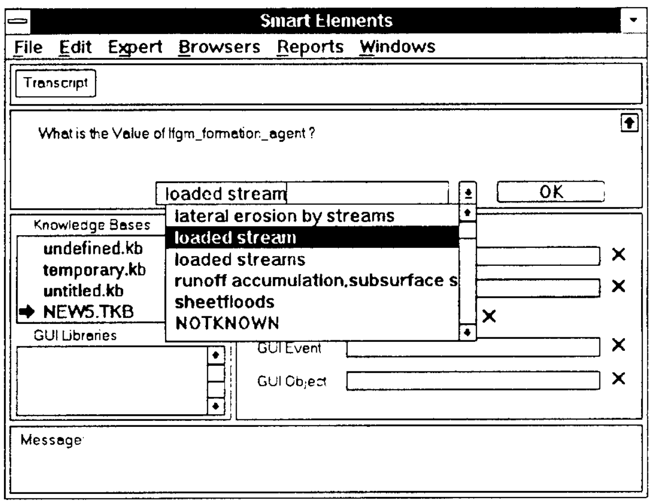


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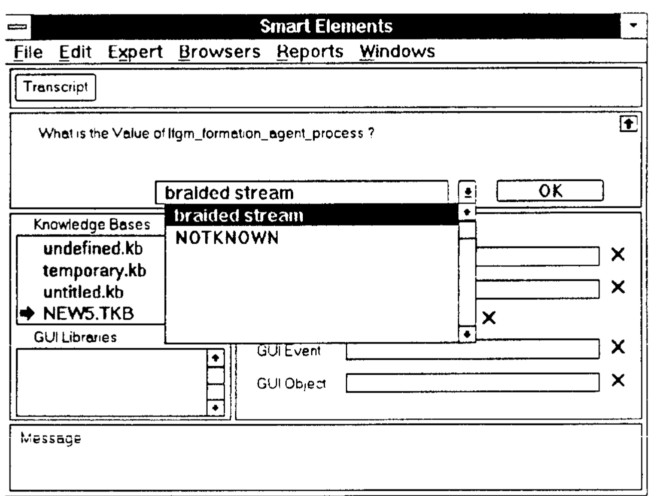


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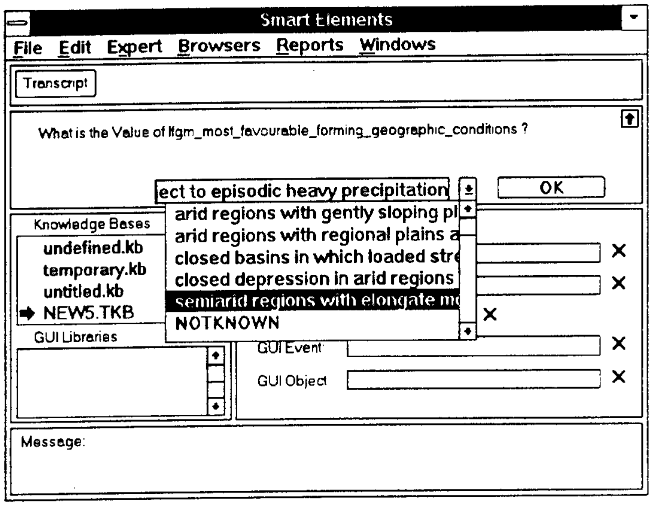


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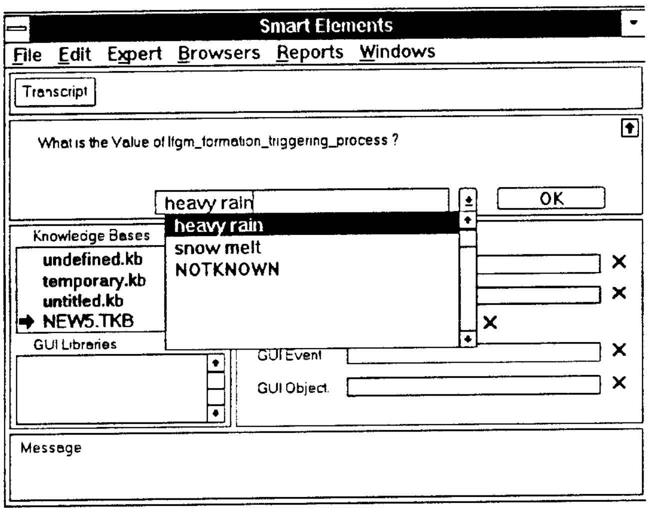


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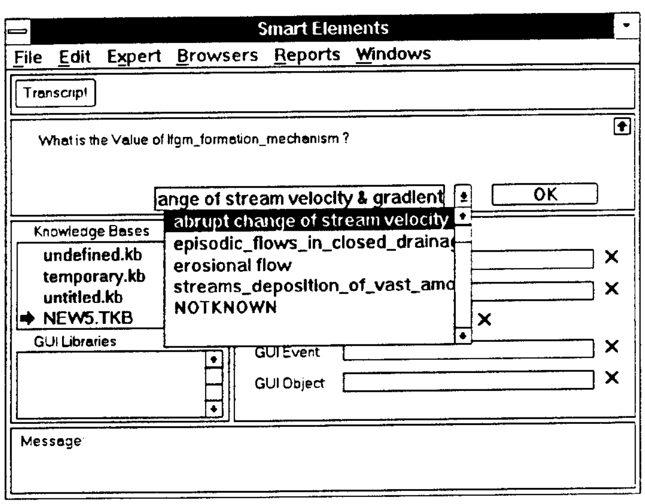


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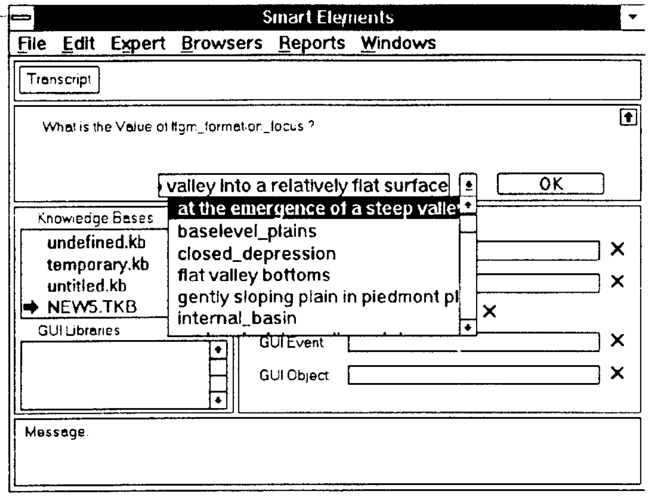


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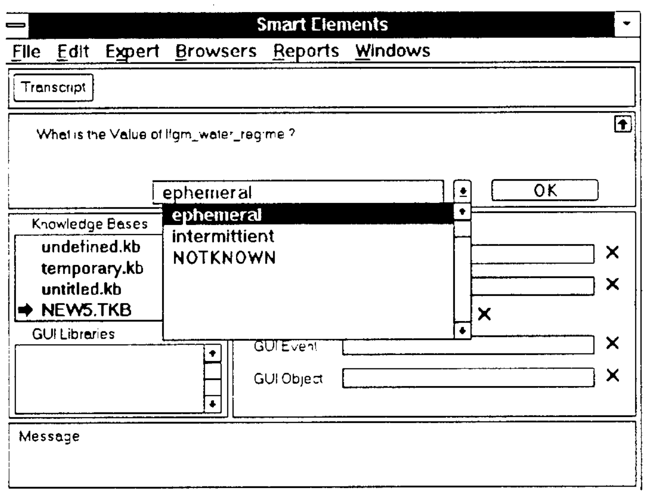


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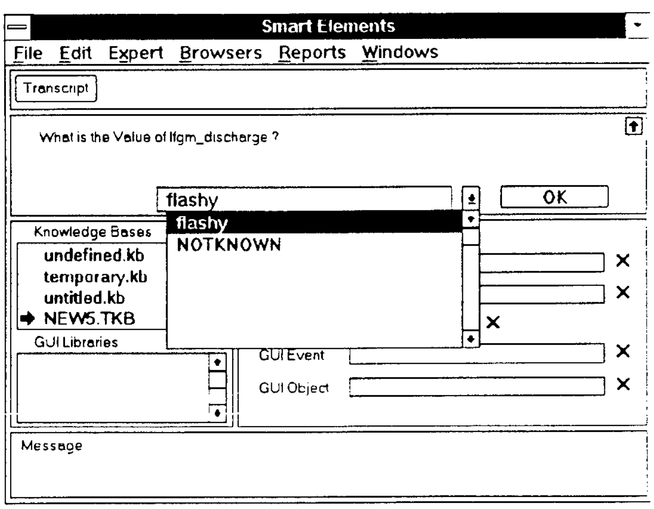


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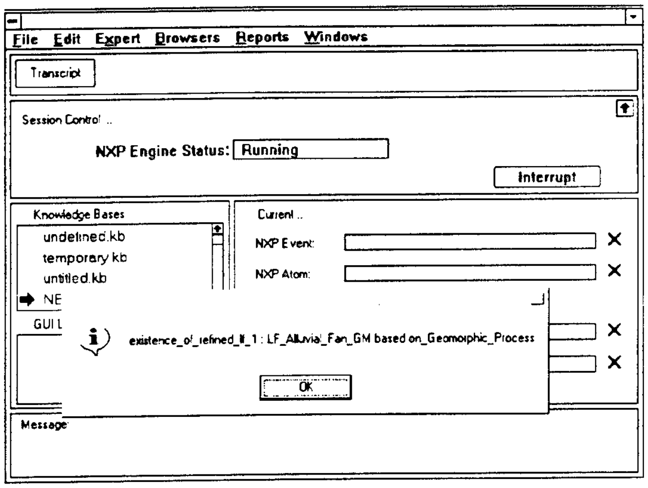


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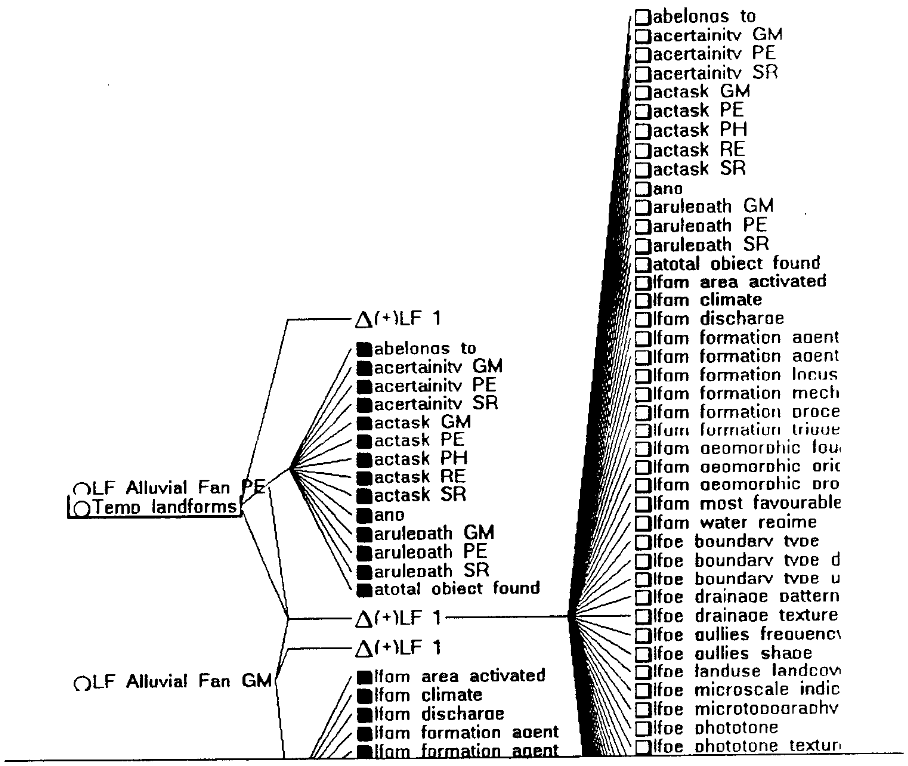


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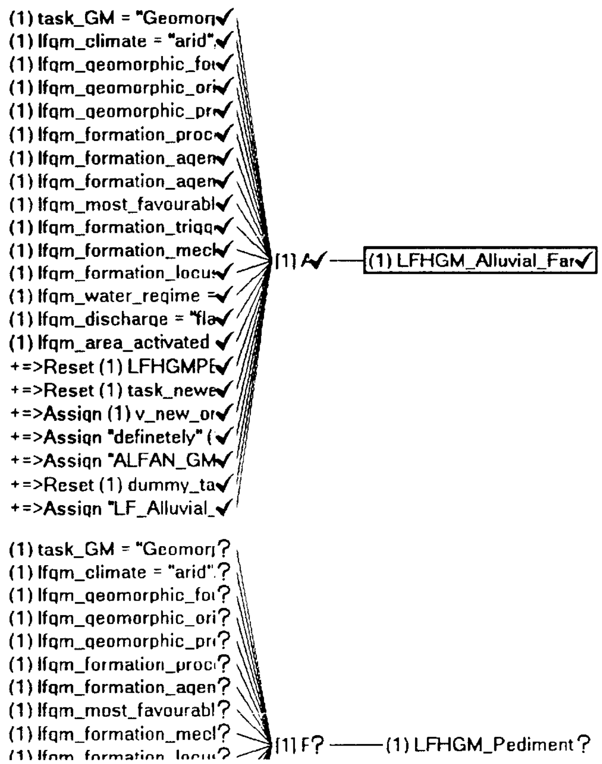
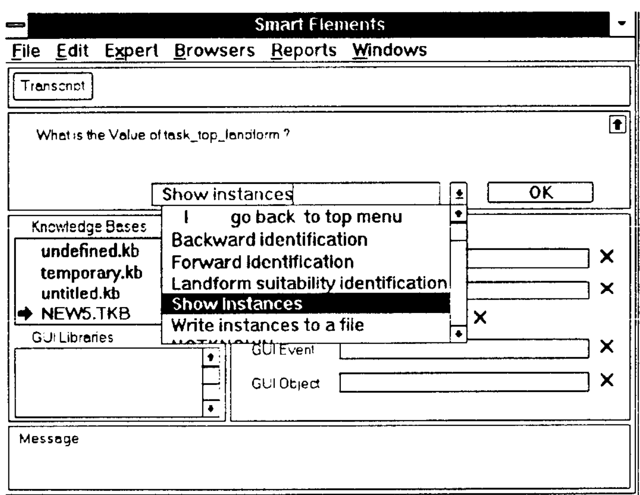



Figure 1-47

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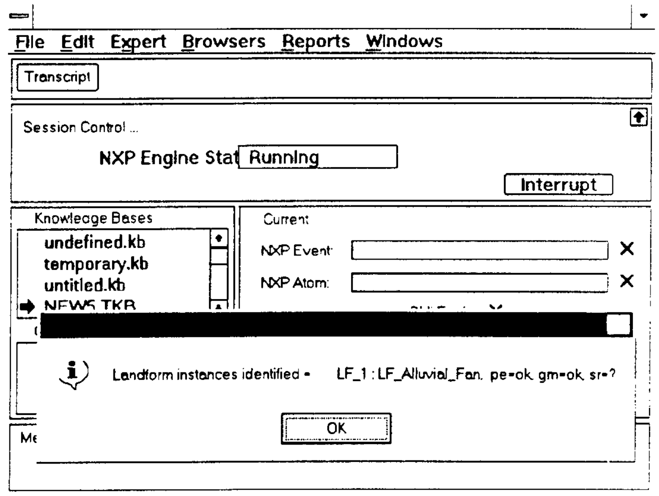


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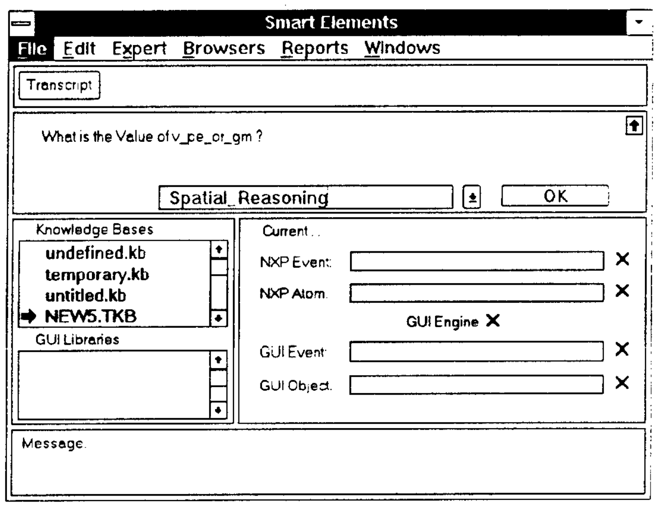


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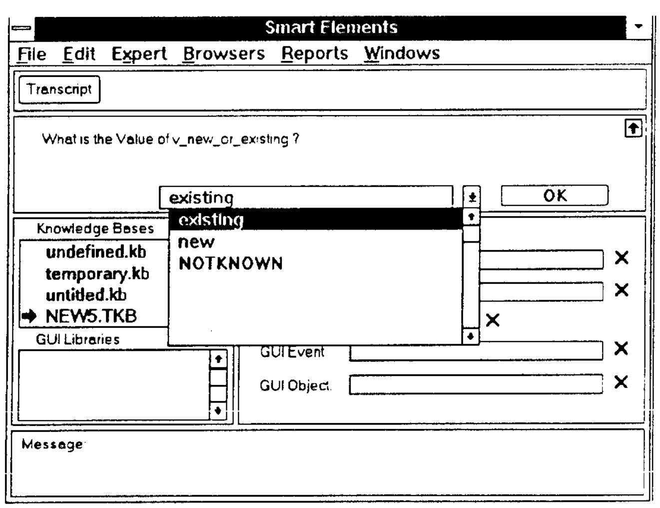


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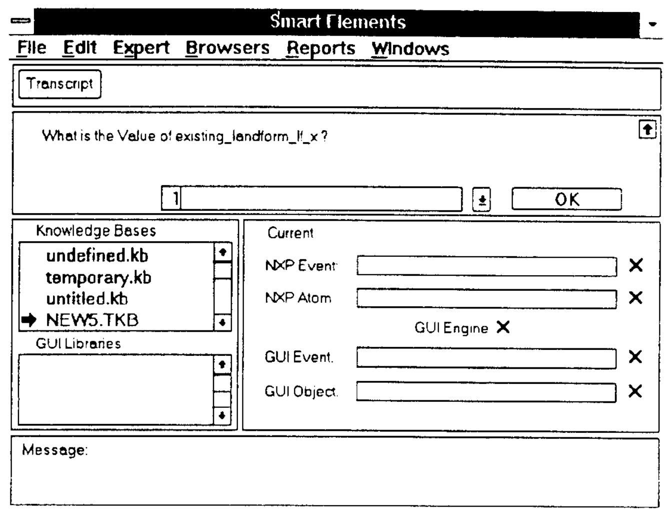


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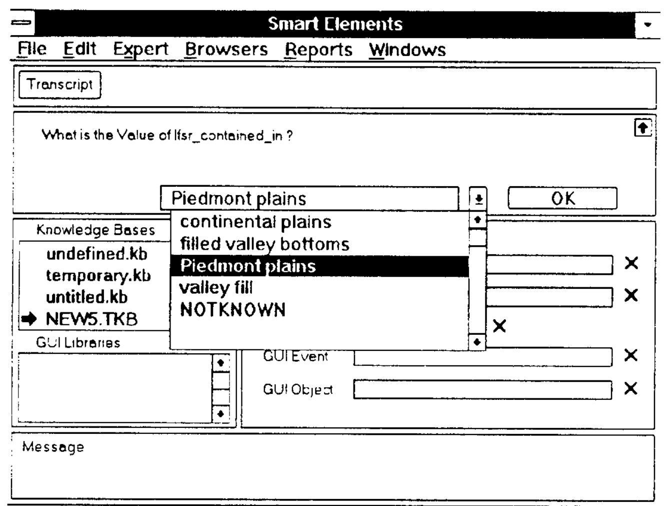


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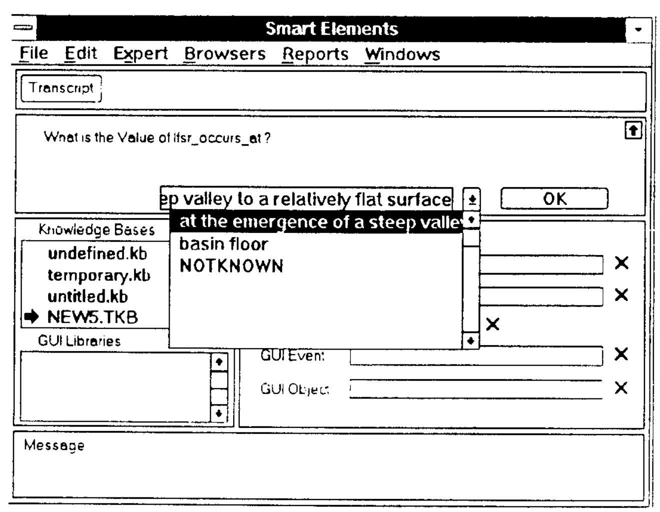


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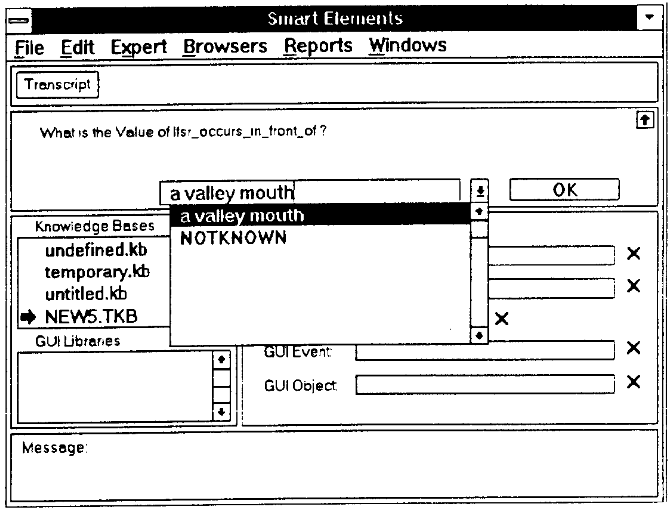


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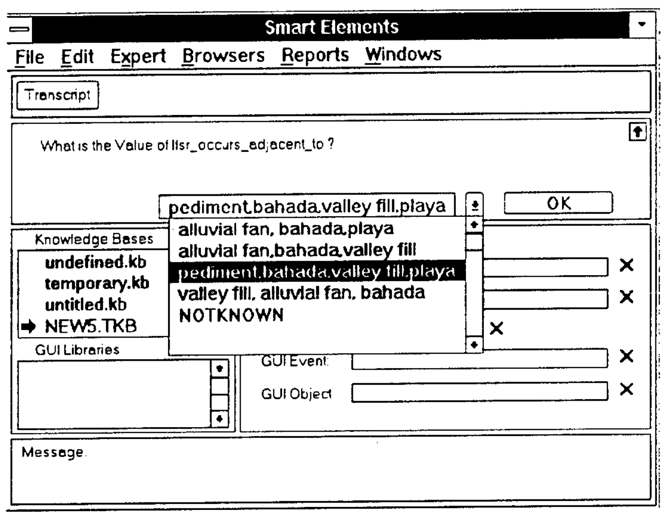


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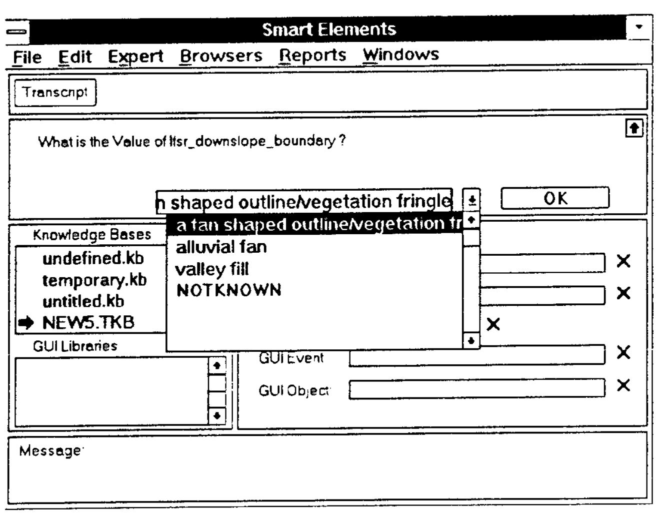


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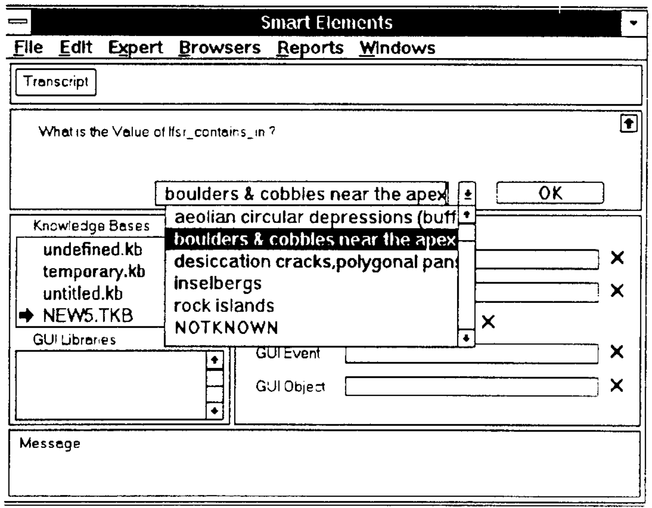


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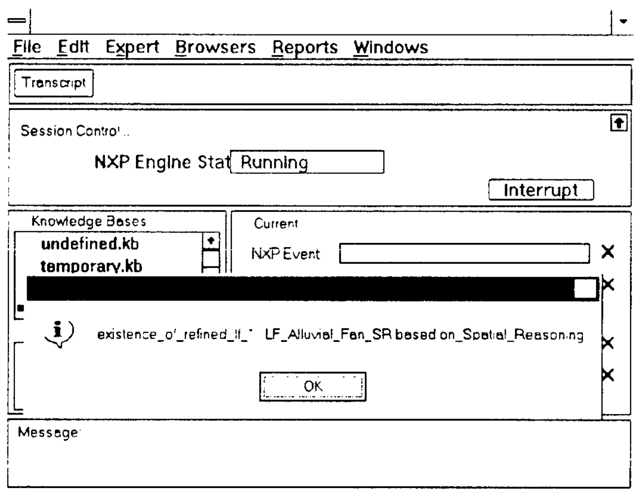


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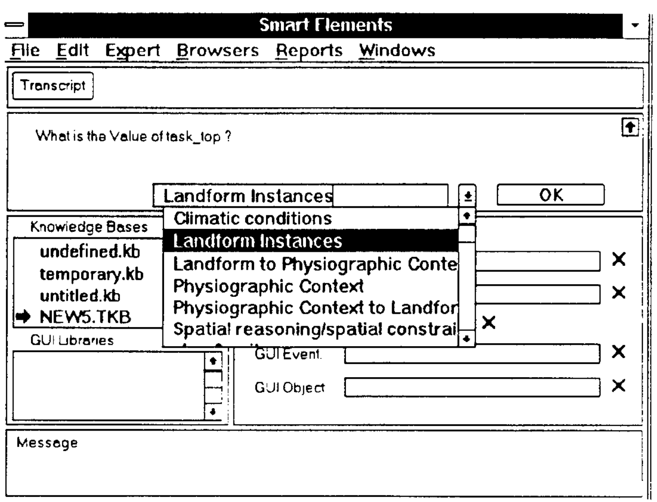


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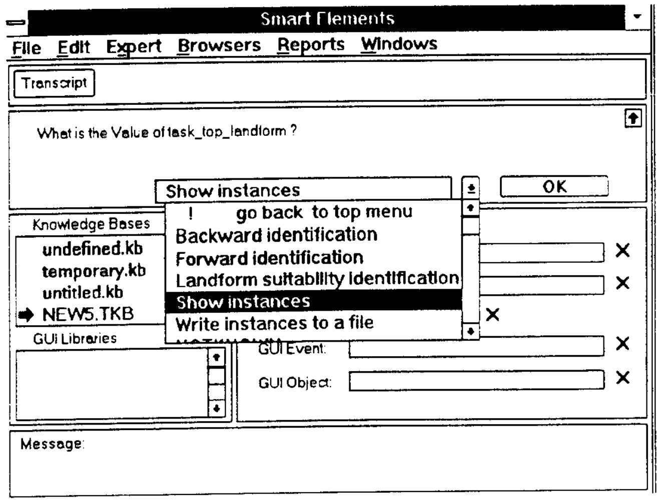


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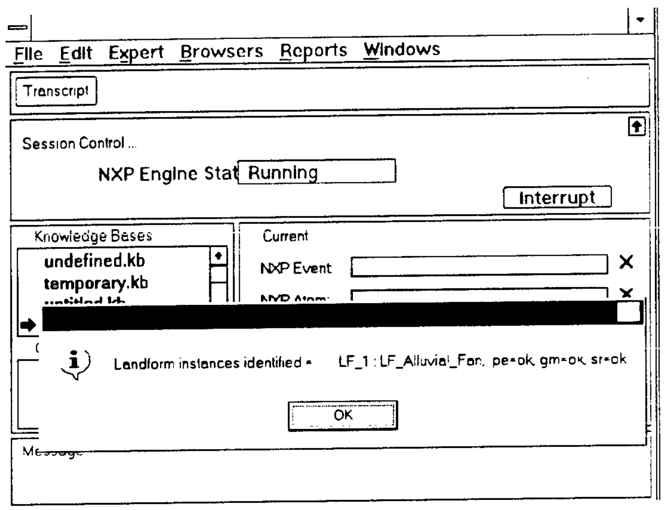


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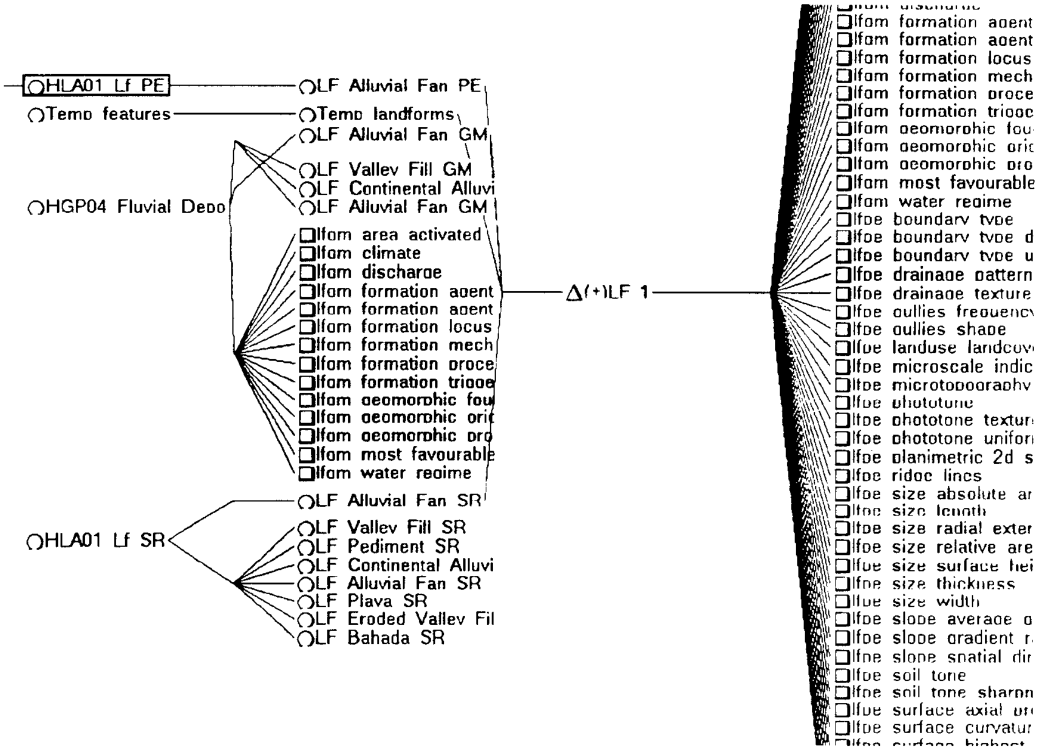


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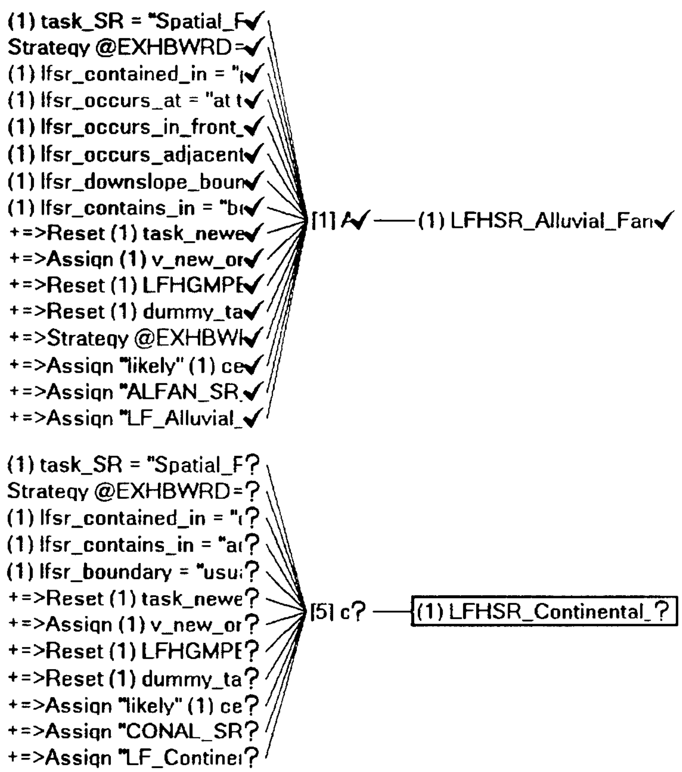



Figure 1-64

## 2. APPENDIX 2

| No | Description / Caption |
|---|---|
| | CASE STUDY: The physiographic context is suggested from an existing landform. (Landform instance to physiographic context instance). The existing landform is an alluvial fan. The topographic form to which the alluvial fan is assigned it is a piedmont slope. The physiographic feature is first determined (it is an Intermontane Basin) and then it is further refined to be of bolson type. At the end, the physiographic context of the Basin and Range is suggested backwardly for evaluation. |
| 1. | Select "Landform to Physiographic Context" option from the main menu |
| 2. | Select "from a previously identified landform" |
| 3. | Specify the existing landform instance (LF_x, where x=1) |
| 4. | ⇒ The specified landform instance LF_1 is an alluvial fan and thus a text about alluvial fans is displayed. |
| 5. | ⇒ Next task: determine the topographic form to which the landform belongs |
| 6. | Select "Deduce" the topographic form (from indicators) |
| 7. | • Select a value for "topographic form occurs downslope of" |
| 8. | • Select a value for "topographic form overall slope gradient" |
| 9. | • Select a value for "topographic form upslope boundary" |
| 10. | • Select a value for "topographic form downslope boundary" |
| 11. | • Select a value for "topographic form overall description" |
| 12. | ♦ Object network showing that the **identified topographic form instance TF_1** contains the previously identified landform instance LF_1. They are also indicated the corresponding classes, that is, the topographic form instance TF_1 is a kind of Piedmont Plain while the landform instance LF_1 is a kind of alluvial fan. |
| 13. | ♦ Rule Network showing few of the rules involved in determining the type of a topographic form assuming that the identity of a landform instance is known. |
| 14. | ⇒ Next task: You should specify the physiographic feature to which TF_1 belongs to. |
| 15. | The physiographic feature can be selected (provided by the user) or deduced by the system after the user provides the indicators of the physiographic feature (part). At this point, the user chose the deduced option. |
| 16. | • Select a value for "physiographic feature overall topographic shape" |
| 17. | • Select a value for "physiographic feature geomorphic origin" |
| 18. | • Select a value for "physiographic feature relative geomorphic size" |
| 19. | • Select a value for "physiographic feature relief order" |
| 20. | • Select a value for "physiographic feature formation process" |
| 21. | • Select a value for "physiographic feature major adjacent topographic feature" |
| 22. | • Select a value for "physiographic feature geomorphic origin of erosional products" |
| 23. | ⇒ **An Intermontane Basin physiographic feature was identified** and a brief description is given.<br>⇒ Next task is the refinement of the Intermontane Basin to bolson or semi-bolson (drainage basin type). |
| 24. | Select to deduce the Intermontane Basin type from own indicators |
| 25. | • Select a value for Presence of an axial stream |
| 26. | • Select a value for Overall topographic shape |
| 27. | • Select a value for Drainage pattern |
| 28. | • Select a value for Presence of destructive erosion |
| 29. | • Select a value for Topographic possibility of external drainage |
| 30. | ⇒ **An intermontane basin of bolson type was identified**. The hypothesis |

| | |
|---|---|
| | of the physiographic context of Basin and Range is suggested backwardly for evaluation and therefore the user will be prompted for the values of the physiographic indicators. It is suggested that the intermontane basin is rather an instance of a youthful erosion stage (Great Basin). |
| 31. | ♦ Object network showing that the newly **identified physiographic feature PF_1 is a kind of intermontane basin of bolson type** that contains the topographic form instance TF_1. The last contains the previously identified landform instance LF_1. They are also indicated the corresponding classes, that is, the topographic form instance TF_1 is a kind of Piedmont Plain, while the landform instance LF_1 is a kind of alluvial fan. |
| 32. | ♦ Rule Network showing few of the rules involved in determining the type of a physiographic feature assuming that the identity of a topographic form instance is known. |
| • | COMMENT: As suggested in #30 the user will be prompted for the values of the physiographic indicators as follows. |
| 33. | • Select a value for Frequency of Mountain ranges |
| 34. | • Select a value for Geomorphic origin of Mountain ranges |
| 35. | • Select a value for Relative relief of the region |
| 36. | • Select a value for Relative proportion of Ranges versus Plains versus Piedmonts |
| 37. | ⇒ Verification of the existence of a Basin & Range class instance (note: the refinement to either youthful of maturity stage failed due to the values selected for the physiographic indicators - not showing here). |
| 38. | ♦ Object network showing that the newly **identified physiographic region PH_1 is a kind of Basin & Range** that contains the physiographic feature PF_1, which contains topographic form instance TF_1. The last contains the previously identified landform instance LF_1. They are also indicated a number of the attributes of these objects. |
| 39. | ♦ Rule Network showing few of the rules involved in determining the type of a physiographic region (Basin and Range here). |
| 40. | The user selects the "Show physiographic context instances" option |
| 41. | ⇒ The system responds that has **identified the physiographic region instance PH_1** which is a kind of Basin and Range. |

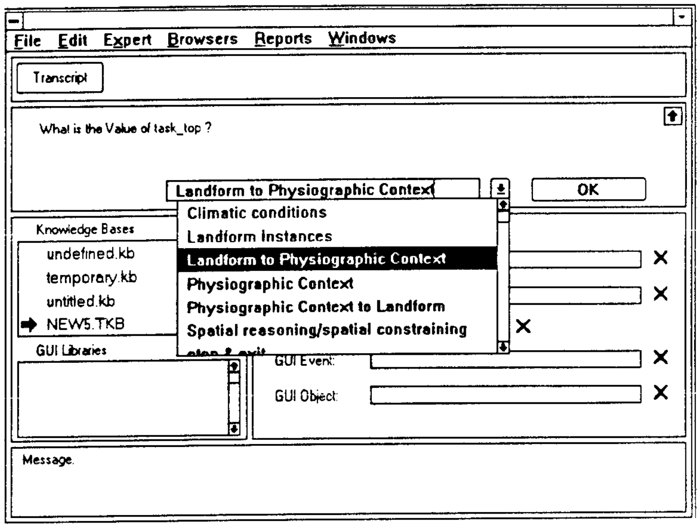
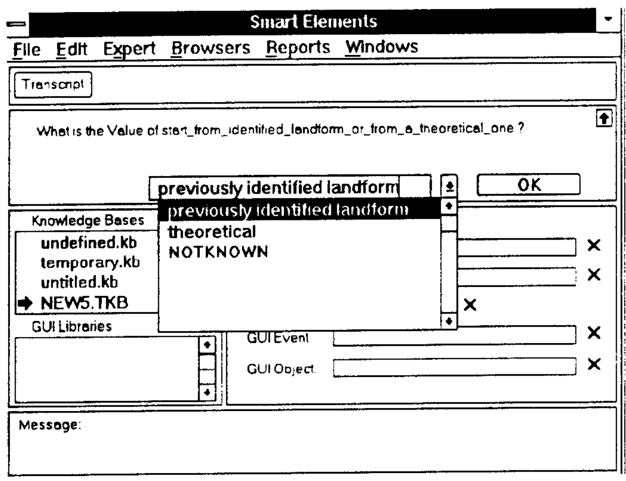



Figure 2-1

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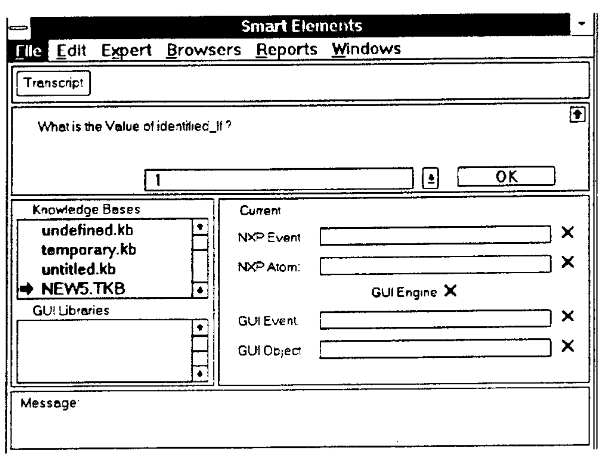


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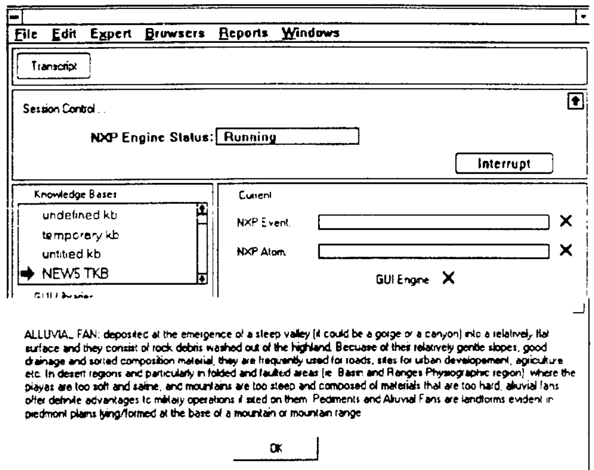


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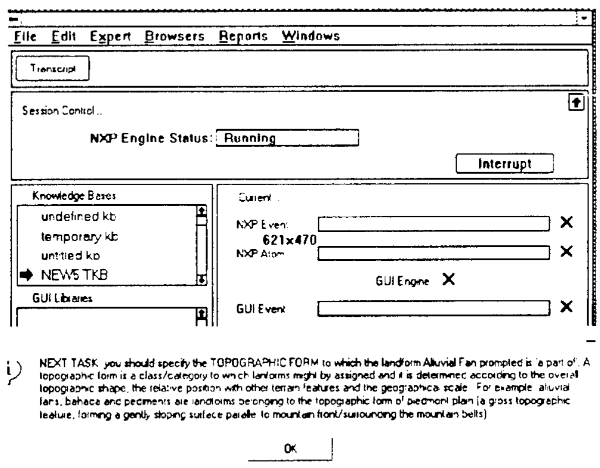


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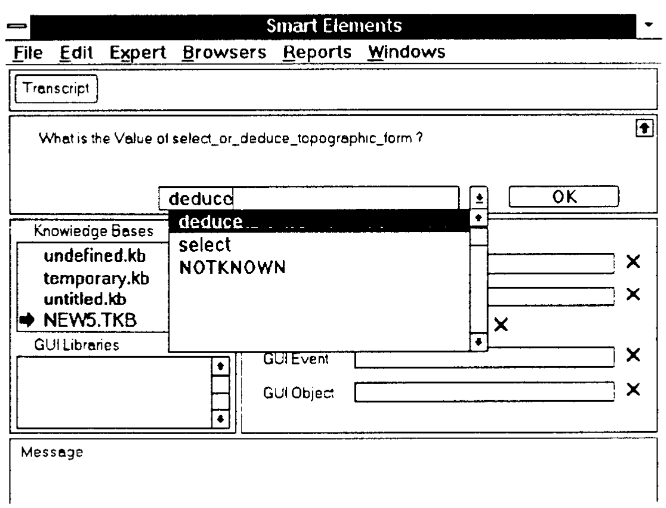


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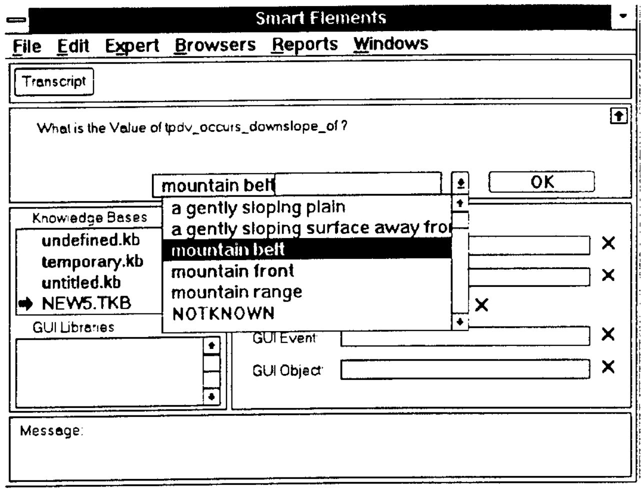


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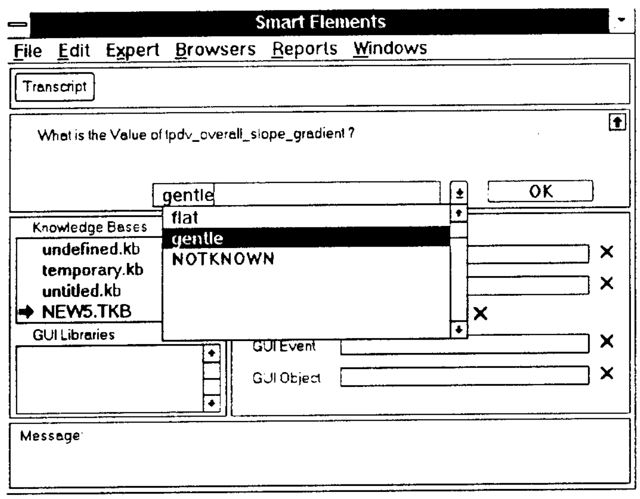


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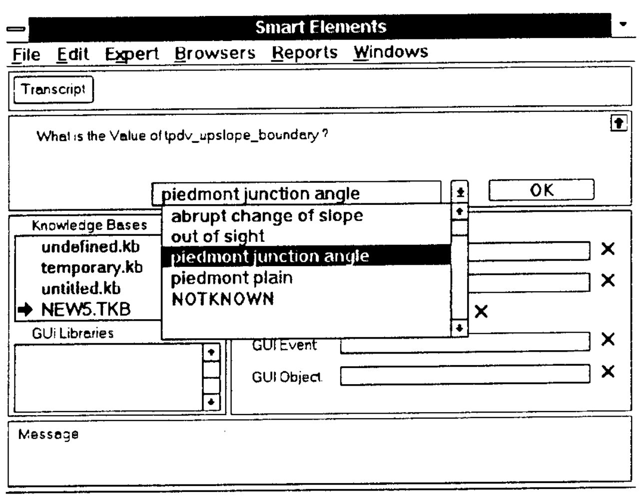


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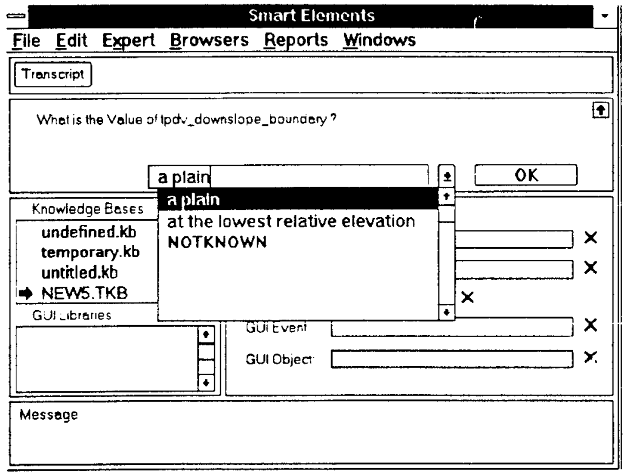


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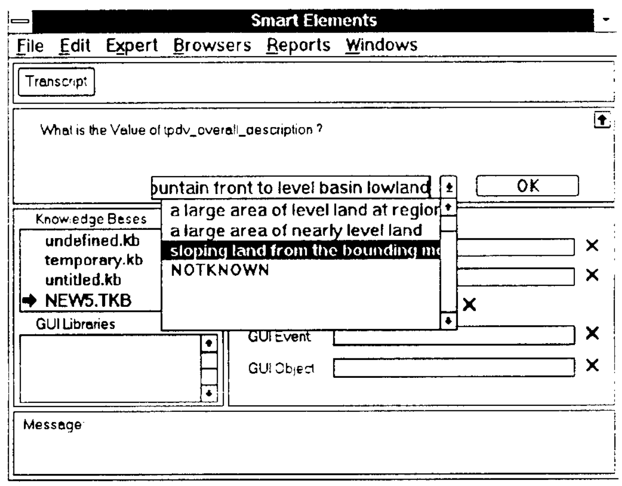


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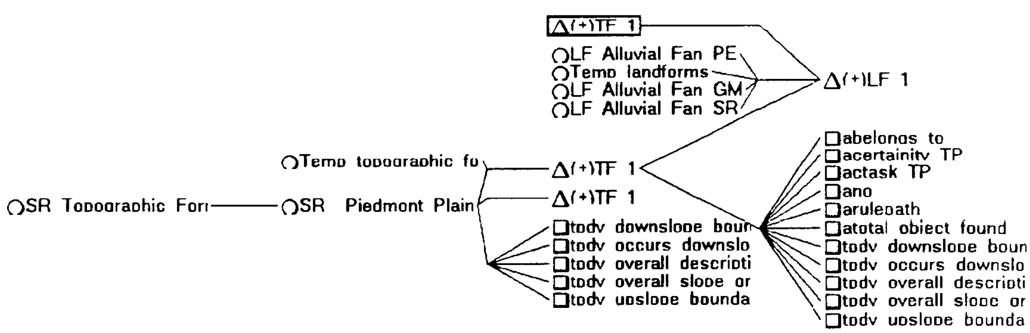


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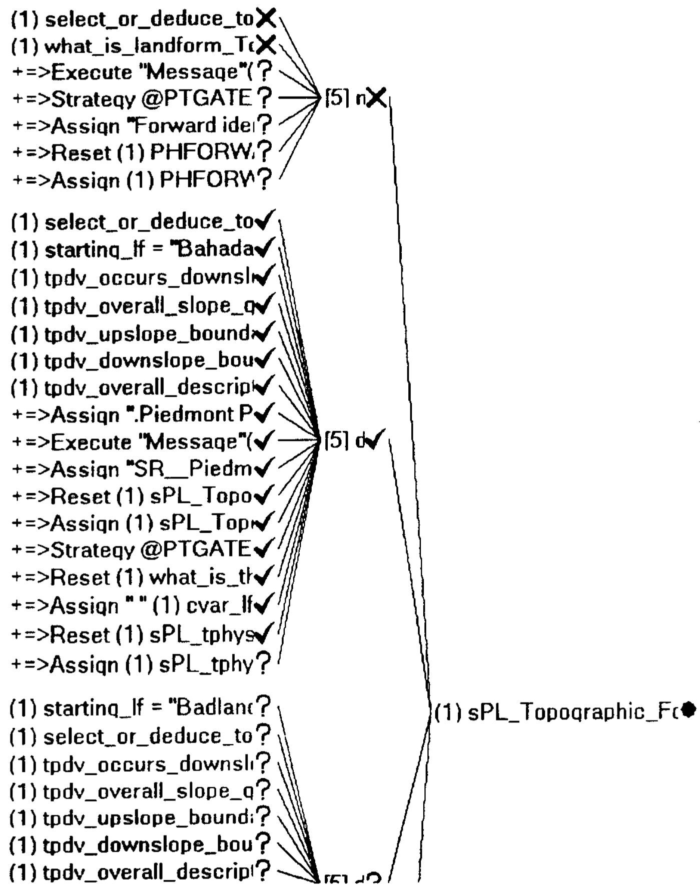


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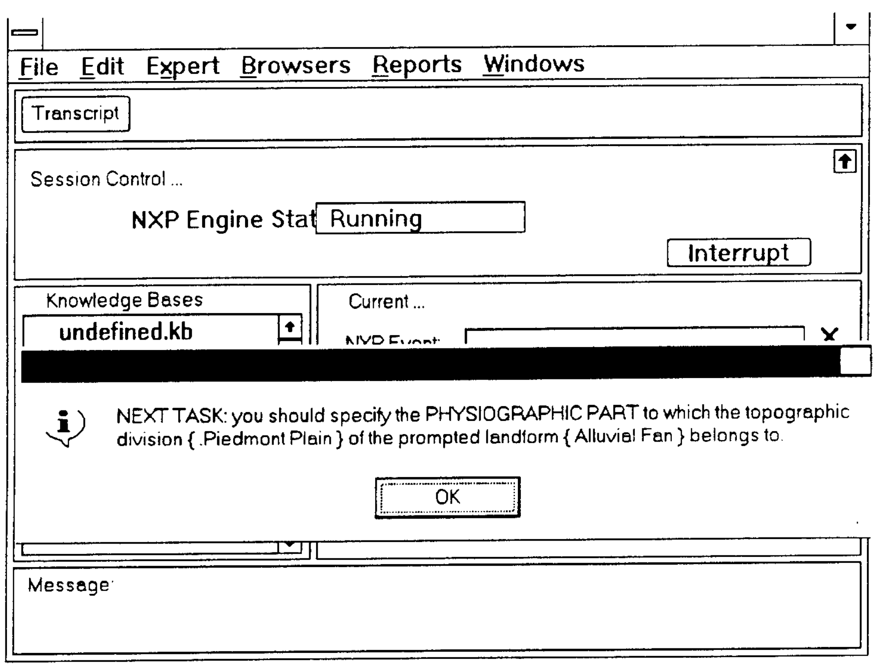


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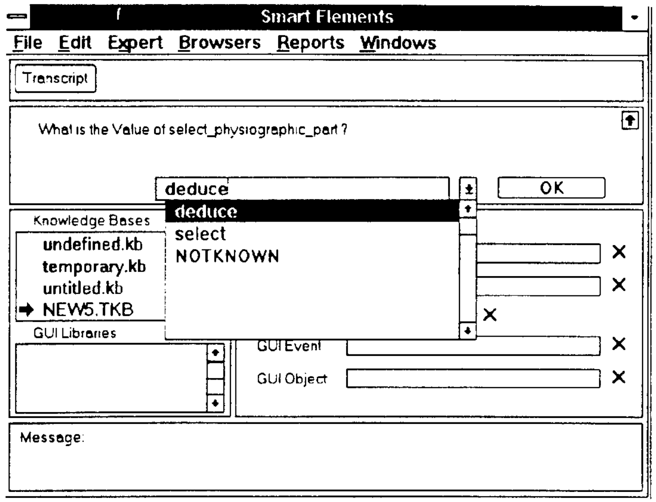


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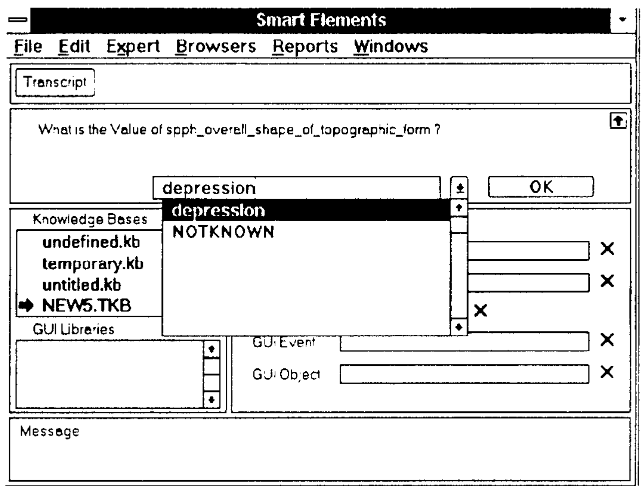


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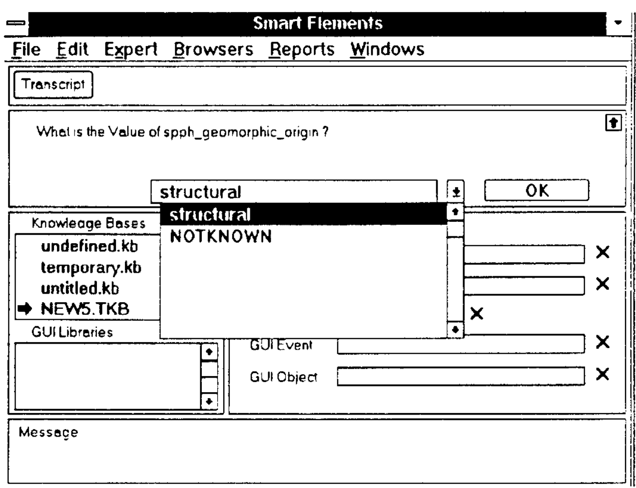


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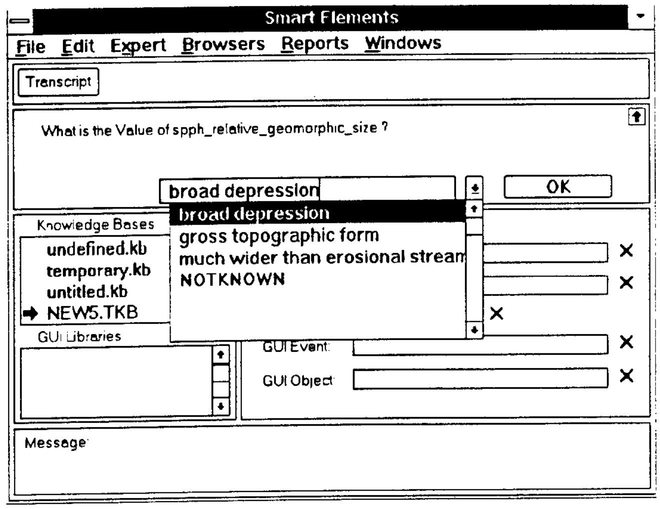


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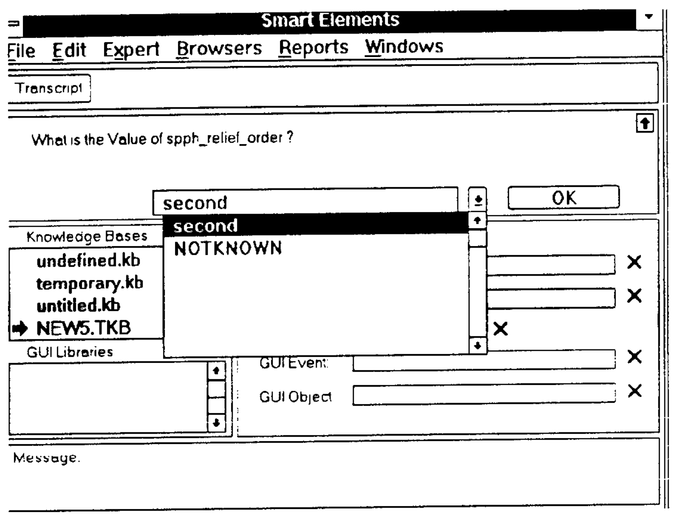


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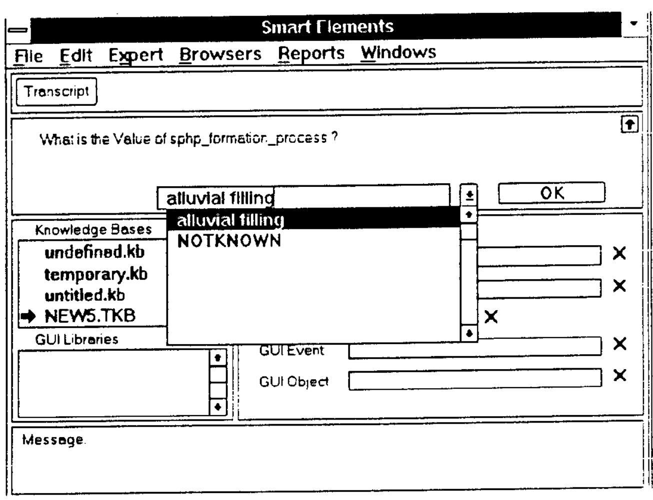


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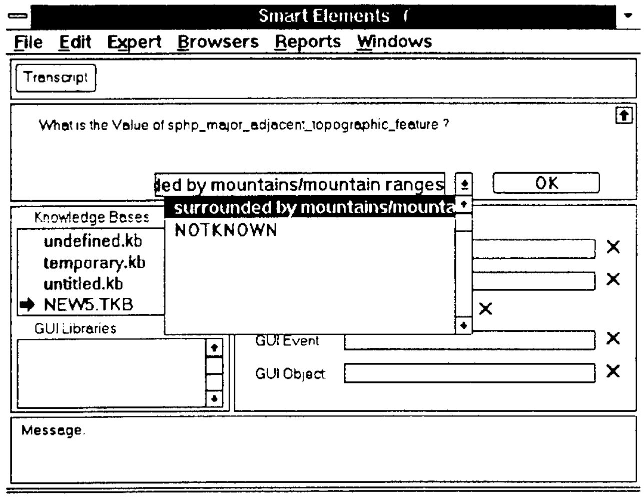


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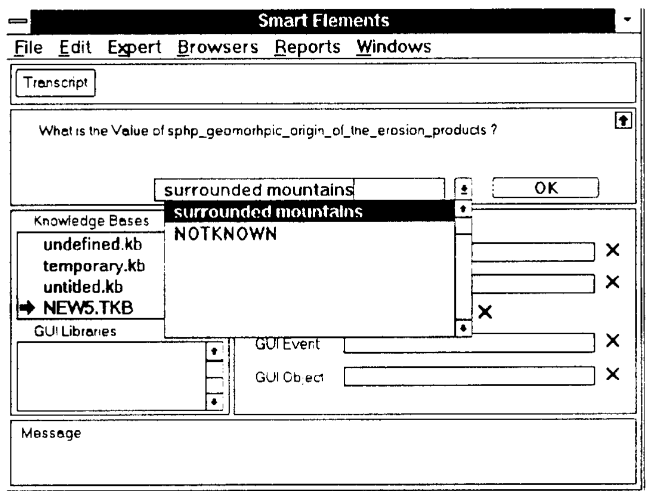


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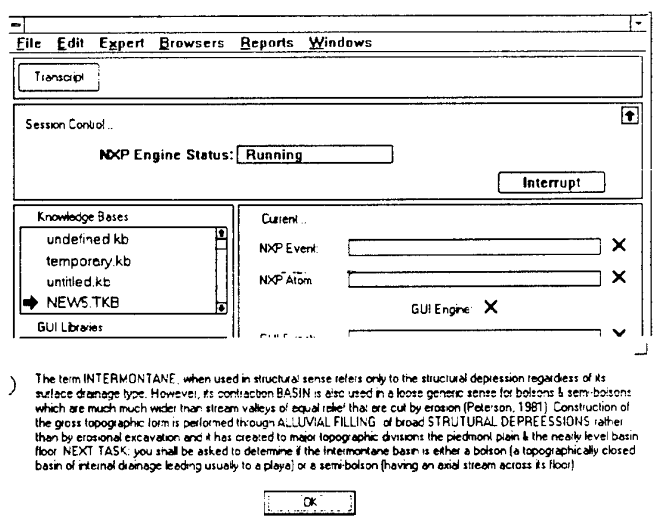


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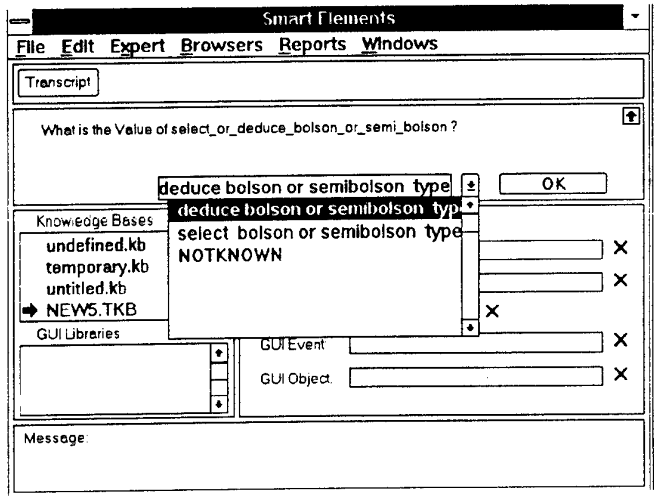


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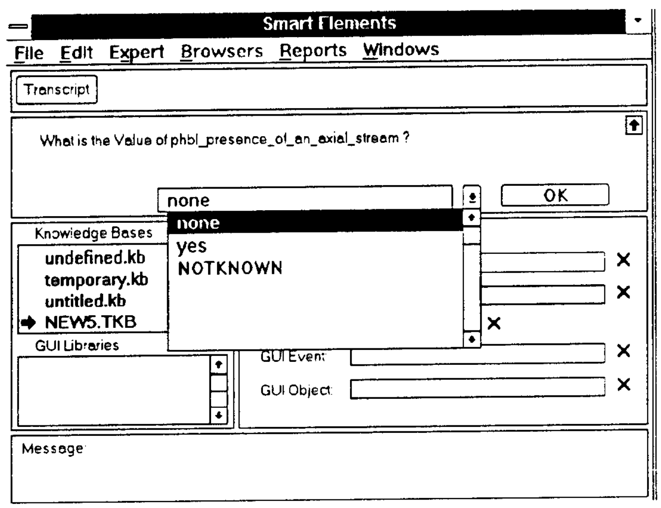


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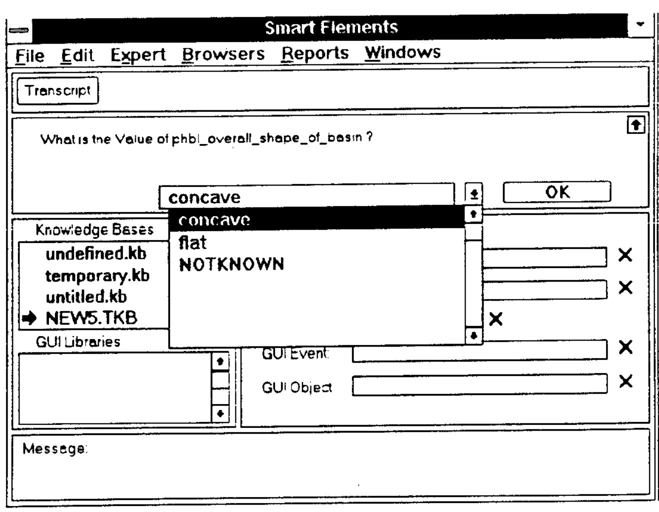


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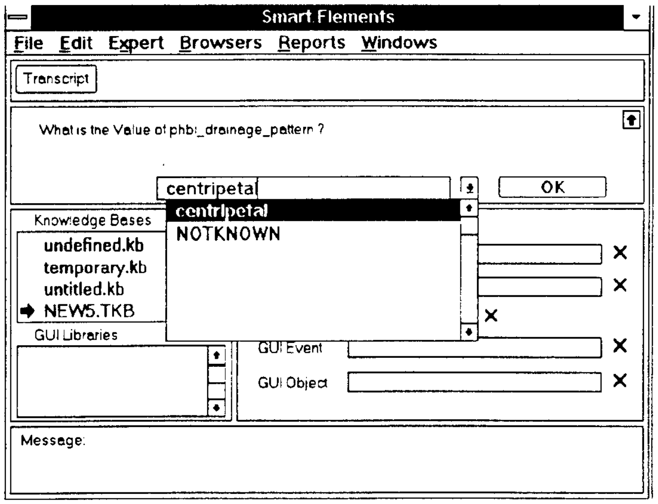


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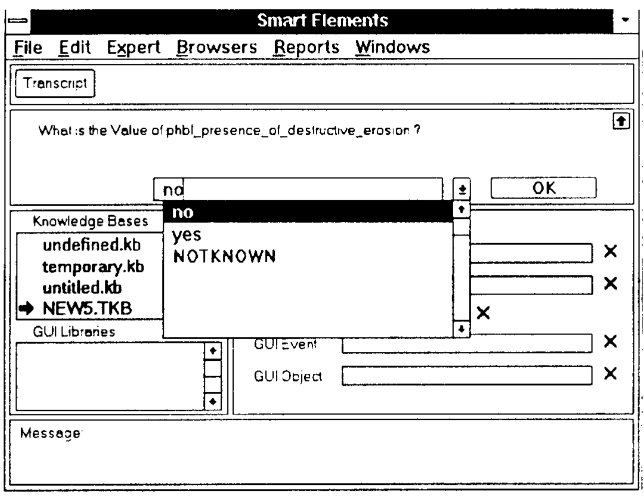


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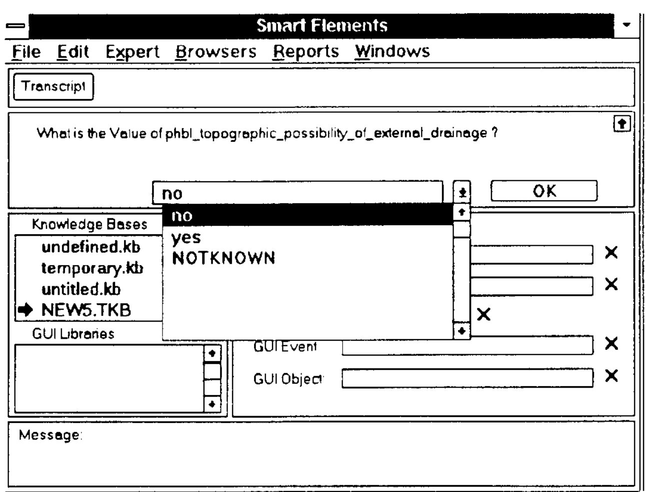


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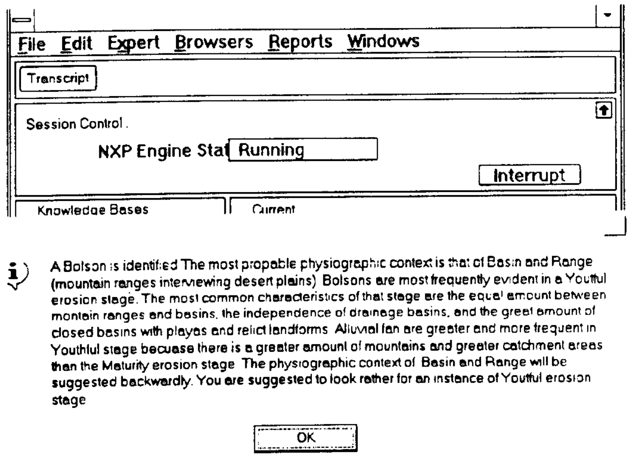


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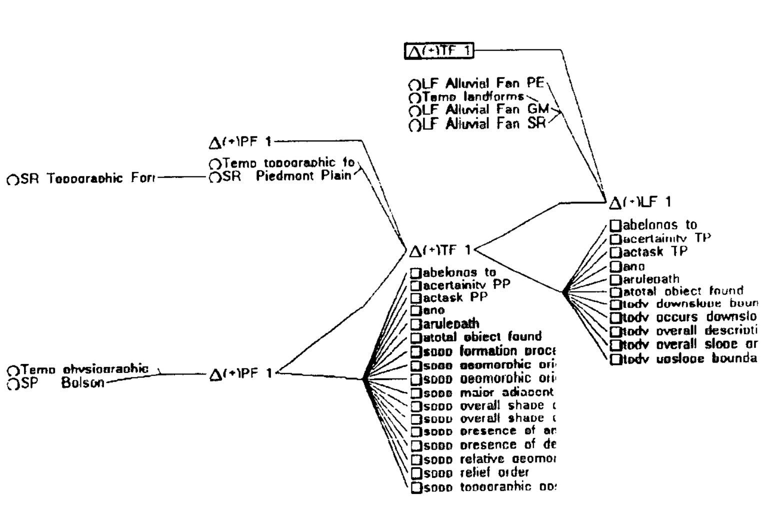


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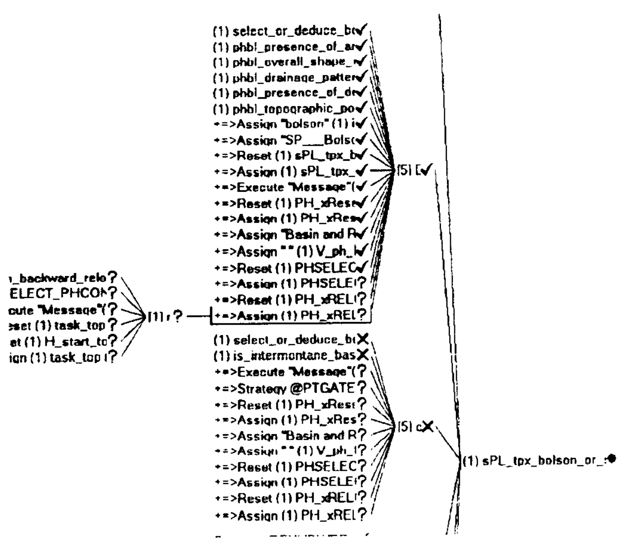


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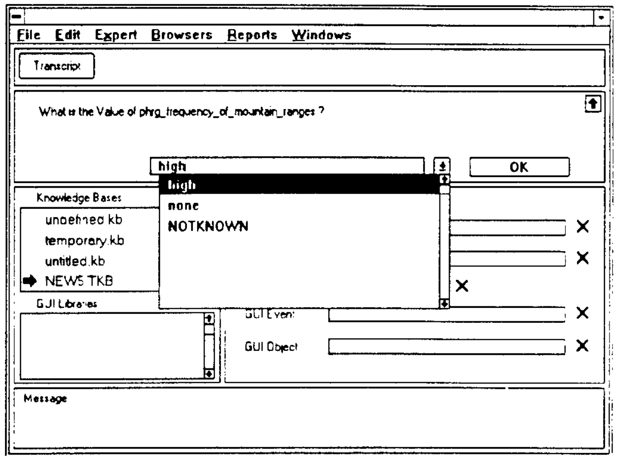


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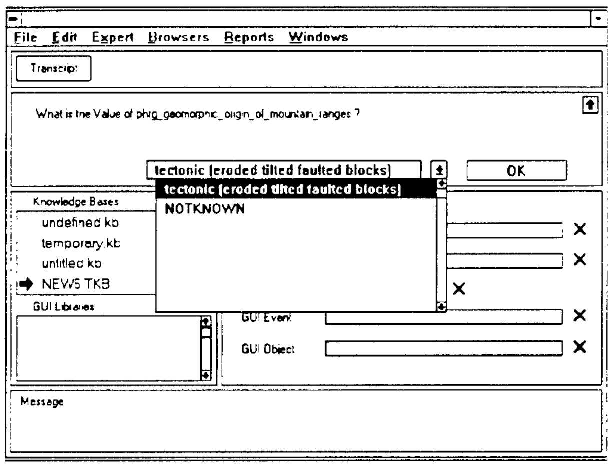


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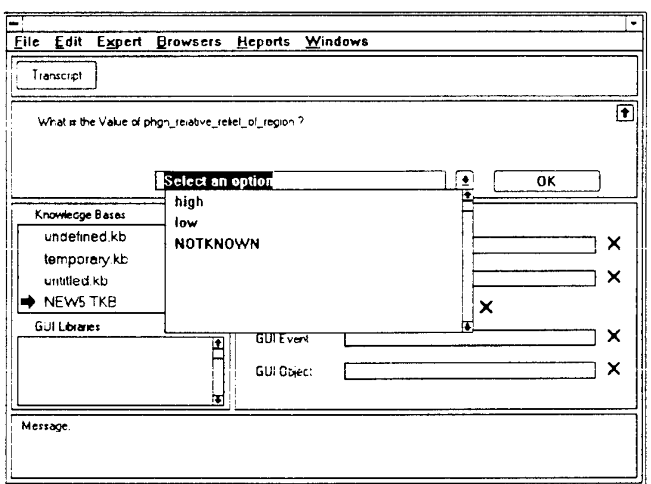


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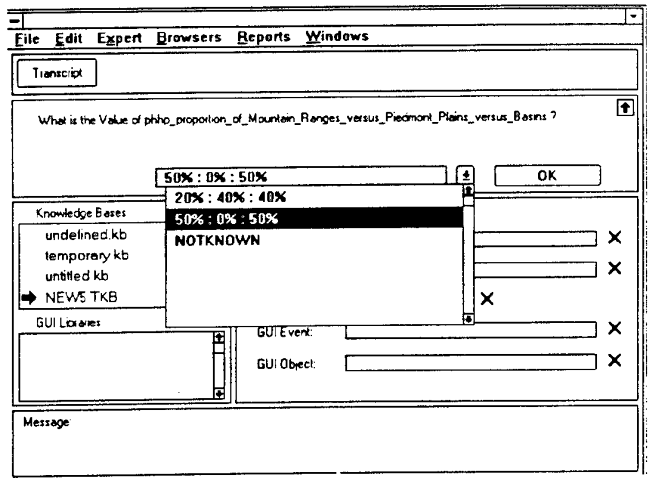


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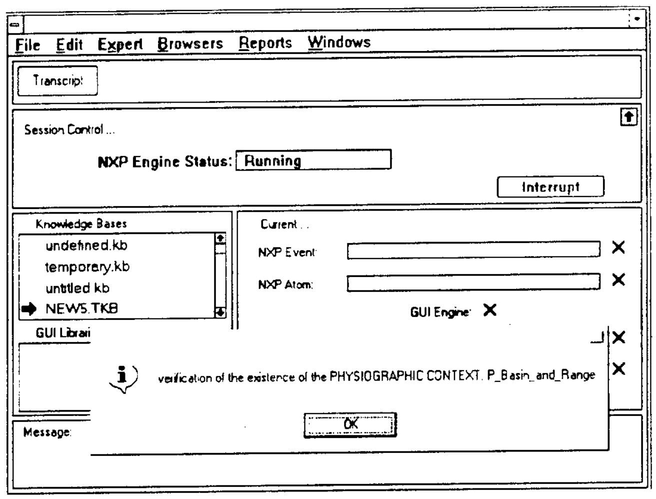


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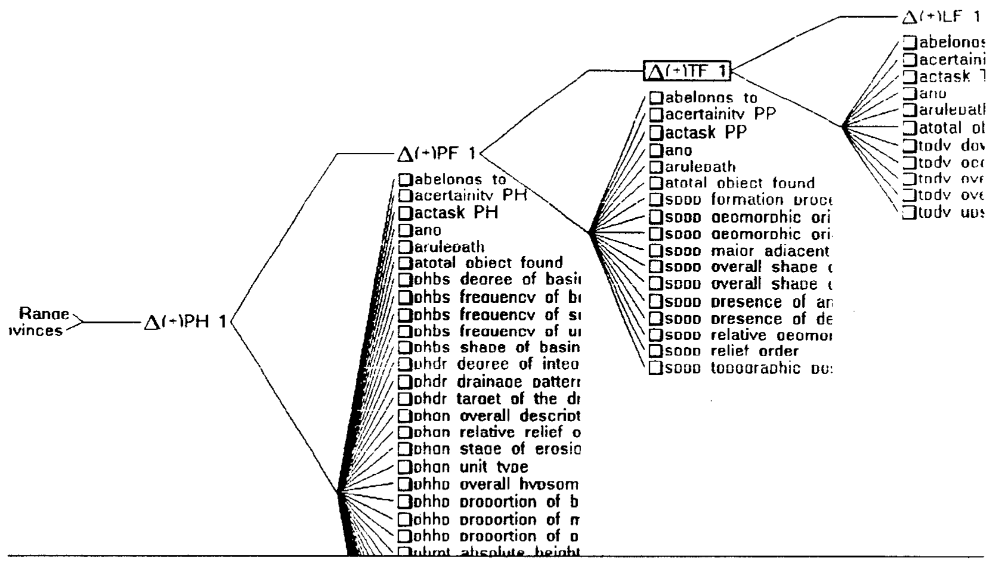


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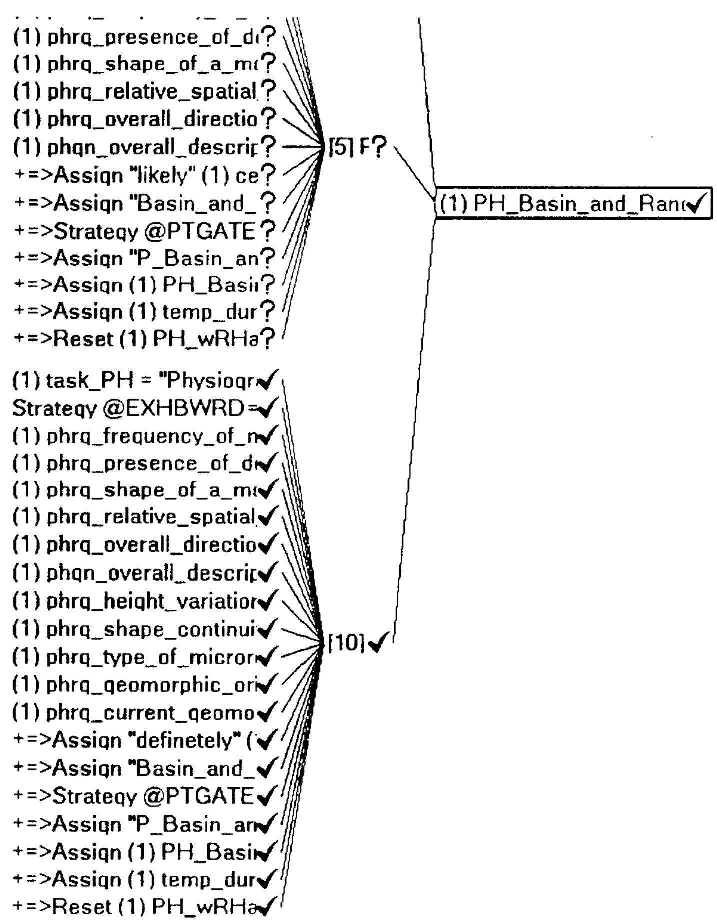


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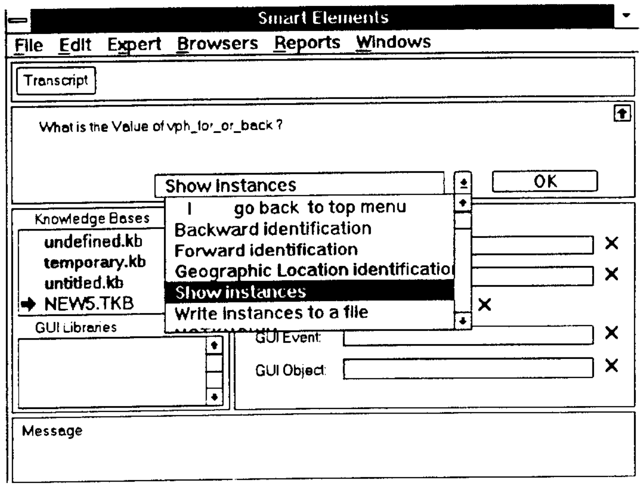


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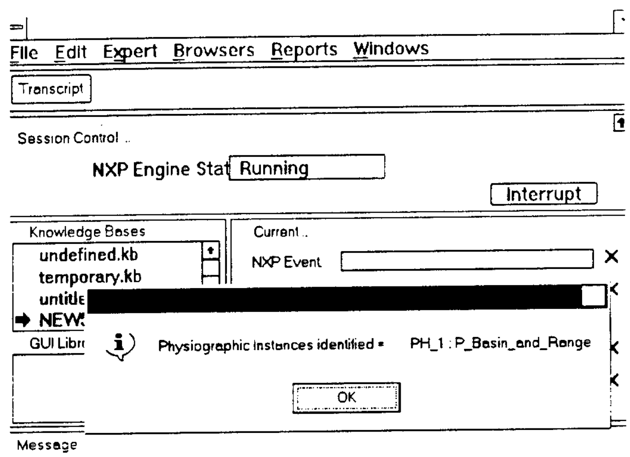



Figure 2-41

# 3. APPENDIX 3

| CASE STUDY: The determination of the physiographic context from physiographic indicators | |
|---|---|
| **No** | **Description / Caption** |
| 1. | Select from the main menu "Physiographic context" identification |
| 2. | Select "Forward identification" |
| 3. | • Select a value for Frequency of mountain ranges |
| 4. | • Select a value for Presence of desert basins |
| 5. | • Select a value for Shape of mountain ranges |
| 6. | • Select a value for Relative spatial position of mountain ranges |
| 7. | • Select a value for Overall direction of mountain ranges |
| 8. | • Select a value for Overall description |
| 9. | • Select a value for Height variation within mountain ranges |
| 10. | • Select a value for Shape continuity of mountain ranges |
| 11. | • Select a value for Microrelief dissection in mountain ranges |
| 12. | • Select a value for Geomorphic origin of mountain ranges |
| 13. | • Select a value for Current geomorphic process in mountain ranges |
| 14. | • Select a value for Relative relief of the region |
| 15. | • Select a value for Relative proportion of Ranges versus Basins versus Piedmont plains |
| 16. | • Select a value for Relative size of mountains |
| 17. | • Select a value for Slope change at piedmont angle |
| 18. | • Select a value for Absolute height of mountains |
| 19. | • Select a value for overall hypsometric distribution within the section |
| 20. | • Select a value for drainage pattern |
| 21. | • Select a value for degree of integration of drainage pattern |
| 22. | • Select a value for stage of erosion cycle |
| 23. | • Select a value for degree of drainage basin integration |
| 24. | • Select a value for frequency of bolsons |
| 25. | • Select a value for shape of basins |
| 26. | • Select a value for outlet of the drainage network |
| 27. | ⇒ Verification of the **Physiographic Context Basin & Range Youthful stage** |
| 28. | ♦ Object network showing the creation of the **newly identified physiographic region instance PH_2** which was determined to be a kind of Basin & Range, in particular a kind of the youthful stage of Basin and Range. It is noticed that the earlier identified physiographic region instance PH-1 had as parent class only the Basin and Range Concept, while the newly identified physiographic region instance PH_2 has as parent class the Basin and Range Youthful Stage which is a specialization of the Basin and Range class. In the first case only the rule concerning the Basin and Range Hypothesis was fired, while in the second case, in addition to this rule, was also fired the rule concerning the Basin and Range Youthful Stage Hypothesis. In the first case they were used 4 physiographic indicators, while in the second case they were used 24 physiographic indicators. The reason being that the user did not recognize the whole set of indicators in the earlier example, while he did in the second case. |
| 29. | Select "Show Instances" |
| 30. | **PH_2= Basin and Range Youthful stage instance** |

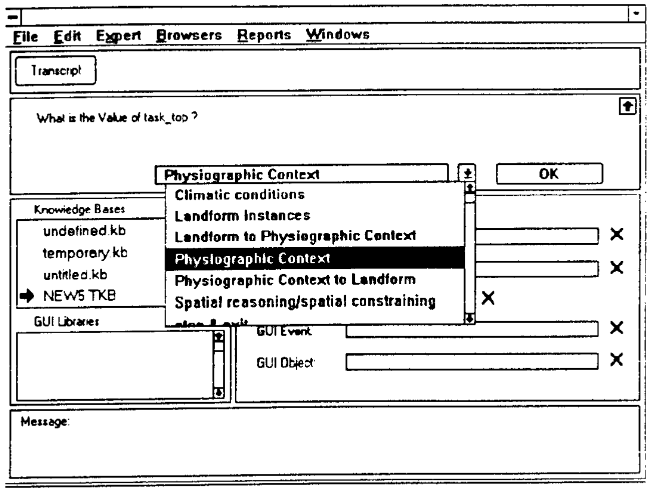
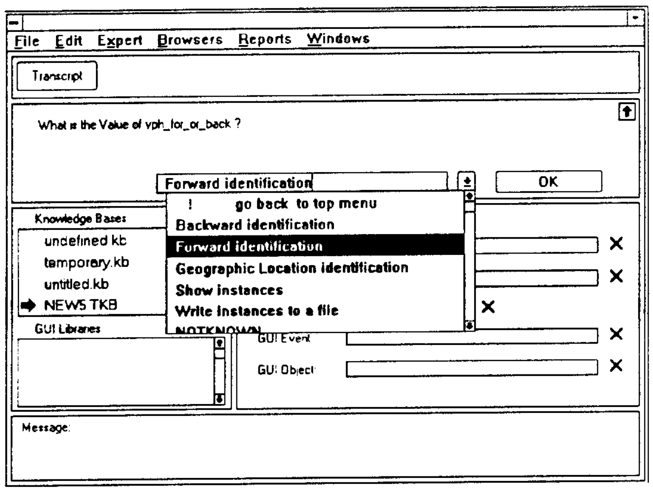



Figure 3-1

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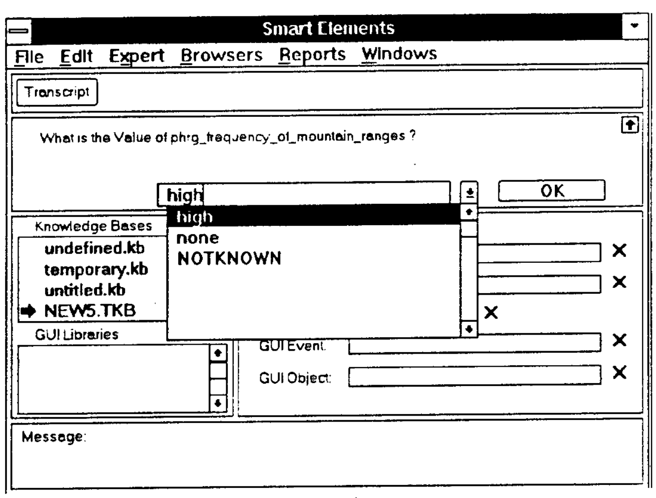


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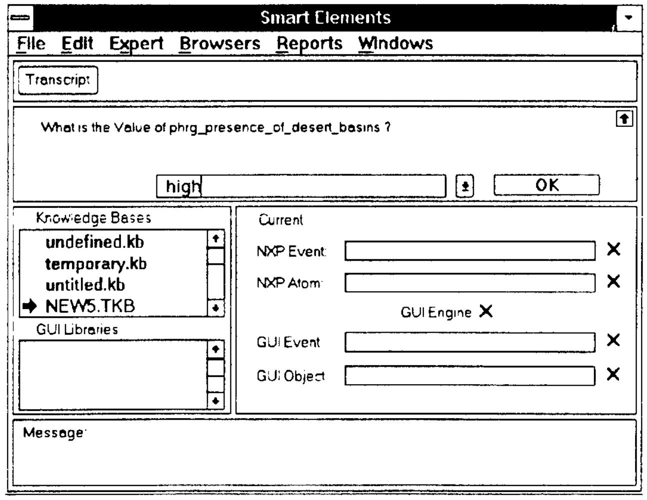


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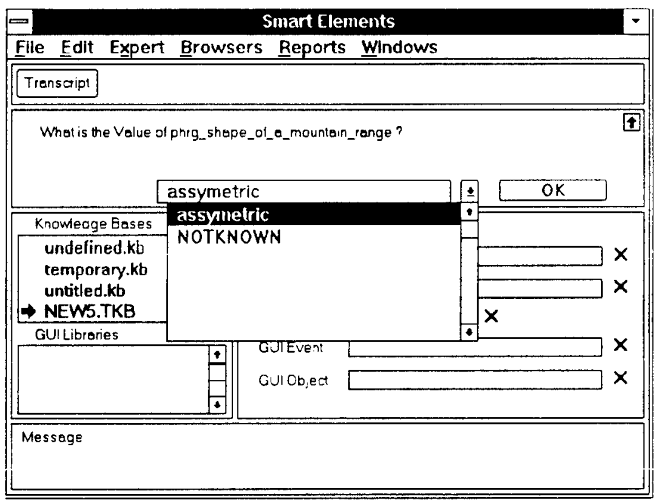


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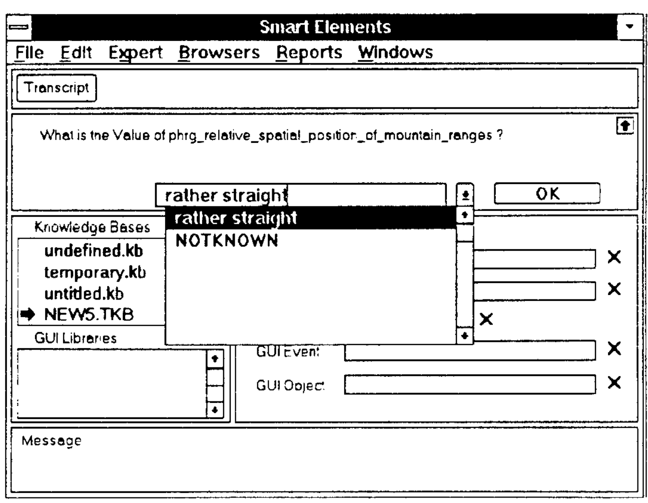


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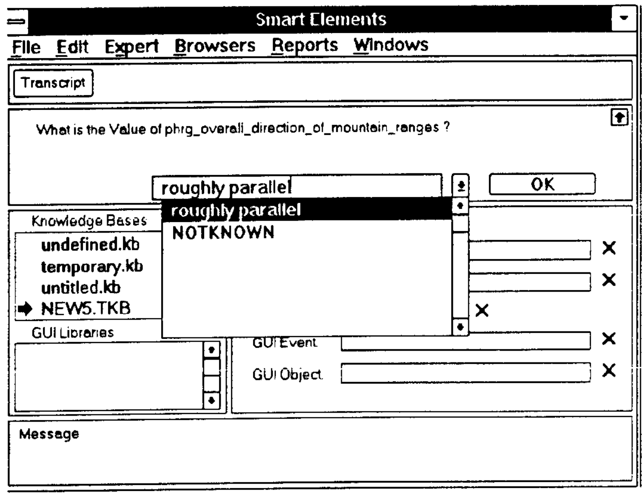


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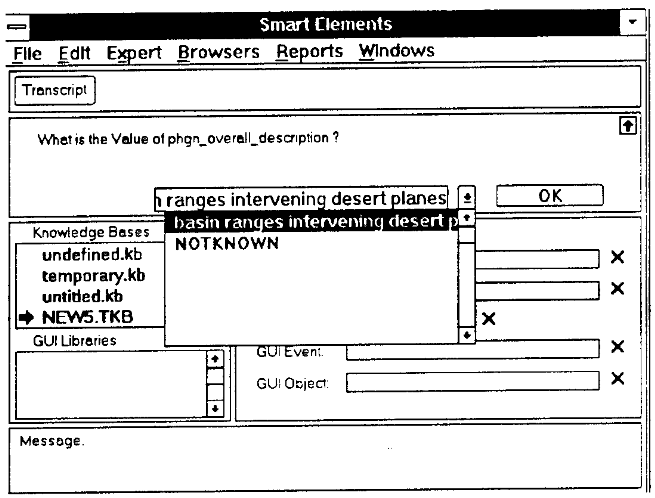


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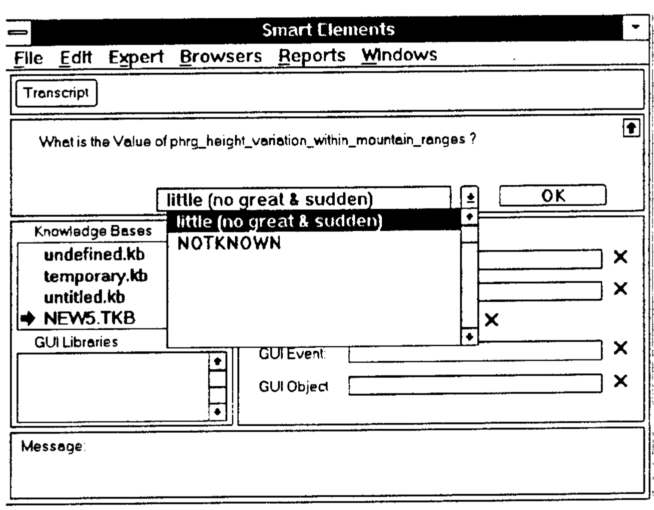


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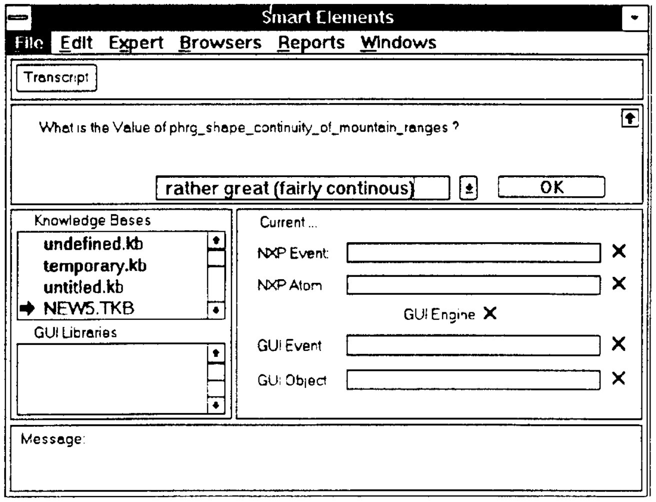


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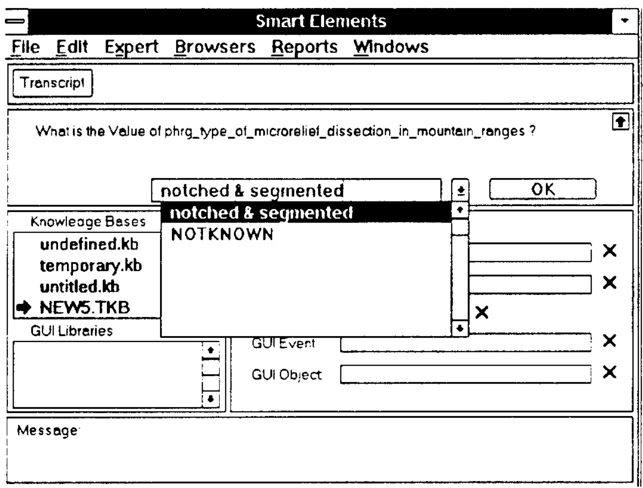


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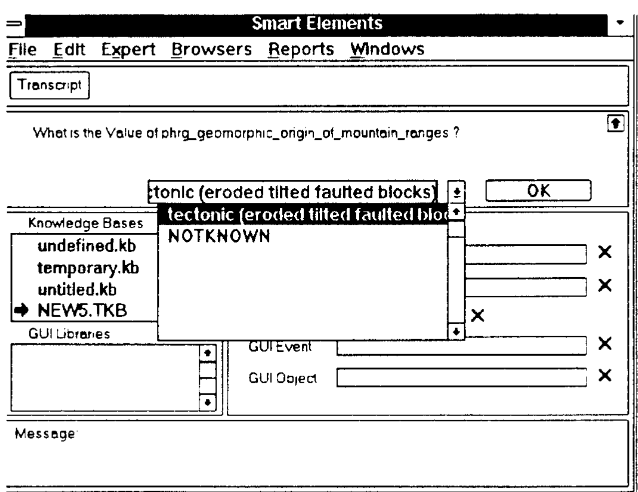


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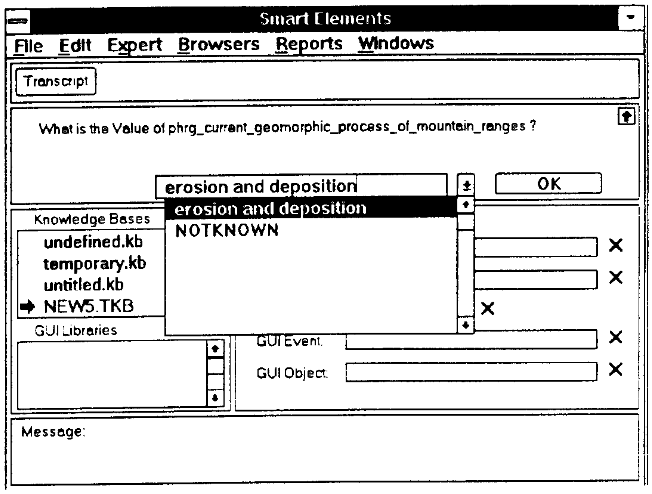


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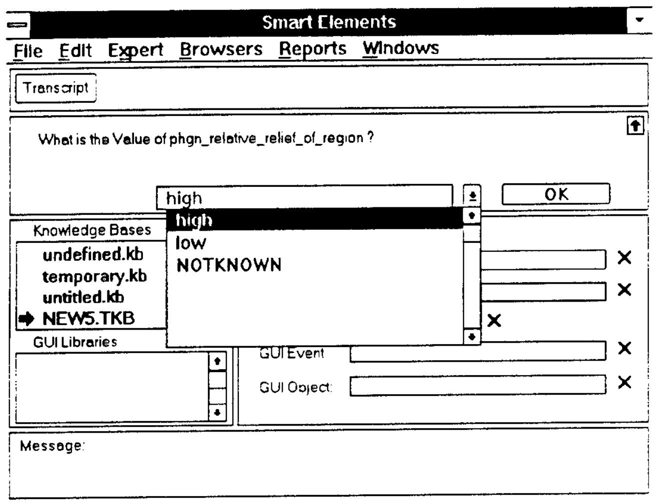


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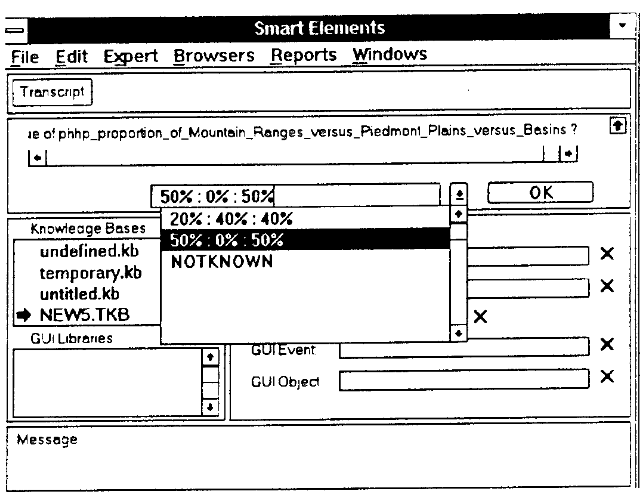


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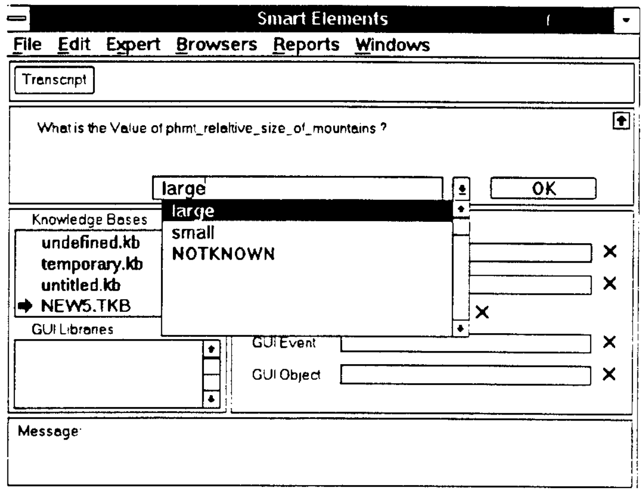


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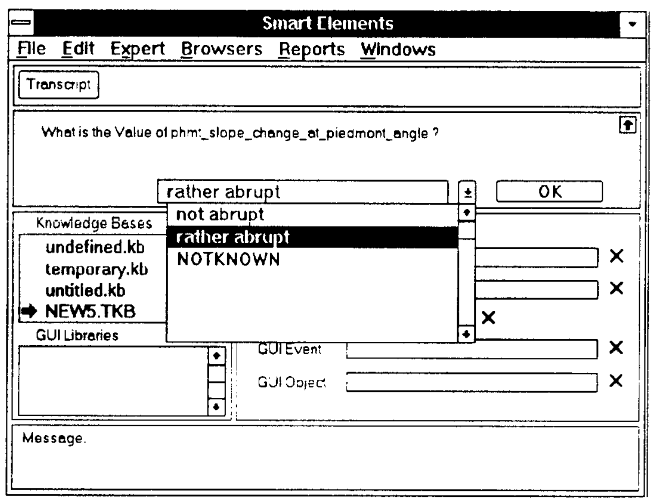


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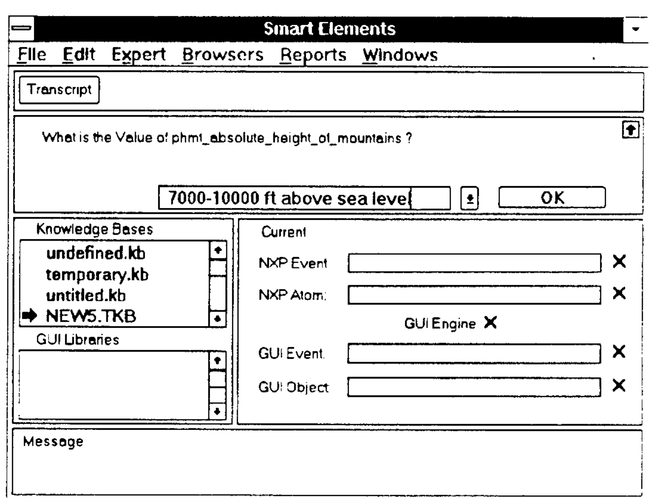


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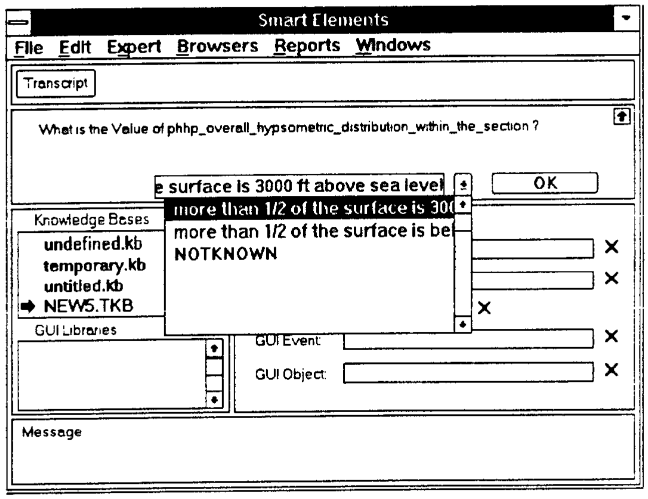


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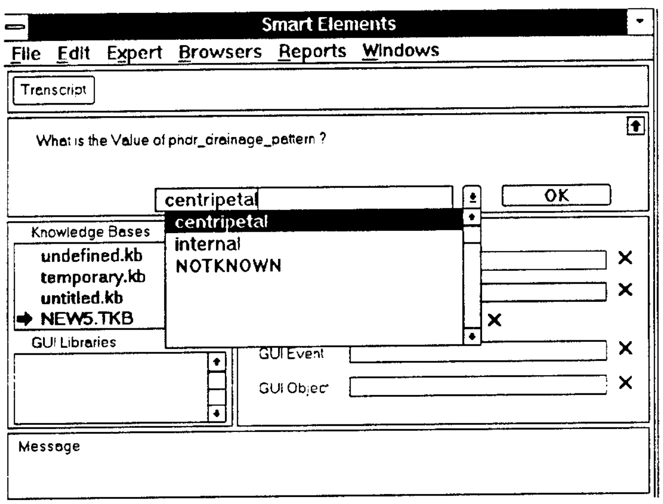


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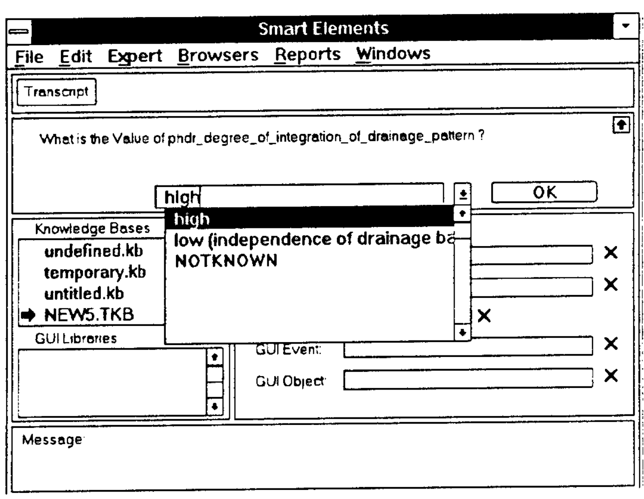


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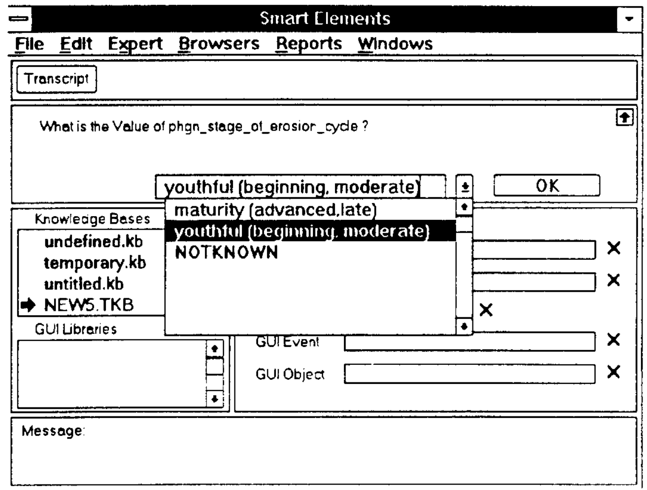


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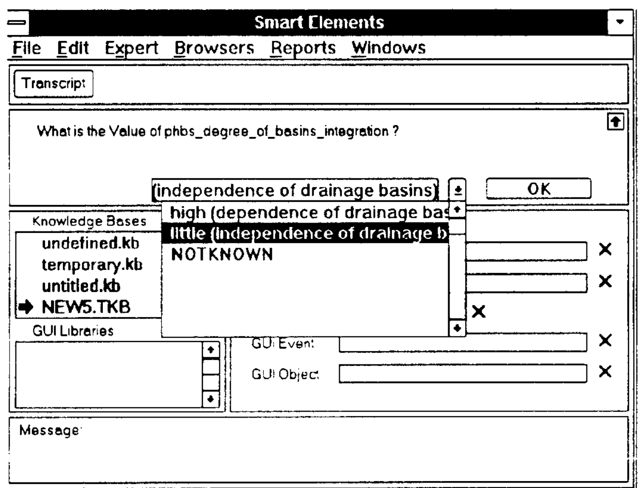


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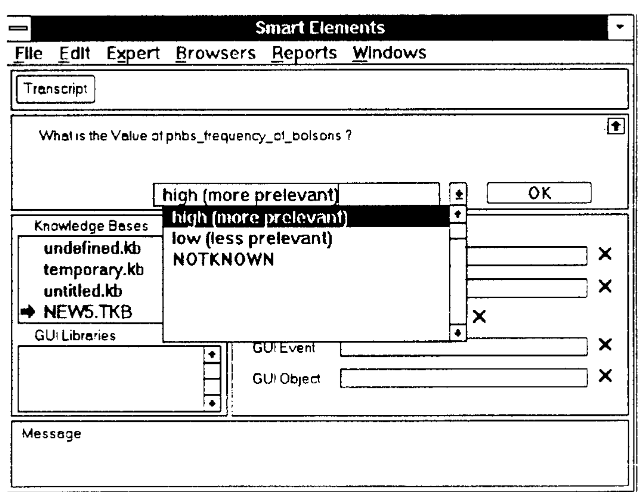
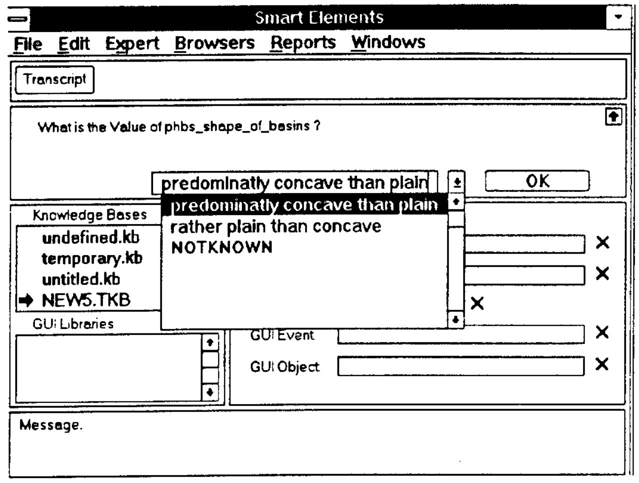



Figure 3-24

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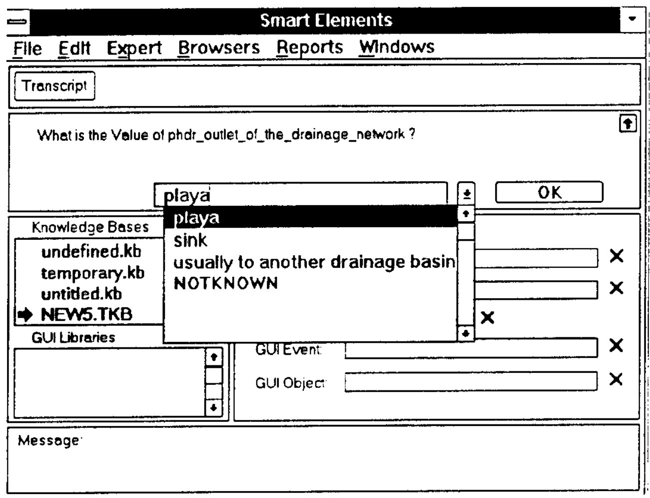



Figure 3-26

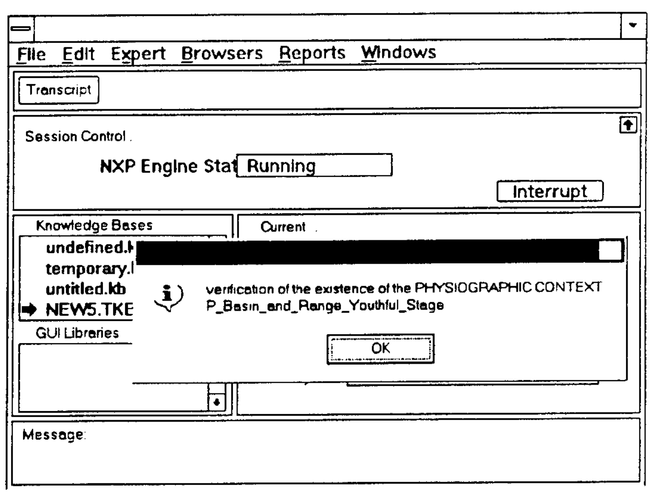
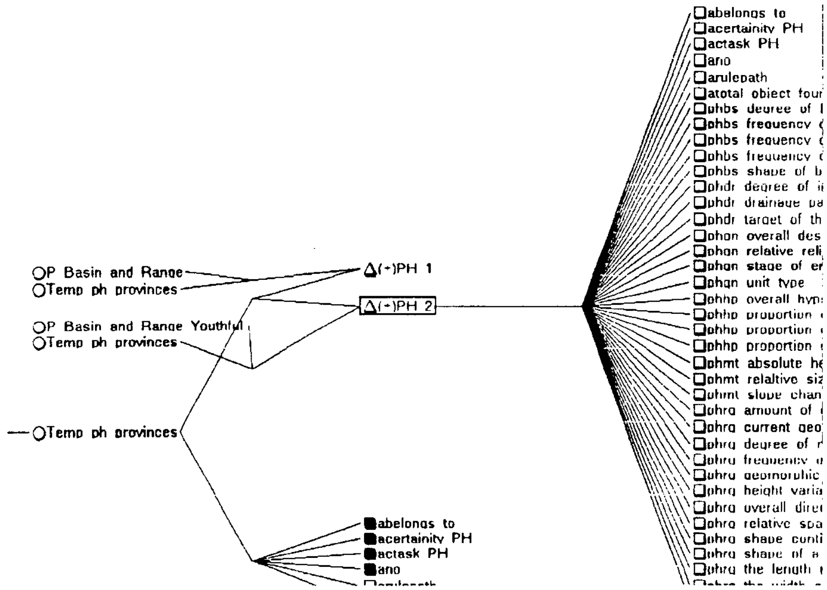



Figure 3-27

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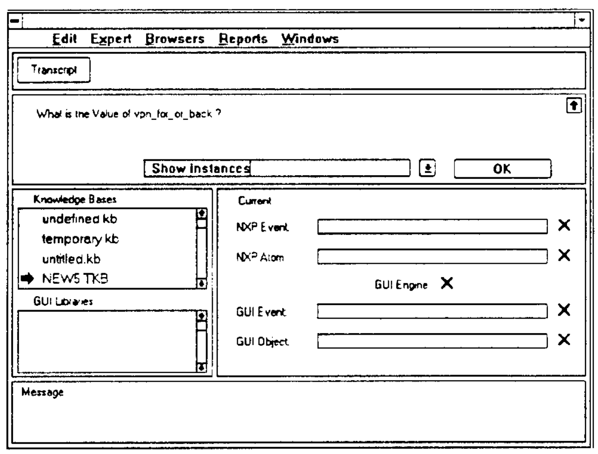


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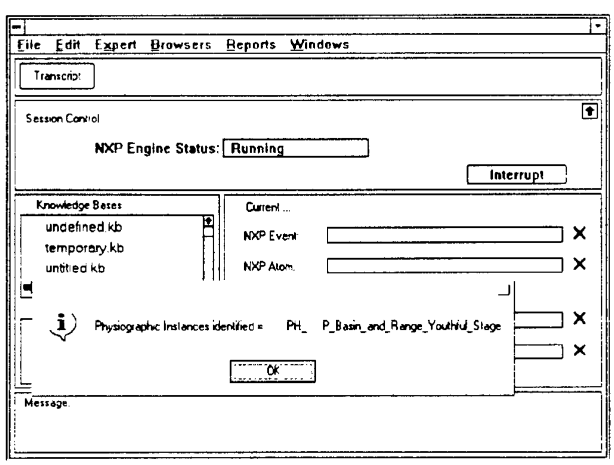
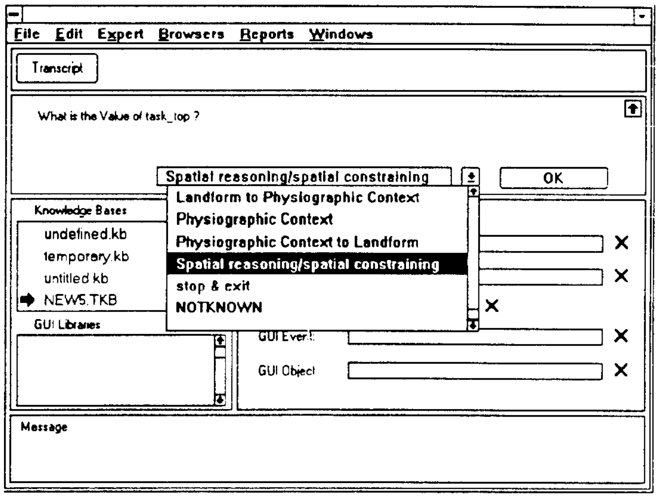



Figure 3-30

# 4. APPENDIX 4

| CASE STUDY: Suggestion of spatially associated landforms (an existing landform is specified and then adjacent landforms are suggested in backward direction according to the topographic form of the existing landform and the spatial direction specified). | |
|---|---|
| **No** | **Description / Caption** |
| 1. | Select from the main menu option "Spatial Reasoning/Spatial Verification & constraining" |
| 2. | Select option "Suggestion of spatially associated landforms" |
| 3. | Specify if an existing landform (previously identified instance) or a hypothetical one will be used |
| 4. | Specify which existing landform will be used (LF_1) |
| 5. | ⇒ The system has retrieved the fact that the existing landform LF_1 is an alluvial fan and displays relevant text regarding alluvial fans. |
| 6. | Specify topographic form containing the suggested landform (user response was piedmont slope) |
| 7. | Specify the "spatial direction to given landform" for the system to suggest possible landforms (user response was downslope of given landform). |
| 8. | ⇒ The system displays the landforms that could be adjacent to the existing landform: Valley fill, Pediment, Playa. And suggest that the user could proceed to identify them by pattern elements. The user is giving some pattern elements as follows. |
| 9. | • Select value for drainage pattern |
| 10. | • Select value for slope average gradient |
| 11. | ⇒ The attempt was failed since the pattern elements given do not correspond to three landforms backwardly suggested. This process was demonstrated earlier in and therefore for economy of space it was lead to failure here so that to avoid a repetition. |
| 12. | Select from the main menu once more "Spatial Reasoning/Spatial Verification & constraining" |
| 13. | Select option "Suggestion of spatially associated landforms" |
| 14. | Specify if an existing landform (previously identified) or a hypothetical one will be used. |
| 15. | Specify which existing landform will be used (LF_1) |
| 16. | ⇒ The system has retrieved the fact that the existing landform LF_1 is an alluvial fan and displays relevant text regarding alluvial fans. |
| 17. | Specify topographic form containing the suggested landform (user response was piedmont slope) |
| 18. | Specify the "spatial direction to given landform" for the system to suggest possible landforms (user response was transverse to slope of given landform). |
| 19. | ⇒ The system displays the landforms that could be adjacent to the existing landform: Bahada, Pediment, Alluvial Fan. And suggest that the user could proceed to identify them by pattern elements. The user is giving some pattern elements as follows. |
| 20. | • Select value for planimetric shape |
| 21. | • Select value for drainage pattern |
| 22. | ⇒ The attempt was successful another alluvial fan was detected |

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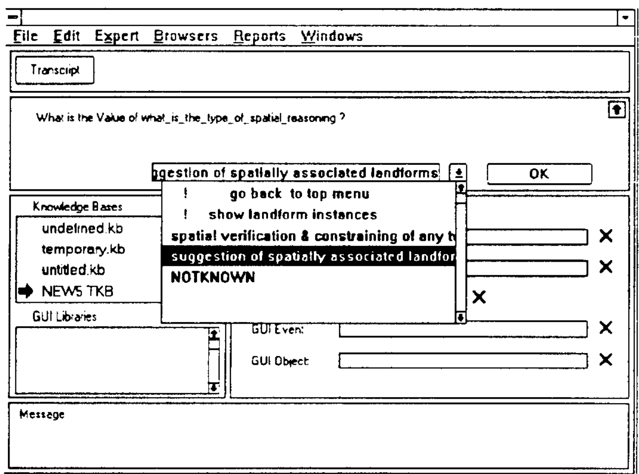
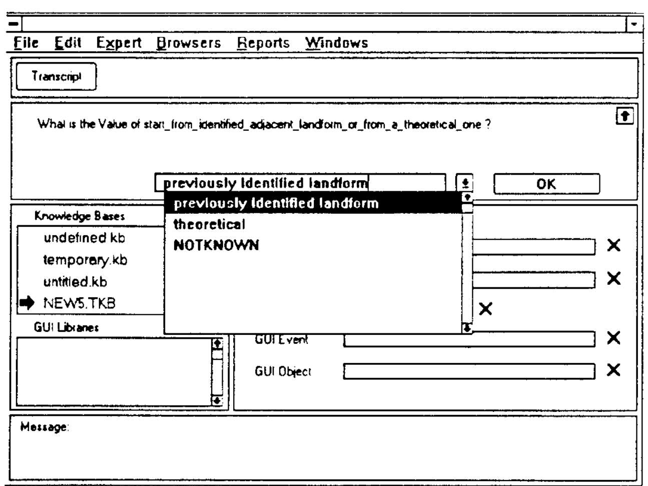



Figure 4-2

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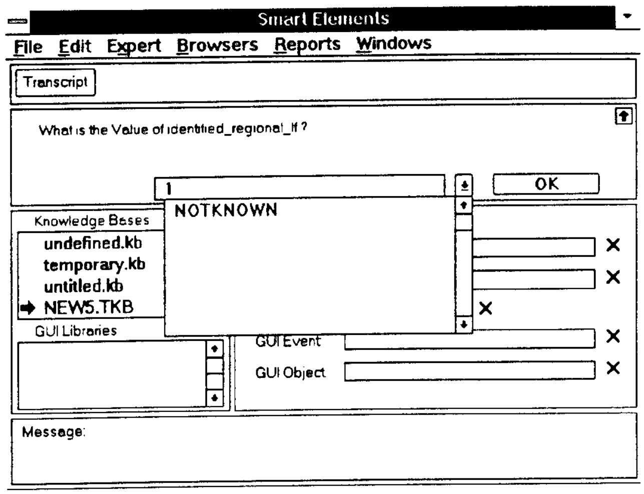


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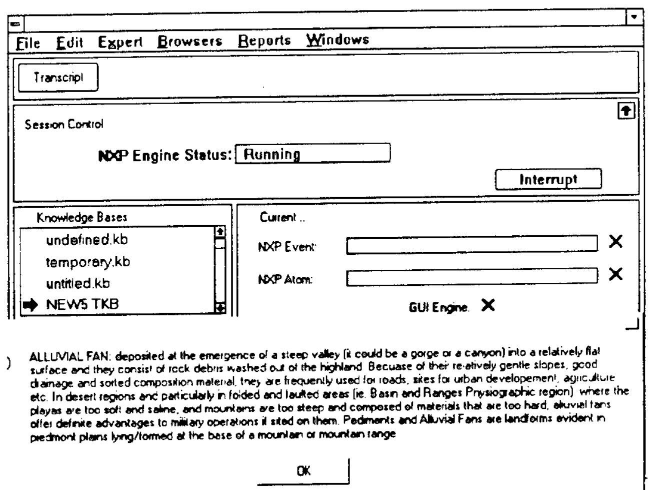
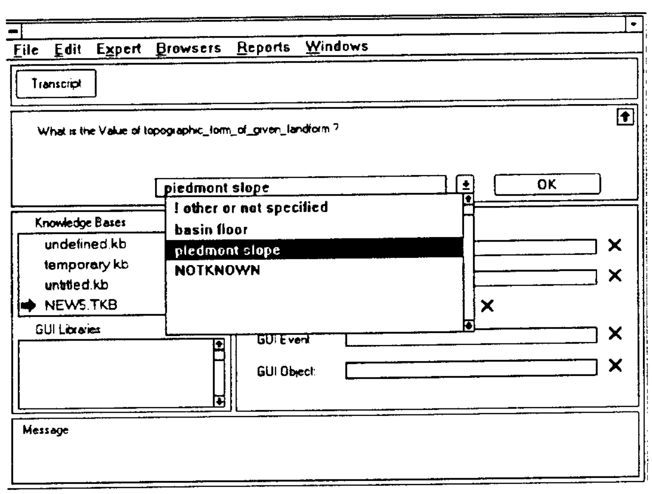



Figure 4-5

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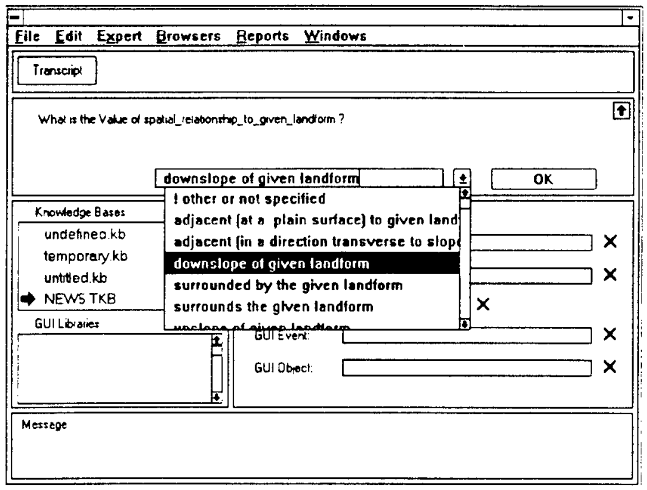


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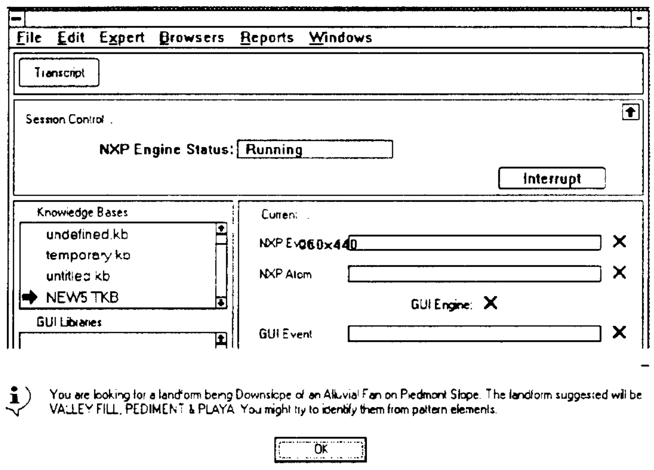
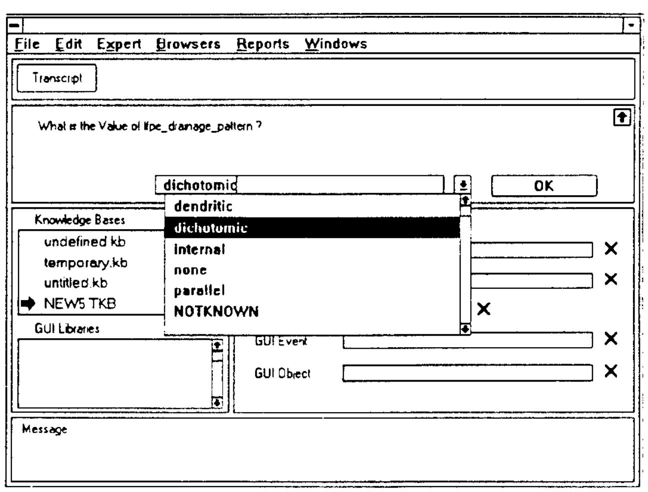



Figure 4-8

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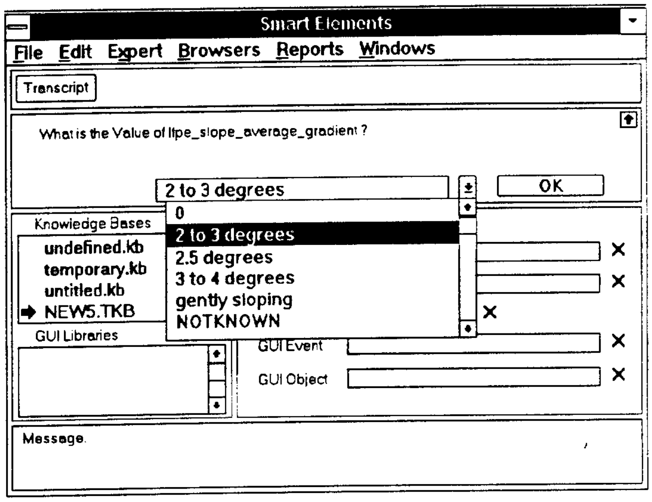


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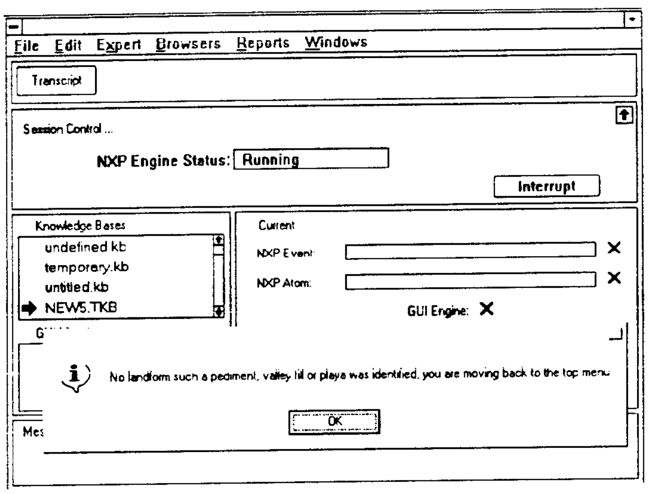


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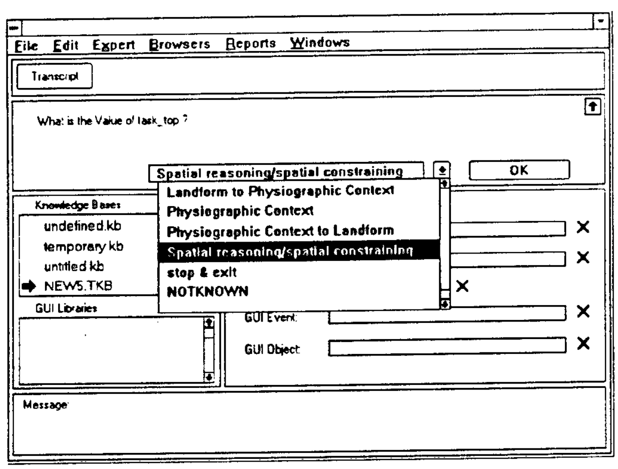


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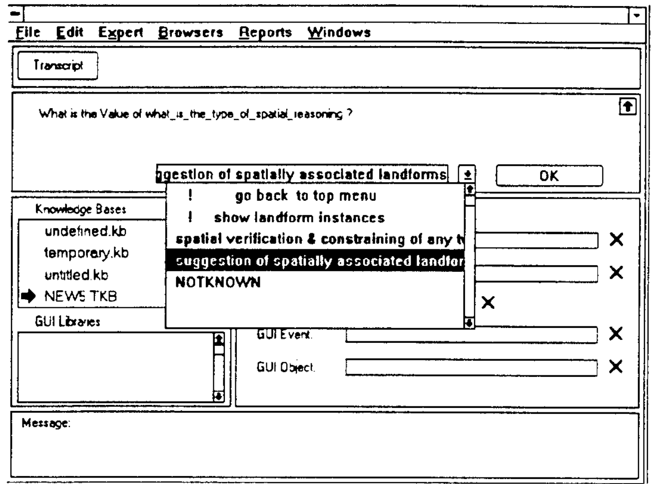


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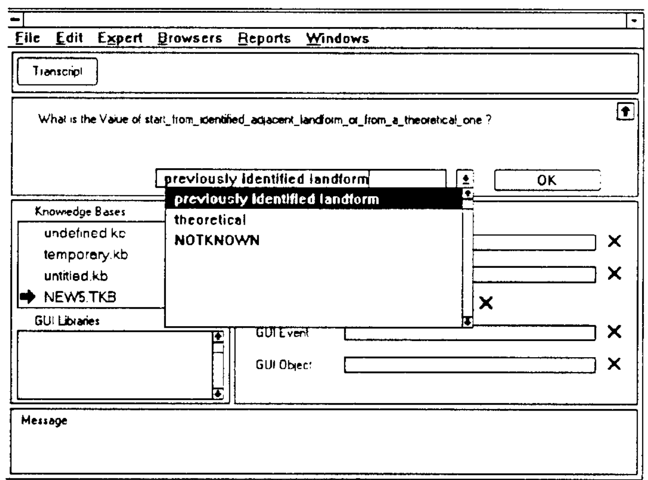


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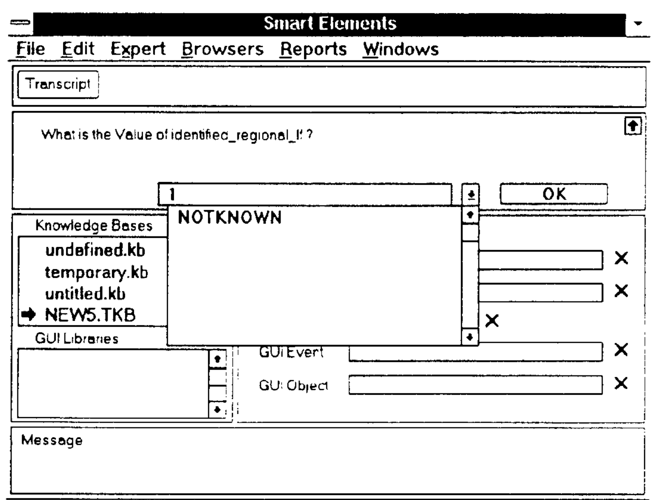


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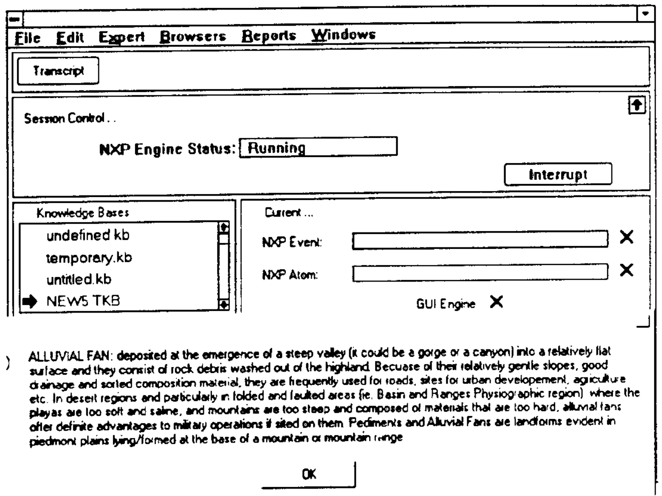


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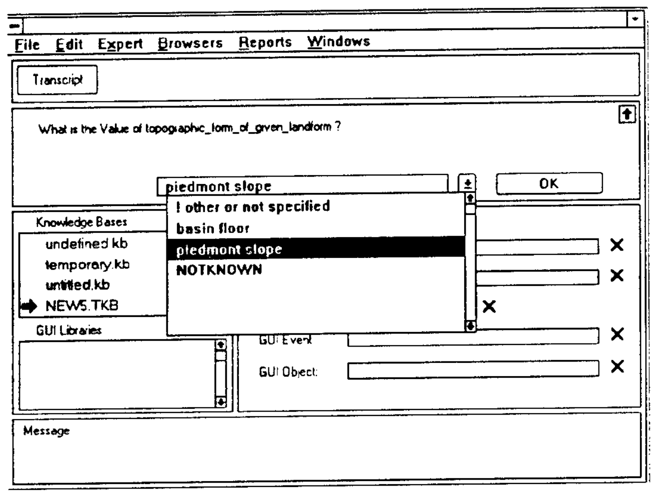


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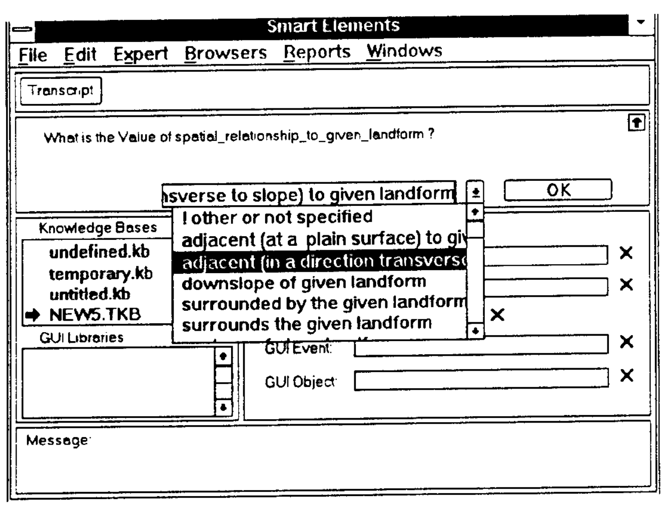


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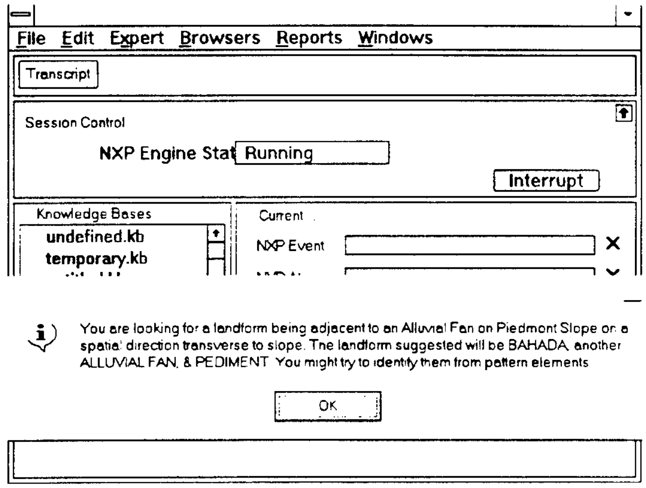


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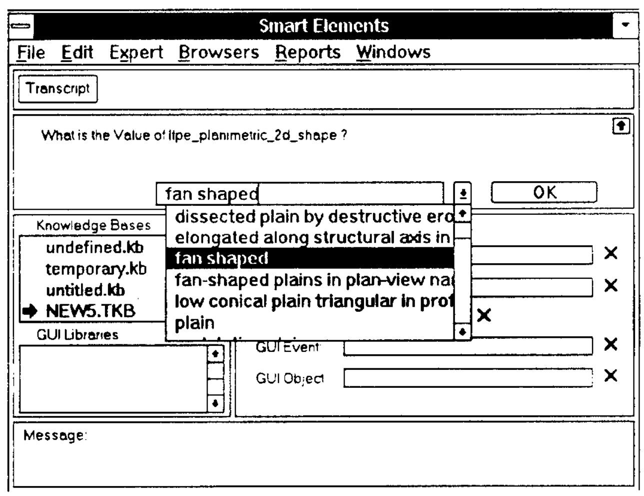


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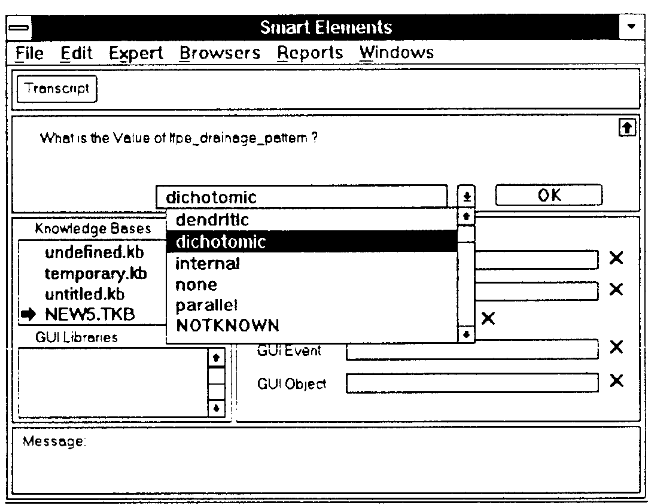


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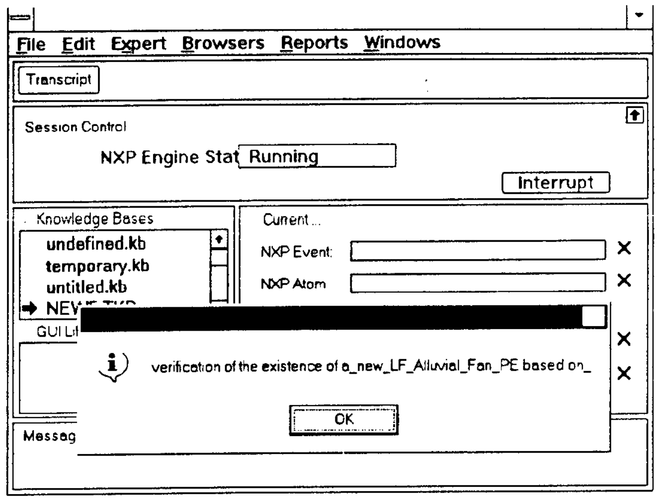
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Transcript
Session Control
NXP Engine Stat Running
Interrupt
Knowledge Bases
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temporary.kb
untitled.kb
Current...
NXP Event:
NXP Atom
verification of the existence of a_new_LF_Alluvial_Fan_PE based on_
OK

Figure 4-22