TOTAL GEOLOGICAL HISTORY: A MODEL APPROACH TO THE ANTICIPATION, OBSERVATION AND UNDERSTANDING OF SITE CONDITIONS

Peter G. Fookes[1], Frederick J. Baynes[2] and John N. Hutchinson[3]

ABSTRACT

One of the principal uncertainties in geotechnical engineering is the risk of encountering an unexpected geological condition. This is because geological materials are often irregularly arranged and highly variable in their material and mass properties. Failure to anticipate site ground conditions generally results from an inadequate geological understanding. The paper presents an approach to site evaluation designed to assist anticipation of geological conditions, from desk study to project construction, that is based on developing an understanding of the total geological history of the site and its environs.

The *premise* of the paper is that the conditions and geotechnical characteristics of the ground are the product of the geological and geomorphological history of the site, including past and present climatic conditions, in short, its total geological history. The engineering performance of the site results from the influence of the engineering works on the total geological history.

The *object* of the paper is to show how knowledge of the geological environment aids anticipation of the site ground conditions by development of a *preliminary* engineering geological model which guides the planning of the investigation and the design and construction of the project. This model develops progressively to be *site specific*, as the understanding of the local geology improves during the development of the project.

The *approach* starts with an *initial* series of simple, related, geological and geomorphological models to generate questions that should be asked about the site and to provide the basis for making a check list. The models presented in the paper represent the end members of a continuous range of possibilities. One or more of these initial models will be identified to represent the particular site to enable the earliest planning to take account of the broadly anticipated geology and geomorphology. The geological concepts embodied in the selected initial models and the specific check lists made for the site are then investigated thoroughly as the site specific engineering geology model develops during the project studies.

To help anticipate the regional scale geology, ten two-dimensional initial *global scale Tectonic models* based on the concepts of plate tectonics are presented. To help anticipate the local scale geology, seventeen three-dimensional initial *site scale Geological models* are presented, each with an anticipation list, encompassing the rock-forming environments and tectonic and diagenetic modifications to these environments. To help anticipate the local geomorphology, eight three-dimensional initial *Geomorphological landform models* are presented, each again with an anticipation list, related to climate and geomorphological processes .

The approach is supported by background discussions of site investigation philosophy and some essential global geological/geomorphological history, and is illustrated by many case histories from different geological and geomorphological settings around the world.

1.0 INTRODUCTION

The *premise* of this paper is that the ground conditions at any site are a product of its total geological and geomorphological history (generally abbreviated to 'total geological history' in the paper) which includes the

[1]Consultant Engineering Geologist, 'Lafonia', 11A Edgar Road, Winchester, Hampshire, SO23 9SJ UK
[2]Consultant Engineering Geologist, Baynes Geologic Pty., Ltd. 9 Chester Street, Subiaco, WA 6008 Australia
[3]Emeritus Professor, Department of Civil and Environmental Engineering, Imperial College, London SW7 2BU UK. Consultant in Geotechnics, Engineering Geology and Geomorphology.

stratigraphy, the structure, the former and current geomorphological processes and the past and present climatic conditions. The total geological history is responsible for the mass and material characteristics of the ground. To help understand the total geological history, the development of a site specific geological model is required, based on consideration of the regional and local geological and geomorphological history and of the current ground surface conditions (Fookes, 1997). The engineering performance of the site during and after construction results from the influence of the engineering works on the total geological history.

The *object* of the paper is to describe and evaluate how:

- initial *desk study knowledge* of the engineering geology environment can help in the anticipation of geological and geomorphological conditions at a project site, such anticipation being used to help construct the *preliminary* geological model for the site, plan the investigation and assist geologists and engineers in the conduct of the investigation and design of the project. This model develops progressively to be site specific as the understanding of the local geology improves with the development of the project.
- improved *understanding* of the site as observations are made during investigation and construction also helps the anticipation and definition of ground conditions.

The paper is *targeted* at site investigators and financial decision makers who will probably never be aware of its existence.

1.1 The Observational Method in Projects

The approach advocated in this paper is based on the use of the observational method. Such an approach is by no means new.

It is probably the writings and work of Terzaghi in the early and middle parts of the last century that have illustrated the importance of this approach more than any other. The term '*observational method*' appears to have been coined by Terzaghi and Peck in 1948 (p. 494): it became '*observational procedure*', in Terzaghi and Peck, 1967 (p.294). In his Rankine lecture, Peck (1969) made the following comments on the observational method. He said, "*If the governing phenomena are complex, or are not yet appreciated, the engineer may measure the wrong quantities altogether and may come to dangerously incorrect conclusions.*" This is where the observational method is particularly useful. Peck briefly gives the application of the method as follows:

" (a) *Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.*

(b) *Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major rôle.*

(c) *Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.*

(d) *Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.*

(e) *Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.*

(f) *Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.*

(g) *Measurement of quantities to be observed and evaluation of actual conditions.*

(h) *Modification of design to suit actual conditions.* "

We believe that all of Peck's items (a) to (h) are needed for the approach to be classed as the Observational Method (OM). For the method to be workable, all parties need to pay particular attention to contract arrangements and relationships that will influence the OM's implementation. Variations of the OM are being increasingly used on 'design and build' (i.e. engineer, procure and construct) contracts. Such contracts often do *not* have a clause about unforeseen ground conditions and may have only a little on-site involvement from the designer's geological/geotechnical specialist. We believe that these variations are often not true OM: the term OM may be used to obscure, or as an excuse for, or as compensation for, the inadequate skills and resources being put into a project's investigation and design.

Peck makes the point that, for the method to be applicable, the character of the project must be such that it can be altered during construction. He also distinguishes between situations where the use of the OM is envisaged from the inception of the project, and those where the method is introduced part way through a project as offering almost the only hope of success. In the latter situation, there may be contractual problems to overcome.

In our experience, for those contracts where the Contractor is not taking all the ground condition risk:

- For the OM to work well, it is essential that it is pre-planned prior to provision of the tender documents and that the Contractor is fully aware of the procedures that will be adopted. **This requires identifying the range of likely geotechnical conditions and the range of construction activities required to construct the appropriate design when a particular geological condition is found.** It is therefore advisable for the construction work, at tender, to be priced in a manner that is flexible, so that an agreed price can be applied immediately to a required activity, whether it is changed because of the geology encountered, or remains the same. Without a flexible price structure built into the contract, the method would inevitably generate claims We believe that where the method has been applied successfully, claims related to unforeseen geotechnical conditions have been minimal or non-existent.
- It is also necessary to have the appropriate geological, geomorphological and geotechnical staff on site to observe and monitor the geological and hydrogeological conditions as they are revealed during construction, and to liaise directly with the appropriate supervisory staff who in turn must be fully aware of the method.
- In the last decade or two, the 'fast-track' approach has been developed. A consequence of this approach is that the degree of initial ground investigation is often much reduced below normal good practice and great reliance is often placed on the succeeding OM. It should be noted that this can also occur with non-fast-track construction. The risk in such a procedure is that, because of a lack of 'thinking time' and investigation time, the important characteristics of the site are not identified early enough, so that the less critical features are chosen for observation, i.e. there is poor application of the OM. The worst credible ground behaviour is not envisaged and thus the appropriate course of action is not considered and preplanned, and may well not be feasible at a later stage.

The implications from the above are that each site requires a reliable *preliminary* model on which to build subsequent investigations which will, of necessity, modify and improve the model. It is the early development of this model, by consideration of all the reasonably possible geological and geomorphological characteristics of the site, which becomes the *first* objective. It is essential to have an understanding of the site acquired from knowledge of the fundamental basics of earth-building and surface-modifying processes, to help in the anticipation of the likely geology/geomorphology. The *second* objective is to substantially improve the understanding of the geology during the remaining investigation and construction.

Thus, this approach becomes the thread that runs through the paper: how *anticipation* of the site geology and geomorphology allows for better engineering at all stages - the desk study, the ground investigations and the construction.

1.2 Approaches to Geological Observation

McMahon (1985), in his Davis Memorial Lecture, says ".... *It has always seemed to me that uncertainty is the very essence of geotechnical engineering. Our materials are natural in origin, often irregular in form and highly variable in their properties. They are usually obscured from sight and can be investigated only to a small extent at great expense. The resulting uncertainty is often large and can have enormous economic consequences,* ....." He then goes on to develop the theme of geotechnical uncertainty, of which his first uncertainty **is the risk of encountering an unknown geological condition.**

Much has been written on acquiring geological knowledge of the site. Most publications concerned with site investigation recommend, albeit usually loosely, the practice of making regional and local desk studies, followed by specific investigations of the local geology. Some also counsel continuing to develop an understanding of the geology as project implementation proceeds. Hoek and Bray (1977), in their authoritative work on rock slope engineering, say, in the context of regional geological investigations, "*A frequent mistake in rock engineering is to start an investigation with a detailed examination of drill cores. While these cores provide essential information, **it is necessary to see this information in the context of the overall geological environment .... and it is therefore useful to start an investigation by building up a picture of the regional geology.***" [Our bold for emphasis]

Professor Stapledon, the doyen of Australian engineering geology, has for at least the past three decades been advocating a carefully considered approach to site investigations. For example, Stapledon (1983) says that he believes that the geotechnical investigation should include some of the following geo-aspects which we have quoted:

" * *a suitable site investigation team*
* *an objective orientated approach to the site investigation*
* *geological material displayed clearly at appropriate scales*
* *a high standard in the collection of basic exploratory data*
* *studies continuing through all stages of project development*
* *high quality project management staff and machinery*
* *adequate time and funds*
* *independent review* "

Stapledon (1982), on dams (he notes that he was inspired by a similar suggestion by Peck,1962), suggested that desirable attributes for those wishing to contribute to sub-surface engineering should include:

" *1. Knowledge of precedents*
2. Knowledge of geology
3. Knowledge of soil and rock mechanics "

His accompanying recommendations for study of world and regional geological settings are reproduced here as Table 1.1. He introduces this table by saying that in order to determine a *"semi-quantitative model (engineering-geological)"*, geological studies "***should commence with consideration of the site location with respect to global tectonics, and include studies of the geology of a broad region surrounding the site****. The main objectives and suggested activities for work on a regional scale are set out in* [Table 1.1]." He goes on to say, "*The regional geological studies should be followed by studies on intermediate and detailed scales, a principal purpose of which is to ensure that the site geology "fits" into the regional geological picture, i.e. that the country adjacent to or containing the site is in situ, not displaced by major landslide or fault movements.*" [Our bold for emphasis]

TABLE 1.1 : STAPLEDON'S STUDIES OF WORLD AND REGIONAL GEOLOGICAL SETTINGS (1982)

Objectives	Activities
Understand geology of region surrounding the dam and storage, in particular: 1. Geological history - past processes and resulting model 2. Active (or potentially active) processes 3. Locate main geological features, especially faults. Such features may pass through or near the site but may not be exposed or evident in the site area.	Review published and other existing geological data. Interpretation of satellite imagery and air photographs. Ground geological surveys to fill relevant gaps in geological picture. Prepare plans and sections on scales usually ranging from 1:50 000 to 1:250 000; these must show the lay-out of the proposed works.

We recommend the adoption of this *first* wise dictum, of starting with a broad regional understanding. However, this approach does not appear to be widely recommended. For example, the Australian Standard 1726 (1993), on Geotechnical Site Investigations, Item 4.7, says the process of evaluating the geotechnical character of a site "may include ... evaluation of the geology and hydrogeology of the site". It is silent on the construction of a geological model and on the understanding of regional geology and processes. The British Standard on Site Investigations, BS5930 (1981) has a somewhat similar silence. Even Peck's (1969) list quoted above, which starts with item (a) on 'Exploration', might be construed as starting without a desk study of the local and regional geology and his item (b) says only, 'In this assessment geology often plays a major rôle'.

We believe that in general the use of engineering geologists and geomorphologists and the application of intuitive and knowledge-based approaches which characterise good engineering geology do not occur at a level of involvement in projects that is commensurate with the worth of their contribution. In the authors' experience, it is not uncommon for engineering geologists to become involved *after* problems have developed rather than before.

There are many examples in the literature of retrospective analysis of what has gone wrong with various site investigations and related studies and the consequences that these have had on the subsequent design and construction. One such study is by Matheson and Keir (1978) who examined site investigations for road works in Scotland during the preceding decade. Although over twenty years ago and techniques are improving, we consider that Table 1.2, modified from their publication, is just as relevant today: it is a simple matrix of the most

TABLE 1.2 : FAILINGS AND CONSEQUENCES

Site Investigation Failings / ***Consequences***	1. Cost increase	2. Unforeseen ground conditions	3. Additional work	4. Variation order	5. Design change	6. Claim	7. Workability wrongly assessed	8. Time increase	9. Working more difficult	10. Additional expenditure on foundations	11. Instability (cuttings)	12. Water and drainage problems	13. Rock head wrong	14. Instability (embankments)	15. Realignment	16. Working easier	**Row Maximum**
1. Techniques used not optimum	6	7	6	3	4	4	6	4	5	3	3	2	3	1	1		**7**
2. Methods used inappropriate	5	7	5	5	4	3	6	3	4	2	2	2	2			2	**7**
3. Available information not fully utilised	6	6	5	4	5	3	4	5	5	5	3	3	2	1	1		**6**
4. Stability poorly or wrongly assessed	6	2	6	6	5	5		4	3	2	6	3	2	2	2		**6**
5. Facts misleading	4	5	3	4	5	4	2	3	3	3	1	1	2				**5**
6. Rock condition inaccurately assessed	4	4	5	4	4	3	3	1	2	2	4		4			1	**5**
7. Workability wrongly or poorly assessed	4	1	4	5	2	5	5	4	4	2	2	2		1	1	1	**5**
8. Ground water condition wrongly assessed	4	4	3	3	2	3	3	4	3	3	2	3		1	1		**4**
9. Route not covered	3	3	3	2	3	2	2	3	2	2	1	2		1	1	2	**3**
10. Logging poor or inadequate	3	4	3	2	2	2	1			1	1		1				**4**
11. Interpretation wrong	1	1	1	2	2	2	1	1	1	1	1	2	1				**2**
12. Samples unrepresentative	2	2	2	1	2	1	1	1	1	2		1					**2**
13. Meteorological data not used	1	1	1	1	1	1	1	1	1	1		1					**1**
14. Mis-identification	1	1	1	1	1	1					1		1				**1**
Column Maximum	**6**	**7**	**6**	**6**	**5**	**5**	**6**	**5**	**5**	**5**	**6**	**3**	**4**	**2**	**2**	**2**	

Notes:
- The consequences may be the result of more than one failing.
- Each failing is given a penalty score out of a possible 16. 7 is the worst found.
- To be considered significant, failings have to affect the overall budget or scheduling by an amount greater than approximately 5%, or for individual quantities by an amount greater than 50% of the original estimates. Individual quantities would be, for example, earthworks, suitable rock excavation, unsuitable rock excavation, imported fill.
- Attempts were made to quantify accurately the consequences as time and cost but this proved impractical because of the complexity of the situation, the interdependence of the factors involved, and the long term nature of the drained settlements of the earthworks.
- Differences in ground conditions have been related not to the shortcomings in 'state-of-the-art' but to poor phasing of the investigation, to the selection of inappropriate investigatory techniques and to the acquisition of unrepresentative data on ground conditions.

(based on Matheson and Keir, 1978)

common consequences to the project of the 'failings' of the site investigation. It will not come as a surprise: many of the failings relate to poor investigation technique and lack of geological understanding or assessment. Regrettably, the message from such studies often either falls on the ears of the converted or simply fails to reach the point of impact with the designers and those who award investigation contracts.

1.2.1 Staged Understanding of the Geology

As a result of their study of the Scottish road projects, Matheson and Keir (op. cit.) suggest that the effectiveness of site investigations can be increased by efficient planning and by placing particular emphasis on the preliminary phase. A critical point: they strongly recommend that a planned preliminary site investigation should be included in all [road] projects. They go further and say that the preliminary site investigation should be of a qualitative to semi-quantitative nature, and that a high level of detail is neither necessary nor desirable: it is sufficient to indicate rather than to define potential problems. Without some prior knowledge of the ground conditions, it is difficult to plan an effective main investigation. **Optimum methods and techniques cannot be chosen to suit unknown geological conditions. Information obtained at the preliminary phase is thus of paramount importance to the planning of a main site (i.e. ground) investigation**. [Our bold for emphasis]

We agree with Matheson and Keir and in our paper recommend the adoption of this *second* wise dictum, that of a staged approach with a preliminary investigation which itself starts with a desk study, to plan the main investigation phases. However, this approach is not always seen as appropriate. For example, Ground Engineering (Anon, 1999) in an article called 'Time to Investigate', written as a result of a survey of practitioners in UK where the response *'as usual was high, reflecting the strong feelings held by firms that something had to be done ....',* wrote in red for emphasis - *'An average of only 39% of investigations include a desk study, which could be considered the most important stage of the work. It appears that this is a result of ever-decreasing timescales'.* Also in red, *'Worryingly, it seems that only 30% of clients appreciate the value of good geotechnics. There is a lack of awareness of the benefit of sound site investigation strategy by clients and their advisers .... some 38% of clients see site investigation as a "necessary evil"'.*

It appears to us that the current trend around the world is for complex civil engineering projects to be carried out within very short time scales. Such projects often involve difficult and protracted planning consultation which leads to increased pressure on all the professionals involved to work at a very fast rate and, on occasion, at an erratic pace that is dictated without regard for good practice. In no situation is this more so than with the collection and utilisation of ground information for the design and construction phases of the project. Hence, the preliminary stage, as a precursor to a fast and efficient main site (ground) investigation, becomes all the more important and there is even greater emphasis on the engineering geologist's role in the assessment of risk arising from the uncertainty about ground conditions (Eddleston, Murfin and Walthall, 1995).

It is worth repeating that at the preliminary stage the engineering geologist probably can have the most significant influence on the project by indicating potential hazards and their consequence on the economy of design, matters of construction and expected performance of the works. Our experience shows, however, that all too often engineering geological advice is not adequately taken into account at this or following stages. Difficulties also often arise when geological conditions are relatively simple yet the significance of the conditions may not be understood or is lost sight of in a mass of other data, due to lack of understanding on the part of the decision makers.

An incomplete appreciation of the ground conditions, which is subsequently presented at the construction tender stage, can only cause the Contractor problems, which will almost inevitably increase the final cost to the Client. The adage, *'you pay for a site investigation whether you have one or not'* (Anon, 1991), is backed up by many publications, for example, in UK by Rowe (1972), Clayton, Simons and Mathews (1983) and by Attewell and Norgrove (1984).

These publications and many others have established that one of the largest elements of technical and financial risk in civil engineering projects is unforeseen ground conditions. Experience has shown that a modest increase in ground investigation expenditure at the outset could have been repaid many times in reduced project cost over-runs. It is also conceivable, at least in principle, that expenditure on ground investigation might be excessive, far outweighing any possible savings for the project. Thus, in between these two positions, there must be an optimum level of expenditure on ground investigation.

To arrive at this optimum level, Goldsworthy (1999), based on theoretical possibilities and assumptions, considers the total project cost, T, as given by:

$$T = P + G + E$$

where P = planned project expenditure (excluding that for ground investigation)

G = ground investigation expenditure

E = cost of unforeseen conditions = a proportion, k, of P

assuming that k depends on P/G gives k = SP/G, where S is a parameter which reflects the sensitivity of a project to ground conditions.

Hence:

$$T = P + G + SP^2/G$$

and, in terms of the ratio of total project cost to planned expenditure,

$$T/P = 1 + G/P + SP/G$$

If R is the ratio of ground investigation expenditure G to the total project cost P,

$$G = RP \text{ and } T/P = 1 + R + S/R$$

Illustrative plots of this last relationship for three typical projects indicate that values of the predicted optimum expenditure G, as a percentage of P are, for:

a low sensitivity (S = 0.0005) building project, around 1.5%
a typical (S = 0.002) civil engineering project, about 4%
a high sensitivity (S = 0.005) tunnel project, between 6% and 8%.

Goldsworthy speculates that *'regional differences relating to typically encountered ground conditions and to contractual practices may affect the sensitivity factor distributions'*.

The above estimates can be compared with current levels of expenditure on ground investigation, which are reported to be well below 1% of the total construction costs (Institution of Civil Engineers, 1991; Littlejohn, et al., 1994). The cost of claims due to unforeseen ground conditions is usually far in excess of this, let alone the extra costs of over design to cover risk of unknown ground conditions. Note, however, that we believe that the scope of investigation should be sufficient to answer the important questions, and not simply be determined as a percentage of the project costs, although they can give some guidance.

1.2.2 Our Approach Introduced

The typical stages of geotechnical studies required for the design and construction of large civil engineering works are more or less similar around the world. Figure 1.1 is a fairly common well established 'traditional' arrangement, although many variations exist. A 'fast track' approach puts all the activities on the critical path, but decision milestones would remain. The stages of the site investigation and the build-up of the geological model in a manner that embodies OM during the preliminary and the main investigations and again during construction, are critical to a successful outcome.

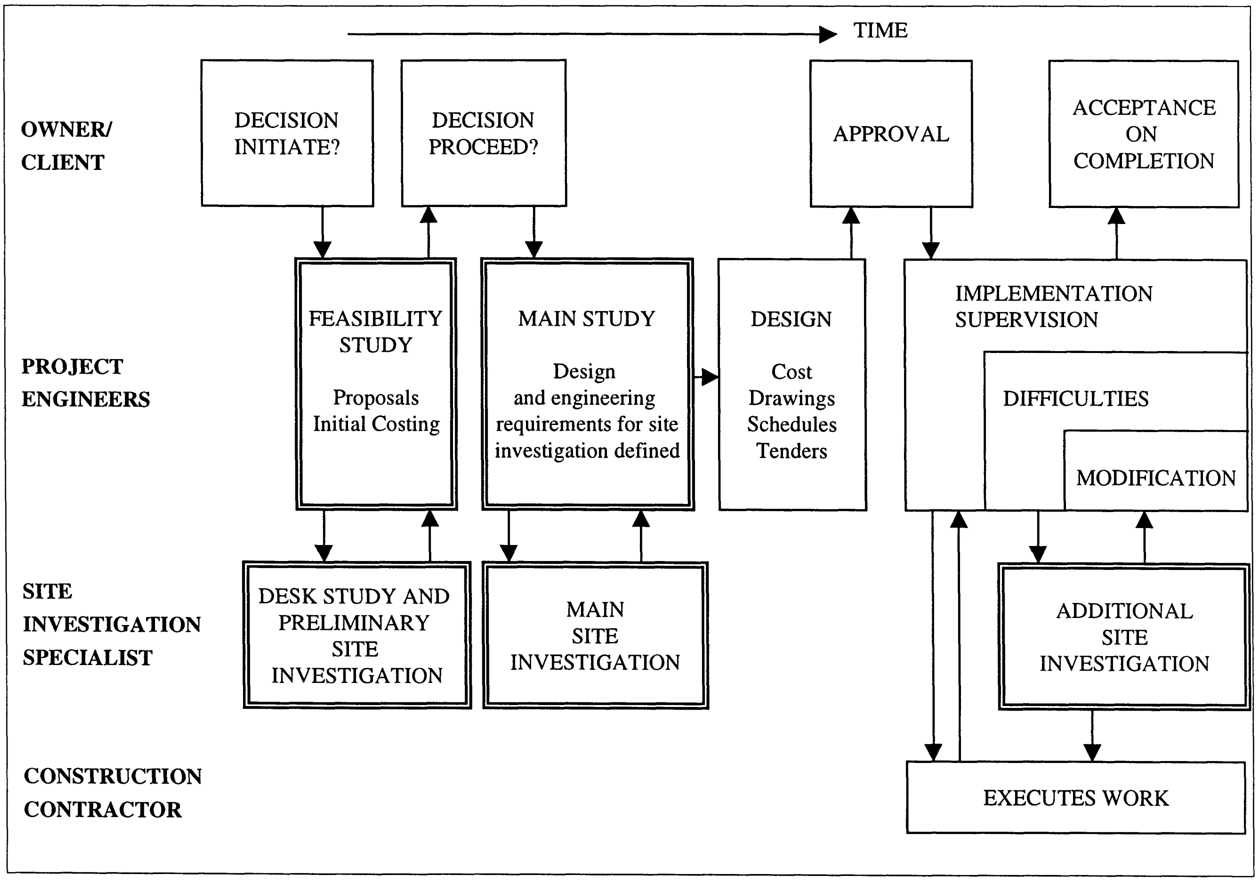


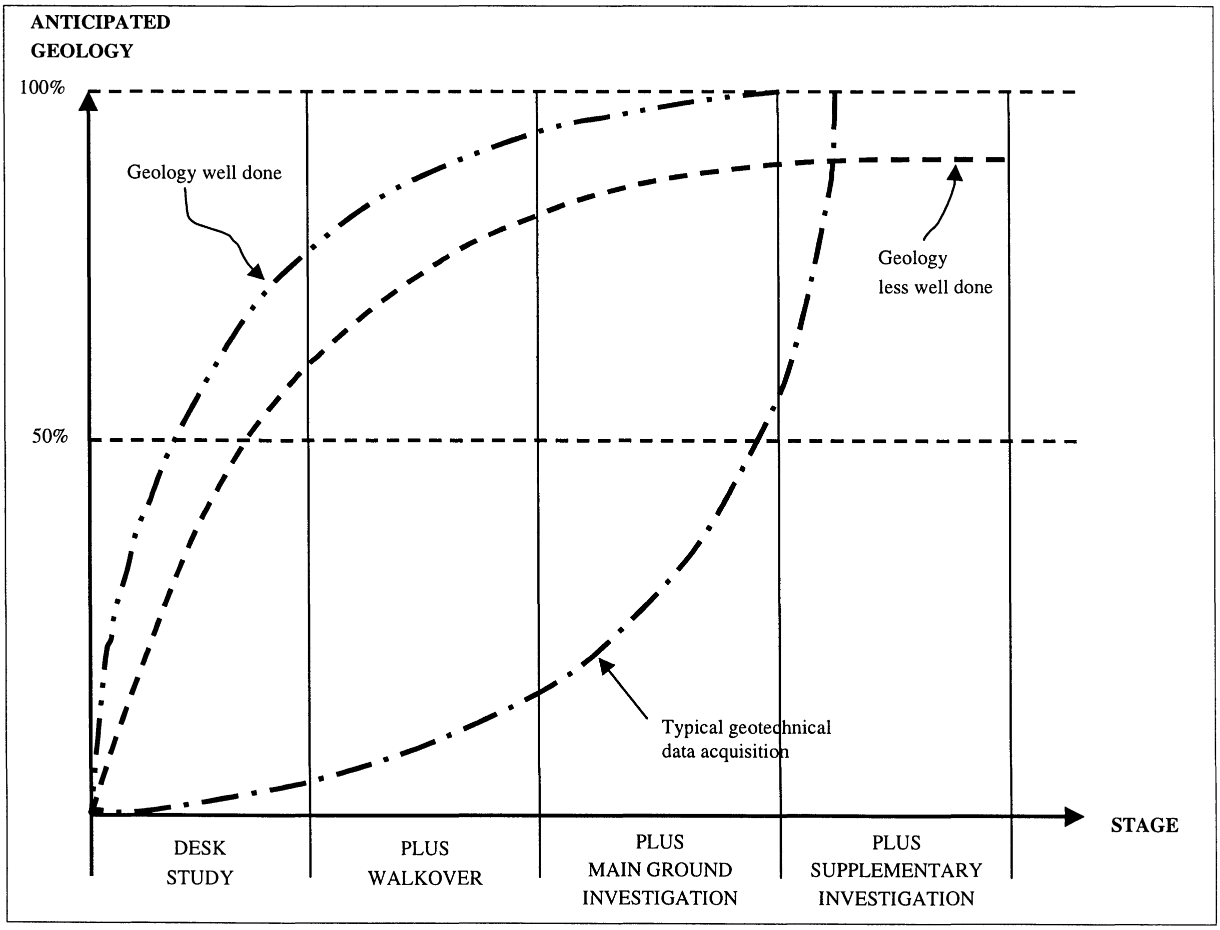
Figure 1.1 : Common Project Organisation for Engineer Designed Construction

Our approach starts with the broad anticipation of the geology, from a desk study of that location, where the geological knowledge may be minimal, or a lot may be known already. Whichever the situation, it is necessary to:

- form an understanding of what is found from the desk study;
- anticipate what geology conditions might be associated with the findings;
- develop this through subsequent stages of the investigation, design and construction.

Conventional approaches to the desk study work for the feasibility and early phases of site evaluation typically use the local maps and literature which commonly exist from many developed areas around the world. The Transport Research Laboratory Report (TRL 192), 1996, by Perry and West, on *Sources of Information for Site Investigations* in Britain (Revision of TRL Report LR 403) is a good example from the UK. Such works also often describe various forms of maps and remote sensing for engineering purposes.

In locations where much may be known already, e.g. geological maps do exist or there are good air photographs or other imagery, the initial local geology can be quite well anticipated by site specific models prior to any preliminary inspection (see Fookes 1997, page 348 and Figures 10, 41a to 41e, and Table 5). The site inspection, preliminary and full ground studies can then be progressed quite quickly at such a location, to give as detailed a picture of the geology as is considered sufficient or necessary. Nevertheless, this may result in some shortfall in *anticipation of the total geological picture* if a fundamental understanding of the regional and local geology has not been formed.



(Fookes, 1997)

Figure 1.2 : Estimated Upper and Lower Bounds of Geological Information anticipated during the stages of a Site Investigation

By 'anticipation of the total geological picture', the authors mean that all the geological and geomorphological characteristics of the site have been anticipated together with **the range of possible variation** (e.g. sizes, locations, properties) of these characteristics identified, **i.e. ideally there should be no condition that comes as a surprise during construction.**

Figure 1.2 shows a crude approximation of how well-designed site investigation studies, from desk stage to the project in-service stage, develop increasing geological and geotechnical knowledge. Note that it is suggested that geological knowledge rises more quickly than geotechnical in the earlier stages of a project: the gathering of geotechnical data develops faster when in situ and laboratory testing and rigorous description is introduced during the latter stages of investigations (Fookes, 1997). Rather fewer publications describe investigation activity during construction but the principle and techniques are essentially those used in pre-construction investigations. For guidance, see Eddleston, et al. (1995).

1.2.3 Different Types of Model

Even when no local geological information or imagery is available a very preliminary desk study can be made, by identifying the local stratigraphical, lithological, structural, and geomorphological controls for the site. Knowledge of these controls is used to give a very broad picture of the possible engineering geological conditions and geometric (spatial) relationships at that location, and *initial*, i.e. wide-ranging and not rigorous, geological model(s) can be assigned to predict geological features that might reasonably be expected in the site area.

In this paper, three series of *initial* models are introduced. These are all presented together at the end of the paper, in the Models Appendix:

- **Global scale Tectonic models based on plate tectonics.** There are ten of these models, presented two-dimensionally, i.e. as sketch sections. They cover large areas of terrain, typically many tens to many hundreds of kilometres and set the scene for anticipating the regional structure and rocks of the area. See Section 2.3.
- **Local or site scale initial Geological models**. There are seventeen of these models, presented three-dimensionally, i.e. as sketch block models, which typically cover areas from kilometres to tens of kilometres. They relate to the *rock-forming environments* - igneous, sedimentary, structural and metamorphic and to the initial *stratigraphy*, and to *tectonic and diagenetic* changes modifying the stratigraphy. Such models form a part of the relevant global Tectonic model(s) and are locally modified by the processes involved in the Geomorphological models. See Section 3.1.
- **Local or site scale initial Geomorphological models which characterise the landforms**. There are eight of these models, presented three-dimensionally, i.e. as sketch block models, which also typically cover areas from kilometres to tens of kilometres. They relate directly to the local geomorphology, *i.e. the earth's surface landforms, and to the earth surface processes which have modified or are modifying the local geology*. These processes are related to current climates and the relatively recent past climates, i.e. they are essentially a product of the later Tertiary and the Quaternary Ages. Such models also help to portray conditions of deposition in ancient equivalents to the models. See Section 3.2.

The approach to be adopted is as follows:

- At the Desk Study stage one or more of the initial global scale Tectonic and site scale Geological and Geomorphological models are identified. They form a simple, related series to help develop the questions about the site that should be asked. It thus becomes the first task to identify the *relevant initial models* for the project area and the second to develop a *check list* of questions to be answered during the investigations. These will be the responsibility of the engineering geologist. The geologist may need assistance with the geomorphology.
- Combination of the initial site scale models and the site check list(s) will form the *preliminary site engineering geology environment model* to enable the earliest planning to take the potential broad geology and geomorphology of the area into account. The initial models and their check lists will need to be investigated thoroughly and developed by the subsequent studies.
- Development of the subsequent *specific site engineering geology environment model* as the investigation progresses is discussed in some detail in Fookes (1997). Initial models help plan the site investigation: subsequent development of these models to form the specific models in the Walkover and Ground Investigation stages help engineering design and construction. See Section 4.0.

Check list questions are not new in engineering geology but to date have generally been developed for selected terrain types, e.g. extrusive volcanic, valley glacier (e.g. Fell, et al., 1992; de Freitas, 1993). The approach described in this paper is based on the concept that global end members representing the entire spectrum of possibilities can be identified and presented. An initial check list for each Geological and Geomorphological model is embodied in both the annotation on the figure and in the text under the figure with the heading 'anticipate'. The more detailed site specific check list and site specific model then needs to be made, once the clear outlines of the geology at the location are identified beyond the desk study stage.

The essence of the approach involves understanding the geology and geomorphology to be able to evaluate the anticipated conditions. To do this and to understand the models there must be some appreciation of the history of the world. Thus a brief account of this follows.

2.0 A SHORT ACCOUNT OF THE EARTH'S STRUCTURE AND HISTORY

2.1 Global Structure and Processes

This is very much a simplified summary and any reader wishing to read more should refer to, for example, Park (1983), Press and Siever (1986), Dott and Batten (1988), Moores and Twiss (1995), or Kearey and Vine (1996).

Text boxes have been included to give pertinent background information for the less geological reader. The first is on the Earth's Core and Structure of the Crust.

2.1.1 The Stratigraphic Column

The sequence of rocks formed during geological time may be represented by the stratigraphic column which lists them in their order of age: the oldest rocks are at the base of the column and the youngest at the top. Rocks are grouped by age into broad *Periods* and *Epochs*, most of which are named after the areas where they were first studied, many of these being in Britain. They are characterised by distinctive assemblies of rock types and tectonic episodes and reflect identifiable periods in the Earth's history. Epochs are subdivided into finer and finer units, often having only local significance. In order to help understand geological models, Table 2.1 gives the basic stratigraphic column, showing the divisions of geological time, together with the age of important global scale events. The dates of the naming of the divisions are also given to help illustrate the way the stratigraphic column was developed by geologists, mainly throughout the nineteenth century.

2.1.2 Tectonic Elements of the Crust

The crust may be subdivided into distinctive structural features or 'tectonic elements' and related to the global scale Tectonic models discussed in Section 2.2.

'Tectonics' describes the structural behaviour of large areas of the crust through geological time and explains the formation and relationship of the principal geological structures.

To illustrate the following text in pictorial form, Figure 2.1 shows the major morphological features of the earth and the plate boundaries. Figure 2.2 is a cross-section of an imaginary continental land mass to show some of the major structural components and Figure 2.3 shows the major collision mechanisms.

The crust and the lithosphere (see text box) can be divided into two major groups of tectonic elements:

Inactive areas with little seismic and volcanic activity:

- continental cratons - low, flat regions, subdivided into large down-warped basins and up-warped arches (Figures 2.4, 2.5 and 2.6)
- oceanic abyssal plains - deep, flat areas of the sea floor (part Figure 2.8)

Active areas with much seismic, volcanic and other tectonic activity:

- continental rifts - areas of extensional tectonics within cratons (Figure 2.7)
- ocean ridges - shallow seismicity, basaltic volcanism, and extensional faulting or rifting (part Figure 2.8)
- magmatic arc orogenic belts - long zones of shallow and deep seismicity, andesitic volcanism, large granite batholiths, regional metamorphism and compressional structures, including overthrust faults (Figures 2.9, 2.10, 2.11 and 2.12 and 2.13).

Earth's Core and Structure of the Crust

The radius of the earth at the equator is 6370 km and at the poles it is shorter by about 22 km; thus the earth is not quite a perfect sphere. It has a surface area of 510 x 10^6 km^2.

The earth's solid core is very dense material and rich in iron and nickel. This is inferred from the earth's bulk density, the magnetic field, and comparison with metallic meteorites. The outer part of the core, dimensions and liquid character are established from seismology: the interaction between the spinning solid mantle and liquid outer core is thought to drive the magnetic field. The core's average density is 10.7 gms/cm^3 and its radius about 3470 km.

The earth's mantle, some 2300 km thick, lies between the core and the Moho layer (Mohorovicic discontinuity), and is chiefly composed of ultramafic peridotite and its high pressure cousin, eclogite, i.e. it is similar to 'garnet'. These rocks are rich in magnesium and iron and their bulk composition approximates to that of stony meteorites. A low seismic velocity zone of low rigidity defines the base of the *lithosphere*, the upper part of the mantle, which is 60 to 250 km thick. The *asthenosphere* is the weak zone within the upper mantle under the lithosphere where the mantle rocks deform by plastic flow in response to applied stresses of *ca.*100 MPa. The whole mantle forms some 84% of the volume of the earth, or 68% of its mass: its average density is about 4.5 gms/cm^3.

The lithosphere has resulted from complex, poorly understood processes of differentiation from the upper part of the mantle, and is driven by thermal energy resulting in large part from radioactive decay. The relatively thin *earth's crust* 'floats' on the lithosphere; it comprises the thinner oceanic crust and the thicker continental crust and accounts for 1.4% of the solid earth. The surface of the crust is the Earth's surface. Parts of the crust are displaced relative to each other by what are thought to be convection currents in the upper mantle, resulting in 'plate tectonic' movements which slowly destroy and rebuild the earth's surface.

The distribution of the *topographic level* of the earth's surface shows that there are two dominant levels corresponding to the continents, with average height of about 1 km, and the ocean basins, with an average depth of about 4 km. The current proportion of total area occupied by the extremes of height and depth (mountain ranges and ocean trenches) is quite small. Elevations greater than about 3 km make up only some 1.6% of the total area of the earth's crust and depressions deeper than 5 km only 1%.

The ability of rocks to flow at depth means that material within the upper part of the mantle can be transferred so as to maintain isostatic equilibrium and allow each part of the crust to sink or rise to the appropriate level. The difference of over 4 km of mean elevation between the continents and oceans is therefore explained by the buoyancy of the thicker continental crust (Park, 1983).

The *continents* cover only 29% of the earth's surface, distributed in a rather uneven way with some 65% of the total land area being in the Northern Hemisphere. If the continental shelf and slope area are added to the land area of the continents, the total continental surface area is 40% compared with that of 60% for the ocean basins. This reflects the relative proportion of continental crust to oceanic crust.

The existence of such a large difference is explained primarily by the difference in thickness between the continental and oceanic crust. The principle of gravitational balance (isostasy) means that topographically higher sections must contain a greater proportion of lower density material to keep the total weight the same. At the base of the crust, the Moho marks a very significant change in composition and density of the rocks. The mean density of the crustal rocks is about 2.8 to 2.9, whereas the peridotic rocks of the upper mantle have a mean density of around 3.4. Continental parts of the crust have a average thickness of about 33 km and a mean composition close to that of granite (acid) whereas the ocean basin parts have an average thickness of only some 7 km and are formed mainly of rocks of gabbroic or basaltic (basic) composition.

The *atmosphere* and *sea water* must have also formed by global scale differentiation and their present compositions have resulted from various processes, including loss of gas consisting of the lightest elements from the interior of the earth and photochemical dissociation of early formed compounds. The ocean-atmosphere system provides important regulatory functions and feed-back interactions between the atmosphere, sea water and crust, which together with biological systems have maintained a near steady state chemical and thermal equilibrium through much of geological time (Dott and Batten, 1988).

TABLE 2.1 : THE STRATIGRAPHIC COLUMN SHOWING THE DIVISIONS OF GEOLOGICAL TIME AND THE AGE OF CERTAIN GLOBAL TECTONIC EVENTS

Eon	**Era**	**Period**	**Epoch**	**Approximate Duration and Cumulative Age (10^6y or Ma)**		**Mountain Building Orogenies (Europe)**	**(N. America)**
PHANERO-ZOIC ('evident life')	CENOZOIC ('recent life' 1841)	Quaternary	Holocene (1885) or Recent (1883) (last 10,000 yrs)	0.01	PRESENT		Coast Ranges
			Pleistocene (1839)	1.8	1.8	(Himalayan)	
		Tertiary (Neogene 1853)	Pliocene (1833)	3.5			
			Miocene (1833)	18.5	23.8		
		Tertiary (Palaeogene 1866)	Oligocene (1854)	9.9			
			Eocene (1833)	21.1			
			Palaeocene (1874)	10.2	65	Alpine	Laramide
	MESOZOIC ('middle life' 1841)	Cretaceous (1822)	Each of these Periods is divided into numerous Epochs which can be recognised throughout the world	77			Nevadan
		Jurassic (1795)		63.7			
		Triassic (1834)		42.5	248.2		
	PALAEO-ZOIC ('ancient life' 1838)	Permian (1841)		42			
		Carboniferous*(1822)		64		Hercynian (Variscan)	Appalachian
		Devonian (1837)		63			Acadian
		Silurian (1835)		26		Caledonian	
		Ordovician (1879)		52			Taconian
		Cambrian (1835)		50	545	Assyntic	
PRE PHANERO-ZOIC (or PRE CAMBRIAN)	PROTERO-ZOIC	Edicarian (1982) All rocks older than the Palaeozoic can be collectively described as PRECAMBRIAN	Many Precambrian rocks are severely deformed and metamorphosed, but large areas of undisturbed Precambrian strata are known. Epochs that can be correlated throughout the world have not been defined	c. 1910	c. 2500	c. 750 Rare primitive fossils c. 2000 First stable crustal plates	) Numerous) orogenies) possibly not) involving) plate tectonics,) prior to the) development) of stable) crustal plates.
	ARCHEAN			c. 2100	c. 4600	c. 3750 Oldest dated rocks	)))

*Equal to Pennsylvanian (1891) and Mississippian (1870) in USA.
Dates in brackets when Divisions were named.

(After several sources)

2.1.3 Plate Tectonics Theory

Plate tectonics is a unifying theory that explains the structure of the Earth's near surface. The plates (lithospheric plates) are delineated by the earth's major earthquake zones and plate motions are thought to be driven by thermal convection in the upper mantle as well as the gravitational pull of cold dense parts of plates descending into the mantle. Plates move apart at ocean ridges, or divergent plate margins, and towards one another along magmatic (island) arcs or orogenic belts at convergent plate margins. Some important aspects of the plate tectonic theory are: *Ocean ridges* are approximately linear zones of extensional faulting or rifting, characterised by basaltic volcanism.

Sea floor spreading occurs as new ocean floor is added thus spreading occurs away from the ocean rifts. Continents may be rifted apart to drift passively along as new oceans spread between them. Distribution of heat flow, ages of volcanic islands and fringing reefs, barrier reefs, atolls and volcanic sea mounts, all support the view of slow cooling and subsidence of ocean floor as it moves away from spreading centres. Sea floors have the following features:

- *Transform faults,* which offset sections of ocean ridges and move continually as the adjacent segments spread. They help to accommodate the greater widening of spreading ocean basins in equatorial regions.
- *Linear magnetic anomalies* in the ocean crust, which are symmetrical and parallel to the ridges, record reversals of the polarity of the magnetic field as the sea floor spreads. The polarity reversals may be used to establish a universal time scale which provides the basis for both the dating of spreading histories and the reconstruction of shapes of ocean basins and positions of continents during the past c.200 million years, during which time the present ocean basins have been forming.

Deformation of the continental crust has occurred throughout most of geological time. A typical orogenic episode is preceded by subsidence of marginal troughs in which sediments accumulate; plate convergence then initiates deformation in a belt that extends hundreds of kilometres from the original troughs. The marginal sediments are deformed by folding or faulting; thrust sheets ten to twenty kilometres thick slide over one another, often for distances of tens to hundreds of kilometres. Huge foreign terranes (a group of rocks with similar history) brought in with the subducting plate may accrete to the continental plate. Intrusions of batholiths and metamorphism typically occur with the orogeny. The mountains are raised in a deformed belt and erode after the orogeny ends. Renewed stages of uplift, or block faulting, that again raise the region, account for many of the large-scale topographic features we see today.

Plate collisions are the main cause of these orogenic episodes, i.e. orogenesis. Collisions may involve either two continents, or varying combinations of magmatic arcs, continents or micro continents. Orogenic belts appear to be made up of collages of diverse terranes jammed together by successive collisions. Suture zones mark the boundaries of such collisions: they are often characterised by crumpled mafic and ultramafic ocean rocks. The collision of two or more continents forms a supercontinent. Plate margins can exhibit the following features:

- *Subduction*, the process of underthrusting one lithosphere plate beneath another at a convergent margin. Much ocean floor is lost by subduction.
- *Magmatic arcs,* dominated by andesite eruptions that form at the surface above subduction zones. Once a plate breaks down and begins to subduct, gravity helps to pull it downwards into the mantle where it is slowly heated and assimilated.
- *Obduction*, the process of overthrusting of one plate over another at a convergent margin.
- *Passive continental margins,* where the edge of a continent is not on a tectonically active convergent margin but moves with the adjacent oceanic crust, to which it is welded.
- *Subsidence associated with plates*, important as it provides room for accumulation of thick strata in sedimentary basins of various types during periods of tens to hundreds of millions of years.

Hot mantle plumes rising from the lower mantle seem to cause the initial break up of the crust at triple junctions, e.g. the Indian Ocean Ridge connects with the East African Rift System in a triple junction where three rifts meet.

Aulacogens are sediment filled troughs associated with initial rifting of continents at triple junctions.

2.1.4 Sedimentary Basins

Sedimentary basins can be distinguished by their plate tectonic settings and characteristic rock types. At least six types can be recognised. These are summarised in Table 2.2 and related to our Tectonic models.

Within these global sedimentary basins, as deposition environments shift through time, patterns of sedimentary facies are produced, related to their depositional environment. As depositional environments change position, adjacent sedimentary facies will succeed each other in vertical deposition sequences, i.e. vertical changes of the lithology, due to transgression or regression, reflect similar lateral changes (e.g. sediments will coarsen laterally as well as upwards). Change may be caused by:

- Tectonic downward or upward movement giving transgressive facies patterns with a reduction of the land area due to the encroachment of the sea, or a regressive facies pattern due to withdrawal of the sea.
- Worldwide regressions and transgressions caused by the waxing and waning of continental glaciers, or by large-scale down or up warping of the earth's surface due to glacial loading or unloading.
- Local transgression and regression by subsidence or uplift of the crust due to rapid coastal sedimentation or erosion (e.g. the loading on the crust by large deltas).

TABLE 2.2 : TYPES OF MAJOR SEDIMENTARY BASINS

Basin Type	Characteristic sediments	Depositional environments	Examples of Global Tectonic Models in figures of paper
Rift or aulacogen	Earliest rocks volcanic overlain by thick gravel and sand; younger rocks may include evaporites and limestones. Long lived sediment-filled grabens. Little deformation.	Rivers and lakes changing to shallow-marine	Fig. 2.4, 2.7
Intra cratonic	Homogeneous quartz-rich sands and limestones, but may include muds, evaporites, or coal at certain times. Little deformation.	Mostly shallow-marine with some deltaic	Fig. 2.6
Passive margin	Quartz-rich sands and limestones passing seaward to muds. Diapirism.	Shallow-marine shelf to deeper-marine	Fig. 2.6
Trench	Fine sediments overlying ocean-floor basalts. Extensive. Deformed accretionary wedge.	Deep marine	Fig. 2.9
Forearc\Backarc	Varied thick sediments ranging from pelagic through turbidites to alluvial fans, much derived from adjacent orogenic belts. Volcanoclastics common. Deformed accretionary wedge.	Non-marine to deep marine	Fig. 2.9, 2.10
Foreland	Heterogeneous gravels, sands and muds derived from the orogenic belt and shed on to the continental craton; may be coal-bearing. Relatively stable areas.	Mostly river and deltaic	Fig. 2.13

(Partly after Dott and Batten, 1988)

2.2 The Global Tectonic Models

The vast geological knowledge of the structure and history of the world unified by the plate tectonic theory has been synthesised with much simplification into the Tectonic models. Ten *'global tectonic'* models are presented as Figures 2.4 to 2.13 in the Models Appendix. We have added to Figure 2.2 and Table 2.2 the approximate correlation with our Tectonic models, where appropriate. Where there is no close single equivalent, we have quoted two or more models.

The models must be considered quite idealised. They represent conceptual end members defined from the plate tectonic theory and are not drawn to represent any specific location but to indicate the particular association of rock types and structure that typically occur. It is emphasised that all the models are meant to be self-explanatory, drawn for engineering geology purposes, and to help lead the site investigator on to the site scale models. Each drawing lists the possible lithological and structural associations within the model. A real area is likely to contain parts of a variety of models brought together during a long geological history.

The Tectonic models also list as a guide the more likely initial *'site scale geological'* models that could occur within the parent Tectonic model. However, this list is not exhaustive and judgment on each locality must be made. Thus, by identifying the Tectonic model, the site scale models for the project site can be narrowed down to a limited number.

Three principal groups of global Tectonic models have been produced to relate to the foregoing discussion: a group of three relating to *intra plate systems* (cratonic cores, mobile belts, platforms/basins); a group of two relating to *divergent plate boundaries* (continental rift, ocean rift) and a group of five relating to *convergent plate boundaries* (fold and thrust belts, magmatic arc, collision complexes, foreland basins, accretionary prisms).

In Section 5.0, case histories related to the models have been added.

2.3 A Very Short History of the Earth

An understanding of the eons of geological time - deep time - is essential to understanding how the earth and the Tectonic models work.

Some regularly repeating (or cyclic) changes, like the advance and retreat of glaciers during the ice ages, are reflected in the stratigraphic record. Catastrophic irregular or episodic changes are more common, however, and they have interrupted the record with large scale unconformities which bound the major rock sequences. The stratigraphic record is thus punctuated, rather than being either continuous or gradual in character.

Unconformity bounded sequences of strata, comprising many formations and covering large areas provide insights into the histories of plates, continental margins and cratonic interiors. Recognition of the same unconformities on different continents show a considerable degree of global synchronisation which suggests worldwide causes of, for example, sea level fluctuations.

The following relates to the stratigraphic column showing the larger divisions of geological time given in Table 2.1, and the gross distribution of tectonic elements on the Earth's surface in Figure 2.1.

2.3.1 The Prephanerozoic or Precambrian Time

This includes some 80% of the earth's history from its birth about 4.6 billion years ago (i.e. 4600 x 10^6 y, or 4600 Ma years ago). The record in the rocks of the Prephanerozoic is much more obscure than for Phanerozoic times because the lack of datable fossil assemblages in rocks older than 600 to 700 Ma. Correlation must, therefore, be based on physical field criteria and isotopic dating.

Prephanerozoic time may be divided into the oldest rocks, the Archean, followed by the Proterozoic.

The *Archean*, from 4600 to 2500 Ma, was dominated during its early part by a massive heat flux which was so great that little permanent crust could survive; an oxygen rich atmosphere had not yet developed. It has two main assemblages of rocks:

- Mobile greenstone belts with mafic igneous rocks (e.g. komatite and basalt) associated with heterogeneous immature clastic sediments rich in feldspar and volcanic rock fragments.
- Gneiss and granitic belts.

By *Proterozoic* times, from 2500 Ma to 545 Ma, heat generation had apparently declined sufficiently to allow much larger masses of continental crust to survive. Importantly, clearly recognisable cratons bordered by well-defined orogenic belts suggested that plate tectonic processes may have been operating much as today.

Early Proterozoic sediments differed from the Archean ones in that they were texturally and compositionally more mature. They included terrigenous (land derived) clastic material, with well sorted and well rounded quartz grains, and non-terrigenous chemical carbonate and evaporate strata. Stromatolites formed by algae or bacteria occurred quite widely in carbonate rocks all of which were deposited in broad shallow seas on stable cratonic areas.

By late Proterozoic times, important large-scale rifting accompanied by eruption of widespread flood basalts was occurring. Climates, as far as they can be deduced, seem not to have been too dramatically different from Phanerozoic ones except that more carbon dioxide may have caused warmer global temperatures, due to the greenhouse effect. There is clear evidence of extremes of both glaciation and aridity. The more the later Prephanerozoic sedimentary record is studied, the more it seems to resemble that of Phanerozoic times, but with the absence of animal remains.

2.3.2 Phanerozoic Time - the Palaeozoic and Mesozoic

These eras (which started some 545 Ma ago) are dominated by the presence of two supercontinents, *Gondwanaland* mainly in the south and *Laurasia* mainly in the north. Gondwanaland came into existence through several continental plate collisions associated with Cambro-Ordovician orogenesis: shallow inland seas covered parts of Gondwanaland until the Devonian and there was a distinct southern marine assemblage of fossils. Laurasia still comprised scattered small continents in the warm Tethyan sea until the late Palaeozoic, when they began to merge.

Soon after the Permo-Triassic Gondwana orogeny the new super-supercontinent, *Pangea*, was formed by the collision of Gondwanaland with the newly assembled Laurasia.

The palaeoclimate of Gondwanaland, and later, of early Pangea, was clearly zoned since glacial centres can be shown to have shifted as different parts of the continent drifted across the South Pole. When the Gondwanaland part finally drifted away from the South Pole and the landmass became larger with the formation of Pangea, the overall climate became warmer and drier. It was not until the break-up of Pangea at the end of the Permo-Triassic period some 250 million years ago and the eruption of basalts associated with rifts, that the formation of the Atlantic rift began at the margins of the present central Atlantic basin.

During the Cretaceous, new Atlantic and Indian oceanic zones opened and rifting of micro continents from northern Africa developed with the widening of the Tethyan Sea. The destruction of the former Gondwanaland/ Pangea was completed about 100 million years ago: the last continental breaks were between Australia and Antarctica (in the late Cretaceous/early Tertiary) and South America and Antarctica (in the Miocene).

Young rifts between the newly separated continents first received non-marine clastic and evaporite sediments followed by deep marine sediments as the ocean basins widened. Shallow marine transgressions then flooded the adjacent cooling and subsiding passive continental margins.

2.3.3 Phanerozoic Time - the Cenozoic

During this period (the last 65 million years), the world began to take on broadly the landforms and landscapes more or less as we know them today, i.e. *the basic engineering geology environment* of the regions began to form.

In **the Americas** the Cordilleran orogenesis was complete during Palaeocene and Eocene times, when the Rocky and Andes Mountains were formed by compression of Palaeozoic or Mesozoic strata. Inter-mountain basins were then filled with river and lake deposits, scattered granites and ore deposits were also produced during tectonic episodes.

Regional up-warping during the late Cenozoic (mainly Neogene) times rejuvenated rivers in the Rocky Mountain-Colorado Plateau region, resulting in deep canyon cutting. Extension and transform movements of the crust of the westernmost parts of North America characterised Neogene times in contrast with the compressional tectonics of Palaeogene times and caused:

- block faulting resulting from crustal extensions across the Basin and Range province.
- plateau basalts to erupt from deep fissures over much of the northwestern American states.
- lateral movement forming the San Andreas Fault System, the long transform zone that offset the east Pacific spreading ridge by some 3,000 kilometres, and decoupled the Baja California and Californian coast ranges from the continent.

A passive continental margin coastal plain and the deposition of continental shelf strata succeeded many of the former tectonically active Palaeozoic margin structures.

The Gulf of Mexico Province is now underlain by the thickest sequence of any passive margin and is characterised by abundant rising salt domes, which produced important petroleum traps: the Arctic Province also possesses evaporite domes reflecting the dramatically different hot climate that existed during sediment deposition, in contrast to today's cold one. The Atlantic Coast Province of Northern America also experienced a rejuvenation of the Appalachian Mountains by crustal up-warping and river down-cutting.

The **Pacific Ocean region** underwent major changes from Palaeogene to Neogene times.

The distribution of equatorial sediments and the track of the Hawaiian mantle plume indicate a change of Pacific plate motion about the same time that California collided with an ancient ocean ridge.

- Most modern western Pacific magmatic arcs were either born or modified in mid-Cenozoic time (as was the Cascade Volcanic Arc of western North America).
- The modern configuration of the Central American-Caribbean Region was achieved during the Neogene, and the Drake Sea was formed by the separation of South America from Antarctica. The full development of the circum-Antarctic current resulted.

Eurasia experienced major late Cenozoic tectonic events, viz.:

- The Alpine-Himalayan orogeny was caused by the collision of Africa and Turkey with Europe, as well as Arabia, India and Thailand with eastern Europe and Asia. Very complex folded structures, including recumbent nappes, resulted and south eastern Asia was squeezed eastward towards the Pacific along several large transcurrent fault zones by the force of India's collision.
- The Tethyan Sea disappeared as the collisions occurred. The Mediterranean Sea, a partial remnant of Tethys is still being closed. Blocking of the Strait of Gibraltar in late Miocene times led to evaporation of the sea with repeated evaporite formation, followed by Pliocene refilling.
- Cratonic Eurasia, Africa and Antarctica all experienced important rift faulting and volcanism as a byproduct of Neogene global plate reorganisation. Most obvious was the start of the separation of Africa from Arabia along the Red Sea-Aden rifts.

Australia is currently on a collision course with the Indonesian Arc and ultimately with south east Asia, converging at the rate of some 6 cm/year.

2.3.4 The Quaternary

The Quaternary is the last and shortest period of the Cenozoic, but it deserves special treatment, as the recent past is within this period and the top few tens of metres of the Earth's surface, i.e. the part of the earth in which engineering geologists, geomorphologists and civil engineers work, was predominantly shaped, certainly in detail, by the events of the Quaternary. These events were mainly climatically controlled and typified by glacial and interglacial periods. Details of the Quaternary Ice Age are given in the accompanying text box.

Quaternary Glaciation

Recognition of continental scale glaciation occurred about a century and a half ago and replaced the diluvial hypothesis. Initially, four major glacial episodes, with interglacials, were proposed but modern interpretation and oxygen-isotope curves from deep sea sediments suggest many more alternating cold and warm episodes extending back well over two million years. On land, the younger glacial episodes obliterated most of the evidence left by the older ones.

The effects of glaciation, in addition to well-known eye-catching features like erratic boulders and scratched bedrock surfaces, resulted in situations of engineering significance which include:

- Worldwide sea level falls or rises, responding to glacial and interglacial oscillations, which resulted in:
  - buried valleys
  - complex river terraces along valleys
  - dead coral reefs, marine beaches and deltas, now high and dry
  - temporary land bridges drowned by high sea levels
  - submerged beach ridges and other drowned features on continental shelves
  - submarine canyons extending from continental shelves to the deep sea
- Extensive covering of much of the world's land (and sea bed) surface by complex tills (i.e. morainic material) both from valley glaciers and continental glaciers.
- Vast volumes of granular fluvio-glacial debris issuing from the margins of continental glaciers and snouts of valley glaciers; on the retreat of the glaciers these materials covered the till laid down by the glaciers themselves.
- Repeated glaciations which built up sandwiches of fluvio-glacial material overlying true glacial (till) material, perhaps overlying older till material, all of which became weathered and overlain by alluvial and other deposits of the interglacial or postglacial warmer climates.
- Overdeepening of valleys and other glaciated terrain with production of irregular bedrock profiles.
- Numerous lakes of all sizes forming near the glaciated regions, often containing annual varve laminations (which can be counted like tree rings).
- Enormous volumes of silt carried away by the wind from valleys that drained the melting glaciers and deposited as loess over vast areas of northern hemisphere continents.
- Extensive periglacial conditions, i.e. freeze-thaw activity over many, many summer/winter cycles, significantly disturbing near surface profiles affected by these conditions (covering about a third of the earth's land surface at times of maxima) and producing, along with glacial deposits, their own features, e.g. solifluction debris, cambering, valley bulging, pingos, all of which have a significant effect on engineering.
- Many tens of metres of isostatic rebound, much still continuing, of the crust formerly warped downwards by the load of ice sheets thousands of metres thick .
- Extensive changes to margins and characteristics of hot deserts, equatorial and monsoonal rainforests and other climatically related landforms.

3.0 THE ENGINEERING GEOLOGY ENVIRONMENT

In some countries (including the UK) little geomorphology is taught to geologists: it is often taught as part of a general or specialised geography degree. We consider it essential that engineering geologists have a good grounding in geomorphology. In this paper, the term 'engineering geology' implies that the geology component includes geomorphology.

In the same manner, the *engineering geology environment of a site* reflects the product of its total geological *and* geomorphological histories. Engineering geology environments may thus be described by the site scale stratigraphy and structure models concerned with 'bedrock' geology - the *geological models*; and those concerned with the superficial deposits and landforms - the *geomorphological models*.

It is important to state that these initial models speak also for themselves and, like the Tectonic models, are extremely simple and must be considered quite idealised. They are conceptual and reflect existing geological and geomorphological knowledge, and aim to help anticipate the association and possible geometric relationship of geological and geomorphological characteristics and features of the project. This approach is loosely based on, but is different from the GEM (Geological Environmental Matrix) approach described in Fookes (1997), p.395, which is constructed by considering the results of interaction of rock *forming* processes with rock *modifying* processes.

The *purpose* of the models is to:

- anticipate and stimulate thoughts on associations of geological and geomorphological characteristics and features;
- give some idea of their spatial and possibly temporal relationship and, importantly;
- enable development of check lists of characteristics and features which need to be considered in the design of the site investigation and the project. In these it becomes necessary to establish whether such features occur on site or not and, if so, what is their location, form, range of characteristics and engineering significance.

The models are also a crude teaching aid to the understanding of geology and geomorphology. As a result of the simplifications made in developing the models, many geological and geomorphological concepts may have been omitted or inadequately illustrated. Those wishing to develop their understanding further must read well beyond this paper. The models are intended to help engineers not so well versed in the ways of geology and geomorphology. However, to understand them fully requires considerable training, usually gained on a degree course at University in these subjects, and subsequent relevant experience in the field. A little geological or geomorphological knowledge can be dangerous unless its limitations are fully appreciated.

3.1 The Site Scale Geological Models

These models represent the 'building blocks' of the project site geology and comprise associations of geological materials and geological structures, *igneous* and *sedimentary* rock types in various *structural* and *metamorphic* settings. The models can be considered as site or 'local' scale geology. They relate to the global scale Tectonic models discussed in Section 2.2, as their characteristics relate to their global setting. The Tectonic models can be considered as parents to the 'regional' geology.

Geological materials at a site will be part of one or more of the three main groups of rocks, igneous, sedimentary and metamorphic, which are directly or indirectly related to the plate tectonic setting:

- *Igneous rocks* are divided, on the basis of origin, into intrusives and extrusives, the former are usually coarse grained: the latter fine grained or glassy. They are also classified as felsic (acid) or mafic (basic), depending on the kinds and relative amounts of light and dark minerals. Volcanic rocks are further divided by texture.
- *Sediments* and *Sedimentary rocks* fall into two main groups: the detrital, those formed from particles eroded from pre-existing rocks and the chemical, those formed by chemical precipitation of minerals from salt or fresh water. Detrital sediments are subdivided on the basis of genesis, grain size and mineralogy. The chemical sediments are subdivided primarily on the basis of chemical composition. Subsequent to deposition, new sediments are subject to diagenesis. *Diagenetic* changes to sediments are those which occur at lower temperatures and pressures than common in metamorphic processes: with increasing pressure, diagenesis grades into metamorphism. Diagenetic processes include compaction, dissolution, cementation, replacement and recrystallisation, which are the means by which unconsolidated or loose sediment is turned into sedimentary rock, e.g. sand becomes a sandstone. For related discussions see the following text box on weathering, erosion and deposition.
- *Metamorphic rocks* are the products of either regional metamorphism in which large volumes of in situ rock are transformed by regional increases in pressure and temperature, or contact metamorphism in which rocks close to igneous intrusions are transformed primarily by heat. Metamorphic rocks are classified according to their nature of foliation or cleavage and mineral assemblage or facies.

Detail may be found in any good basic geology or petrology textbook. Engineering geology discussions can also be found in many good texts, e.g. Bell (1993) and Blyth and de Freitas (1996).

Geological structures are produced by forces acting on the geological materials within the crust. Tectonic forces can deform large regions of the continents and produce earthquakes when released quickly.

- In some cases the regional movements are simple up and down displacements, i.e. *epeirogeny*, without serious deformation of the rock formations. In other cases, horizontal forces connected mainly with plate collisions, i.e. *orogeny,* can produce extensive and complex folding and faulting.
- Most of today's continental crust can be divided into belts that have been deformed during different orogenic

periods. Africa and North America, for example, contain large stable central regions that have been relatively undisturbed (except for gentle vertical epeirogenic movements and erosion) since undergoing episodes of intense deformation in the Precambrian, i.e. they are now *cratons*. Surrounding these stable interiors are younger orogenic belts - mountainous areas which were deformed at various times in the Palaeozoic, Mesozoic and Cenozoic eras (see Tables and Figures 2.1, 2.2 and 2.3).

On the project site, geological structures can result from: tectonic forces related to plate movement; unloading by erosion; loading by deposition; cooling of igneous rocks, or drying out of sediments, and can occur on different scales at different times depending on the circumstances. The stress from such activities can be accommodated either by the flow and deformation of rocks over long periods of time or by fracture, the latter being common in the brittle rocks of the upper crust, often in a shorter period of time. In engineering geology, *fractures* are called discontinuities (or defects) in the rock mass. Fractures in geological materials develop in response to stress and form joints or faults. Joints are structures of small dimension formed in tension or shear but lacking any significant shear in the plane of the joint. Faults are typically larger structures commonly formed by shear but where significant movement occurs in the plane of the fault. Fault movement ranges from up to a few centimetres on shallow faults to tens, or hundreds of kilometres on faults extending to the base of the lithosphere. Most faults can be broadly classified according to the direction of slip of the adjacent blocks, e.g. dip-slip, strike-slip.

Very commonly structural geology features occur in families ('sets') or patterns related to their formation. Knowledge of these sets is helpful in anticipating the nature of such features.

While fracturing is a common response to stress at the surface, sustained stress under high confinement pressures can cause bedrock deformation by *folding*. Most folds originate at some depth, the simplest forms being the monocline, anticline and syncline. Recumbent folds occur where rocks are overturned and both limbs of the fold are nearly horizontal. The horizontal compression that creates recumbent folds may eventually lead to shearing of the upper part of the fold, along a thrust fault. Fold patterns relate to the geological stress history, and again an understanding of this can help in anticipation of the nature of the geological structure of the site.

3.1.1 The Geological Models

Seventeen site scale geological models have been built from personal experience and geological knowledge briefly described in Section 2.0, Section 3.1 and the text boxes, and by further discussion following in Section 3.2. They are presented together in the Models Appendix at the end of the paper as three-dimensional models. Figures 3.1 to 3.17 have been subdivided into three interrelated groups, i.e. *the igneous group*, comprising basic volcanic; acid volcanic; and intrusions of plutonic rock; *the sedimentary group*, comprising continental fluvial, colluvial and lacustrine; deltaic; shelf carbonates and evaporites; and deep marine deposits; *the structural and metamorphic group*, comprising jointing patterns in undeformed sediments; normal fault systems; strike-slip fault systems; thrust systems; open folds and joints; plastic folded with cleavage; multiple-folded/sheared; mélanges; schistose; and gneiss and migmatite.

It is likely that more than one site Geological model will be required to describe adequately a site because the models are idealised end members whereas project sites are underlain by real, often complex geological and geomorphological conditions.

3.2 The Site Scale Geomorphological Models

3.2.1 Climate and Geomorphology

The role of climatic factors in influencing the nature and rate of operation of geomorphological processes has led to the suggestion that different climates are associated with characteristic landform assemblages, i.e. over a period of time climatic environments can generate a distinctive association of landforms of regional extent. Areas characterised by landforms associated with a particular climate are called *morphoclimatic zones*.

Table 3.1 shows the earth's current major morphoclimatic zones which relate to the global distribution of the morphoclimatic zones of Tricart and Cailleux (1972) and the important geomorphological processes in that zone. We cannot over emphasise the importance of such processes in the site near-surface geology. We have added to Table 3.1 the approximate correlation of our initial Geomorphological models with the appropriate morphoclimatic zone. Where there is no close equivalent, we have quoted two models, the first quoted probably being the closer to the given zone. The validity of the assumptions behind climatic geomorphology has been strongly challenged by those who see little evidence of a close relationship between current climate and landform morphology, except under the most extreme climatic contrast. Suffice to say that with the exception of landforms which have a very short *relaxation time* (i.e. response of the landscape to changing climate), most elements of the landscape are likely to be, to a greater or lesser extent, out of equilibrium with the prevailing climate conditions because of the rapidity and magnitude of global climate changes that have occurred over the last few million years. Indeed, in some regions, such as central Australia and central Southern Africa, there is generally a very low rate of geomorphological activity and the landscape is dominated by relic landforms developed over millions of years, often under climates somewhat different from those prevailing now. See, for example, the helpful discussions in Stoddart (1969), Thornes and Brunsden (1977) and Büdel (1982).

TABLE 3.1 : THE EARTH'S MAJOR MORPHOCLIMATIC ZONES

Morphoclimatic Zone	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Relative Importance of Geomorphological Processes	Examples of Site Scale Geomorphological Models in this Paper
Azonal Mountain Zone	Highly variable	Highly variable	Rates of all processes vary significantly with altitude; mechanical and glacial action become significant at high elevations.	Fig. 3.18 Fig. 3.21
Glacial	<0	0-1000	Mechanical weathering rates (especially frost action) high; chemical weathering rates low; mass movement rates low except locally; fluvial action confined to seasonal melt; glacial action at a maximum; wind action significant.	Fig. 3.18 Fig. 3.19
Periglacial	-1 to +2	100-1000	Mechanical weathering very active with frost action at a maximum; chemical weathering rates low to moderate; mass movement very active; fluvial processes seasonally active; wind action rates locally high. Effects of the repeated formation and decay of permafrost.	Fig. 3.20
Wet mid-latitude	0-20	400-1800	Chemical weathering rates moderate, increasing to high at lower latitudes; mechanical weathering activity moderate with frost action important at higher latitudes; mass movement activity moderate to high; moderate rates of fluvial processes; wind action confined to coasts.	Fig.3.21
Dry continental	0-10	100-400	Chemical weathering rates low to moderate; mechanical weathering, especially frost action, seasonally active; mass movement moderate and episodic; fluvial processes active in wet season; wind action locally moderate.	Fig. 3.22
Hot dry (arid tropical)	10-30	0-300	Mechanical weathering rates high (especially salt weathering); chemical weathering minimal; mass movement minimal; rates of fluvial activity generally very low but sporadically high; wind action at maximum.	Fig. 3.22
Hot semi-dry (semi-arid tropical)	10-30	300-600	Chemical weathering rates moderate to low; mechanical weathering locally active especially on drier and cooler margins; mass movement locally active but sporadic; fluvial action rates high but episodic; wind action moderate to high.	Fig. 3.21 Fig. 3.22
Hot wet-dry (humid-arid tropical)	20-30	600-1500	Chemical weathering active during wet season; rates of mechanical weathering low to moderate; mass movement fairly active; fluvial action high during wet season with overland and channel flow; wind action generally minimal but locally moderate in dry season.	Fig. 3.21 Fig. 3.23
Hot wet (humid tropical)	20-30	>1500	High potential rates of chemical weathering; mechanical weathering limited; active, highly episodic mass movement; moderate to low rates of stream corrasion but locally high rates of dissolved and suspended load transport.	Fig. 3.23

(partly based on various sources summarised in Summerfield, 1991)

Weathering, erosion and deposition

Weathering is chemical change and physical fragmentation, under the conditions at the earth's surface, of rocks and minerals that were formed, for the most part, at higher pressures and temperatures below the earth's surface. The breakdown of rock masses to fragments ranging from boulder to clay size is the result of chemical weathering combined with the forces of physical disintegration. Soluble rocks (e.g. limestones) weather by going into solution and may leave little insoluble debris. The intensity of weathering depends upon the climate, tectonics, original rock composition and time. Given enough time, the effects on landform of factors other than climate are less important. The weathering process produces the residual clays and dissolved substances that are carried by rivers to the oceans.

Following the weathering, processes of active *erosion and transportation* take over to create more varied topography. Landslides and river activity erode landscapes and, together with other agents of erosion, help repeatedly shape the land surface. The forms and slopes of valleys are clues to the agents of erosion that shaped them - water, ice and wind forces, that act in opposition to tectonic forces that elevate mountains. The evolution of landscape is thus a balance between uplift, erosion and deposition over the course of time.

Most of the debris resulting from erosion is carried downhill by rivers eroding channels and moving particles downstream. The ability of a river to transport particles in different amounts and sizes depends on current velocity and form, the total amount of water carried downhill and the downhill slope of the channel. Currents form ripples, dunes and bars in channels, deltas or lake sediments. The river can be analysed as a complex system with drainage patterns which form in response to the conditions of climate, bedrock and particles produced by the weathering. Such *sediment* in transport may be temporarily stored as alluvium and other deposits on its journey to the sea.

Sediment brought to the sea by rivers or eroded from the coast by wave action is distributed along shores as beaches or transported by currents on the continental shelf and into deeper parts of the ocean. Coastal features express the balance between the supply of sediment provided by erosion of the shore and the transport of material by rivers, wave erosion and longshore currents. The continental slopes and abyssal plains are shaped by turbidity currents that transport much material from the shallower to the deeper parts of the sea. The current patterns of the general circulation of oceans influences the distribution of the fine grained pelagic sediment that mantles the topography of the sea bed.

Physical sedimentation is a deposition of such materials in the lowest places to which ice, air or water currents can transport them. Chemical sedimentation is the principal process by which seawater maintains a reasonably constant composition by depositing precipitates to balance dissolved weathering products brought in by the rivers. Calcium carbonate makes up the largest volume of such chemical sediment. Much of it is extracted from sea water by invertebrates and secreted as shells. Silica-rich sediments are also largely produced by organisms, mainly diatoms. Bacteria and evaporation also play important parts in these processes.

The original deposition patterns of sediments are strongly affected by the geomorphological environment in which they were deposited. Tectonism largely controls subsidence in the deposition area and, to an extent, the rates of weathering of the source of the erosion debris. Chemical and physical changes after deposition convert the weak sediment to rock and cause many other alterations of composition and texture by diagenesis.

Wind, although less powerful than water currents, can erode sand and silt effectively, particularly in periglacial and arid regions. The deserts of the world are sites of intensive wind and sometimes salt action, and display special topographies and erosional and depositional processes more intense than those of humid regions. Sand dunes, depositional landforms created by wind, are heaps of sand that accumulate in different shapes and move in response to the abundance of the sand supply, the strength and direction of the wind and the nature of the bedrock surface. Loess (windblown silt deposits) cover large areas adjacent to glaciated terrain where rock flour (silt sized particles) were produced and carried away by the wind.

The low temperatures and precipitation of snow that are typical of polar regions and high mountains contribute to the formation of glaciers and snowfields. As snow accumulates, it becomes compacted, gradually changing from snowflakes to granules to solid massive ice. As local glaciers move down valleys, they sculpt the topography by eroding rock and transporting the debris to locations where melting takes place. Glaciers of continental size, like those in Greenland and Antarctica, produce a variety of erosional and sedimentary landforms. The glacial landforms of the recent past are evidence of the Pleistocene glacial epoch during which huge areas of North America and Eurasia were covered by ice. See also the text box on Quaternary Glaciation in Section 2.3.4.

For further discussion on weathering, erosion, transportation and deposition, see for example the excellent discussions in Press and Siever (1986).

If the concept of relaxation time is accepted, then distinctive processes and landforms may be associated with certain climatic environments and that association clearly demonstrates that major differences in climate can have a profound effect on landscape development. Uncertainty comes with the finer distinctions between degrees of humidity and temperature evident in attempts to characterise morphoclimatic zones uniquely. There also have been many discussions relating climatic controls to the magnitude and frequency of meteorological events, e.g. Douglas (1978).

We present some simple Geomorphological models related to the basic climate classifications, so that the association of processes and possible landform elements can be considered, together with key annotations and descriptions which go with the particular model for the purposes of the engineering geology site evaluation.

Basic details of weathering, erosion and deposition are given in the accompanying text box.

TABLE 3.2 : A HIERARCHICAL RELATIONSHIP BETWEEN TIME AND SPACE SCALES IN LANDFORM EVOLUTION

Spatial Scale	Dimensions		Examples of Landforms				Major Controlling Factors		Time Scale in years	
	Linear (km)	Areal (km^2)	Endo-genic	Fluvial	Exogenic Glacial	Aeolian	Endogenic	Exogenic		
Micro	<0.5	<0.25	Minor fault scarps	Pools and riffles in a small river channel	Small moraine ridges	Sand ripples	Individual earthquakes and volcanic eruptions	Microclimates meteorological events	Steady time	Tens
Meso	0.5-10	0.25-10^2	Small volcanoes	Meanders	Small glacial valleys	Dunes	Local and regional isostatic uplift; localised volcanism and seismicity	Local climates short-term climatic change	Dyna-mic time	Thousands
Macro	10-10^3	10^2-10^6	Block-faulted terrain	Flood-plains of major rivers	Highland ice caps	Sand seas	Regional uplift and subsidence	Regional climates; long-term climatic change (glacial-interglacial cycles)		
Mega	>10^3	>10^6	Major mountain ranges	Major drainage basins	Continental ice sheets	Large sand seas	Long-term patterns of uplift, subsidence and continental motion	Major climatic zones; very little climatic change (ice ages)	Cyclic time	Hundreds of thousands to millions

(after Summerfield, 1991)

3.2.2 Scale and Time in Geomorphology

In general terms, any change in an input to a geomorphological system, such as an increased rate of uplift or decrease in river discharge, is reflected in a change of form. The time this takes may be particularly important for the life of an engineering structure, as it can range from a few minutes for changes in a small section of an alluvial channel, to tens of millions of years, say, for the uplift of a major mountain range. The form of a channel in unconsolidated alluvium may change in a few hours in response to marked changes in river discharge, whereas a channel of similar size, cutting into dense, resistant bedrock, may take hundreds or thousands of years to adjust, assuming that the change in discharge persists. It is therefore useful to categorise this range of scale and to talk of, for instance, micro-scale or macro-scale forms. Such a classification is presented in Table 3.2.

The table gives some suggested ranges of linear and areal dimensions, though it should be emphasised that the divisions between each scale are somewhat arbitrary. Clearly the micro- and meso-scales are of most importance to engineering projects and on occasion perhaps the macro-scale, e.g. flood plains of major rivers. In environments in which rates of erosion and deposition are high, landforms can be modified rapidly and the effects of occasional high magnitude/low frequency events can be obliterated fairly quickly. In such environments a steady state of equilibrium can be reached in a short period of time. There are many factors affecting this, an important one being the degree of resistance of the material being eroded.

Such scale effects are not implicit in the models and their annotation, and need further evaluation during the project investigations.

For further discussions on geomorphological processes on various scales, see for example the several excellent discussions in Thorn (1982).

3.2.3 The Geomorphological Models

The Geomorphological models are designed to be combined with the selected site scale Geological model(s) for the site. It is the combination of these *initial* Geological and Geomorphological models that provide the simple *preliminary* model of the engineering geology environment. It is again stated that the objective is to help identify and predict associations and spatial relationships of geological and geomorphological features and to develop check lists for further evaluation of the site.

Eight models have been devised and are presented together in the Models Appendix, as three dimensional models, see Figures 3.18 to 3.25. These portray: mountain glaciation; continental glaciation; periglacial; temperate; hot/dry; hot/wet; coastal; and soluble. They are based on our experience and the geomorphological knowledge synthesised in Table 3.1. This table indicates how the models have been combined to cover all the zones described.

It is likely that more than one Geomorphological model will be required to describe a site adequately because the models are idealised end members, whereas project sites exhibit real, often complex, landforms and superficial deposits. These will reflect past morphoclimatic regimes, varying relaxation times and the local geology.

4.0 PREDICTIONS FROM THE INITIAL ENGINEERING GEOLOGY ENVIRONMENT MODELS

In summary: the global Tectonic models provides the setting for the other two groups of models. The site scale Geomorphological and Geological models have annotations and key descriptions to form the basis for the check lists, since it is these models which provide the initial basic conceptual picture of the local potential conditions. Of course, an understanding of the actual geology/geomorphology of the site must come from the subsequent ground investigation.

We also repeat, we consider it essential that an engineering geologist/geomorphologist of experience be involved in important projects. It is his/her training and experience that are needed to interpret and develop the engineering geology history and to input to the planning and the investigation design.

At the *desk study stage*: the relationship of the initial models for identifying and building the site check list is:

Identify Relevant Global Tectonic Model(s)

↓

Identify Relevant Initial Site Scale
Geological + Geomorphological Model(s)

↓

Preliminary Site Check List(s)

↓

Preliminary Site Engineering Geology Environment Model

When the preliminary site engineering geology environment model has been developed, it is used for overall planning and for the design of the preliminary ground investigation or the full ground investigation, should there be no preliminary investigation stage.

At the *ground investigation stage(s)*: a well designed ground investigation should now progressively identify site conditions, answer check list questions and give information to build the site real model(s). It is not the intention here to elaborate on the development of the specific site geological/geotechnical model(s) and the conduct of the ground investigations - guidance is given in numerous publications, but it is worth emphasising that the site check list should continue to be systematically evaluated and developed, using geological/ geomorphological judgement and the findings from the investigation.

It is also necessary to emphasise that the investigation should not consist solely of boreholes. Adequate engineering geology/geomorphology mapping should be carried out or be in place early in the investigations, and pits and other high return ground observation techniques should figure largely in the investigation. Engineering geological/geomorphological interpretation of the situation must be continuous and early observation and deductions continuously reviewed, objectives defined and questions asked (see for example Stapledon, 1983 and 1996). This process must continue into construction and the service life of the project.

5.0 THE CASE HISTORIES

5.1 Introduction

Case histories have been used for many years to illustrate reasons for various failures. For example, Stapledon (1976) reviewed what he called 'factors which contributed to dam incidents' which we have reproduced in Table 5.1. This table illustrates the need for good geological advice and good interaction and communication between engineers and geologists, in short, good engineering geology.

The case histories which follow are presented to show how the use of the models, described in this paper, could have helped in anticipating the various geological causes of failure that were identified. These cases resulted from a considerable review of worldwide literature. There was some difficulty in choosing them since many of the cases reviewed contained insufficient geological information to make hindsight judgements on the relevance of appropriate models, and in many cases the causes of the failures were not clear. Such case histories were not used. The coverage by case histories is therefore not complete and it should be noted that:

TABLE 5.1 : FACTORS WHICH CONTRIBUTED TO DAM INCIDENTS (from Stapledon, 1976)

Physical Factors	
Factor	*No. of Cases*
Sliding	3
Uplift	2
Displacement on fault	2
Internal erosion	2
Earthquake	2
Weakening of foundation on inundation	1
Slope creep	1
Landslide into storage	1
Excessive deformation of foundation	1
Excessive deformation of dam	1
Flood scour	1
Technological Factors	
Description	*No. of Cases*
Limit of state of art was reached in one or more aspects	6
Lack of engineering knowledge by geologist	4
Geological advice was incorrect or insufficient	3
Inadequate project management machinery	3
Inadequate subsurface exploration	2
Communications problem - geological language not understood by engineer	1
Error in design or construction	1
Magnitude of project introduces extraordinary site investigation problems	1

- examples illustrating the relevance of some site scale models (and two global Tectonic models) are not provided through lack of *leading case histories*;
- where it is not clear which particular model would have prompted the inclusion in the check list of the condition that was the cause of the failure (due to lack of information published within the case history), i.e. identifying the single most significant model, two site scale models have been given as potentially containing the appropriate check list item.
- some site scale models were over-represented with cases, e.g. the soluble, open folds and joints, mountain glaciation and periglacial models. Where this occurred these models have been limited to three or four leading case histories.

- the majority of case histories are somewhat negative; they are, by necessity, all about failures.
- some of the case histories are from many decades ago, and investigation techniques have moved on.

As the models are all part of a continuous series, i.e. any one model can merge with any other model, and many of the potential check lists will repeat items. For example, *sheared clay* might appear in several models, as also do many situations leading to *mass movements* or the presence of *weathered* material. The case histories are not in particular order: developing a systematic scheme for presenting them was not found practical and, therefore, the case histories have been simply numbered in the order in which they appear in the text to illustrate the model. Models are presented in their figure number order related to the site scale models.

It is important to note that many of the models illustrate contemporary conditions as well as ancient, i.e. fossil conditions or activity at the time of formation. For example, 'fluvial, colluvial and lacustrine' (Fig. 3.4) illustrates both modern river systems and evidence of the existence of ancient river systems, now preserved in their sedimentary rocks. 'Basic volcanics' (Fig. 3.1) serves to illustrate both modern volcanic situations (e.g. common in island arcs) and long cooled ancient volcanic rocks. 'Hot dry climate features' (Fig. 3.22) illustrates both modern deserts, and ancient deserts such as those found in the Permo-Trias in Europe. In southwest England, tropical residual soils still exist in the weathered profile of near surface rocks, although the climate that was largely responsible for them ceased to exist in Britain before the Quaternary as its plate moved northward into cooler latitudes. 'Hot wet' (Fig. 3.23) therefore illustrates this situation, as well as modern conditions in tropical rainforests.

5.2 Global Tectonic Models and Case Histories

These models are large scale and are primarily intended to help identify site scale initial models and to put these models into the broader setting. No anticipation list has been given with the global Tectonic models for this reason; anticipation annotation is only supplied with the site scale models. Therefore, the case histories are not specifically based on the global models although the relevant global model is indicated in each case history; where more than one model pertains, this is also indicated.

Identification of the appropriate Tectonic model for any particular site would be made by the geologist, either from his local knowledge or reading of the literature. Since the theory of plate tectonics was developed in the 1960s, many of the subsequent geological papers published of a particular area identify the relevant tectonic setting. Such papers can be used to identify one or more of the models. Appropriate modern text books carry maps of the world divided into various plate-related subdivisions, which can be used to help identify the relevant model or models. Our Figures 2.1, 2.2 and 2.3 and Sections 2.0 and 3.0 are to help broadly in this.

Each Tectonic model contains a list of the principal lithologies associated with the model, the gross structure, examples and, in particular, related site scale Geological models. However, the site scale list must not be considered fully comprehensive as, within reason, each Tectonic model has the potential to contain parts of the great majority of the site scale Geological models and, therefore, only the most likely models have been listed. The engineering geologist using this system should be aware of this.

Each figure portraying the model is meant to be essentially self-contained and requires little further comment. The way the figures relate to each other is broadly indicated in Section 2.2, in Figure 2.2 , and in Tables 2.2 and 3.1. Discussion of the fundamental geology of the global structure and processes is given in Section 2.0. The following are short notes on each global Tectonic model and indicate their relevant case histories.

Cratons (Fig. 2.4) - Refer especially to Figure 2.2 to see how these ancient land masses merge into adjacent systems: see Case Histories 16 and 17 below.

Mobile belts (Fig. 2.5) - These rocks are the remains of ancient collision zones: see Case Histories 14, 26 and 27.

Platform sediments and basins (Fig. 2.6) - This model covers large parts of the world and produced many case histories. For example, see Case Histories 4, 12, 18, 19, 20, 21, 22, 24, 26 and 31.

Continental rifts (Fig. 2.7) - We thought that this would produce several case histories: in fact, we could not find a good one - no doubt they exist.

Oceanic rifts (Fig. 2.8) - Much of this model exists on sea floors and where these emerge, for example in Iceland, conventional case histories become possible. See Case History 6.

Accretionary prisms (Fig. 2.9) - In the formative stage of this model the system is under deep water and therefore did not produce conventional case histories, and we did not find any good examples from the older parts of the stratigraphic column.

Fold and Thrust belt (Fig. 2.10) - This model is generally found as a distinct zone in orogenic belts, after the deep water sequences of forearc or backarc basins have been subjected to orogenesis (see Figs. 2.2 and 2.3). See Case History 27 which is one of a few that we have tested ourselves by work in the field, using key words and check lists that we developed and which were very successful in identifying problems, some of which were hitherto unforeseen (although not unforeseeable) in the original site investigation. Though the model and key words were only used after the original site investigation had been completed, problems were quickly identified. Note that this same case history is used to illustrate the magmatic arc model as the site setting contained elements of both models.

Magmatic arc (Fig. 2.11) - Modern examples of this are found in the world's active island arc zones and are illustrated by our Case History 27.

Collision complexes (Fig. 2.12) - This proved one of the easier models for which to find case histories as much engineering and building construction seems to have been carried out in such zones. See Case Histories 1, 11, 13, 14, 23 and 28.

Foreland basins (Fig. 2.13) - Again, another area in which construction is active. See, for example, Case Histories 3, 4, 5, 10 and 15.

5.3 Site Scale Models and Case Histories

Selection of the case history number was based on what was considered to be the site scale model most relevant to that case history, i.e. it becomes *the leading case history*: each case history invariably had several other, i.e. associated, site scale models that could also be related to it.

It is opportune to emphasise again that in the figures the models are portrayed simply for clarity. Each model will inevitably require considerably more detail to be added to it and the engineering geologists are encouraged to do this from their experience and from relevant literature studies. The check lists produced should therefore be much more comprehensive than the model. For example, Fell, et al. (1992), their Section 3.2.7, gives a check list of questions for intrusive and flow volcanic rocks, and a separate check list of questions for pyroclastic rocks in Section 3.3.3. The discussions they give with the development of their check list are very helpful in understanding the function and derivation of such lists.

5.3.1 Geological Models

Basic volcanics (Fig. 3.1) - Although potentially a common model, no case history was found where it was thought this model would be the leading one providing the check list. However, several of the case histories also include this particular model as an associated model. These cases are identified in the following text.

Acid volcanic (Fig. 3.2) - Similar comments to those for the basic volcanic model apply also to this model.

Plutonic intrusions (Fig. 3.3) - This is an example of a model with geological processes that do not have an active expression on the ground surface, so that all the examples of such a model are ancient. See Case History 1.

Case History 1: Grand Coulee Dam, USA
(Berkey, 1935; Anderson and Trigg, 1976; Blyth and de Freitas, 1996)

The concrete gravity Grand Coulee Dam on the Columbia River is 168 m high. It was constructed in 1942 on a granite batholith, which is overlain above dam foundation level by Tertiary basalts and pyroclastics. The Grand Coulee itself is a gigantic abandoned glacial overflow channel of late Quaternary age, 3 km to 5 km wide and over 600 m deep. Its floor, beneath glacial outwash and alluvial deposits, was initially believed to be fairly smooth, but explorations involving around 10,000 m of drill holes showed it to be diversified by numerous faults, potholes and erosion trenches. Concern about possible earthquake activity on the faults was alleviated when giant potholes intersected by these were found to be undisplaced, showing there to have been no activity since late Quaternary times.

On excavating into the granite, horizontal sheeting joints were encountered, which did not appear to diminish in frequency with depth. It was eventually realised that these joints were opening in response to the unloading produced by the excavations. Thus, on the advice of Dr. Berkey, excavation was stopped, the dam built and any remaining open joints sealed by grouting.

This dam site was carefully explored geologically and the geomorphological situation well exploited. The granite, from which virtually all Tertiary and weathered material had been removed by the overflow channel

erosion, provided an excellent foundation for the dam once the sheeting joint problem had been dealt with.

Associated models: Cratonic cores (Fig. 2.4); Collision complexes (Fig. 2.12); Continental glaciation features (Fig. 3.19)

Continental, fluvial, colluvial and lacustrine (Fig. 3.4) - A good example of a model representing both modern and ancient situations, illustrated by Case Histories 2, 3 and 4. Case History 2 is one of the cases with which the authors have had direct experience. In their view the existence of initial models would have helped anticipate the problems that occurred.

Case History 2: Ok Ma tailings dam site, Papua New Guinea
(Fookes, et al., 1991; Fookes and Dale, 1992; Griffiths, et al., in prepn.)

The site is located in the Star Mountains of western Papua New Guinea, which form part of the active boundary between the Pacific and Indo-Australian plates. In connection with the nearby Ok Tedi gold and copper opencast mine, a permanent tailings disposal system was required and a site at Ok Ma was chosen for the construction of the tailings dam.

At the proposed dam location, the southward flowing Ok (River) Ma has eroded an asymmetrical valley 150m to 200 m deep through a sequence of Middle Miocene sediments dipping at 8° to 10° in a south-west direction. Partly because of the component of dip across the valley to the west, the average slopes of the left and right valley sides are around 12° to 13° and 20°, respectively. The slopes are capped by the Warre Limestone, around 80 m thick. This is underlain conformably by the mudstones and siltstones of the Pnyang Formation, probably around 1000 m thick, which forms most of the valley slopes and tends to behave as an engineering soil. As a result of the strong, tectonically stimulated river erosion and the high rainfall, up to 10 m per year, both valley slopes are mantled by landslides. They are well forested, but reconnaissances by helicopter and on foot after the failure showed that the presence of pre-existing landslides on the left valley side could have been established beforehand.

The foundation for the earth/rockfill tailings dam was prepared by excavating a "footprint" through the variable soft colluvium in the valley floor, to a depth of about 14 m in the left abutment. These excavations were in progress in December, 1983, when a landslide of about 3 million cubic metres occurred in the lower part of the left valley slope, moving about 6 m towards the river. The works were halted and further investigations instigated. In early January, 1984, a further landslide of some 35 million cubic metres took place, affecting most of the remaining left valley slope. The works were eventually abandoned.

There are numerous examples of serious landslides being generated by removing the toe from an unstable or marginally stable slope. In this case, 76 boreholes and 3 test pits were put down and 20 seismic refraction lines explored, but these were concentrated largely in the footprint area and the wider geological/ geomorphological setting, particularly the presence of a large pre-existing landslide, with its toe being eroded by the river, was not properly appreciated. Also, despite high liquid limits and clay fractions in the Pnyang Formation, its residual strength was initially somewhat over-estimated, with the result that the few stability checks made indicated high apparent factors of safety and generated a false sense of security.

Associated models: Magmatic arcs (Fig. 2.11); Open folds and joints (Fig. 3.12); Hot wet climate features (Fig. 3.23)

Case History 3: Goldau rock slide, Switzerland
(Heim, 1932; Eisbacher and Clague, 1984)

The rock slide-avalanche of 1806 at Goldau took place in a dip slope forming the south face of the Rossberg Massif. Approximately 35 million cubic metres of rock, chiefly conglomerates of the Tertiary Molasse, slid down a shaley bedding plane dipping south at around 15° (steepening to more than 20° near the crest) to destroy the town of Goldau with the loss of 457 lives. Although apparently not brought out previously, the toe of the dip-slope was undercut by probably both glacial and fluvial erosion, and the shales were doubtless pre-sheared as a result of tectonically induced flexural slip. The failure was triggered by the rapid melting of an unusually thick snowpack, followed by heavy rainfall. The *fahrboschung* was 11° to 11.5°.

Translational slides on dip slopes (and overdip slopes, Cruden, 1985) are especially dangerous, particularly where undercut. This is because their geology and geometry facilitate the involvement of large volumes of rock, commonly sliding on pre-existing tectonic shears, which being kinematically unrestrained, encourage rapid movement.

Associated models: Collision complexes (Fig. 2.12); Foreland basins (Fig. 2.13); Open folds and joints (Fig. 3.12)

Case History 4: Avulsion of the Kosi River fan, India, and the Mississippi River and its delta, USA (Freeman, 1922; Gole and Chitale, 1966; Schumm, 1977)

An avulsion is a major change in the position of a river channel, greater than, for instance, the cutting off of a meander. One of the most dramatic was the 1851 avulsion of the Yellow River, China, which shifted its mouth over 300 km to the north of its former position. Avulsions are a feature of fluvial fans, rivers and deltas. Between 1731 and 1963, the course of the Kosi River across its fluvial fan shifted laterally on over ten occasions by a total of over 110 km. In the Mississippi delta, 14 different lobes have formed during the past 7500 years, each one probably marking an avulsion upstream.

Avulsion is generally a response to two factors: channel aggradation due to progressive extension of a delta into the sea (necessary in order to maintain the gradient upstream) and the availability of a shorter, steeper route for the river to the sea. Indeed, without the control structures built by the Corps of Engineers, the Mississippi would probably already have avulted to the shorter course to the Gulf of Mexico offered by the Old River-Atchafalaya channel.

In an engineering geological context, avulsion can be of great importance in its effects on drainage, irrigation and agriculture, on the stability of river crossings (bridges and pipelines) and on the viability of major ports and industrial complexes (such as New Orleans).

Associated models: Platform sediments and basins (Fig. 2.6); Continental deltaic (Fig. 3.5)

Continental deltaic (Fig. 3.5) - Although this incorporates ancient coal measure systems, which commonly occur, we could not find a leading case history. However, this model is given elsewhere as an associated case history.

Shelf carbonates and evaporites (Fig. 3.6) - Again, this is a good model to illustrate local modern and ancient environments. See Case History 5.

Case History 5: Col de Braus and Caranca tunnels, France (Legget, 1939)

In the construction of the Col de Braus tunnel, between Nice and Coni, France, just before the first World War, rock consisting of almost pure anhydrite was encountered over a length of one kilometre. Groundwater reaching the exposed anhydrite from adjacent Jurassic limestones caused it to increase in volume by around 30% in transforming to gypsum. The problem was worsened by the fact that the works were halted between 1914 and 1919. On completion of the tunnel excavation it was lined with masonry. However, the groundwater was not completely drained and the anhydrite continued to swell. As a result, part of the masonry lining was severely disrupted. Reconstruction was carried out using a combination of further drainage and aluminous cement and appears to have been effective.

This experience was utilised in the adjacent Caranca tunnel, completed in 1921, which passed through a few hundred metres of anhydrite. Immediately after mucking out, the tunnel face was coated with coal tar and the lining was built with the least possible delay, using aluminous cement. Finally, coal tar was injected under pressure behind the lining. The tunnel has given satisfactory service.

The swelling of anhydrite on wetting, exposed in tunnel or other excavations, to form gypsum can be very damaging. The problem can be controlled by a combination of rapid construction, drainage and sealing with, for example, coal tar.

Associated model: Foreland basins (Fig. 2.13)

Deep marine deposits (Fig. 3.7) - Although offshore oil exploration is extending into deeper water, and we hoped would provide good examples of case history studies, we have found only Case Histories 6 and 7 to illustrate this site scale model.

Case History 6: Submarine slides on the Hawaiian Ridge
(Normark, et al., 1993)

Major submarine slides up to 200 km long and with volumes of about 5,000 km^3 have been mapped on the flanks of the volcanic Hawaiian Ridge. They are intimately connected with the growth and development of the volcanoes, tending to widen the base of the ridge and fill the Hawaiian Trough. The more rapid slide movements lead to tsunamis, some of which in the past are inferred to have been extremely large.

The Hawaiian Ridge submarine slides are among the largest on earth. Tsunamis resulting from their rapid movement constitute a potentially catastrophic hazard, particularly around the Pacific Rim.

Associated model: Oceanic rifts (Fig. 2.8) (?)

Case History 7: Cape Fear submarine slide
(Popenoe, et al., 1993)

The Cape Fear slide is one of the largest and best documented of those on the US continental margin. Its crest is on the continental slope off North Carolina and it extends about 430 km downslope, with an average width of around 60 km, into the Hatteras abyssal plain at more than 5000 m depth. Failure dates range from about 12,000 to 20,000 years BP, at a time when world sea levels were eustatically depressed. Triggering mechanisms are considered to include earthquakes, increased pore-water pressures deriving from the decomposition of gas hydrate within the sea bed (facilitated by lowered sea levels) and the growth of salt diapirs which fractured and over-steepened the lower slopes.

The headwall scarp of the Cape Fear slide may constitute a hazard to offshore hydrocarbon operations. Otherwise the main hazard from a significant reactivation of slide movement would be a tsunami.

Associated model: Platform sediments and basins (Fig. 2.6)(?)

Normal faults (Fig. 3.8) - Although such features are relatively common and often encourage landslide occurrence, only one suitable, but small scale, case history was found. See Case History 8.

Case History 8: Opening-out of the Cofton Tunnel, England
(McCallum, 1931; Legget, 1939)

There are many cases where a fault plane provides a pre-existing shear surface which is partly exploited by a nearby landslide, generally to form its rear or side scarp. A small scale, but clear example of this occurred in 1925 during the opening out of the Cofton Tunnel just south of Birmingham on the railway line to Gloucester, new traffic requirements necessitating that the tunnel be reconstructed as a cutting.

It was anticipated from the geological map that the cutting, through Lower Keuper sandstones and marls, would be traversed obliquely by the Longbridge Fault system and this proved to be the case with both normal and reverse faults being encountered. Upon removal of its lateral support, a rock mass forming the hanging wall of a fault slipped from the west side of the cutting, exploiting the fault plane as its right-hand side scarp.

Pre-existing shears of all types are of great significance in the stability of slopes, partly because of their persistence, partly because of the weak, approximately residual strength surface which they provide and partly because of associated, often adverse modifications of the groundwater conditions.

Associated model: Hot dry climate features (Fig. 3.22) (?)

Strike-slip faults (Fig. 3.9) - Again, a relatively common model. The 1906 San Franciscan earthquake on the San Andreas Fault is used to illustrate this model. Case History 9.

Case History 9: San Andreas Fault, U.S.A.
(Yeats, et al., 1997; Thatcher and Lisowski, 1987)

The San Andreas is perhaps the best known example of a strike-slip (right lateral) fault. Its line is marked by fault scarps, offset streams and rivers, sag ponds and *en echelon* ruptures. The total offset on this fault since the Pliocene is estimated at 55 km; offsets of 5.2 m or more occurred on it during the 1906 San Francisco earthquake. Its late Holocene slip rate is about 34 mm/year.

As the San Andreas Fault passes through the major built-up areas, serious damage generally results from each earthquake, partly through direct shaking and partly through subsequent fires. The risks posed by further seismic activity on this fault, although capable of being mitigated by earthquake engineering, are clearly considerable. More than 14 earthquakes are known or inferred to have occurred since about 700 years A.D., but the location and timing of the next event is not readily predictable.

Associated models: —

Thrust systems (Fig. 3.10) - Again, a relatively common phenomenon in active plate tectonic areas but no leading case history was found.

Jointings in undeformed sediments (Fig. 3.11) - Again, we thought this would produce several case histories, but no leading case history was found.

Open folds and joints (Fig. 3.12) - This particular model produced many case histories from which we have selected three. Case Histories 3 (again), 10 and 11.

Case History 10: Mangla Dam, Pakistan
(Binnie, et al., 1967; Fell, et al.,1988; Hutchinson, 1988; 1995)

Tectonic deformation of strata is accompanied by differential movement between the beds involved. This tends to concentrate in the less competent members, particularly clays and mudstones, and to generate shears at or near residual strength. As with all pre-existing shears, these can have profound effects on the stability of the system and, as they generally have no geomorphological expression, they are easily missed.

Such shears had a significant influence on the Mangla Dam Project in West Pakistan (Binnie, et al., 1967), constructed on folded alternations of sandstones and shales of the Siwalik Series. Although to be expected in such strata with dips up to around 45°, the flexural shears were not observed until construction of the earth dams began and a costly design modification became necessary. Although flexural shears were already known in structural geology, this was the first occasion where they were reported to have had a significant influence on engineering works.

The very widespread nature and significance of flexural slip shears, particularly in sedimentary rocks, has now become evident to engineers. Fell, et al.(1988) and Hutchinson (1988) report such shears in beds with dips down to about 1° and Hutchinson (1988; 1995) provides theoretical models which accord well with the available case records. Had the initial model existed, there is little doubt that the shears would have been looked for.

Pre-existing shears formed by flexural slip, predominantly in sequences of sedimentary strata, are very widespread. Usually having little or no geomorphological expression, they may be missed in site investigation. They should be expected even in slightly deformed strata with dips down to about a degree, particularly if these contain argillaceous beds of medium to high Brittleness Index.

Associated models: Foreland basin (Fig. 2.13); Continental, fluvial, colluvial and lacustrine (Fig. 3.4)

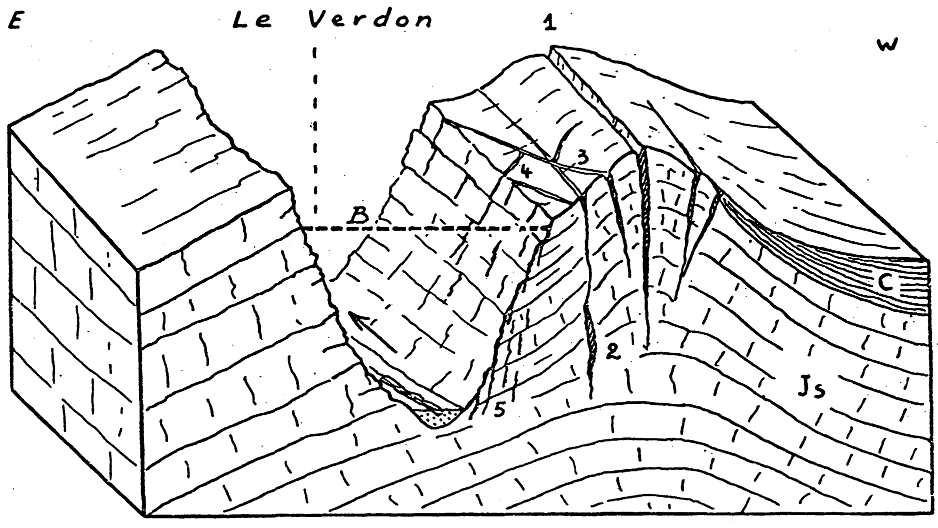
Case History 11: Barrage de Castillon, France
(Ischy, 1948; Gignoux and Barbier, 1955)

The 80-100 m high Barrage de Castillon in the gorge of the Verdon, Basses-Alpes was completed in 1949. As shown by Fig. 5.1, the Upper Jurassic limestones there exhibit an anticlinal fold running parallel with the gorge within the right bank of the river and dipping upstream. This folding has provoked major fractures in the right bank, of recent tectonic rather than karstic origin, where the beds dip towards the gorge. The left bank, further from the anticlinal axis and with beds dipping away from the gorge, is only slightly fissured.

Concrete infilling and intensive grout injection were necessary to ensure the watertightness of the right abutment and its ability to take the thrust of the arch dam. In the left abutment, however, only modest grouting was required.

Conditions at the dam site could have been progressively anticipated using the model approach.

Associated models: Collision complexes (Fig. 2.12); Shelf carbonates and evaporites (Fig. 3.6); Soluble rock features (Fig. 3.25).



B = dam crest; Js = Upper Jurassic limestones; C = Lower Cretaceous marls;
1 = principal fissure; 2 = other, deeper fissures; 3 and 4 = secondary fissures; 5 = stress relief fissures

(Gignoux and Barbier, 1955)

Figure 5.1 : Barrage de Castillon - block diagram

Plastic folded with cleavage (Fig. 3.13) - This model is again potentially fairly common in convergent boundary systems. However, we did not find any readily identifiable case histories and thought that this could be because the cleaved nature of the rocks involved was not brought out in the case histories we reviewed.

Multiple folded sheared (Fig. 3.14) - This model related to several of the case histories, though not always as the leading case. It is again a potentially very common model, especially for convergent boundaries, and we illustrate it with Case History 12.

Case History 12: Malpasset Dam, France
(Habib, 1987; Londe, 1987a; Wittke and Leonards, 1987)

The 66.5 m high, double curvature concrete arch dam at Malpasset was completed about 1954. Its first filling took place very slowly. In December, 1959, when the reservoir level was 0.3 m below spillway crest level, the dam suddenly failed. The resulting flood wave killed 424 people in the town of Frejus downstream.

The dam is sited in the crystalline Tanneron Massif and consists of banded gneiss, striking generally N-S. The foliation dips between 30° and 50° downstream and towards the right bank. Tectonic disturbances from the Hercynian orogeny onwards have led to close jointing of the rocks, with associated low moduli, and numerous shears and faults. The site investigation was very restricted, consisting of just a few boreholes and visual inspection of the excavation bottom (Londe, 1987b).

Subsequent investigations, conveniently summarised in Leonards (ed. 1987), found no fault with the design or construction of the dam itself. Its collapse was brought about by excessive deformations of the rocks forming the left abutment, culminating in the development of high groundwater pressures which caused the uplift and removal of a large wedge beneath the dam foundation. This wedge was defined upstream by a foliation surface, partially opened by cracking, and downstream by the "downstream fault", missed by the site investigation. The high sensitivity of the permeability of the broken rock mass to applied stress contributed to the development of the high groundwater pressures. Monitoring was very limited, depending entirely on geodetic measurements of targets on the downstream face of the dam, made approximately annually. It is probable that piezometric and displacement measurements in the foundation combined with strain meters in the arch would have given a warning of at least several months before failure (Londe, 1987a).

The failure of the Malpasset arch dam was due entirely to geological and hydrogeological conditions which, because of inadequate site investigation, were not foreseen. In addition, instrumentation that would have permitted the observational method to be applied was not provided. Subsequent events demonstrated that it would have been wise to discard the arch design (Londe, 1987a; Terzaghi, in Goodman, 1999).

Associated models: Mobile belt (Fig. 2.5); Gneisses and migmatites (Fig. 3.17)

Tectonised mélanges (Fig. 3.15) - A potentially fairly common situation in convergent boundaries but also one for which we found no leading case history.

Schistose rocks (Fig. 3.16) - A potentially fairly common situation in convergent boundaries but also one for which we found no leading case history, but see Case Histories 14 and 30.

Gneiss and migmatite (Fig. 3.17) - A potentially fairly common situation in convergent boundaries but also one for which we found no leading case history, but also see Case History 30.

5.3.2 Geomorphological Models

Mountain glaciation (Fig. 3.18) - This model is related to many case histories and itself merges into the continental glaciation and periglacial models and potentially into the temperate model, so that there is a lot of overlap in this area. This particular model is illustrated by Case Histories 13, 14 and 15.

Case History 13: Lötschberg Tunnel, Switzerland
(Heim, 1908; Buxtorf, 1910; Anon, 1911; Gignoux and Barbier, 1955; Anderson and Trigg, 1976; Eyles, 1983)

The double-track Lötschberg rail tunnel, 14.8 km long, was built to link Berne to the Simplon. It runs through granite and gneiss of the Aar Massif and, at its northern end, Upper Jurassic/Lower Cretaceous limestone of the Doldenhorn nappe. Where the tunnel passed beneath the Kander Torrent, occupying a previously glaciated valley, the tunnel crown had a cover of 190 m. Doubts whether most of this consisted of solid rock were dismissed.

On 24th July, 1908, the northern tunnel in the limestone had reached just past the Kander Torrent. When the next charge was blown, glacial deposits burst into the tunnel under the high head from this stream. All but one of the 26 miners were killed by the inrush. Above in the Kanderthal, a collapse about 150 m in diameter and a vortex in mid-torrent formed. Following test boreholes in the Kanderthal to depths of up to 220 m, a diversion passing upstream of the deep buried channel was constructed, passing the Kander where in situ rock was exposed in its bed. The tunnel was completed 5 months behind schedule.

The disaster arose because the depth of the glacial material filling the buried valley of the Kanderthal was seriously under-estimated. The longitudinal bedrock profile of such glaciated valleys should be expected to be strongly irregular, commonly by hundreds of metres (e.g. Loch Morar, Scotland), as a result of overdeepening.

Associated models: Collision complexes (Fig. 2.12); Shelf carbonates and evaporites (Fig. 3.6)

Case History 14: Barrage des Échelles d'Annibal, France
(Gignoux and Barbier, 1955)

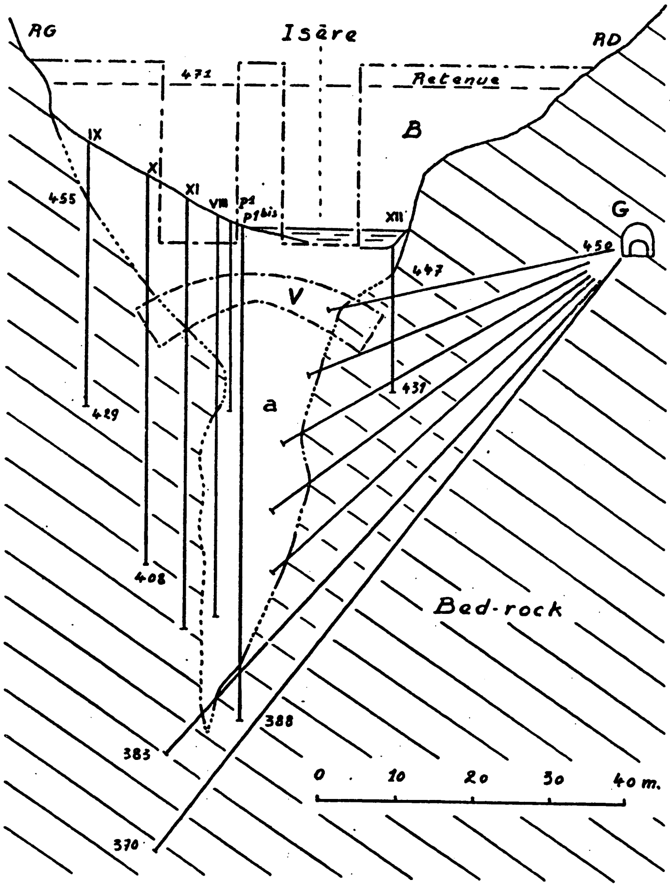
In glaciated mountain valleys, sub-glacial torrents commonly erode narrow, steep-sided gorges well below the general level of the valley floor. An example of such a gorge at the Barrage des Échelles d'Annibal in the Savoy Alps is given (Fig. 5.2). The gorge was found to be about 11 m wide and approaching 60 m deep, cut in a very hard calcareous schist. It was successfully explored using a combination of vertical and inclined drill holes, the latter bored from a gallery. In this case, as the alluvium filling the gorge was of low permeability, it was left in place. Gorges may also be explored using exploration shafts and galleries, as at the Waggital Dam in Switzerland, where the gorge was about 2 m wide and 15 m deep.

There are many examples of successful definition of the profile and contents of deep gorges created by sub-glacial torrents, allowing safe dam construction in glaciated mountain valleys.

Associated models: Collision complexes (Fig. 2.12); Schists and phyllites (Fig. 3.16)

Case History 15: Tsho Rolpa proglacial lake, Nepal
(Reynolds, 1998)

The Tsho Rolpa proglacial lake in the Himalayas of northern Nepal is dammed by an ice-cored moraine. The lake contains an estimated 80 million cubic metres of water. It is feared that breaching of the natural dam, for example through the thawing of its ice core, could result in a serious glacier lake outburst flood which would destroy villages, roads and bridges downstream. Initial hazard mitigation measures have consisted of the installation of a pilot 16 cm diameter siphon to reduce the lake level. The ultimate aim is to supplement this scheme to achieve a lake lowering of 15 m to 20 m.



RG, RD = left bank, right bank; a = morainic, colluvial and alluvial material;
B = dam; V = reinforced concrete vault; G = gallery

(Gignoux and Barbier, 1955)

Figure 5.2 : Barrage des Échelles d'Annibal - cross section of gorge cut by sub-glacial torrent

Floods generated by the breaching of proglacial lakes are a common hazard in high mountain areas. Whilst such situations can be fairly readily identified by normal engineering geological techniques, theremoteness of most of the sites renders their remediation difficult.

Associated model: Collision complexes (Fig. 2.12)

Continental glaciation (Fig. 3.19) - Again, this is a potential, common model which we illustrate with Case Histories 16, 17 and 18. This model merges into mountain glaciation, periglacial and temperate models.

Case History 16: Pärve Fault, Sweden
(Lundqvist and Lagerbäck, 1976; Ambraseys, 1985)

An historical study of Western Scandinavia by Ambraseys (1985) found subdued seismicity in this intraplate area, consisting of the Fennoscandian Shield, bounded on the north-west by the Caledonian belt, and concluded that this is compatible with the very low tectonic activity of the area. However, in the 1970s a major Late-glacial fault, the Pärve fault, was discovered in north-western Sweden. This most extensive and continuous fault scarp is over 150 km long and is generally between 5 m and 10 m high. Related fault systems lie to the east and northeast and show evidence of associated landsliding and liquefaction. From this evidence and the fault dating it is inferred that the fault generated a significant earthquake around the time of deglaciation, 9000 years ago. The fault movement was a neotectonic reactivation of weathered fault zones of presumed pre-Quaternary age.

The Pärve fault lies just north-west of the area of greatest contemporary isostatic rebound following deglaciation and seems likely to have resulted from the accompanying crustal deformations. This evidence of neotectonic activity in an area previously considered to have very low seismicity has an important influence on plans for the disposal of radioactive wastes in the region.

Associated models: Cratons (Fig. 2.4); Mobile belts (Fig. 2.5); Basic volcanics (Fig. 3.1); Plutonic intrusions (Fig. 3.3); Periglacial features (Fig. 3.20)

Case History 17: Silent Valley, Northern Ireland
(McIldowie, G.,1936; Legget, 1939; Walters, 1962)

The Silent Valley earth dam in the Mourne Mountains of Northern Ireland is 27 m high and was constructed in 1924-1932. In the initial site investigation, granites encountered at a depth of 15 m were interpreted as bedrock. The specified minimum depth of penetration into rock of these boreholes is not known. Subsequent shafts, taken down to 65 m below ground level (partly for dewatering purposes), and further boreholes showed that this "bedrock" actually consisted of boulders. This was confirmed by the cut-off trench, which had to be taken, with great difficulty, to a depth of 55 m through running silt under compressed air.

Binnie (Disc. on McIldowie, 1936) said that it was not surprising that the boulders had been misinterpreted as bedrock, as one was as big as a cottage. However, their non-local provenance, which would have clearly identified them as boulders, was not realised. For all subsequent boreholes a minimum penetration of 6 m into rock was required. Legget (Corr. on McIldowie, 1936) regretted the "complete absence of reference to geology in Mr. McIldowie's paper".

Reliable determination of firm bedrock is a fundamental part of site investigations and a minimum penetration by coring is commonly specified. The errors on this project sprang entirely from ignorance of geology and especially glacial geology.

Associated models: Cratons (Fig. 2.4); Plutonic intrusions (Fig. 3.3); Mountain glaciation (Fig. 3.18)

Case History 18: Wabamum Lake, Canada
(Tsui, et al., 1989; Hutchinson, 1988)

Slope failures occurred in the large open pit coal mine of Highvale, situated in flat-lying Upper Cretaceous strata in the western prairies of Alberta. These failures were in a mudstone on deep-seated, sub-horizontal principal shears at approximately residual strength within a remoulded and brecciated layer. They occur in topographic troughs where proglacial water bodies were impounded and thawed the permafrost in front of the ice sheet and hence decreased the resistance of the sub-glacial strata to ice-thrusting. The shears are attributed to glacial shove associated with the Late Wisconsin ice sheet.

In addition to the shearing and deformation in push moraines, glaciotectonics can give rise to through-going pre-existing shears in flat-lying shales and mudstones. These are reported to depths of up to 180m below ground level in western Canada (Kupsch, 1962).

Associated models: Platform sediment basins (Fig. 2.6); Jointing patterns in undeformed sediments (Fig. 3.11); Periglacial features (Fig. 3.20)

Periglacial (Fig. 3.20) - This model is for areas outside the limits of glaciation and may also be superimposed on former glacial areas as glaciation retreats. The model is important because it describes both fossil (i.e. ancient) conditions and currently active conditions. It is illustrated by Case Histories 19, 20 and 21.

Case History 19: Sevenoaks By-pass, England
(Skempton and Petley, 1967; Skempton and Weeks, 1976)

In the mid-1960s, a road by-passing Sevenoaks was routed over slopes below the scarp of the Lower Cretaceous Hythe Beds (weak sandstones) underlain by the over-consolidated Atherfield and Weald Clays. The road was situated on the upper clay slopes, beneath the Hythe Beds. Although the area had never been glaciated, it had been exposed to severe periglacial conditions. The published geological map showed landslipped ground in the area.

After a nominal site investigation, construction of the drainage and low cuts and fills began. This led, almost immediately, to widespread shallow sliding and the roadline had to be abandoned, together with a number of reinforced concrete bridges which had been built early. A much better ground investigation, including trial pits, was then, belatedly, carried out. This revealed that the clay slopes, declining downslope from 7° to below 3°, were mantled by two phases of periglacial solifluction deposits, a lower ubiquitous sheet around 2 m thick formed during the main Devensian (last) glacial period, and overlying discrete lobes about 4 m thick, which were dated to the Loch Lomond stadial, about 11,000 to 10,000 years B. P. (Fig. 5.3). Both these deposits were underlain by pre-existing slip surfaces of low residual strength ($c' = 0$, $\phi' = 12°$ to 13°), which the road construction had reactivated. The road had to be realigned tens of metres further downslope after the pre-existing shears there had been destroyed by excavation and drained.

This failure occurred shortly after published recognition (Skempton, 1964) of the importance of pre-existing shears and residual strength. The shallow shear surfaces could have been easily found by carefully logged trial pitting, but the initial site investigation consisted only of boreholes at nominal intervals along the road centreline. No consideration was given before the start of construction to Quaternary geology or geomorphology. These omissions led to this expensive failure.

Associated model: Platform sediments and basins (Fig. 2.6).

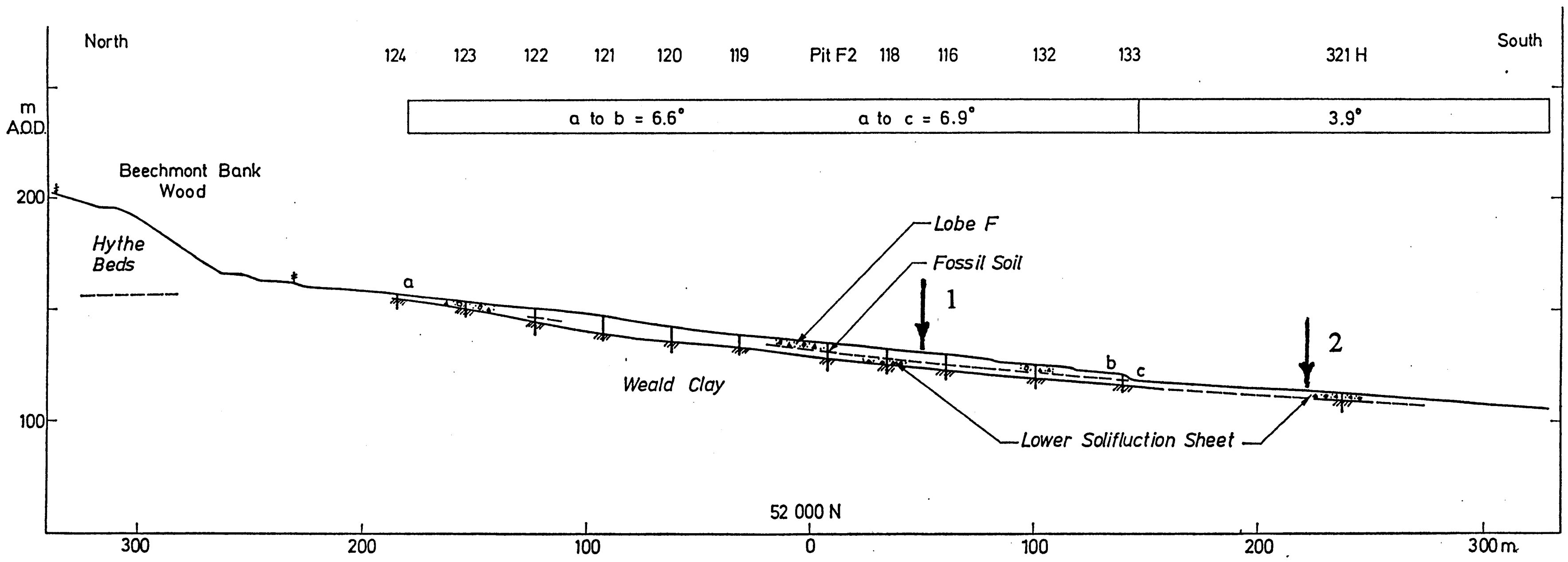
Case History 20: Carsington Dam, England
(Skempton and Vaughan, 1993)

The upstream slope of the Carsington earth dam failed just before its completion in 1984. It was intended to be 37 m high and had shoulders of compacted mudstone and a clay core with an upstream extension ("boot"): the slip scarp was just downstream of the dam crest. The failure surface passed down through the clay core and its boot and then followed a yellow clay layer barely a metre below the original ground level, formed by periglacial solifluction. Both the clay core and its boot were weakened by rutting shears produced by the compaction plant, and the yellow clay by the presence of solifluction shears; the presence of the boot was also detrimental to stability.

Investigations showed that in the initial slip the factor of safety based on measured peak strengths was about 1.4. This value was reduced to 1.2 by the presence of the pre-existing shear surfaces and the final reduction to 1.0 occurred through progressive failure. The considerable spread of the failure across the valley, for nearly 500 m, involving sections of the dam with factors of safety greater than one, is attributed to lateral load transfer.

The initial failure was due partly to the unforeseen presence of pre-existing shears, formed by periglacial solifluction in the natural ground forming the dam foundation, and in the clay core and boot by the rutting action of compaction plant. As these shears were not continuous, some progressive failure also occurred.

Associated models: Platform sediments and basins (Fig. 2.6); Continental deltaic (Fig. 3.5); Open folds and joints (Fig. 3.12)



1 = original road centreline; 2 = realigned centreline

(Skempton and Weeks, 1976)

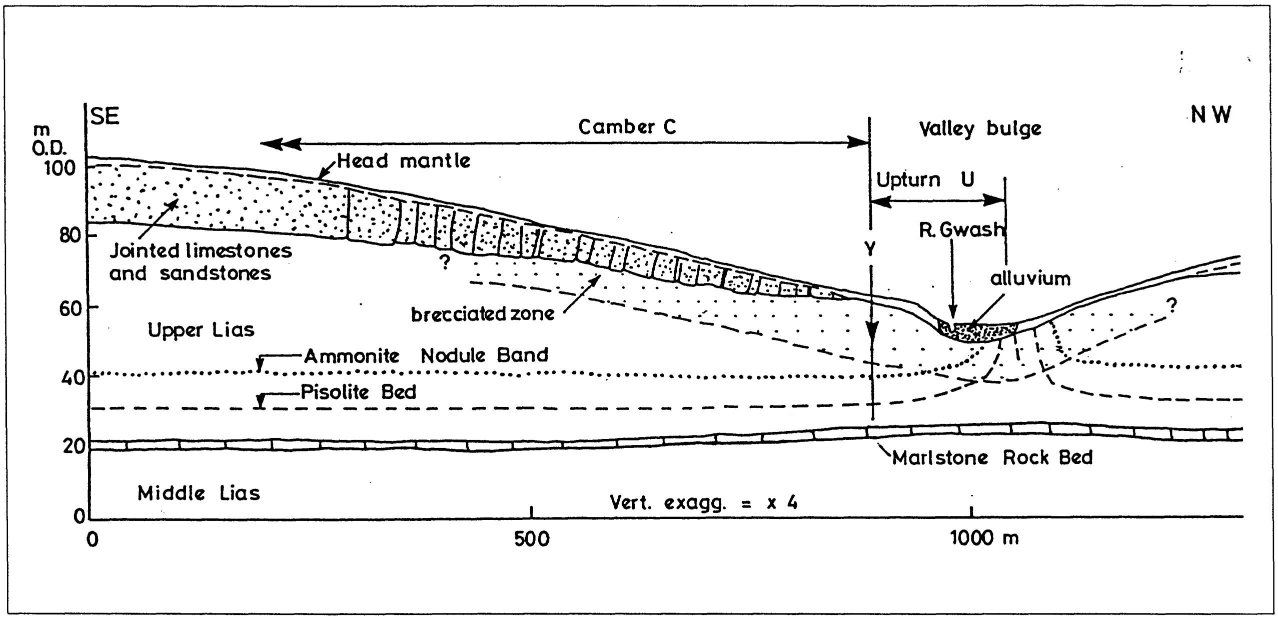
Figure 5.3 : Sevenoaks By-pass - downslope section

Case History 21: Empingham Valley, England
(Horswill and Horton, 1976; Hutchinson, 1991)

Many valleys in England and, to a lesser extent, Wales, exhibit relict superficial disturbances which are very marked in spite of the generally gentle topography. Over 600 cases have been assembled by Parks (1991). They affect strata from the Carboniferous to the Palaeogene and can extend to over 60 m below the present valley floor. They are known chiefly from carefully logged cut-off trenches for earth dams. The disturbances take various forms: the best explored, of the type termed 'cambering and valley bulging', is that in the Empingham Valley. The disturbances are periglacial in origin: they appear to have arisen through the squeezing up of the clayey strata beneath the valley, while these were in a very weak, thawed state, under the weight of the superincumbent rock (Fig. 5.4). The valley bulge thus produced generally has no surface expression, having been eroded down to the present valley floor level. Extrusion of softened clay from below is accompanied by the sinking of the caprock, breaking up on its joints as it does so. This sinking is naturally greatest near the thalweg, fading out towards the interfluve, thus producing a camber in the capping stratum.

These remarkable periglacial features found in the southern half of Britain are extensively described in the literature, but commonly occur elsewhere, particularly where clay beds underlie stronger rock. They can give rise to severe stability and watertightness problems in, for example, earth dams.

Associated models: Platform sediments and basins (Fig. 2.6); Shelf carbonates and evaporites (Fig. 3.6)



(Horswill and Horton, 1976)

Figure 5.4 : Empingham Dam, River Gwash valley - cross section showing camber and valley bulge features

Temperate climate (Fig. 3.21) - This is an important model in that it links the various landscapes between cold conditions and the hot conditions, so it is the model that links Figures 3.18, 3.19 and 3.20 with Figures 3.22, 3.23 and 3.24. It may well contain relict periglacial or glacial conditions or even relict hot dry or hot wet conditions as the climate belts have moved in the Quaternary and a little earlier. It is illustrated by Case Histories 22 and 23.

Case History 22: Hadleigh abandoned cliff, England
(Hutchinson and Gostelow, 1976)

Cliffs that were being eroded by sea or river, but are now abandoned, undergo a process of free degradation in which their future slope development is controlled by their geotechnical properties affected by weathering and climate. At Hadleigh, a 45 m high cliff of stiff, fissured London Clay, was abandoned over 10,000 years ago (Fig. 5.5). After an initial periglacial phase, it is still degrading, largely since the last glaciation. It exhibits an accumulation zone, inclined at about 8°, in the lower cliff with a factor of safety of about 1.05; and a degradation zone, inclined at 11° to 13°, in the upper cliff with a factor of safety of about 1.0. Reconstructions of the old cliff profiles indicate that the cliff crest has retreated by just over 50 m in the past 10,000 years. In the latter stages of this process, the crest encroached onto and destroyed the curtain wall of a 13th century castle built by King Henry III.

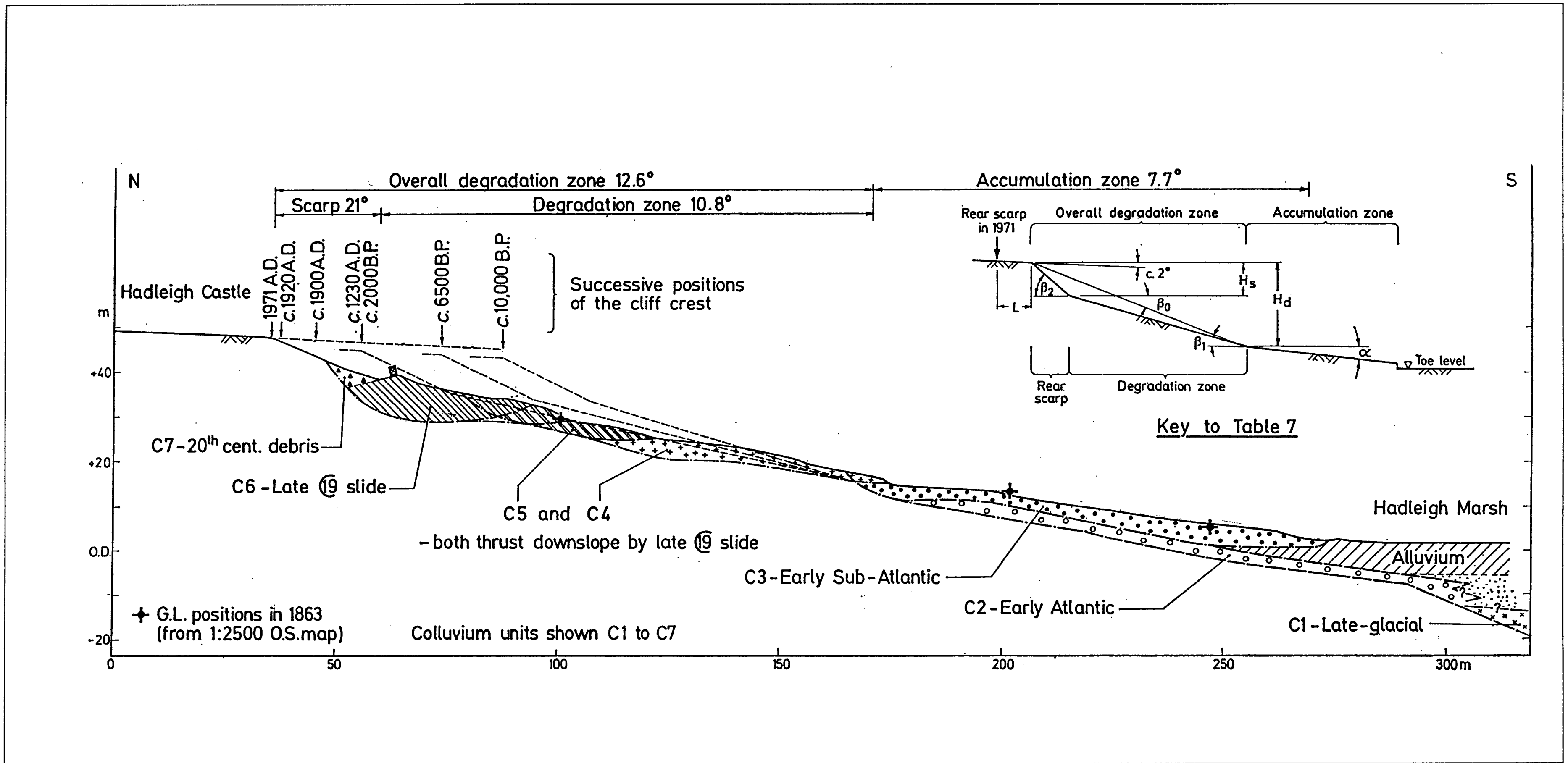
Abandoned clayey cliffs are not uncommon. Their study leads to a better understanding of the dynamic nature of landscape development, provides guidance in the site investigation of similar cliffs and on the question of what setback to allow when building near their crest.

Associated models: Platform sediments and basins (Fig. 2.6); Periglacial features (Fig. 3.20); Coastal features (Fig. 3.24)

Case History 23: Vaiont Reservoir, Italy
(Hendron and Patton, 1985; Leonards, 1987; Hutchinson, 1987)

The Vaiont Reservoir in the southern Dolomites is retained by a 276 m high double-arched dam, completed in 1960 across the Vaiont gorge. The valley walls consist chiefly of Lower Cretaceous strata overlying the Jurassic Malm and Dogger formations. The local strata, consisting predominantly of limestones, some marly, some cherty, with clay interbeds, run sub-horizontally beneath the gorge, but rise to the south into the north limb of an anticline beneath the Massif of Mont Toc. The bedding surfaces south of the river thus form a "chair" shape, which is followed by the failure surface. Filling of the reservoir was undertaken in stages, as there were early indications of slow movements in its left (southern) perimeter. As the completion of final filling was approached, the rate of movement of the left slope increased. When this reached 30 mm/day it was decided to lower the reservoir. The movements continued to accelerate, however, and on 9th October, 1963, when the reservoir level was + 710 m (15.5 m below maximum reservoir level), a very rapid failure of 260 million cubic metres of the left slope took place. The bulk of the reservoir water was displaced by the slide mass and the resulting wave rose high on the opposite slope, then passed over the dam crest at heights of 150 to 210 metres, crashing down onto the town of Langarone 500 m below. 2,040 lives were lost.

The 1963 slide was essentially a renewal of movement in an earlier, prehistoric slide, probably itself exploiting pre-existing flexural shears in the clay interbeds. This older slide also dammed the river. The 1963 failure was prepared for by erosion of the Vaiont River, cutting a 300 m deep gorge through the old slide mass, and brought about by the reduction in overall factor of safety produced by the impounding, with some influence from varying groundwater levels. A perimetral crack, over 2 km long, along the approximate rear scarp of the eventual 1963 failure, appeared in October 1960 at a time of unusually high rainfall, indicating the initiation of general failure. However, despite the very significant further reduction in overall factor of safety produced by the continuing rise in reservoir levels, the total displacements of the failure over the next three years amounted to only a few metres, until its sudden, catastrophic failure. This behaviour is believed to reflect an internal constraint on the early kinematic development of the slide, which was particularly great in this markedly compound slide of considerable internal strength. With the brittle failure on internal shears on 9th October, this constraint was suddenly removed, allowing the slide to accelerate dramatically as its factor of safety fell from effectively unity to around 0.9 (Hutchinson, 1987).



(Hutchinson and Gostelow, 1976)

Figure 5.5 : Hadleigh abandoned cliff - cross section with reconstruction of former profiles

The failure at Vaiont in 1963 focussed attention on the need to assess carefully the stability of reservoir margins, particularly where compound slides are involved, not only against rapid draw-down failures but also against failures due to impounding, together with the hazard from slide-generated waves. The engineers had not envisaged that the slide could move so quickly or generate such a large wave. Unfortunately, despite careful monitoring before failure, no warnings of the latter were provided. The need for a comprehensive site scale Geological model is clear.

Associated models: Collision complex (Fig. 2.12); Foreland basin (Fig. 2.13); Thrust systems (Fig. 3.10); Mountain glaciation (Fig. 3.18)

Hot dry climate (Fig 3.22) - This model is based on hot dry conditions, i.e. hot deserts, but in some cold deserts similar conditions also pertain, the unifying feature being lack of rain and, especially in hot deserts, evaporation exceeding precipitation at all times. This model merges into the temperate and, depending on the location, may also merge into the soluble and various coastal models. It is illustrated by Case History 24 which is an example of an ancient hot dry situation. This is another case where the authors had first hand experience of the successful use of the initial model. It is also illustrated by Case History 25, a modern desert situation.

Case History 24: Abbey Sewer, Leicester, England
(French, et al., 1998; Atkinson, et al., 1998)

The 6.2 km long, 2.8 m diameter (o/d) Abbey Sewer was constructed through Triassic Mercia Mudstone chiefly using a full-face Lovat tunnelling machine. Standard index tests of the mudstones gave LL 30% to 38%, PL 19% to 23% and PI 11% to 15%. The total clay mineral contents (by XRD) ranged from 57% to 71%, with smectite contents ranging between 5% and 27%.

Despite the above indications of low to medium plasticity materials, the tunnelling machine and its belt conveyors were found to clog, particularly in the smectite-rich mudstones. Subsequent research into the effects of passing the materials through mincers showed that while the LL of the mudstone low in smectite increased from 31% to only 43% after ten passes through the mincer, that of the smectite-rich material increased from about 38% to 66% after the same treatment.

The above situation is a reflection of the tendency for the clay fraction of the Mercia Mudstone to be aggregated into silt-sized particles as a result of its formation in hot, dry conditions. Little disaggregation of these particles occurs during the relatively gentle working involved in the Atterberg tests, but under more aggressive mechanical disturbance, the clay size particles are released and influence the mechanical behaviour of the material. This behaviour was not identified in the site investigation.

Associated models: Platform sediments and basins (Fig. 2.6); Continental fluvial, lacustrine (Fig. 3.4); Shelf carbonates and evaporites (Fig. 3.6); Coastal (Fig. 3.24)

Case History 25: Foundation failures associated with dissolution of a salt dome at Jazan, S.W. Saudi Arabia.
(Erol and Dhowian, 1988)

The town of Jazan is situated on a salt dome of gypsum and anhydrite which protrudes by about 50 m above the surrounding coastal plain, piercing the caprock. The salt dome is overlain by a loose aeolian sand mantle, 6 to 15 m thick, and is surrounded by flat, low-lying sabkha deposits.

Severe and widespread damage has occurred in the most populated part of the town, on the salt dome, with settlements of the order of metres. These settlements are related to sinkholes and to linear depressions associated with solution channels. The erratic nature of the settlements may reflect local variations in the inflow of surface water.

Further investigation has also shown that a secondary contributory factor to the settlements in the town is the collapsible nature, upon wetting, of the aeolian sand mantle, because of its weak cementation by evaporites.

The intolerable damage to property in the salt dome area has led to consideration being given to the construction of residential buildings in the surrounding sabkha plains. At shallow depths, undrained shear strengths range from only 5 to 40 kPa, so special foundation methods and protection of the construction materials from the aggressive ground conditions will be required.

The case record illustrates not only the severe problems of building on salt domes, but also the considerable foundation difficulties frequently encountered with the associated sabkhas and blown sands.

Associated model: Soluble rock features (landform scale) (Fig. 3.25).

Hot wet climates (Fig. 3.23) - Again, like hot dry, there are potentially many case histories relating to modern conditions of this model as well as the occasional ancient conditions. Surprisingly, we have found no case history that we could use as a leading case.

Coastal (Fig. 3.24) - This is a particularly important model because it represents most coasts of the world, all being subject to the worldwide sea level changes in the Quaternary, which have made most coasts quite geomorphologically active zones. The coasts themselves would have been further modified by their hinterland - hot wet, hot dry, periglacial, and so on. This model produced many case histories of which three have been selected: Case Histories 22 (already described), 26 and 27. The latter case is again one in which the authors have had first hand experience. By use of the models, all the geotechnical conditions contributing to the during-construction instability were anticipated.

Case History 26: Folkestone Warren, England
(Hutchinson, et al.,1980)

Folkestone Warren is the name of a complex of landslides in Lower and Upper Cretaceous strata which extends about 3 km along the coast between Folkestone and Dover. The slides are predominantly of multiple rotational type, although there is an important component of chalk falls and chalk flows.

Here the emphasis is placed on the interaction of these slides with the littoral drift. The three largest slides affecting the railway which traverses the Warren occurred in 1877, 1896 and 1915. Terzaghi (1950) noticed this apparent 19-year periodicity and attributed it to corresponding maxima in rainfall and thus groundwater pressures. Subsequent work indicates that these three major slides probably occurred largely in response to successive extensions of the west side of Folkestone Harbour, which were completed in 1863, 1883 and 1905. These interrupted the general movement of littoral drift from W to E and caused depletion of the beaches providing toe weight and erosion protection in front of the Warren.

This case provides further evidence of the great sensitivity of landslides to changes in the support of their toe.

Associated models: Platform sediments and basins (Fig. 2.6); Shelf carbonates and evaporites (Fig. 3.6); Joints in undeformed sediments (Fig. 3.11); Open folds and joints (Fig. 3.12)

Case History 27: **Coast of Indonesia**
(Unpublished case history)

A slope on a coast of Indonesia was steepened by a benched excavation, leading to its instability. Subsequent studies showed that, being on an oceanic plate margin/magmatic arc, the area is characterised by geologically young Quaternary volcanism and tectonics, including faults, folds and rapid changes in relative sea level. The slope in question consisted chiefly of fractured andesitic lavas and associated pyroclastic deposits overlying marine sediments. The latter contained through-going pre-existing shears not recognised in the original site investigation.

Stability analyses made prior to the failure were based on an inadequate engineering geological

investigation and over-optimistic characterisation of the soil and rock properties. The analyses thus provided an incorrectly high value of the factor of safety of the slope which prevented the serious potential hazard of instability being recognised at the design stage.

Associated models: Fold and thrust belt (Fig. 2.10), Magmatic arcs (Fig. 2.11), Basic volcanics (Fig. 3.1); Shelf carbonates and evaporites (Fig. 3.6)

Soluble rock (Fig. 3.25) - This model can occur more or less anywhere in the world and is related to those rocks that dissolve in relatively short periods of geological time, particularly limestones: gypsum and other less common evaporite rock types also suffer from similar solubility characteristics to the limestones, but usually dissolve more quickly. This model is illustrated by Case Histories 28, 29, 30 and 31.

Case History 28: Penstock at Saint-Jean-de-Maurienne, France
(Gignoux and Barbier, 1955)

In 1930 the anchorage of a long-established pressure conduit supplying a factory on the alluvial plain of the River Arc in Savoy, was endangered by a sudden collapse, 5 to 6 m in diameter and of similar depth, in a scree/fan slope. Investigations showed that this slope is underlain by Triassic gypsum and that the spillway carrying the overflow from the surge tank above the top of the scree was cracked and leaking.

The collapse was caused by water leaking from the spillway, infiltrating the slope and dissolving the Triassic gypsum, probably at depths of some tens of metres.

Associated models: Collision complex (Fig. 2.12); Shelf carbonates and evaporites (Fig. 3.6)

Case History 29: Sinkholes, Far West Rand, South Africa
(Brink, 1979; 1984)

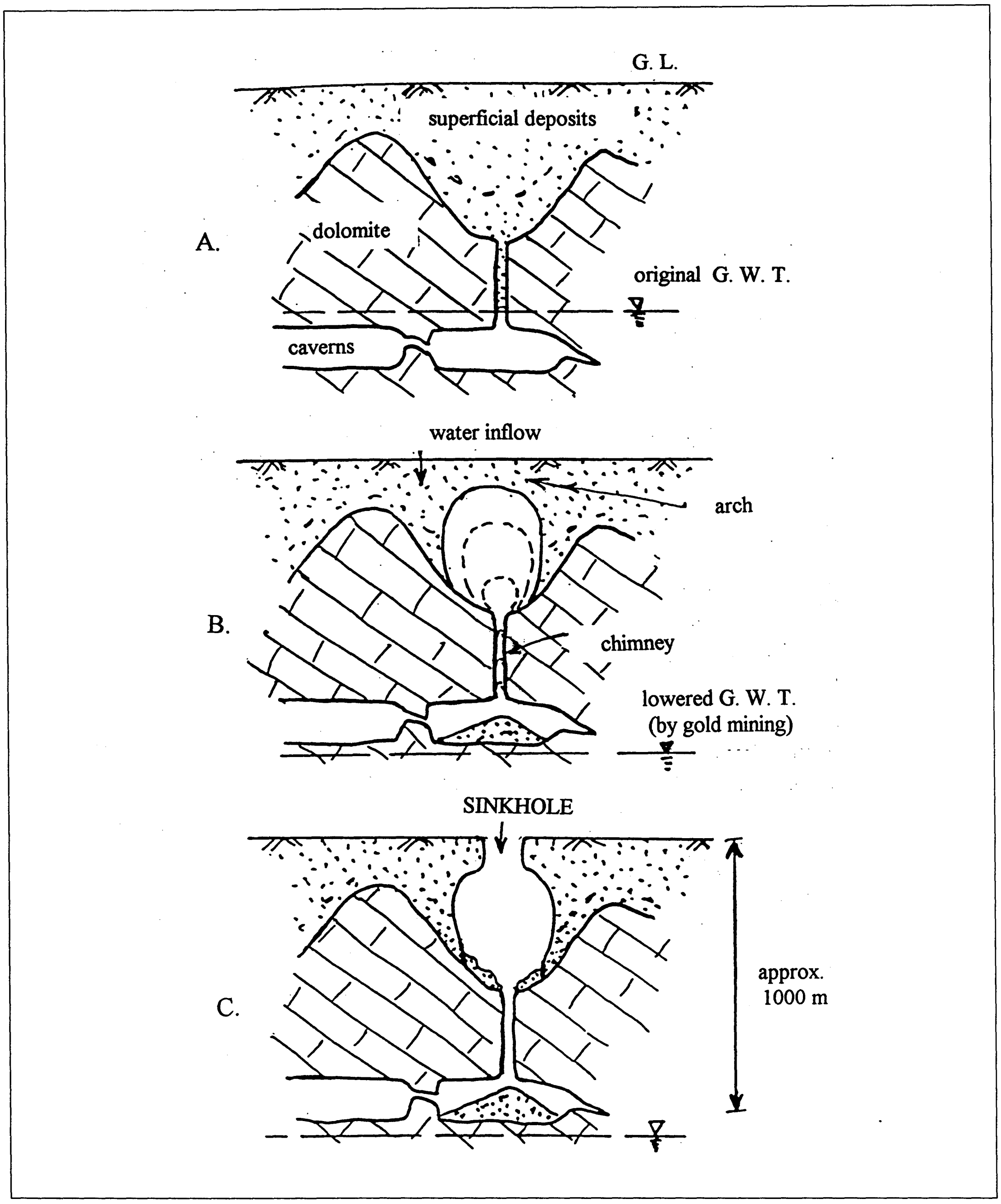
Numerous large sinkholes have formed in the Far West Rand, particularly since pumping for the gold mines intensified in the 1950s. These collapses characteristically occur suddenly and produce a deep crater. That at the West Driefontein mine in December 1962 was 55 m in diameter and at least 30 m deep. It claimed 29 lives. The largest crater still unfilled in the late 1950s formed in 1957 at the West Rand Gardens Estate; it is 100 m in diameter and 40 m deep. The ground consists of residual soils of the order of 100 or more metres thick overlying a highly irregular surface of cavernous early Proterozoic dolomites.

A mechanism of sinkhole development has been proposed by Brink (1979; 1984) (Fig. 5.6). In the initial equilibrium situation, vertical slots, plugged by residual soil, connect the floors of the buried "valleys" in the dolomite surface to flooded caverns located in this rock body at depths of around a kilometre. Dewatering of the caverns by the mine pumping, initiates a process of headward erosion, stimulated by water from leaking pipes, which first flushes out the slots and then leads to the formation of a progressively enlarging vaulted void within the overlying superficial layer. Finally the arched roof of this void collapses, usually as a result of the continued entry of water, earth tremors or vibrations, to form the sinkhole.

Associated models: Platform sediments and basins (Fig. 2.6); Shelf carbonates and evaporites (Fig. 3.6); Hot wet climate features (Fig. 3.23)

Case History 30: Wards Island Sewer Tunnel, New York, USA.
(Berkey, 1911; Anon, 1937; Legget, 1939)

The 3.2 m diameter Wards Island Sewer Tunnel was constructed in 1935-1937 from Manhattan to Wards

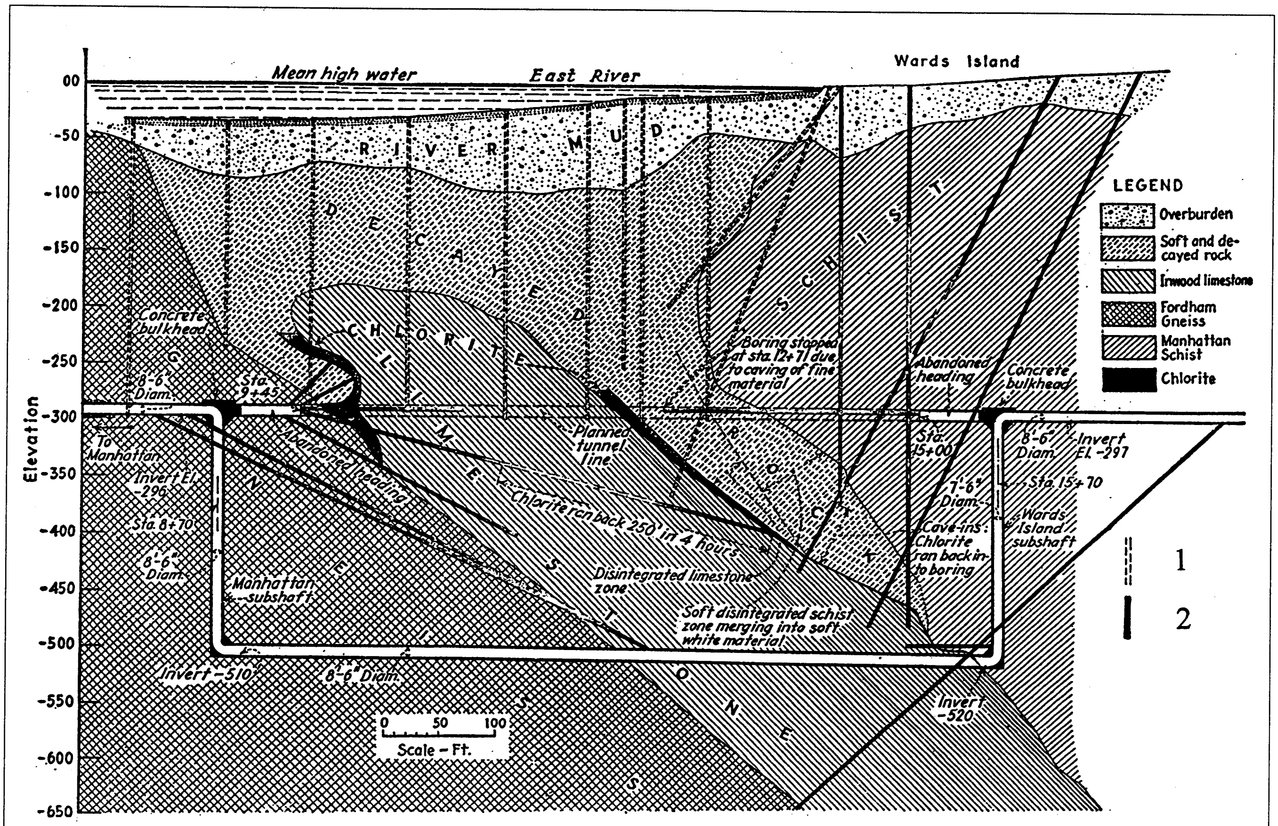


(Brink, 1984)

Figure 5.6 : Mechanism of sinkhole development in the Transvaal dolomites of the Far West Rand

Island in the East River. Preliminary borings showed that, west to east, the sewer trace would pass from Fordham Gneiss (Precambrian), a strongly banded to massive granitic and quartzose gneiss, through an irregular, karstically weathered zone of Inwood Limestone (Cambro-Ordovician?), a white dolomitic marble where fresh, into partially weathered Manhattan Schist (Ordovician?), a coarsely crystalline, chiefly mica schist (Fig. 5.7).

The tunnel drive under the East River, started at 55 m below Mean High Water, and had to be closed temporarily in December, 1936, when a soft, chloritic, muddy mass was encountered. One of the preliminary holes, drilled from the river, had met this material, but its poor quality was not realised. Supplementary drill holes then made (Fig.5.7) disclosed satisfactory conditions at greater depth and work was restarted in March, 1936, the tunnel being completed at a level 65 metres lower than originally planned.



1 = preliminary borings; 2 = supplementary borings

(Legget, 1939)

Figure 5.7 : Wars Island Sewer Tunnel - Longitudinal section

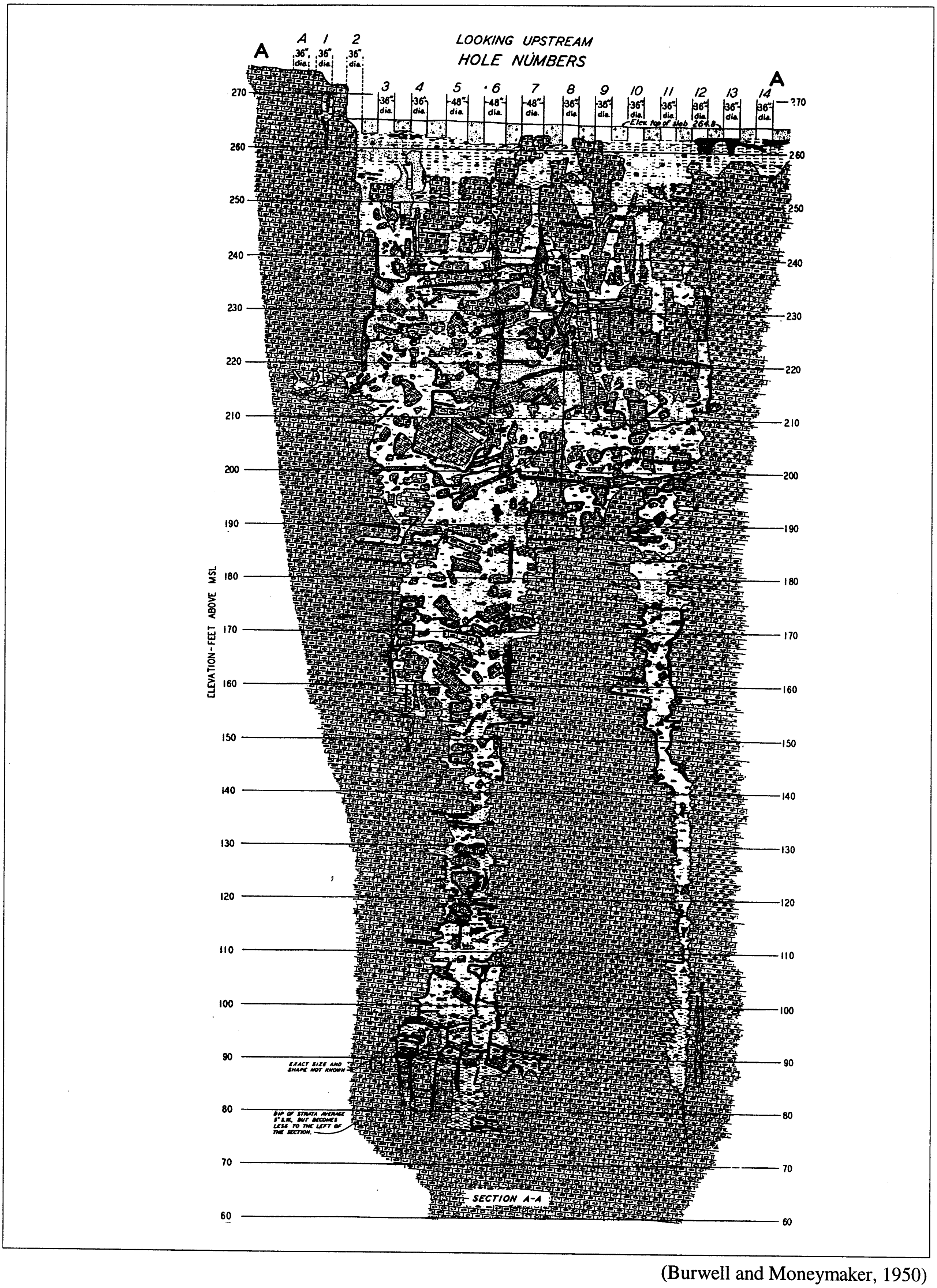
This case illustrates the complexities produced by deep karstic weathering, both spatially and mineralogically in a metamorphic, probably faulted sequence. The preliminary boreholes of which only one penetrated significantly below the originally planned sewer invert, were clearly inadequate. The supplementary boreholes, which included inclined ones, were well conceived and executed, and proved the maximum depth of weathering to be about 147 m in the schist and limestone beneath the west shore of Wards Island, and permitted successful completion of the lowered tunnel.

Associated models: Gneisses and migmatites (Fig. 3.17); Schist and phyllites (Fig. 3.16)

Case History 31: Kentucky Dam, USA.
(Burwell and Moneymaker, 1950)

Kentucky Dam was built in the mid-1940s on the Tennessee River. The site is underlain by the Fort Payne Formation (Mississippian), which consists of fine-grained, dark gray to black siliceous limestone containing nodular masses and interstratified black chert. The strata are very gently inclined and unfaulted, but cut by numerous vertical joints, many enlarged by solution.

Deep solution features, reflecting the lithology and structure of the bedrock, are virtually ubiquitous. The deepest of these, encountered at the lower lock gate, is illustrated in Figure 5.8. This zone extends down to 70 m below normal river level, i.e. about 61 m below rockhead, and is only 0.2 m wide in places. The solution cavities



(Burwell and Moneymaker, 1950)

Figure 5.8 : Kentucky Dam - cross section of deep solution zone in cherty limestone

are filled mainly by residual chert and clay, the insoluble constituents of the original rocks, blocks of undissolved limestone and sand. The limestone blocks are large and sub-horizontal in the upper part of the zone. Those at greater depths are smaller and have random inclinations.

The picture of a solution zone is based partly on information from diamond drill holes, but chiefly from the logging of 0.9 m to 1.2 m (36 inch to 48 inch) calyx holes. The latter were put down primarily to enable the unconsolidated filling of the solution cavities, which might be eroded by moving groundwater under high head, to be removed and replaced by concrete, to form a water-tight cut-off. This case well illustrates how severe solution cavities beneath water retaining structures can be successfully defined and dealt with, provided that the associated high costs are acceptable.

Associated models: Platform sediments and basins (Fig. 2.6); Shelf carbonates and evaporites (Fig. 3.6).

6.0 CONCLUDING REMARKS

From the numerous case histories examined to select those appropriate for summarising in the paper, we reached the overwhelming conclusion that for well over a century there has been a repetition of common reasons which, individually or in association with the others, have led to failure to anticipate geological conditions. This in turn has led to failure in the project engineering. We have learnt little new in this respect and many authors have reached similar conclusions before, e.g. see Tables 1.2 and 5.1 reproduced here from the original author.

We have not carried out a statistical evaluation of causes, or of features leading to causes of the failures, since the case histories differ widely in degree of detail available, and in the numbers of various types of case. However, we have come to some broad principal conclusions:

- There must be a specific and determined endeavour to understand the engineering geology and geomorphology environment of the site and to incorporate that understanding into the project design.
- The engineering geologist must be competent, well trained, experienced and a good geologist if he is to be either the lead engineering geologist in the team, or the only engineering geologist in the team.
- The engineering geologist must have a good knowledge of geomorphology and on occasion will need to work with a geomorphologist. Appropriate experience is most important in the professional development of qualified geologists and geomorphologists.
- Each site evaluation, however small, should ideally have at least one engineering geologist involved in the work. We believe this does not always occur in practice.
- It is at the preliminary stage that the engineering geologist probably can have the most significant influence on the project by indicating potential hazards and their consequence on the economy of design, matters of construction and expected performance of the works.

To help evaluate a site successfully, we have developed a total geological history model approach which is presented in the paper:

- Our use of models to understand the total geological and geomorphological history of the site helps in the identification of the mass and material characteristics of the ground. The approach generates questions and check lists which must be answered to develop a full understanding of the geological and geomorphological history of the site. In this way, anticipation of all possible geotechnical conditions should be achieved. This is accomplished through a staged understanding of the ground from the initial models to the final site-specific model. The initial models help in the planning of the ground investigations which provide information on which to build the subsequent site specific models.
- We consider that there is very little geology or geomorphology which will be *unforeseen* on a site if the evaluation is done properly. Nevertheless, it can be *unforeseeable*, i.e. all geological conditions affecting the engineering performance of the ground should be reasonably foreseen by a considered investigation. However, the detailed variation in their location, form and size or specific engineering characteristics (the potential range of which must be established) might be unreasonable to evaluate within available time and money constraints. A simple example of this would be the presence of a karstic cave system anticipated by the model and proved by drilling. The precise configuration of the cave system would require either underground mapping, which might not be feasible, or an enormously large number of boreholes, which

would be impracticable. i.e. the cave system has been foreseen and allowed for in the contract arrangement, but its detail is unforeseeable. Note that in such circumstances, adoption of the observational method would overcome potential engineering problems

- Engineering geological interpretation of the site must be continuous and early observations and deductions should be continuously reviewed, objectives should be defined and questions should be asked. This process must continue into construction and the service life of the project.

Our initial models and anticipations are offered as aide-mémoires for competent geologists, geomorphologists and engineering geologists. Engineering geological environments around the world, which began to be shaped long ago, can offer a bewildering array of conditions that can impact on projects: there is not enough time in a lifetime to see them all. The models offer assistance to those breaking potentially new ground and therefore will need constant review and addition. Some of the annotations and text on the models can, with little time or effort, be dismissed as inappropriate for a particular site: others may take extensive and expensive investigation to prove their presence and relevance, or otherwise.

ACKNOWLEDGEMENTS

The authors would like to acknowledge with many thanks the support of their families in the preparation of this paper, particularly Edna Fookes for word processing the many drafts, and for helpful suggestions by John M. Manning (retired Civil Engineer, Winchester, UK) and David T. Shilston (Chief Engineering Geologist of W.S. Atkins Consultants Limited, Epsom, UK).

REFERENCES

Ambraseys, N. N. (1985). ' The seismicity of western Scandinavia'. *Earthquake Engineering and Structural Dynamics,* 13, 361-39

Anderson, J. G. C. and Trigg, C.F. (1976). *Case histories in engineering geology.* Elek Science. London

Anon (1911). 'The Lötschberg - Simplon Railway and its construction', No. 4, *The Engineer (London),* 112, 633-635.

Anon (1937). 'Tunnel looped under a fault'. *Engrg News Record,* 119, 220-224.

Anon (1999). 'Time to Investigate', *Ground Engineering,* magazine of the British Geotechnical Society, Vol. 32, No. 11, 52-54.

Attewell, P. B. and Norgrove, W. B. (1984). *Survey of United Kingdom Tunnel Contract and Site Investigation Costs.* CIRIA Report, RP324.

Atkinson, J. H., Pettifer, G. S. and Fookes, P. G. (in press). 'Geotechnical properties of destructured Mercia Mudstone'. *Engineering in the Mercia Mudstone Group.* Report of a meeting at Pride Park, Derby, 25 November 1998, CIRIA, London.

Australian Standard 1726, (1993). *Geotechnical Site Investigations.* Standards Association of Australia, Sydney, NSW.

Bell, Fred G. (1993). *Engineering Geology,* Blackwell Science, Oxford.

Berkey, C. P. (1911). 'Geology of the New York City (Catskill) Aqueduct'. *Museum Bull.* 146. New York State Museum. Albany, New York

Berkey, C. P. (1935). 'Foundation conditions for Grand Coulee and Bonneville Projects'. *Civil Engineering (New York),* 5, 67-71.

Binnie, G. M., Clark, J. F. F. and Skempton, A. W. (1967). 'The effect of discontinuities in clay bedrock on the design of dams in the Mangla project'. *Trans. 9th Int. Cong. Large Dams,* 1, 165-183.

Binnie, W. J. E. (1936). 'Disc. on McIldowie, 1936.' *Min. Proc. Inst. Civil Engrs,* 239, 517-519.

Blyth, F. G. H. and de Freitas, M. H. (1996). *A geology for engineers* (7th edn, 11th impression). London; Arnold.

Brink, A. B. A. (1979). *Engineering geology of Southern Africa.* Pretoria; Building Publications.

Brink, A. B. A. (1984). *Sinkholes: their geology, engineering and environmental impact. Proc. 1st Multidisciplinary Conf. on Sinkholes, Orlando, Florida, 15-17 October, 1984* (Barry F. Beck, ed.). Rotterdam, Boston; Balkema,

British Standard BSS 5930 (1981) *Code of Practice for Site Investigations* (Revision in progress)

Brune, J. N. (1969). *In: American Geophysical Union Monograph* 13, 230-42

Büdel, J. (1982). *Climatic Geomorphology* (translated by L. Fischer and D. Blusche). Princeton University Press, Princeton and Guildford.

Burwell, E. B. and Moneymaker, B. C. (1950). 'Geology in dam construction'. *In: Application of geology to engineering practice*, Berkey Volume, 11-43. Geological Society of America, New York.

Buxtorf, A. (1910). 'Geologische Prognose des Lötschbergtunnels'. *Verhandl. Naturf. Ges. in Basel,* 21, 222-244.

Clayton, C. R., Simons, N. E. and Mathews, M. C. (1983.) *Site Investigation - A Handbook for Engineers.* London, Granada.

Cruden, D. M. (1985). 'Rock slope movements in the Canadian Cordillera'. *Can. Geotech. Jl,* 22, 528-540.

de Freitas, M. M. (1993). 'Discussion in Proc. 26th Annual Conference Engineering Group Geological Society'. *The Engineering Geology of Weak Rocks*. Ed. Cripps, J. C. Balkema., Rotterdam.

Dott, R. H. Jr. and Batten, R. L. (1988). *Evolution of the Earth*, McGraw Hill, New York.

Douglas, I. (1978). *In:* Embleton, C., Brunsden, D, and Jones D. K. C. (eds.) *Geomorphology: Present Problems and Future Prospects.* Oxford University Press, Oxford.

Eddleston, M., Murfin, R. E. and Walthall, S. (1995). 'The role of the engineering geologist in construction'. *In* Eddleston, M., Walthall, S., Cripps, J. C. and Culshaw, M. G. (eds). *Engineering Geology of Construction,* Geological Society Engineering Geology Special Publication No. 10, 389-401

Emery, D. and Myers, K. J. (eds), (1997). *Sequence Stratigraphy*, Blackwell Science, Oxford.

Eisbacher, G. H. and Clague, J. J. (1984). 'Destructive mass movements in high mountains: hazard and management'. *Geol. Surv. of Canada, Paper* 84-16.

Erol, A. O. and Dhowian, A. W. (1988). 'Foundation failures associated with salt rock and surrounding coastal plain' *Proc. Second Int. Conf. On Case Histories Geotechnical Engineering* June 1-5, 1988 St. Louis, Mo., 1, 237-243. Rolla, Missouri; University of Missouri-Rolla.

Eyles, N. (ed.), 1983). *Glacial geology.* Oxford; Pergamon Press.

Fell, R., Sullivan, T. D. and McGregor, J. P. (1988). The influence of bedding plane shears on slope instability in sedimentary rocks. *Proc. 5th Int. Symp. Landslides,* 1, 129-134.

Fell, R., McGregor, P. and Stapledon, D. (1992). *Geotechnical Engineering of Embankment Dams*. Balkema, Rotterdam, Brookfield

Fookes, P. G. (1997). The First Glossop Lecture. 'Geology for Engineers: the Geological Model, Prediction and Performance'. *Quart. Jl. Engrg. Geol.,* 30, 293-431.

Fookes, P. G., Dale, S. G. and Land, J. M. (1991). 'Some observations on a comparative aerial photography interpretation of a landslipped area'. *Quart. Jl. Engrg. Geol.,* 24, 249-265.

Fookes, P. G. and Dale, S. G. (1992). 'Comparison of interpretations of a major landslide at an earthfill dam site in Papua New Guinea'. *Quart. Jl. Engrg. Geol.*, 25, 313-330.

Freeman, J. R. (1922). 'Flood problems in China'. *Am. Soc. Civil Engrs, Trans,* 85, 1405-1460.

French, W. J., Pettifer, G. S. and Fookes, P. G. (in press). 'The occurrence of smectite in the Mercia Mudstone of Leicestershire'. *Engineering in the Mercia Mudstone Group*, Report of a meeting at Pride Park, Derby, 25 November 1998, CIRIA, London.

Gignoux, M. and Barbier, R. (1955). *Géologie des barrages et des aménagements hydrauliques.* Paris; Masson et Cie.

Goldsworthy, M. (1999). 'Optimum expenditure for ground investigation'. *Proc. Inst. Civ. Engrs., Civil Engineering*. 132, 62-64.

Gole, C. V. and Chitale, S. V. (1966). 'Inland delta building activity of Kosi River'. *Am. Soc. Civil Engrs, J. Hydraul. Div.,* HY-2, 111-126.

Goodman, R. E. (1999). *Karl Terzaghi. The Engineer as Artist.* Reston, Virginia; ASCE Press.

Griffiths, J. S., Brunsden, D. and Hutchinson, J. N. *(in prepn).* 'The Ok Ma tailings dam failure: a case study in engineering geology'.

Habib, P. (1987). 'The Malpasset Dam Failure'. *Engineering Geology,* 24, 331-338.

Heim, A. (1908). 'Beweist der Einbruch im Lötschbergtunnel glacial Übertiefung des Gasterentales?' *Vierteljahrschr. Naturforsch. Ges. in Zürich,* 53, 471-480

Heim, A. (1932). 'Bergsturz und Menschenleben'. *Beiblatt zur Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich,* 77, 1-217.

Hendron, A. J. Jr. and Patton, F. D. (1985). *The Vaiont Slide, a geotechnical analysis based on new geologic observations of the failure surface* (2 vols). Technical Report GL-85-5. Washington. D. C.; Dept of the Army, U. S. Army Corps of Engineers.

Hoek, E. and Bray, J. W. (1977). *Rock Slope Engineering.* Revised 2nd Edition. The Institution of Mining and Metallurgy, London.

Horswill, P. and Horton, A. (1976). 'Cambering and valley bulging in the Gwash valley at Empingham, Rutland'. *Phil. Trans. R. Soc. Lond.,* A283, 427-462.

Hutchinson, J. N. (1987). 'Mechanisms producing large displacements in landslides on pre-existing shears'. *Mem. Geol. Soc. China,* No. 9, 175-200. Taipei.

Hutchinson, J. N. (1988). 'General Report. Morphological and geotechnical parameters of landslides in relation to geology and geohydrology'. *Proc. 5th Int. Symp. Landslides,* Lausanne, 1, 3-35.

Hutchinson, J. N. (1991). Theme Lecture. 'Periglacial and slope processes'. *In:* Forster, A., Culshaw, M. G., Cripps, J. C., Little, J. A. and Moon, C. F. (eds), *Quaternary Engineering Geology,* Geol. Soc. Engrg. Geol. Spec. Pub. No. 7, 283-331.

Hutchinson, J. N. (1995). The significance of tectonically produced pre-existing shears. *Proc. 11th European Conf. Soil Mechs and Foundn Engrg,* 4, 4.59-4.67.

Hutchinson, J. N., Bromhead, E. N. and Lupini, J. F. (1980). Additional observations on the landslides at Folkestone Warren. *Q. Jl Engrg Geol.,* 13, 1-31.

Hutchinson, J. N. and Gostelow, T. P. (1976). The development of an abandoned cliff in London Clay at Hadleigh, Essex. *Phil. Trans. R. Soc. Lond.,* A283, 557-604.

Institution of Civil Engineers Ground Board (1991). *Inadequate Site Investigation.* Thomas Telford, London.

Ischy, E. (1948). 'Barrage de Castillon. Lutte contre les érosions souterraines'. *Proc. 3rd Congr. Large Dams, Stockholm,* 2, Question R36, 1-23.

Keary, P. and Vine, F. J. (1996). 'Global Tectonics' (2nd Edn), Blackwell Science, Oxford. 1-333

Kupsch, W. O. (1962). 'Ice-thrust ridges in western Canada'. *J. Geol.,* 70, 582-594.

Legget, R. F. (1936). 'Corres. on McIldowie', 1936. *Min. Proc. Inst. Civil Engrs,* 239, 533.

Legget, R. F. (1939). *Geology and Engineering.* New York and London; McGraw-Hill Book Company.

Leonards, G. A. (ed.) (1987). 'Dam failures', *Proc. Intl. Workshop on Dam Failures,* Purdue University, West Lafayette, Ind., U. S. A., Aug. 6-8, 1985.Amsterdam; Elsevier. Reprinted from *Engineering Geology,* 24, Nos. 1-4.

Littlejohn, G. S., Cole, K. W. and Mellors, T. W. (1994). 'Without site investigation ground is a hazard'. *Proc. Inst. Civ. Engrs., Civil Engineering,* 102, 72-78.

Londe, P. (1987a). 'The Malpasset Dam Failure'. *Engineering Geology,* 24, 295-329.

Londe, P. (1987b). 'Disc. on Malpasset Dam'. *Engineering Geology,* 24, 405.

Lundqvist, J. and Lagerbäck, R. (1976). 'The Pärve Fault: a late-glacial fault in the Precambrian of Swedish Lapland'. *Geologiska Föreningens i Stockholm Förhandlingar,* 98, 45-51.

Matheson, G. D. and Keir, W. G. (1978). 'Site investigation in Scotland'. *TRRL Laboratory Report 828,* Transport and Road Research Laboratory, Livingston.

McCallum, R. T. (1939). 'The opening out of Cofton Tunnel, London, Midland and Scottish Railway', *Min. Proc. Inst. Civil Engrs.* 231, 161-187.

McIldowie, G. (1936). 'The construction of the Silent Valley Reservoir, Belfast Water Supply'. *Min. Proc. Inst. Civil Engrs,* 239, 465-516.

McMahon, B. K. (1985). Australian Geomechanics Society E. H. Davis Memorial Lecture, 'Geotechnical Design in the face of uncertainty'. *News Journal of the Australian Geomechanics Society,* No. 10, Dec., 7-19.

Moores, E. M. and Twiss, R. J. (1995). *Tectonics,* W. H. Freeman and Company, U.S.A.

Normark, W. R., Moore, J. G. and Torresan, M. E. (1993). 'Giant volcano-related landslides and the development of the Hawaiian Islands'. *In: Submarine Landslides: Selected Studies in the U. S. Exclusive Economic Zone.* U. S. Geol. Surv. Bull. 2002, 184-196.

Park, R. G. (1997). *Foundations of Structural Geology (3rd Edition),* Chapman and Hall, London

Parks, C. D. (1991). 'A review of the mechanisms of cambering and valley bulging'. *In:* Forster, A., Culshaw, M. G., Cripps, J. C., Little, J. A. and Moon, C. F. (eds), *Quaternary Engineering Geology,* Geol. Soc. Engrg Geol. Spec. Pub. No. 7, 373-380.

Peck, R. B. (1962). 'Art and Science in Subsurface Engineering'. *Geotechnique,* 12, 60-66.

Peck, R. B. (1969). Ninth Rankine Lecture: 'Advantages and limitations of the observational method in applied soil mechanics'. *Géotechnique* 19. 171-187.

Perry, J. and West, G. (1996). 'Sources of Information for Site Investigations in Britain'. TRL Report 192 (Revision of TRL Report LR403). The Transport Research Laboratory, Crowthorne.

Popenoe, P., Schmuck, E. A. and Dillon, W. P. (1993). 'The Cape Fear landslide: slope failure associated with salt diapirism and gas hydrate decomposition'. *In: Submarine Landslides: Selected Studies in the U. S. Exclusive Economic Zone.* U. S. Geol. Surv. Bull. 2002, 40-53.

Press, F. and Siever. R. (1986). *Earth* (4th edn), Freeman, New York.

Price, N. J. and Cosgrove, J. W. (1990). *Analysis of Geological Structures*, University Press, Cambridge, UK.

Reynolds, J. M. (1998). 'High-altitude glacial lake hazard assessment and mitigation: a Himalayan perspective'. *In*: Maund, J. G. and Eddleston, M. (eds), *Geohazards in Engineering Geology*, Engrg Geol. Spec. Pub. No., 15, Geological. Society, London, 25-34

Ritter, D. F. (1986). *Process Geomorphology (2nd Edition)*, Wm. C. Brown Publishers, U.S.A.

Rowe, P. W. (1972). 'The relevance of soil fabric to site investigation practice'. *In:* D*evelopments in Soil Mechanics*, Thomas Telford, London, 45-152.

Schumm, S. A. (1977). *The fluvial system.* New York; John Wiley and Sons.

Selly, R. C. (1985). *Ancient Sedimentary Environments (3rd Edition)*, University Press, Cambridge, UK

Skempton, A. W. (1964). 'Long-term stability of slopes'. *Géotechnique*, 14, 77-101.

Skempton, A. W. and Petley, D. J. (1967). 'The strength along structural discontinuities in stiff clays'. *Proc. Geotech. Conf., Oslo,* 2, 29-46.

Skempton, A. W. and Weeks, A. G. (1976). ' The Quaternary history of the Lower Greensand escarpment and Weald Clay vale near Sevenoaks, Kent'. *Phil. Trans. R. Soc.* London, A 283, 493-526.

Skempton, A. W. and Vaughan, P. R. (1993). 'The failure of Carsington Dam'. *Géotechnique,* 43, 151-173.

Spencer, E. W. (1977). *Introduction to the Structure of the Earth, (2nd edn).* McGraw-Hill, New York.

Stapledon, D. H. (1976). 'Geological hazards and water storage'. *Bulletin of the International Association of Engineering Geology,* 14, 249-262.

Stapledon, D. H. (1982). 'Subsurface engineering - in search of a rational approach'. *Australian Geomechanics News,* 4, 26-33

Stapledon, D. H. (1983). Keynote address: 'Towards successful waterworks'. *Proceedings of the Symposium for Engineering for dams and canals.* Institution of Professional Engineers, New Zealand. 1.3-1.15.

Stapledon, D. H. (1996). 'Keeping the "Geo"; Why and How'. *Proc. 7th ANZ Conference on Geomechanics,* Adelaide, Institution of Engineers, Australia 3-18.

Stoddart, D. (1969). 'Climatic geomorphology: review and reassessment'. *Progress in Geography,* 2, 159-222

Summerfield, M. A. (1991). *Global Geomorphology: An introduction to the study of landforms.* Longman.

Terzaghi, K. (1950). Mechanism of landslides. In *Application of geology to engineering practice,* Berkey Volume, (Chairman, S. Paige). Geol. Soc. America. New York.83-123.

Terzaghi, K. and Peck, R. B. (1948). *Soil Mechanics in Engineering Practice.* John Wiley and Sons, New York; Chapman and Hall, London.

Terzaghi, K. and Peck, R. B. (1967). *Soil Mechanics in Engineering Practice,* 2nd edn.. John Wiley, New York, London, Sydney.

Thatcher, W. and Lisowski, M. (1987). 'Long-term seismic potential of the San Andreas fault south-east of San Francisco, California'. *Jl. Geophys. Res.*, 92, 4771-4784.

Thomas, W. F. (1994). *Geomorphology in the Tropics, A Study of Weathering and Denudation in Low Latitudes*, John Wiley and Sons Ltd., England.

Thorn, C. E. (ed.), 1982). *Space and Time in Geomorphology*, Allen and Unwin, Boston and London.

Thornes, J. B. and Brunsden, D. (1997). *Geomorphology and Time*, Methuen, London

Tricart, J. and Cailleux, A. (1972). *Introduction to Climatic Geomorphology*, Longman, London.

Tsui, P. C., Cruden, D. M. and Thomson, S. (1989). 'Ice-thrust terrains and glaciotectonic settings in central Alberta'. *Can. Jl Earth Sci.,* 26, 1308-1318.

Tucker, M. E. (1991). *Sedimentary Petrology, An Introduction to the origin of Sedimentary Rocks* (2nd edn), Blackwell Science, Oxford, UK

Walker, H. J. and Prior D. B. (1986). 'Estuarine Environments'. *In* Fookes, P. G. and Vaughan, P. R. (eds), *Engineering Geomorphology*, Blackie and Sons Ltd., Glasgow.180-192.

Walters, R. C. S. (1962). *Dam geology.* London; Butterworths.

Wittke, W. and Leonards, G. A. (1987). 'Modified hypothesis for failure of Malpasset Dam'. *Engineering Geology,* 24, 367-394.

Yeats, R. S., Sieh, K. and Allen, C. R. (1997). *The geology of earthquakes.* Oxford University Press, New York, Oxford.

APPENDIX

Model Figures

Title	Fig.	Leading Case History
Tectonic elements of the world	2.1	---
Section showing major tectonic element of the earth's crust	2.2	---
Simple tectonic crustal collision mechanisms	2.3	---
Tectonic model - intraplate setting - cratons	2.4	16, 17
Tectonic model - intraplate setting - mobile belts	2.5	14, 26, 27
Tectonic model - intraplate setting - platform sediments and basins	2.6	4, 12, 18, 19, 20, 21, 22, 24, 26, 31
Tectonic model - divergent plate boundary - continental rifts	2.7	None found
Tectonic model - divergent plate boundary - oceanic rifts	2.8	6
Tectonic model - convergent plate boundary - accretionary prisms	2.9	None found
Tectonic model - convergent plate boundary - fold and thrust belts	2.10	27
Tectonic model - convergent plate boundary - magmatic arcs	2.11	27
Tectonic model - convergent plate boundary - collision complexes	2.12	1, 11, 13, 14, 23, 28
Tectonic model - convergent plate boundary - foreland basins	2.13	3, 4, 5, 10.15
Geological model - igneous - basic volcanics	3.1	None found
Geological model - igneous - acid volcanics	3.2	None found
Geological model - igneous - plutonic intrusions	3.3	1
Geological model - sedimentary - continental fluvial, colluvial and lacustrine	3.4	2, 3, 4
Geological model - sedimentary - continental deltaic and coal measures	3.5	None found
Geological model - sedimentary - shelf carbonates and evaporates	3.6	5
Geological model - sedimentary - deep marine and continental slope	3.7	6, 7
Geological model - structural - normal faults	3.8	8
Geological model - structural - strike slip faults	3.9	9
Geological model - structural - thrust faults	3.10	None found
Geological model - structural - joints in undeformed sediments	3.11	None found
Geological model - structural - open folds and joints	3.12	(3), 10, 11
Geological model - structural - plastic folds with cleavage	3.13	None found
Geological model - structural - multiple folds and shears	3.14	12
Geological model - structural - tectonised melange	3.15	None found
Geological model - metamorphic - schists and phyllites	3.16	(14, 30)
Geological model - metamorphic - gneisses and migmatites	3.17	(30)
Geomorphological model - valley glaciation features	3.18	13, 14, 15
Geomorphological model - continental glaciation features	3.19	16, 17, 18
Geomorphological model - periglacial features	3.20	19, 20, 21
Geomorphological model - temperate climate features	3.21	22, 23
Geomorphological model - hot dry climate features	3.22	24, 25
Geomorphological model - hot wet climate features	3.23	None found
Geomorphological model - coastal features	3.24	(22), 26, 27
Geomorphological model - soluble rock features (landform scale)	3.25	28, 29, 30, 31

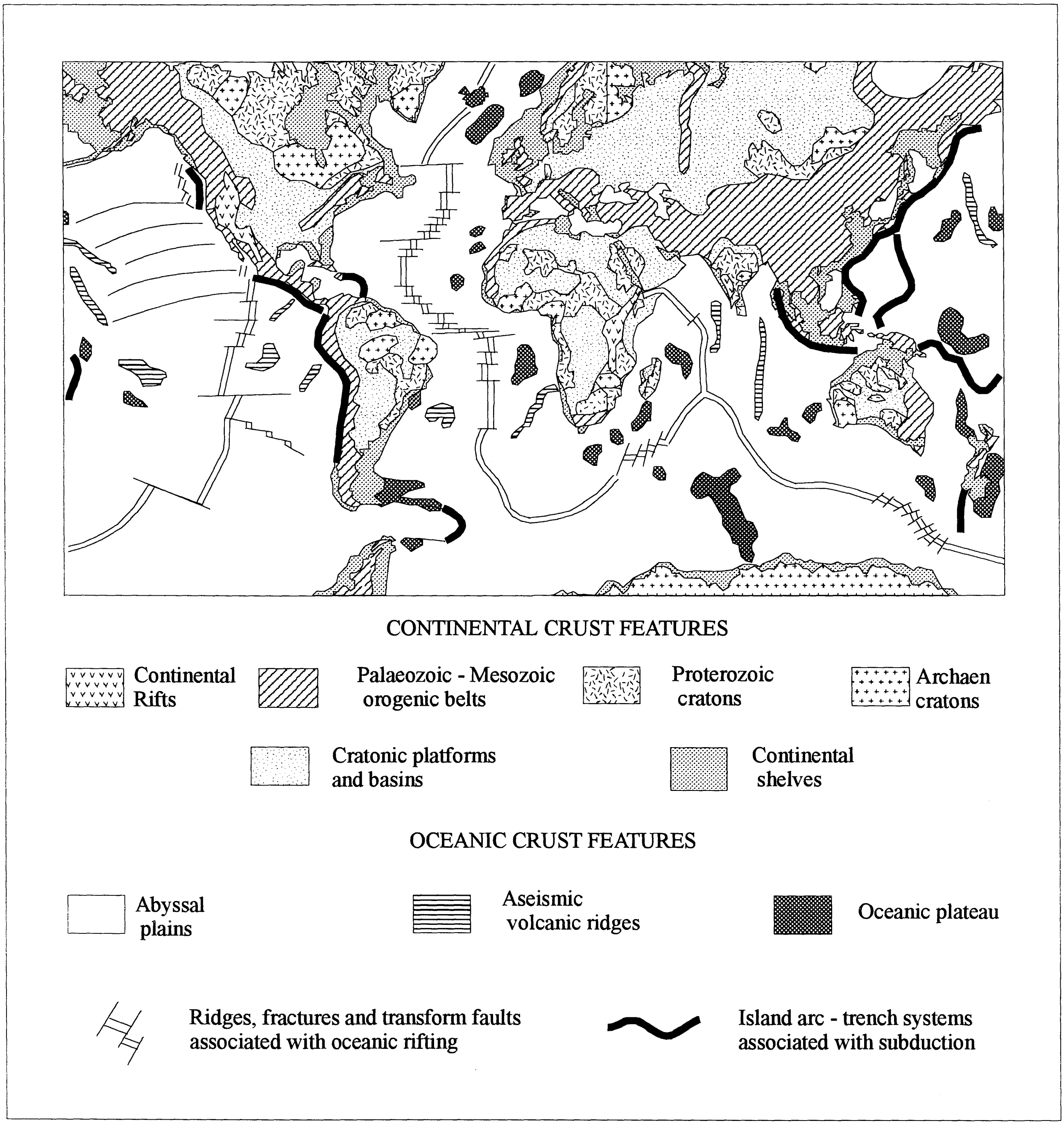


Figure 2.1 : Tectonic elements of the world (based on Moores and Twiss 1995)

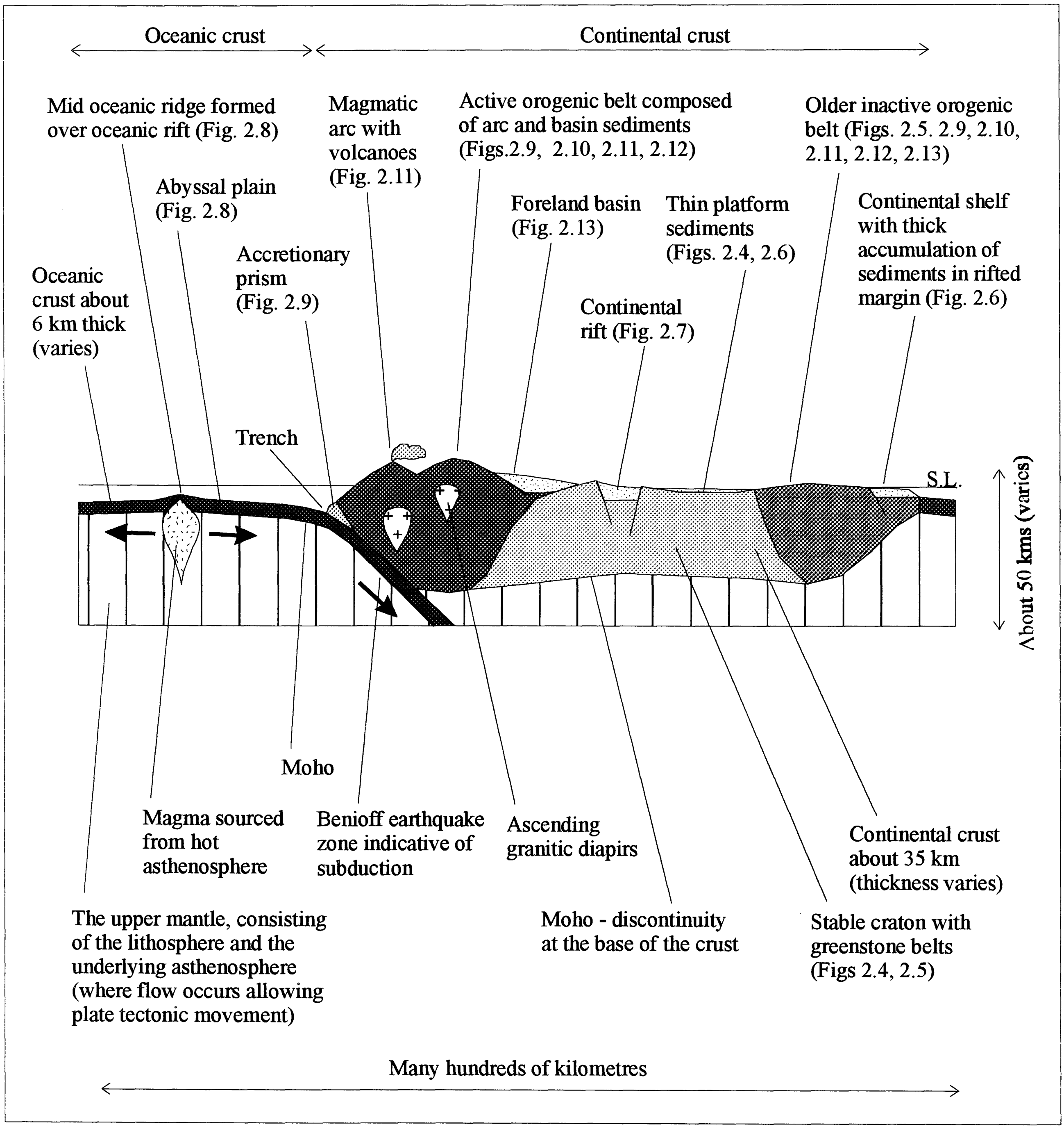


Figure 2.2 : Section showing major tectonic elements of the earth's crust

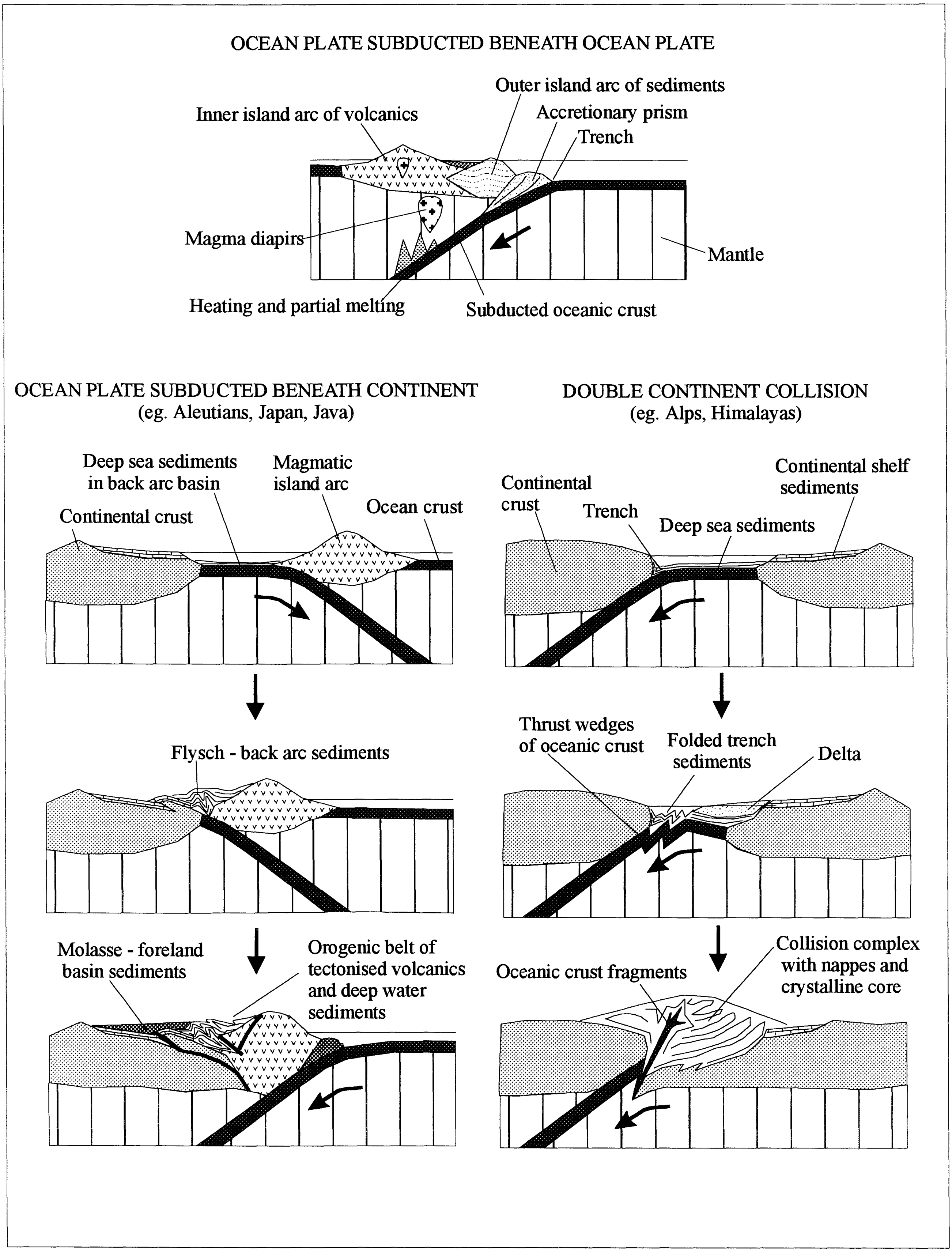
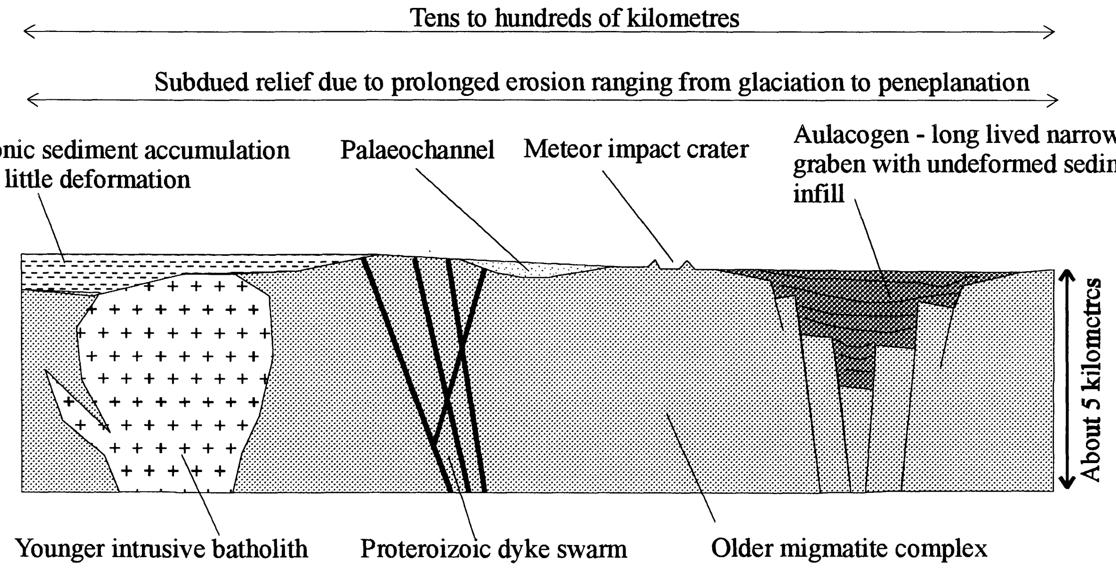


Figure 2.3 : Simple tectonic crustal collision mechanisms



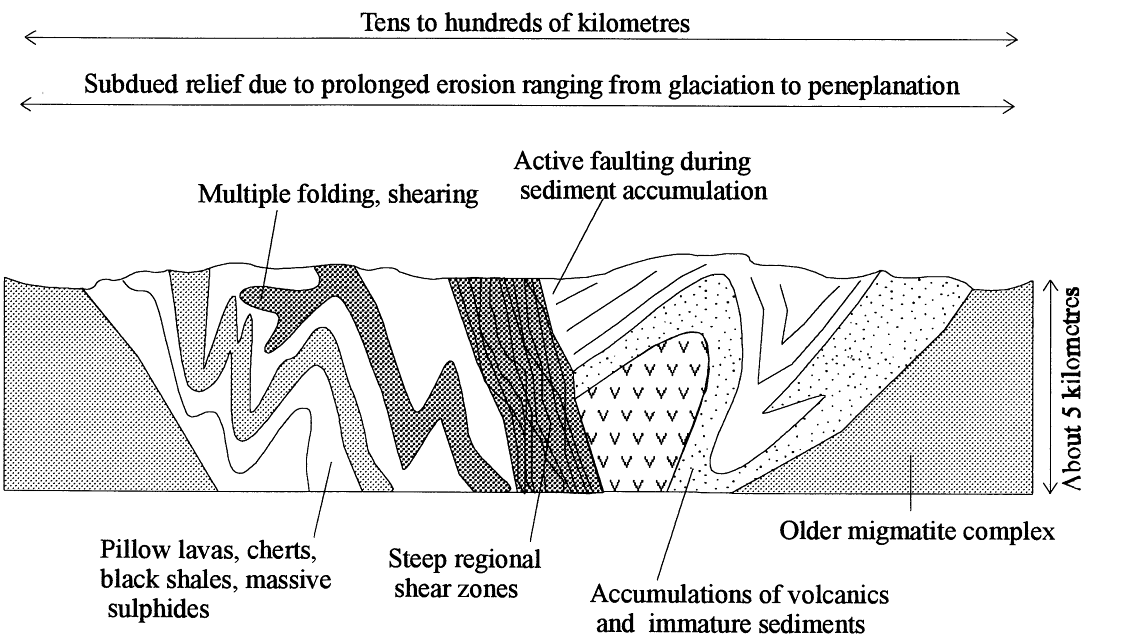
LITHOLOGIES: Precambrian cratons generally form rolling uplands hence called "shields". Archaen systems (>2,500Ma) include granites, gneisses, migmatites, subordinate metasediments, deformed mafic-ultramafic, and quartzite-carbonate-iron formations. Proterozoic systems may have developed after some crust became stable (2,500 - 550 Ma) and includes basic dyke swarms, undeformed sediments, highly deformed orogenic belts, aulacogen infills, stratiform mafic complexes, anorthosite bodies.

STRUCTURE: ductile polyphase deformation, high grade metamorphism, early refolded low angle faults and folds and later upright folds, complex structural relationships to greenstone belts including shear zones, unconformities, and intrusions.

RELATED MODELS: basic volcanic Figure 3.1, acid volcanic Figure 3.2, granite Figure 3.3, continental fluvial, colluvial and lacustrine Figure 3.4, shelf carbonate and evaporites Figure 3.6, deep marine and continental slope Figure 3.7, plastic folds with cleavage Figure 3.13, multiple folds and shears Figure 3.14, schists and phyllites figure 3.16, gneiss & migmatite Figure 3.17.

EXAMPLES: Yilgarn craton of western Australia; Superior Province of Canada.

Figure 2.4 : Tectonic model - intraplate setting - cratons



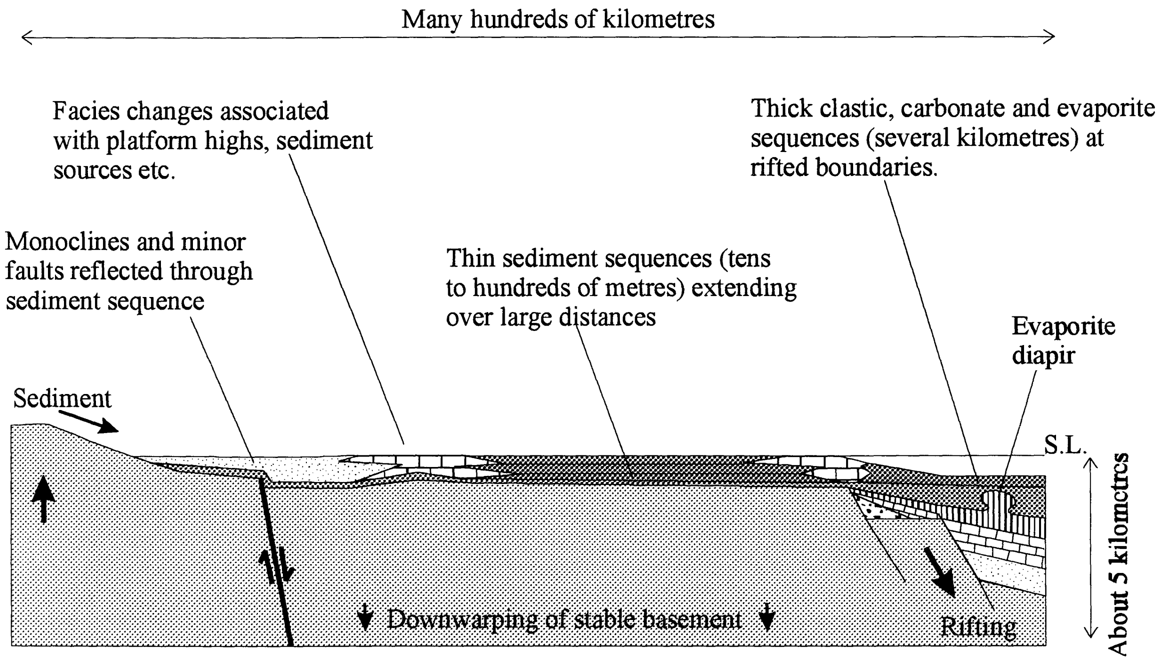
LITHOLOGIES: originally "greenstone" belts, ie. mafic volcanics, but now distinct zones of associated volcanics, deep water sediments and immature sediments, with low pressure regional metamorphism, intruded by intermediate and acid plutonics. Usually three groups, lower komatiitic ultramafics and mafics with pillows, middle intermediate volcanics, and upper clastics including greywackes, sandstones, conglomerates, banded ironstones and limestones. Zones of considerable economic, precious and base metal mineralization.

STRUCTURE: typically in synformal structures 40 - 250 km wide and 120 - 800 km long, multiple folding, throughgoing shears, steeply dipping schistosity.

RELATED MODELS: basic volcanics Figure 3.1, acid volcanics Figure 3.2, deep marine and continental slope systems Figure 3.7, thrusts faults Figure 3.10, plastic folds with cleavage Figure 3.13, multiple folds and shears Figure 3.14, tectonised melange Figure 3.15, schists and phyllites Figure 3.16.

EXAMPLES: Kalgoorlie greenstone belt of western Australia; Barberton greenstone belt of the Kalahari craton, South Africa; Abitibi greenstone belt of the Superior Province, Canada.

Figure 2.5 : Tectonic model - intraplate setting - mobile belts



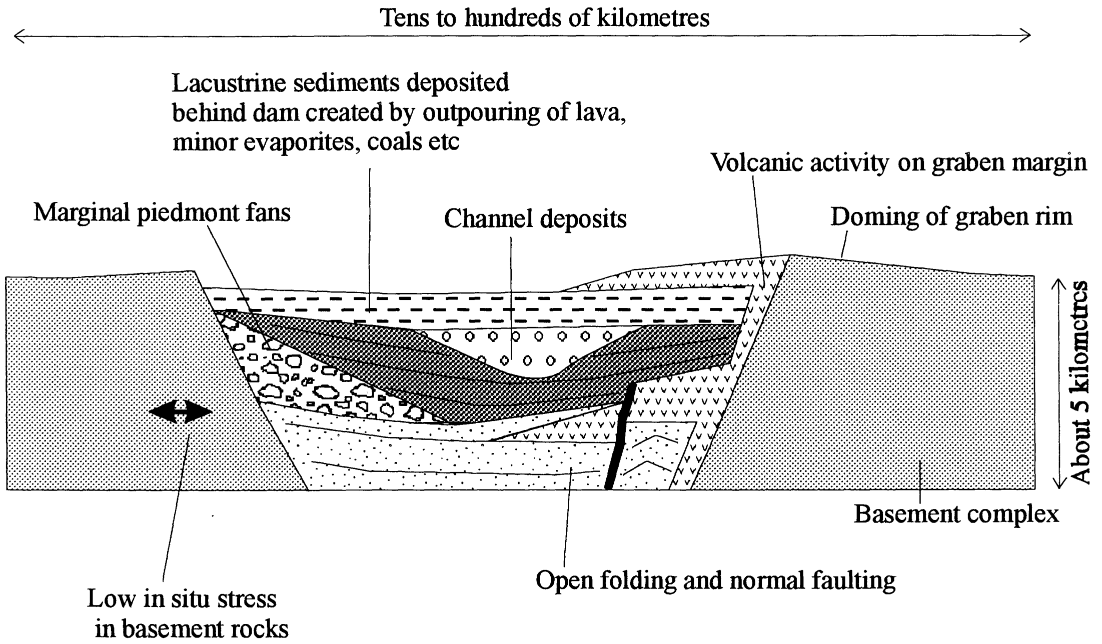
LITHOLOGIES: quartz rich sands, limestones, muds, evaporites and coals; facies changes across basins; thicker sequences in rifted basins; these systems are the main source of coals and hydrocarbons.

STRUCTURES: regional jointing related to basin shape, conjugate jointing, low dip angles, growth faults and monoclinal drapes. Many basins display repeated phases of subsidence throughout the geological record and also inversions, when the sense of differential movement is reversed.

RELATED MODELS: fluvial colluvial and lacustrine Figure 3.4, deltaic and coal measures Figure 3.5, shelf carbonates and evaporites Figure 3.6, undeformed basin accumulations Figure 3.11.

EXAMPLES: Illinois basin, Michigan basin, Williston basin of North America; Mesozoic and Cenozoic sediments of southern United Kingdom.

Figure 2.6 : Tectonic model - intraplate setting - platform sediments and basins



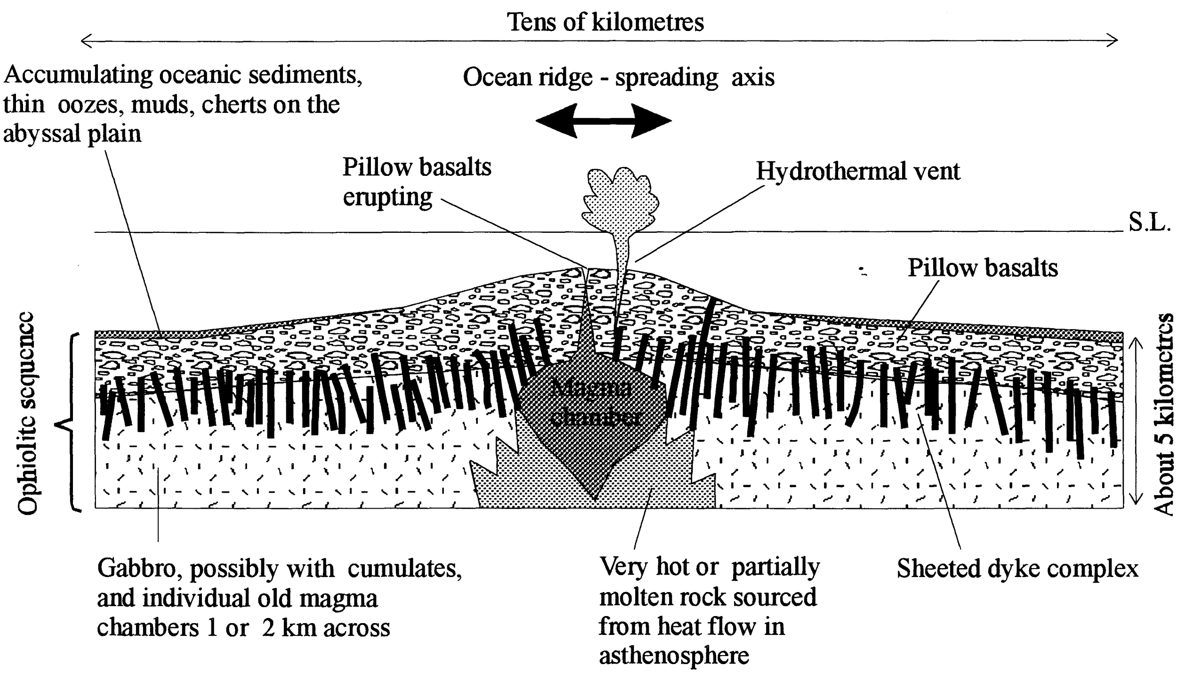
LITHOLOGIES: marginal fans, coarse braided alluvium, meandering alluvium, lacustrine deposits, minor evaporites and coals, basic intrusive and volcanic and their differentiates, but also characteristically alkali rich igneous rocks (trachytes and syenites).

STRUCTURE: extensional tectonics involving doming and uplift above areas of thinner continental crust and high heat flow, horst and graben, minor open folding. Often evolve firstly with volcanism, then doming, then rifting. Some rotation or tilting of blocks can occur during the later phases. Graben are typically 15 to 50 kilometres wide but may occur in swarms. Downfaulting as a result of rifting may involve active deposition occurring well below current sea level. Normal faulting at the margins may be listric and transition to very low angle normal faults called detachments at depth.

RELATED MODELS: basic volcanic Figure 3.1, continental fluvial, colluvial and lacustrine Figure 3.5, normal faults Figure 3.8.

EXAMPLES: Rhine graben; African rift system; Basin and Range Province of North America.

Figure 2.7 : Tectonic model - divergent plate boundary - continental rifts



LITHOLOGIES: The ophiolite sequence ie.

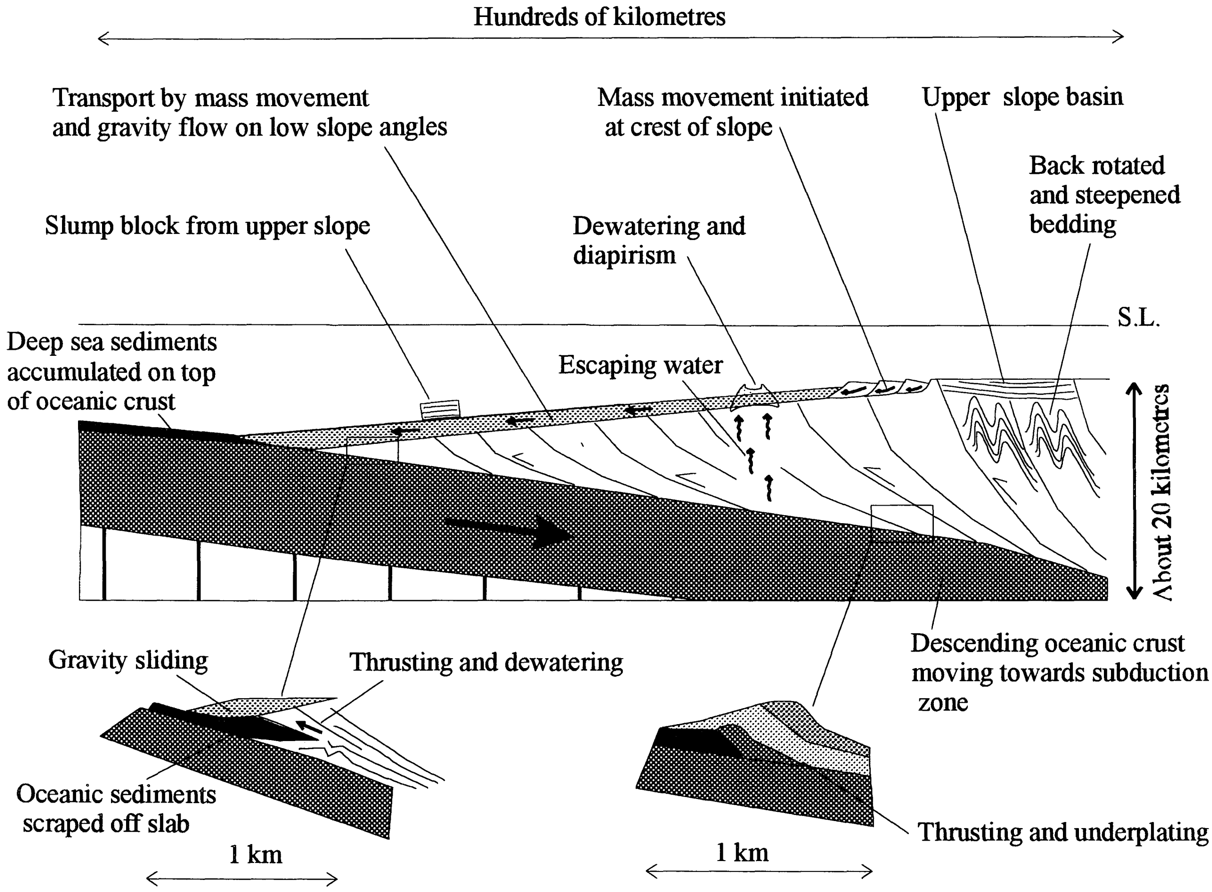
Pelagic sediments, thin oozes, muds ,cherts, metal rich
Extrusive volcanics, massive or pillowed basalts, some breccias, some dykes
Sheeted dyke complex, multiple injections of basic dykes
Top plutonic complex, gabbro, diorite and quartz diorite intrusives
Stratiform plutonic complex, cumulates in magma chambers
Tectonised peridotite, foliated ultramafic.

STRUCTURE: extensional tectonics.

RELATED MODELS: basic volcanic Figure 3.1, plutonic intrusions Figure 3.3, normal faults. Figure 3.8.

EXAMPLES: The mid Atlantic ridge with Iceland formed where the ridge extends above sea level; the Trudos ophiolite complex on Cyprus (inactive remnant of sea floor).

Figure 2.8 : Tectonic model - divergent plate boundary - oceanic rifts
(based on Moores and Twiss 1995)



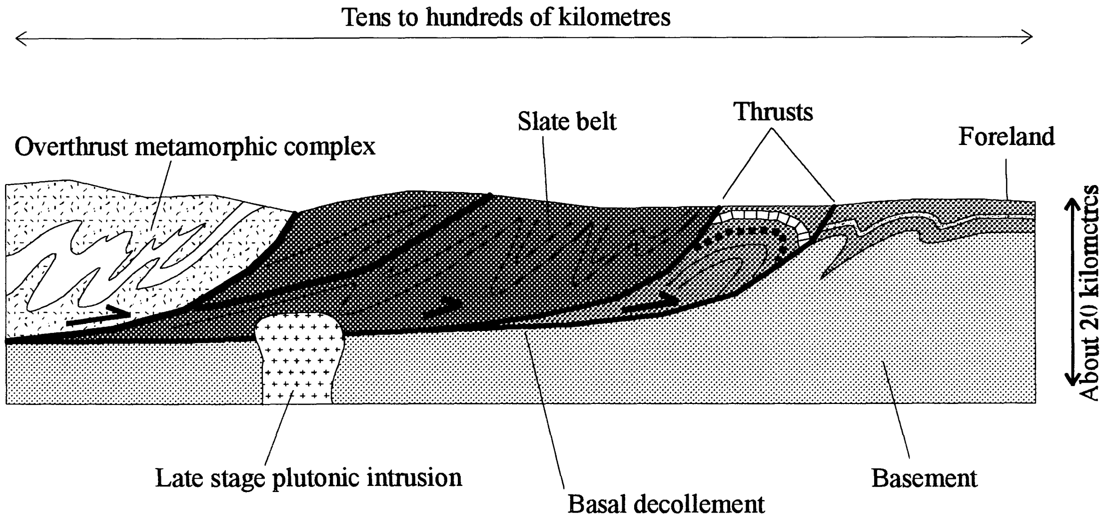
LITHOLOGIES: deep marine sediments, muds radiolarian cherts and oozes, exhalative cherts, pillow basalts, slumped masses from the upper slopes including massive shelf limestones.

STRUCTURE: intense compression and shearing, tectonic melange, imbricate thrusts, high pore water pressures.

RELATED MODELS: deep marine and continental slope Figure 3.7, thrust fault Figure 3.10, plastic folds with cleavage Figure 3.13, multiple folds and shears Figure 3.14, tectonised melange Figure 3.15.

EXAMPLES: south of the Sunda arc; northeast Honshu Japan; Franciscan rocks of west North America.

Figure 2.9 : Tectonic model - convergent plate boundary - accretionary prisms
(based on Moores and Twiss 1995).



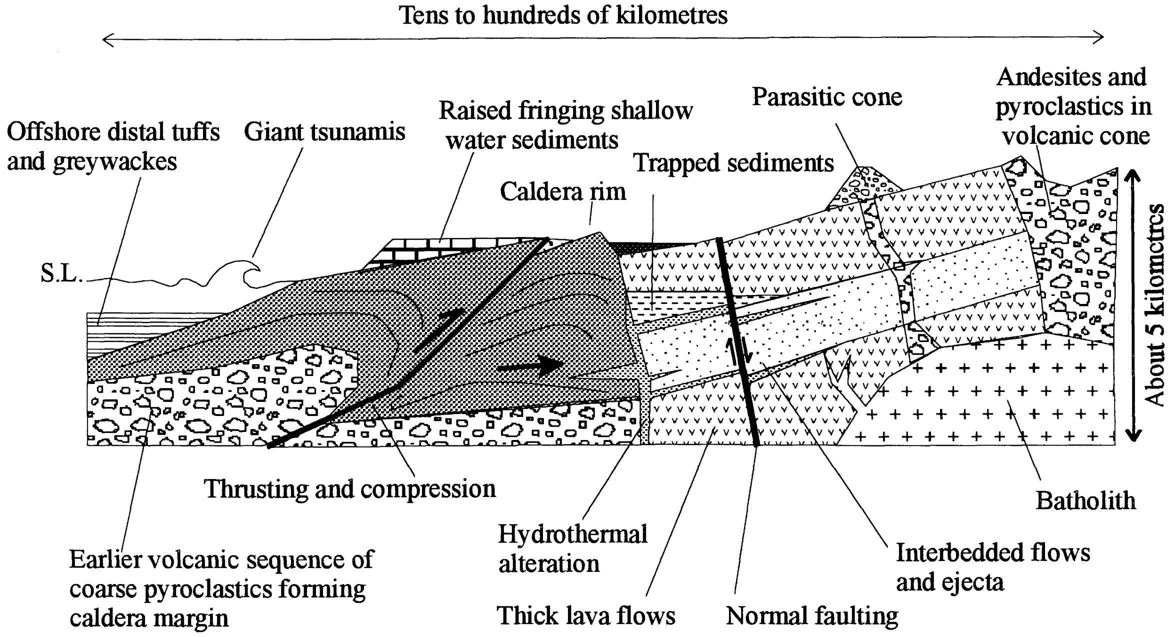
LITHOLOGIES: dominated by deep water marine sediments, flysch, and greywackes with some pyroclastics and volcanoclastics ie. volcanic associations (formerly called eugeosynclinal facies) in deeper parts of the original basin, and with shelf deposits of limestones, sandstones and mudstones with no volcanic associations (formerly miogeosynclinal facies) in shallow parts of the original basin. Epitomised by "slate belts" where thick monotonous sequences of fine grained sediments have accumulated in deep trenches.

STRUCTURES: Towards the centre of an orogenic belt there is generally a fold and thrust belt dominated by deep water marine sediments with volcanic associations which transitions laterally to shallow water shelf sediments. The original basins in which the deep water marine sediments were deposited may be a forearc or a backarc basin with the shallow water shelf sediments deposited on adjacent stable continental crust. There is characteristically a low angle shear that separates the rocks of the fold and thrust belt from the underlying basement. The deep water sediments tend to be close to the orogenic core and are usually metamorphosed to greenschist facies and above with plastic folding that can be inclined or even recumbent and can form nappes. Slaty cleavage and foliation is well developed and multiple folding is common. Towards the shallow margins multiple thrusts with duplex structures are common and bedding parallel faults form in incompetent layers. Shallower thrusts tend to be younger resulting in prograding deformation.

RELATED MODELS: deltaic and coal measures Figure 3.5, shelf carbonates and evaporates Figure 3.6, deep marine and continental slope Figure 3.7, thrust faults Figure 3.9, plastic folds Figure 3.13, multiple folds and shears Figure 3.14, tectonised melanges Figure 3.15.

EXAMPLE: slate belt of north Wales; southern Appalachians in USA; Canadian Rockies.

Figure 2.10 : Tectonic model - convergent plate boundary - fold and thrust belts



LITHOLOGIES: composition dominated by acid and intermediate volcanics ie. andesites, rhyolites, but with some basalts. Texturally the sequences include various lavas, pyroclastics, tuffs, ashes, lahars, and megabreccias. Sequences characteristically include zones of hydrothermal alteration, mineralization, and, locally, proximal black shales and minor limestones from contemporary fringing reefs. Distal volcaniclastics are deposited in trench systems. Young arcs tend to be underlain by thin crust (20 kms) and are dominated by tholeiitic basalts, whereas older arcs tend to have thicker crust (20 - 35 kms) and have more calc-alkali andesites and alkali basalts. In mature arcs plutonic rocks from magma chambers are exposed. Many rich epithermal and mesothermal base metal and precious metal deposits are formed in this environment.

STRUCTURE: caldera collapse, neotectonics, active uplift, surface faulting, high heat flux, seismicity, normal faulting and thrusting. A close association exists between active volcanic activity and present day seismicity.

Magmatic arcs may be grouped as follows:

Active volcanic arcs: consisting of currently active or dormant volcanoes, with typical landforms of cones, craters, calderas, lava flows, ignimbrite plateau etc. especially occurring around the circum-Pacific belt. These tend to be acid or intermediate in composition and may be built up from several cycles of volcanicity, but are generally non-tectonised although they are depositionally complex due to the volcanic processes themselves.

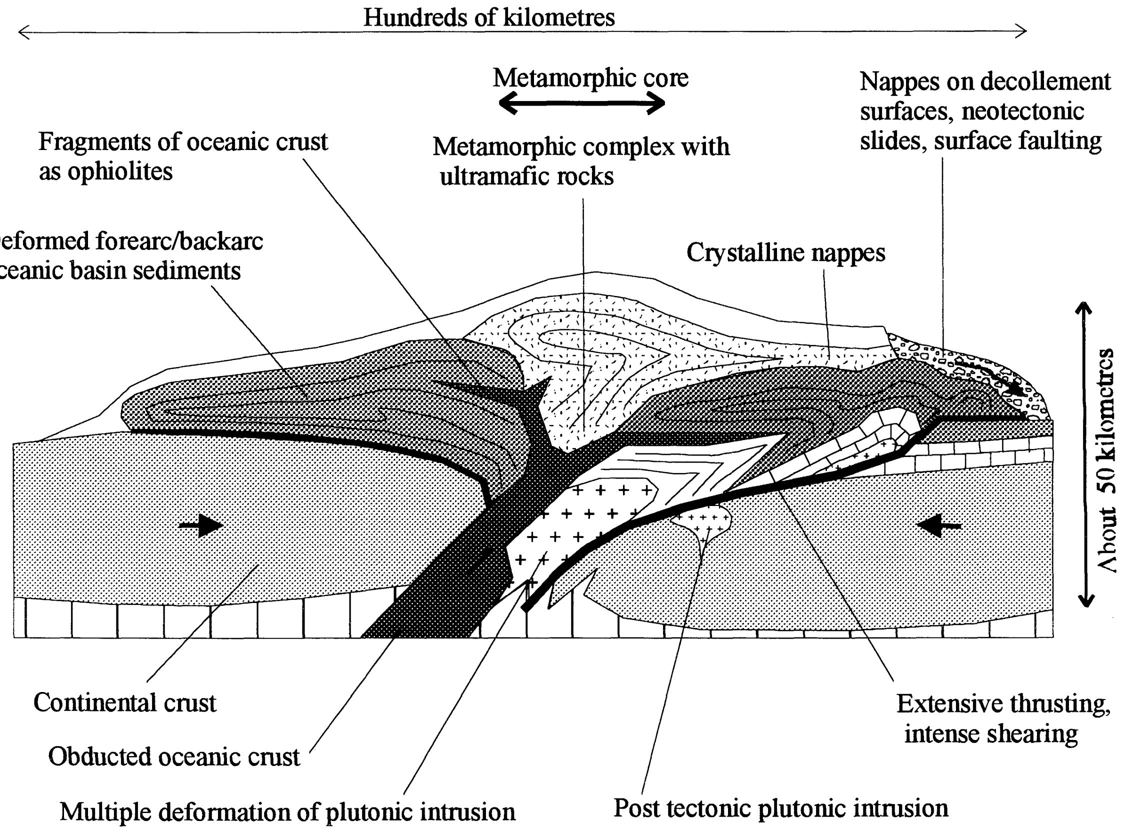
Ancient island arc type systems: with lavas, pyroclastics and volcaniclastics deposited in trenches, associated with crustal shortening involving thrusting, high pressure regional metamorphism, possibly with introduced ultrabasic rocks, and minor plutonic intrusions of intermediate or acid composition although large granite batholiths tend to be absent.

Andean Cordilleran type systems: with lavas and volcaniclastics in continental rifts paired with shelf facies, little crustal shortening, dominated by vertical movements, open folds without cleavage are most common , regional burial metamorphism, batholiths range from predominantly granitic to a calc-alkaline association of gabbro, diorite, granodiorite and granite.

RELATED MODELS: basic volcanics Figure 3.1, acid volcanics Figure 3.2, plutonic intrusions Figure 3.3, normal faults Figure 3.8, thrust faults Figure 3.10.

EXAMPLES: Active volcanic arcs occur in parts of Indonesia such as Bali and Java; Aleutian arc; parts of Japan. Ancient island arc systems occur at Bougainville (Panguna deposit); the Mount Read Volcanics of Tasmania. Andean Cordilleran arc systems occur at the Bolivian tin belt (Cordillera Real) in the Andes; the San Juan field of Colorado in the North American Cordillera.

Figure 2.11 : Tectonic model - convergent plate boundary - magmatic arcs



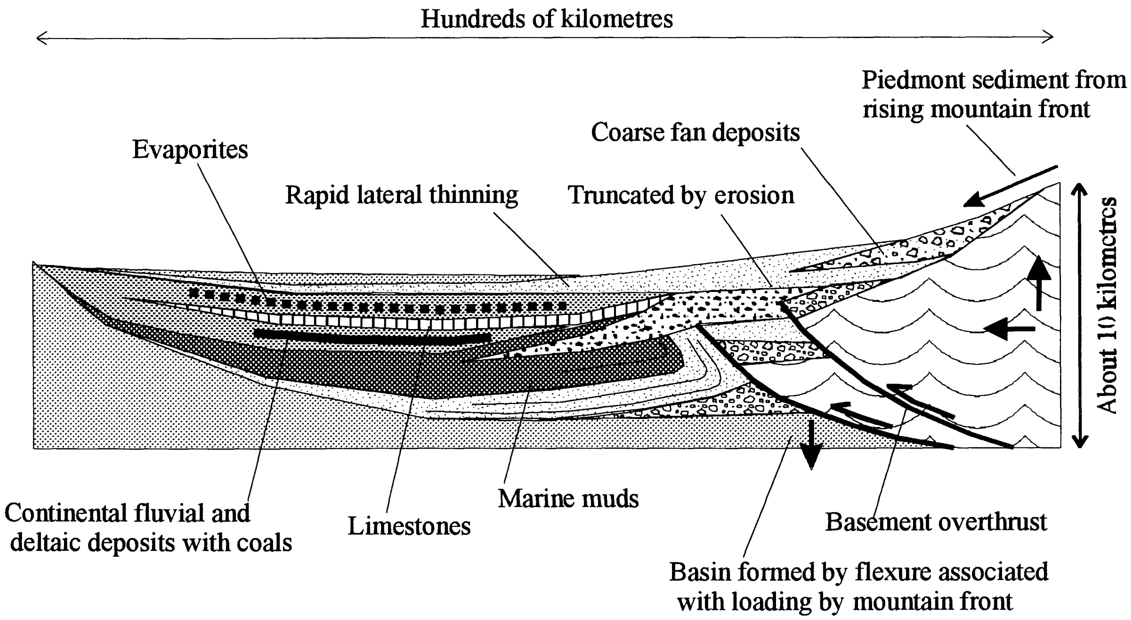
LITHOLOGIES: the system forms when two masses of continental crust collide and continue to converge and hence the entire range of crustal igneous, sedimentary and metamorphic rocks may be entrained, or formed, in the collision complex, together with ophiolite sequences from pieces of oceanic crust that may be caught up in the collision.

STRUCTURE: major crustal thickening due to underthrusting of thick crustal slices and relatively shallow seismic events associated with the thrusting are characteristic, but considerable strike-slip faulting is also common and can form patterns suggestive of indentation of one continental mass by another. Ophiolites may be emplaced by obduction at the tectonic suture that forms between crustal masses and involves detachment of pieces of oceanic crust from the downgoing oceanic plate and thrusting onto the continental plate. Sutures are usually intensely sheared and often separate markedly different stratigraphic or tectonic regimes. Crustal shortening of many hundreds of kilometres can result from an ongoing collision and the immense compression causes deep crustal rocks to be thrust to the surface. This results in intense ductile folding and multiple deformation episodes, intense shearing along regional thrusts, and the development of nappes as the crustal rocks are extruded from the collision complex and flow out close to the surface as huge recumbent fold systems. The rapid uplift and youthful topography combined with the neotectonic movements of nappes and sheets of tectonised crustal rocks can result in surface instability in the form of massive landslides.

RELATED MODELS: entire range of igneous and sedimentary models Figures 3.1 to 3.7, plastic folds with cleavage Figures 3.13, multiple folds and shears Figures 3.14, tectonised melange Figure 3.15, sheared schists Figure 3.16, gneiss and migmatite Figure 3.17.

EXAMPLES: central Alps; Zagros region of southwestern Iran; Himalayan mountain range.

Figure 2.12 : Tectonic model - convergent plate boundary - collision complexes



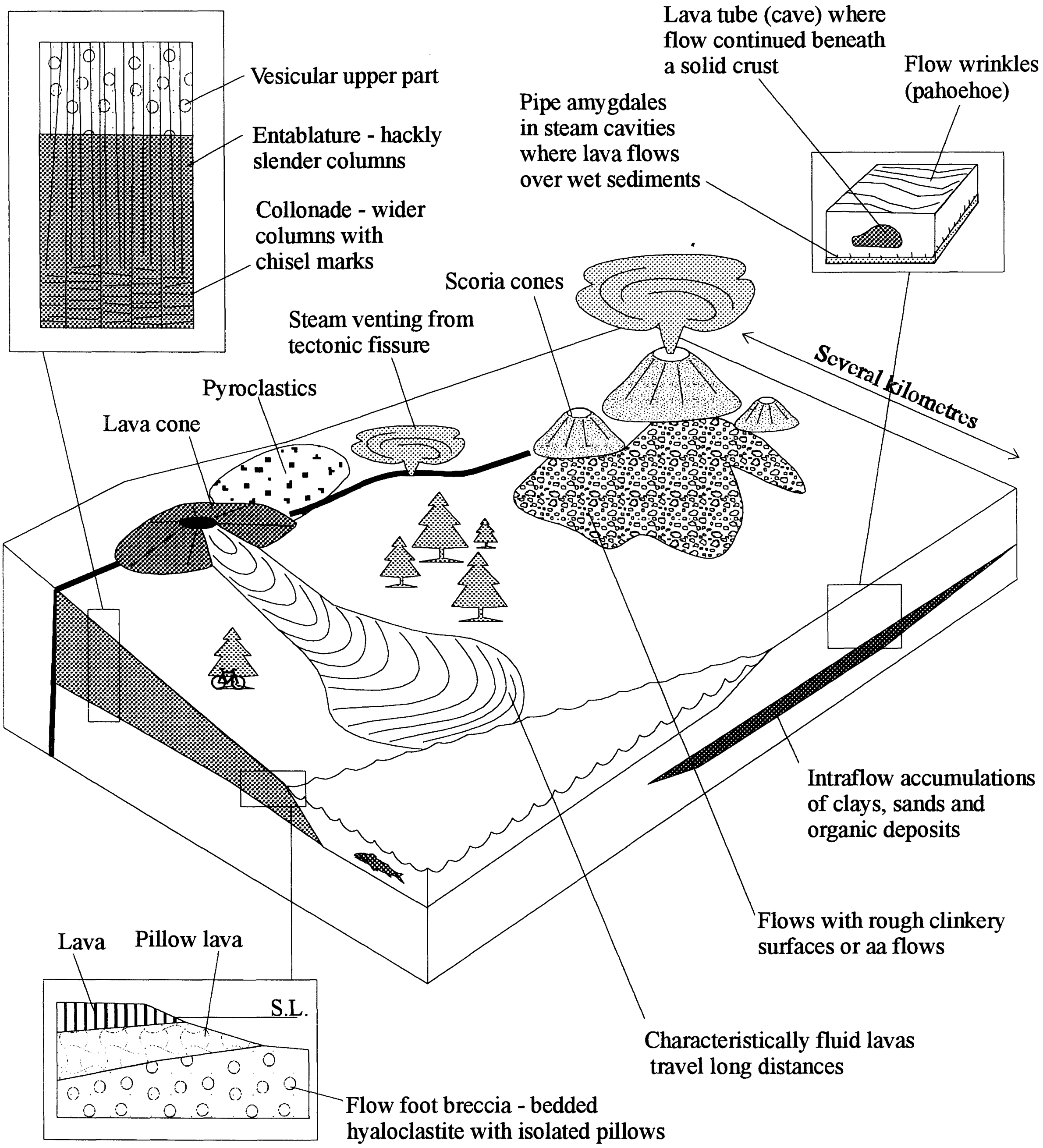
LITHOLOGIES: "molasse" assemblages, coarse clastics, sandstones, mudstones, limestone, coals, evaporites; coarseness decreasing away from mountain front, tend to be fining upwards, may indicate shallowing with time, "unroofing sequences" may display the reverse order to the provenance stratigraphy, and indicate progressive uplift and erosion within the source mountains.

STRUCTURE: slight deformation, open folds with large wavelengths, tighter inclined folds verging towards the stable platform close to the mountain front. These basins are characteristically formed in the later stages of tectonic activity when orogenesis is largely complete, and may be associated with flexure or faulting induced by isostatic adjustment of the crust to the load of the developing mountain front.

RELATED MODELS: fluvial, colluvial and lacustrine Figure 3.4, deltas and coal measure Figure 3.5, shelf carbonates and evaporites Figure 3.6, undeformed basin accumulations Figure 3.11, open folds and joints Figure 3.12.

EXAMPLES: Cretaceous basins to east of the Cordilleran belt in USA; the Swiss Plain between the Jura mountains and the Helvetian Alps.

Figure 2.13 : Tectonic model - convergent plate boundary - foreland basins



ANTICIPATE:

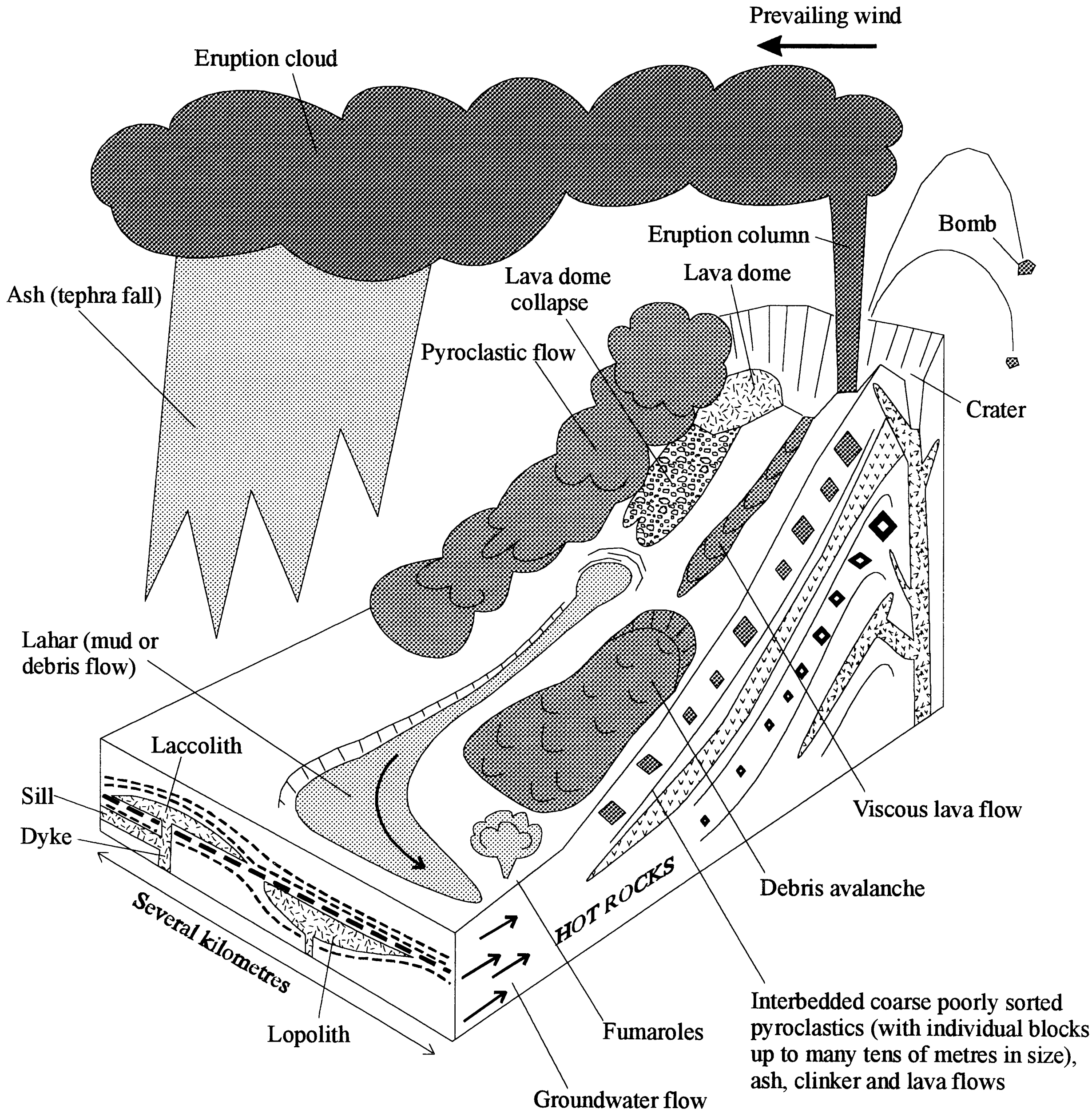
Lithological: oceanic undersaturated olivine basalts, continental saturated tholeiitic basalts, porphyritic, vesicular tops, amydales, scorias and local pyroclastics, pillow lavas where extruded into water, tachylite (basaltic glass) altered by water absorption to brown waxy palagonite, some differentiates into more acid lava types.

Setting: shield volcanoes, plateau lavas, ring complexes, extensional tectonics, flows along drainage lines, relief inversion where resistant flows in valleys are preserved after erosion.

General: local unpredictable variations due to irregular lava flows, pyroclastics, steam vents, sediment diapirs etc., slope instability associated with weak clayey intraflow sediments, locally strong groundwater flow, local faults and folds associated with volcanic episode generally good aggregates, ASR due to opal and zeolites in vesicles.

EXAMPLES: Hawaii; eastern parts of Australia; Deccan plateau of west India; Antrim plateau of Northern Ireland; Columbia and Snake river regions of USA.

Figure 3.1 : Geological model - igneous - basic volcanics



ANTICIPATE:

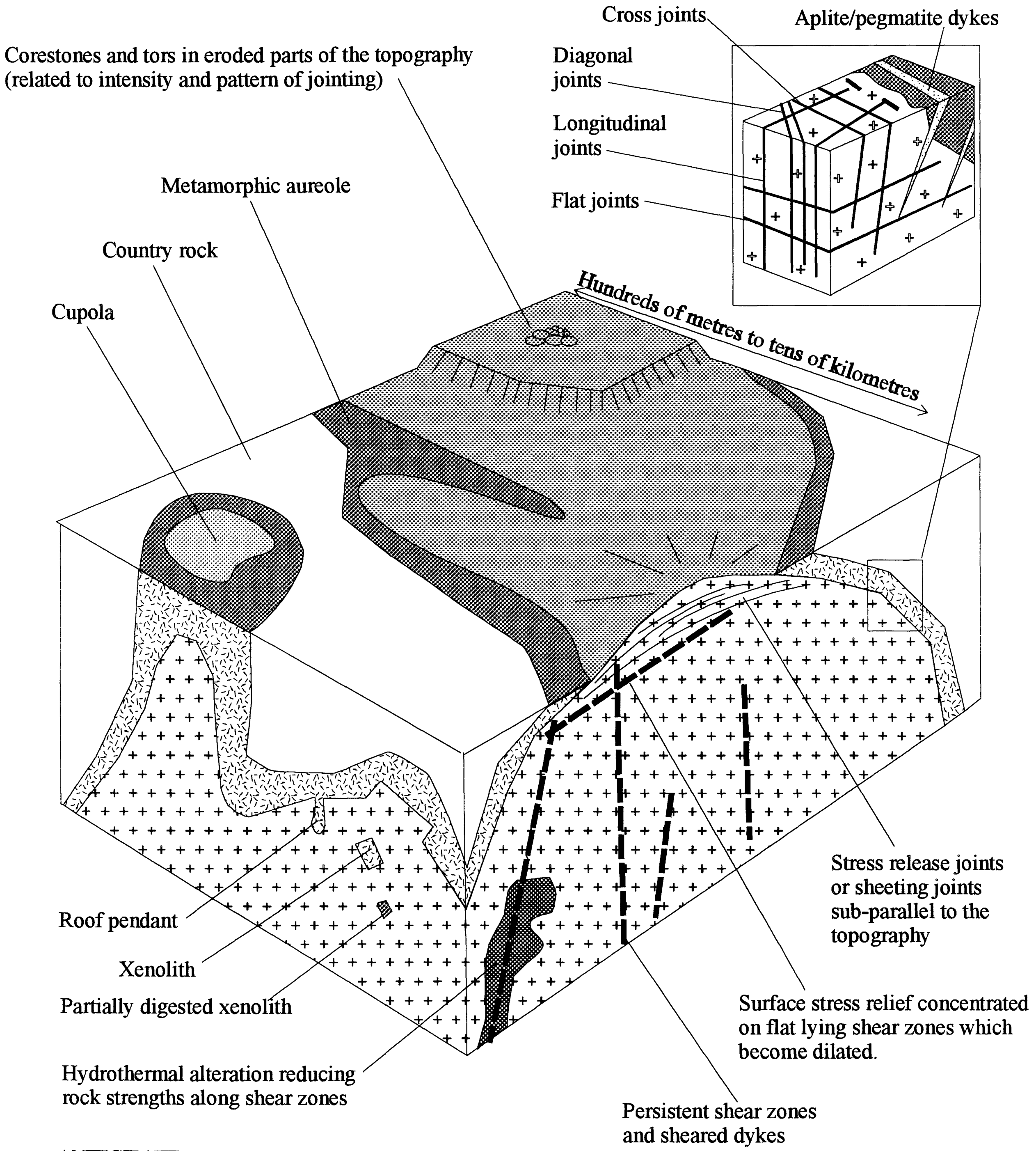
Lithologies: rhyolites, flow banding, dacites, andesites, porphytic textures, vesicular zones, breccias, pyroclastics, mixed lavas and unconsolidated ash and clinker, hydrothermal alteration, mineralisation.

Setting: gravity collapse, caldera collapse, pre-eruptive bulging, very chaotic deposits, columnar jointing.

General: vast hazard zones, pyroclastic surges, poisonous gasses, mobile lahars; gross slope instability; extremes of permeability; low density zones, collapse potential, weathering products include smectites, halloysite, sensitive soils; ASR due to glassy lavas.

EXAMPLES: Mount St Helens in USA; Vesuvius in Italy; many volcanoes in Java; Mont Pelee in Martinique.

Figure 3.2 : Geological model - igneous - acid volcanics



ANTICIPATE:

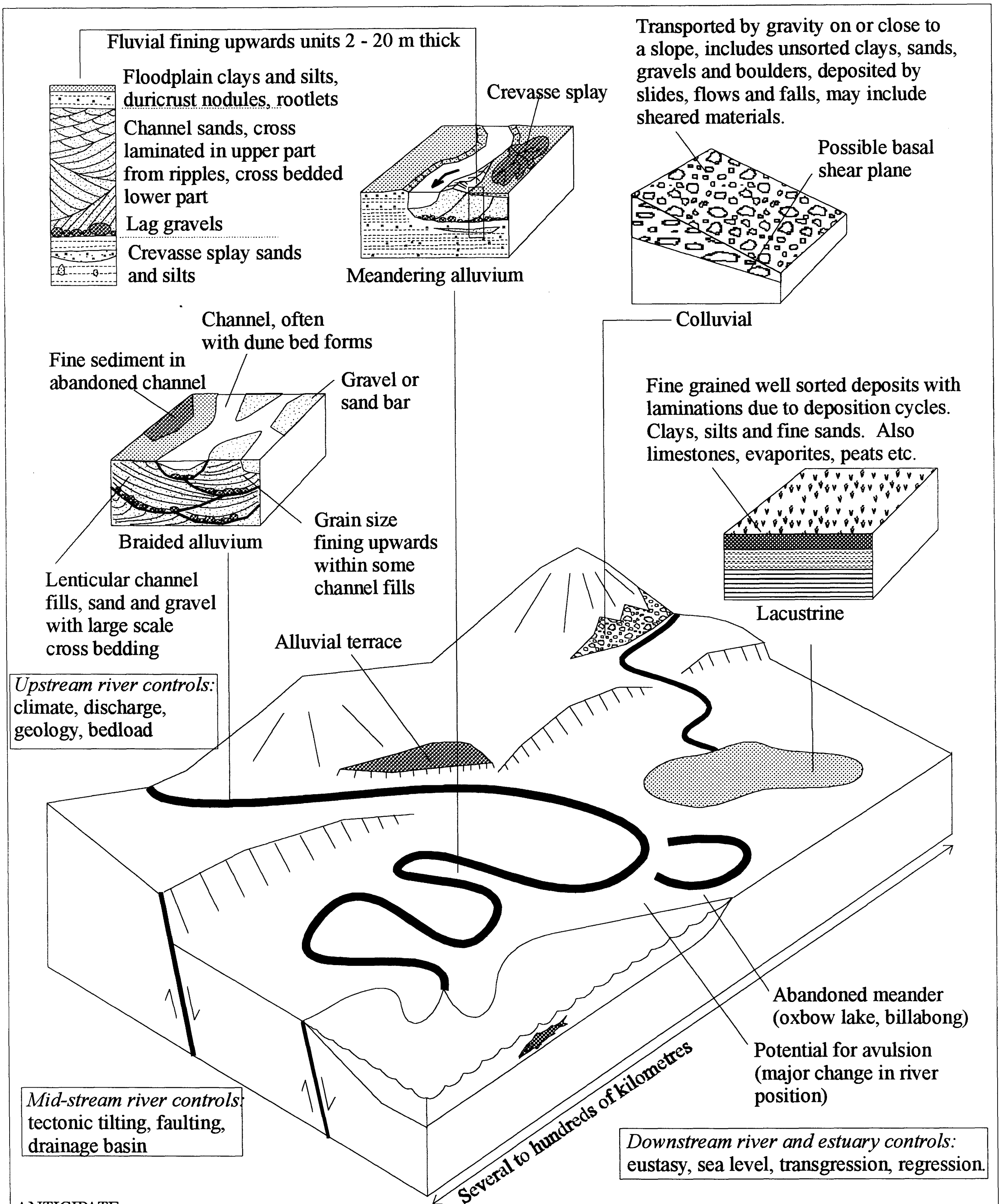
Lithologies: granites, diorites, some gabbros, porphyries, late stage mineralization, metamorphic aureole, hydrothermal alteration

Setting: batholiths, passive (stoping) or forceful intrusion, syn- and post-intrusion shear zones, late stage dykes, flow fabrics,

General: weathering corestones may not be in-situ or may have soils below them, hydrothermal alteration at all levels, deep weathering in warm wet climates and weathering profiles often preserved in temperate climates

EXAMPLES: Dartmoor in UK; Hong Kong; western Saudi Arabia.

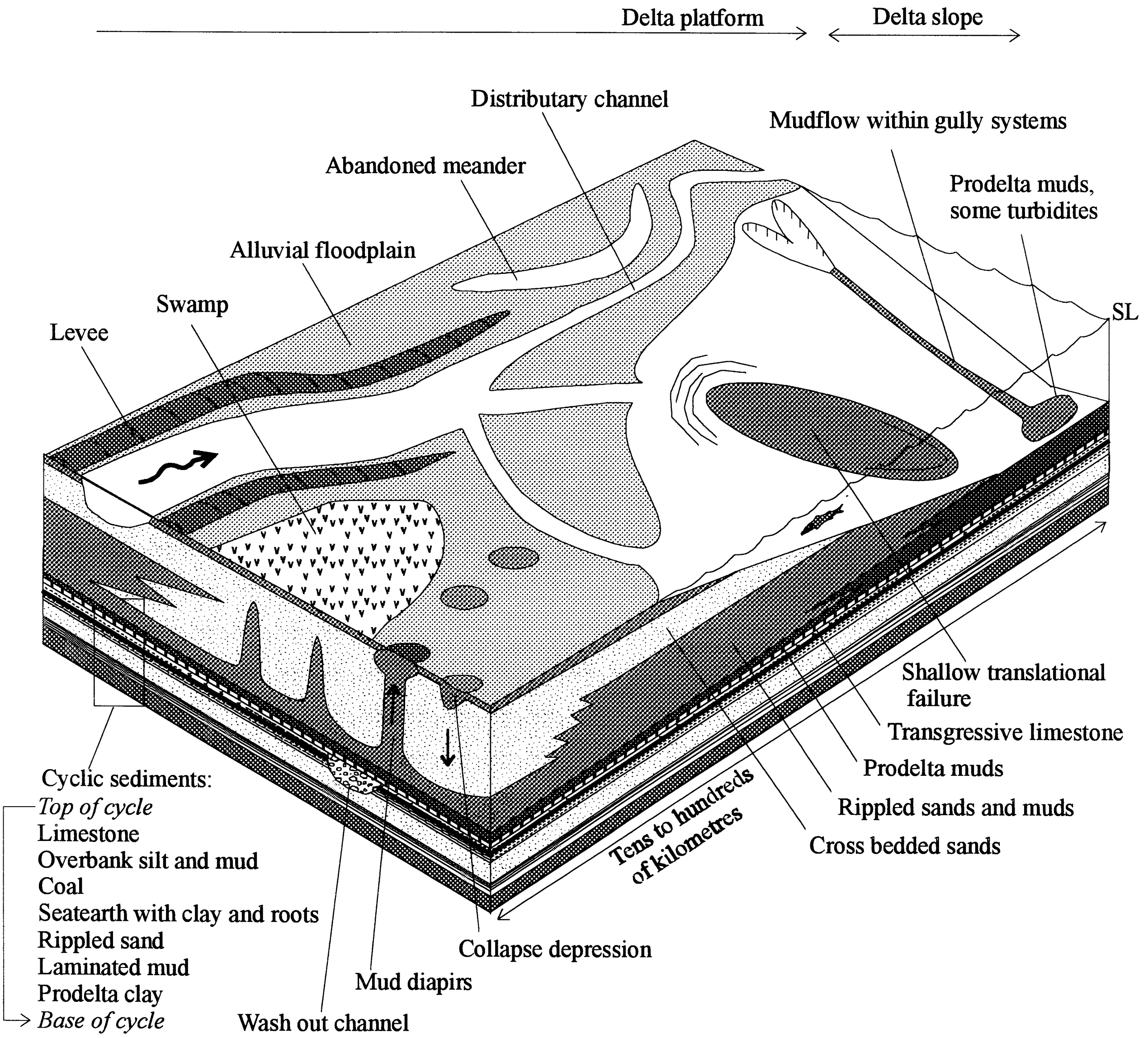
Figure 3.3 : Geological model - igneous - plutonic intrusions



ANTICIPATE:
Lithologies: recent soils range from clays, silts, sands, gravels to boulders, according to depositional environment, ancient rocks include claystones, siltstones, sandstones and conglomerates, often red/brown, may contain evaporites.
Setting: tends to be associated with stable crust and/or post orogenic landscape development, also early basin fill, forms continuum with deltaic and coal measure model (Fig. 3.5) in lower parts. Base level, gradient, water tables all interact.
General: processes such as flooding, scour, mass movement, sediment movement, well graded construction materials.

EXAMPLES: Amazon; Mississippi; Thames; Niger, numerous examples from most major drainage systems.

Figure 3.4 : Geological model - sedimentary - continental fluvial, colluvial and lacustrine (based on Selley 1985, Tucker 1991 and Emery and Myers 1997).



ANTICIPATE

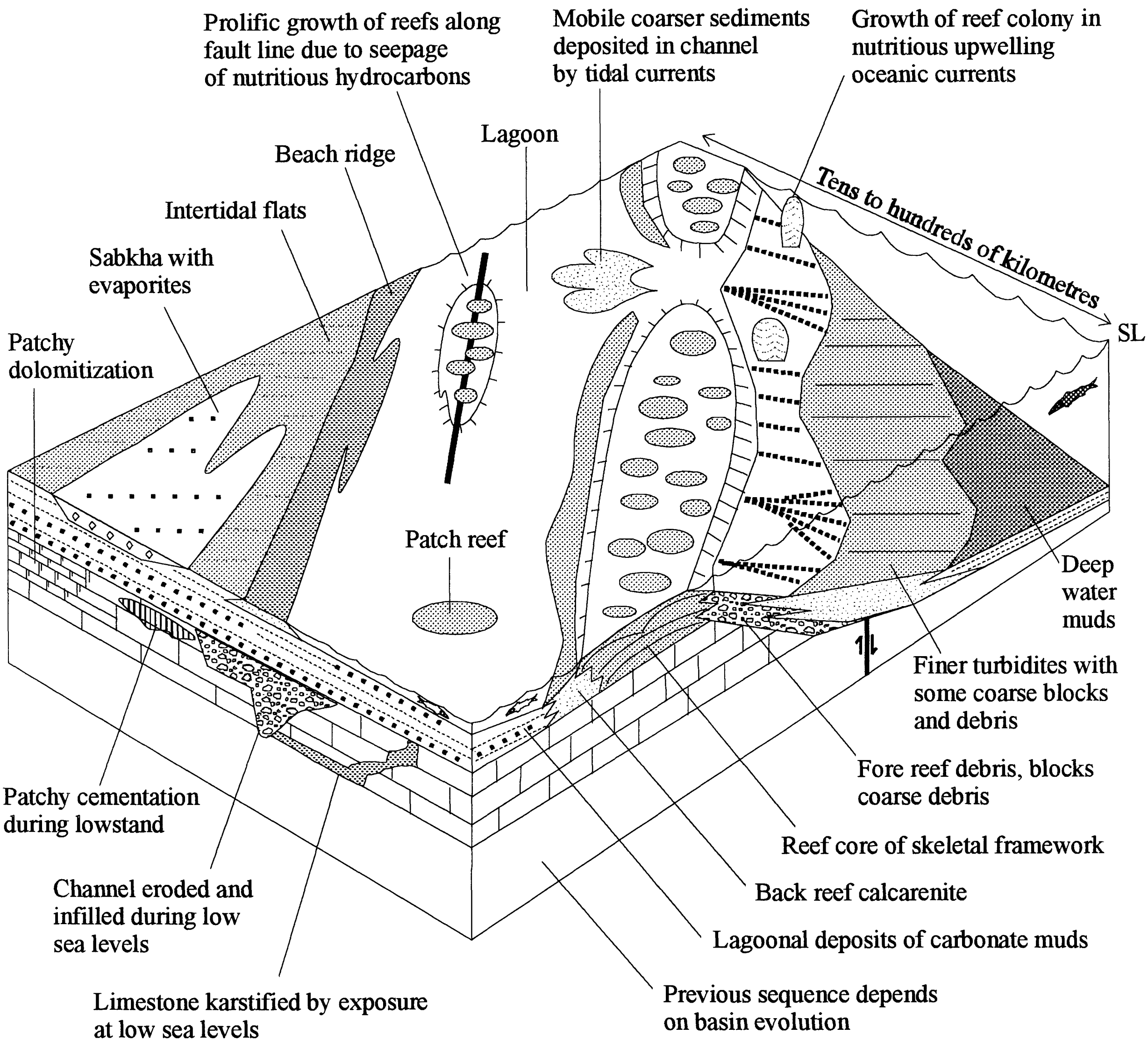
Lithologies: cyclic sediments, coarsening upwards, and fining seawards. Sands, muds, clays, swamps. Extensive bioturbation by organisms and roots. Weathered crusts producing heavily overconsolidated layers within normally consolidated sequences. Environment of deposition for coal measures rocks. Minor dykes on extensional faults at a late stage of basin development.

Setting: downwarps in continental plates, growth faults during deposition, normal faults associated with basin extension,

General: sediments with high water contents, rapid changes in channels and prone to avulsion, ground movements due to differential compaction of sediments.

EXAMPLES: Mississippi delta; Nile delta; Ganges Brahmaputra delta; Hwang Ho delta; coal measure rocks from the Carboniferous; Fly River, Papua New Guinea.

Figure 3.5 : Geological model - sedimentary - continental deltaic and coal measures (based on Selley 1985, Walker and Prior 1986).



ANTICIPATE:

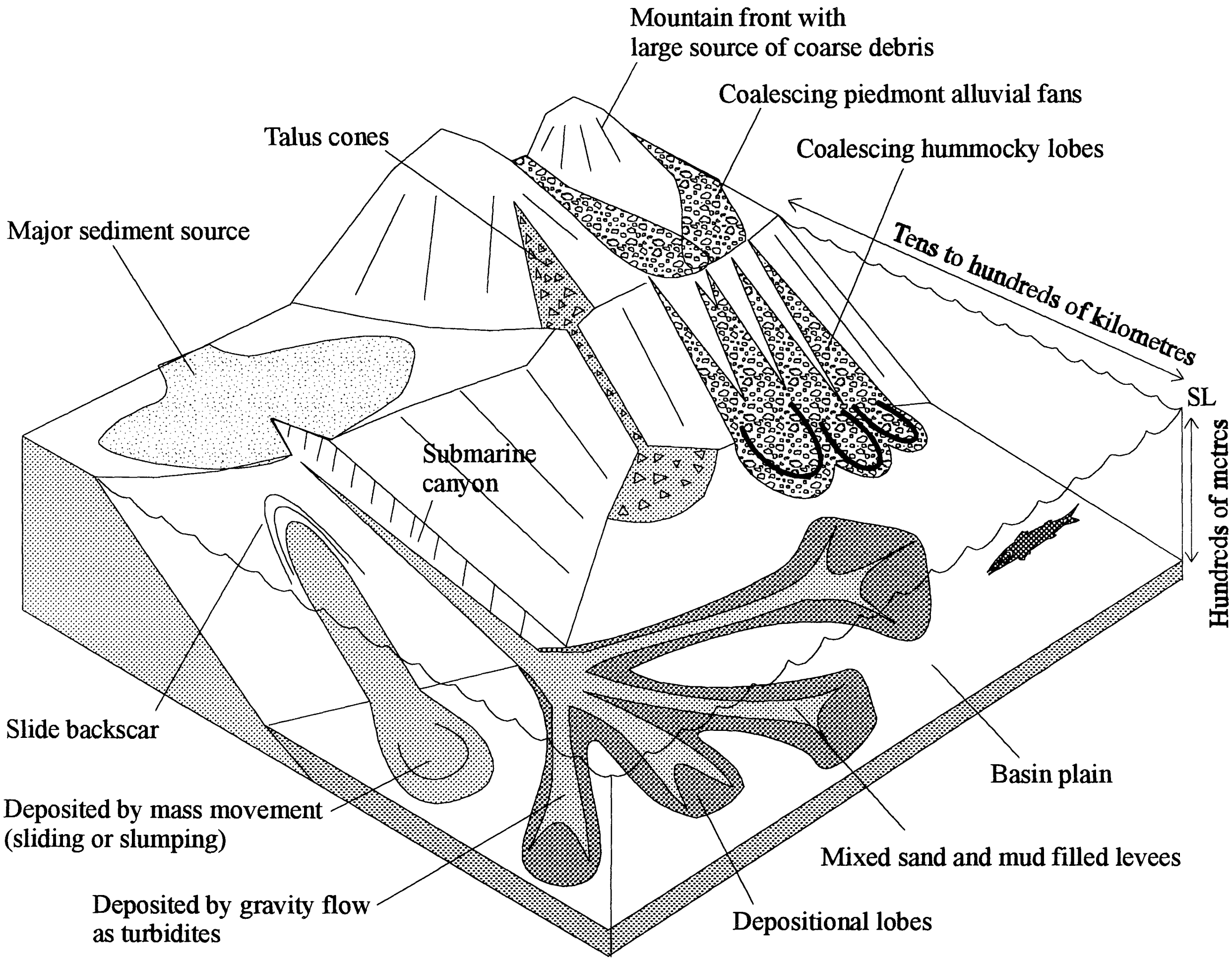
Lithologies(by grain size / constituents / texture):
Flats: calcilutites / clays, muds, pellets, evaporites / mudstone
Lagoons: calcilutite, calcisiltite, calcarenite / muds, pellets, ooids, pisoids, skeletal debris / wackestones, mudstones
Back reef: calcarenite / ooids, skeletal fragments / grainstones, packstones
Reef: calcarenite, calcirudite / insitu skeletons - biolithite / boundstones
Fore reef: calcarenite, calcirudite / skeletal fragments / grainstone, packstone
Slope: calcilutite, calcirudite / muds, skeletal fragments, blocks of biolithite/ mudstones, wackestones

Settings: shallow continental shelfs and edges with "carbonate factory" active when water depth <40 m and within photic zone, carbonate platforms range from rimmed shelfs, ramps, epeiric platforms, isolated platforms, drowned platforms.

General: extreme variability in strength, cementation, porosity, permeability.

EXAMPLES: north west Australia; Great Barrier Reef Australia; Yucatan coast Mexico; Trucial coast of the Arabian Gulf.

Figure 3.6 : Geological model - sedimentary - shelf carbonates and evaporites
(based on Selley 1985, Tucker 1991, Emery and Myers, 1996, Fookes 1997)



ANTICIPATE:

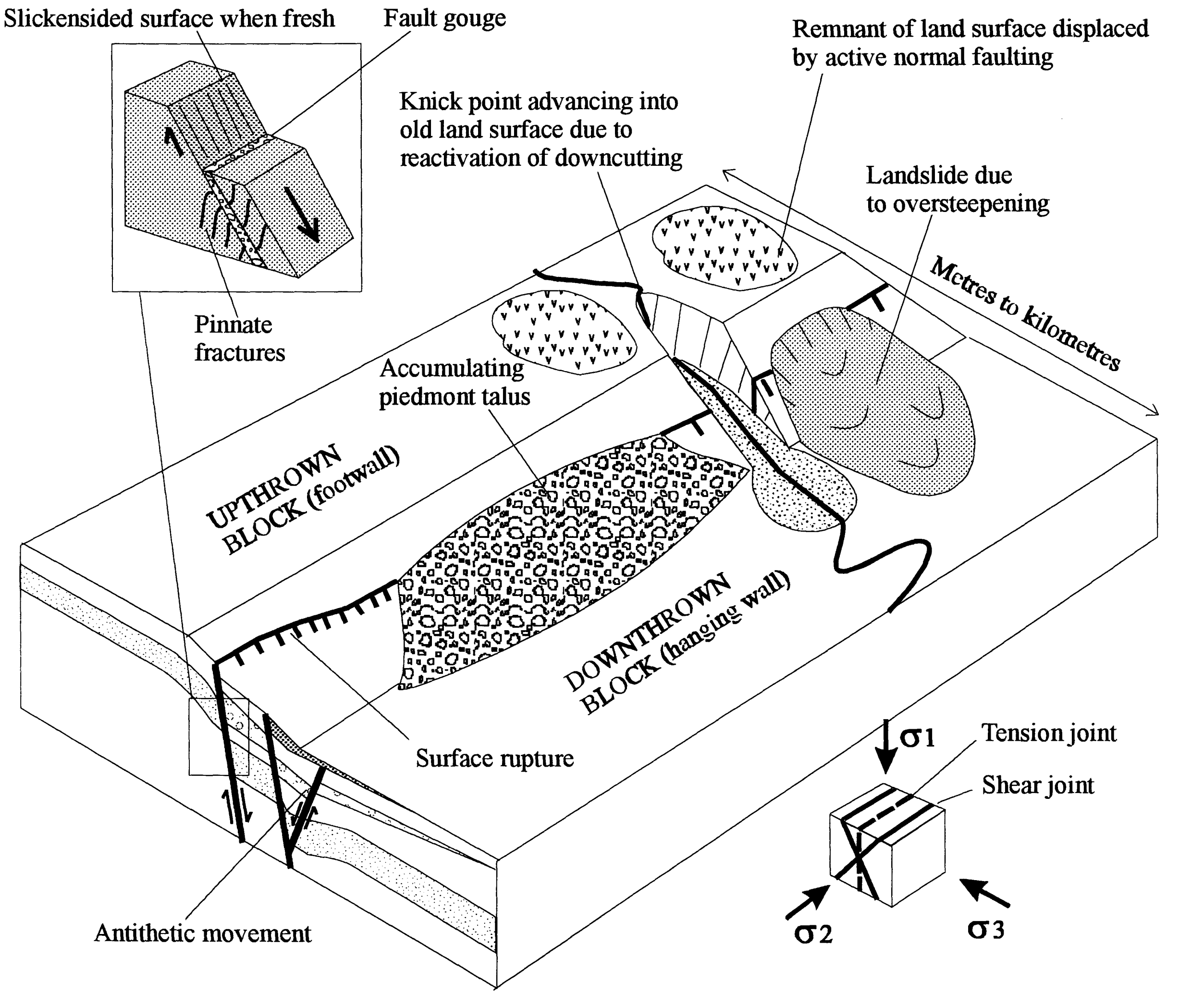
Lithologies: interbedded muds and sands, and mud/sand mixtures with muds rich systems dominating, some coarser deposits if the mountain front is close. Transport by gravity flow (turbidity currents, fluidized flow, grain flows and cohesive flows) and mass movement induced by seismic events and storm loading. Turbidite beds characterised by immature sediments, scours and sole marks, dewatering structures, convolute bedding, inverse bedding, thin, laterally continuous, repetitive beds, generally coarsening upwards and thickening upwards within a sequence. Thick sequences of turbidites referred to as flysch.

Setting: on the continental slopes or just off the continental shelf, within trenches at plate margins, in rifted basins at passive margins, forearc and backarc basins.

General: environment currently being explored for oil and gas, rates of active sediment transport, mass movement and deposition depending upon system equilibrium with high sediment input rates being associated with active mass movement of many cubic kilometres of sediment. Ubiquitous mass movement and gravity flow represents a significant hazard to oil and gas development infrastructure. Tsunamis caused by mass movement.

EXAMPLES: Grand Banks of Newfoundland; Norwegian continental margin (Storegga); Kidnappers slide New Zealand; West Florida slope in the Gulf of Mexico; Atlantic continental margin of northern USA.

Figure 3.7 : Geological model - sedimentary - deep marine and continental slope (based on Emery and Myers 1996)



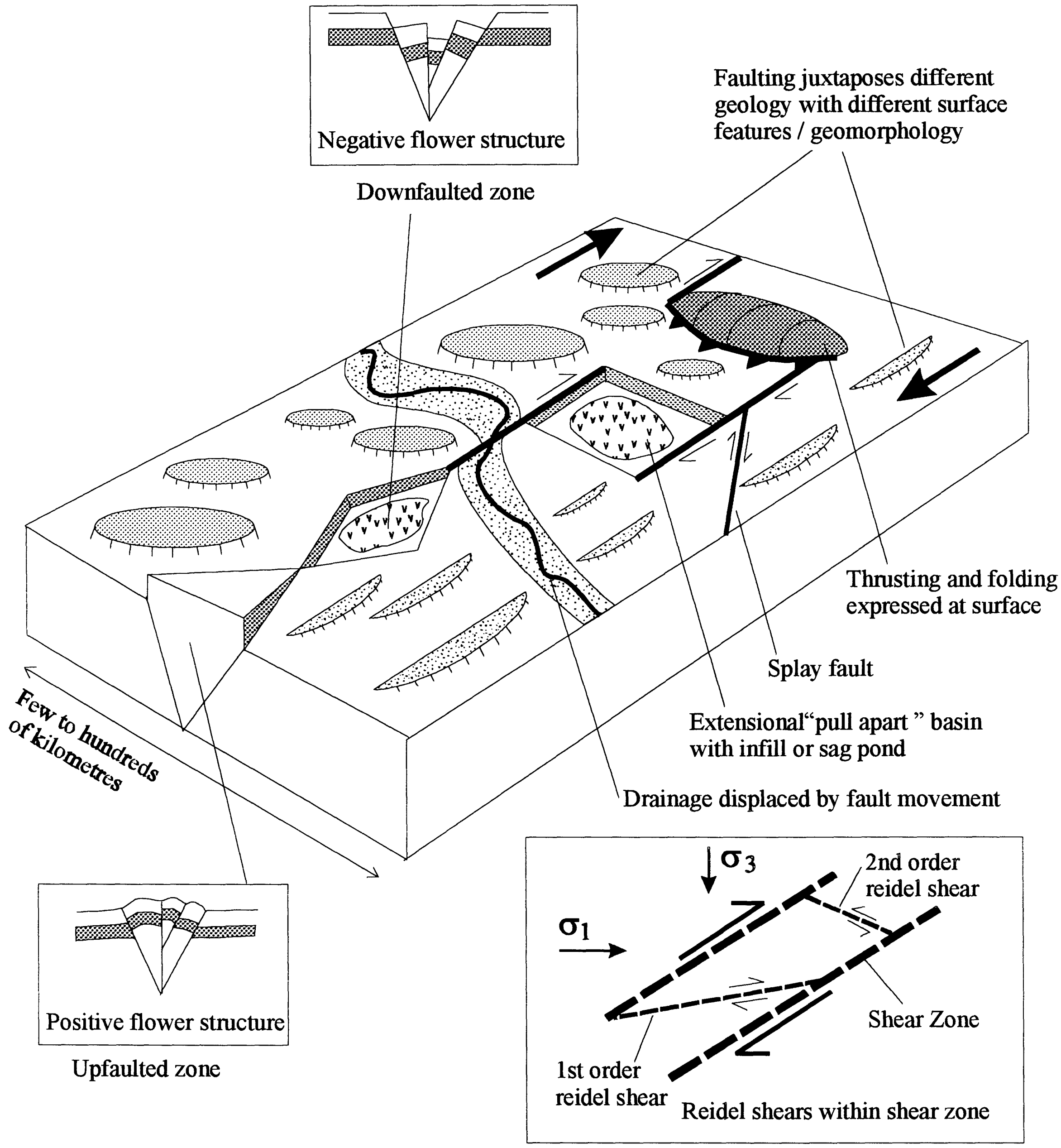
ANTICIPATE:

Associations: basin extension, continental and oceanic rift zones, horst and graben, fracture systems allowing extension formed above salt domes developing by upward movement, growth faults active during sedimentation, scarps, piedmont fans. May displace river terraces, produce lines of springs, vegetation lineaments etc. Prolonged erosion leading to slope retreat may displace and flatten a scarp moving it hundreds of metres from above the initiating fault trace.

General: low horizontal stresses, possibly listric (spoon shaped) surfaces flattening with depth, groundwater dams or conduits, locally deeper weathering. Dating of superficial deposits infilling surface hollows or accumulating against scarps can elucidate fault history. Jointing tends to consist of one set sub-parallel to the fault plane, a second set with similar strike but opposite dip, and a third vertical set striking at right angles to the fault plane.

EXAMPLES: Tetons/Snake river in USA; Derwent graben in Tasmania, Australia; east African rift system; Rhine graben.

Figure 3.8 : Geological model - structural - normal faults
(based on Spencer 1977)



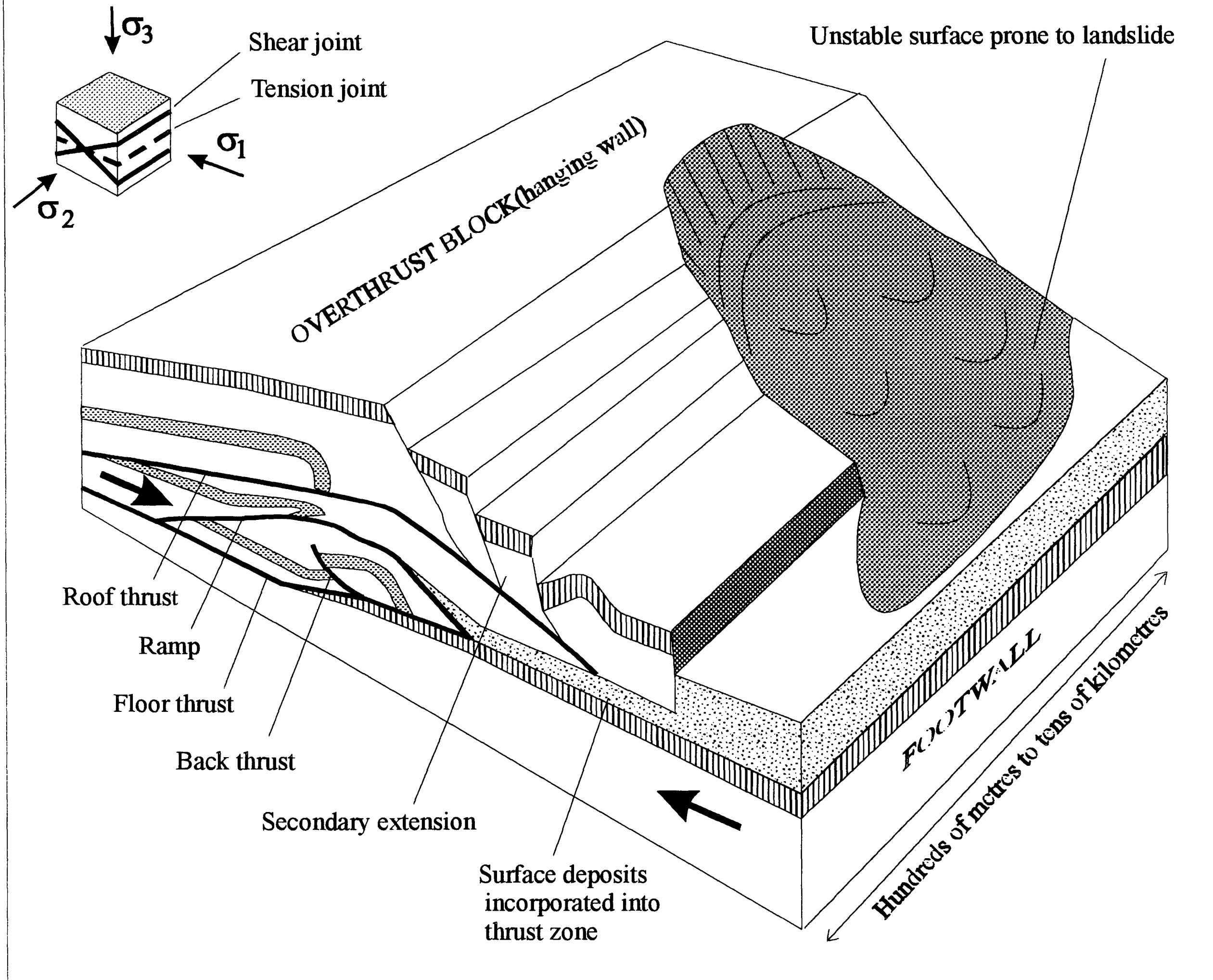
ANTICIPATE:

Associations: movement is dominantly horizontal , may be local or may represent regional or continental shears where developed at plate boundaries ie. major tectonic shears, sinistral displaces to the left, dextral to the right, secondary structures (rhomb shaped pull apart basins, en echelon folds, splay faults, reidel shears) develop in cover rocks or surficial materials depending upon the scale of the shear.

General: also called tear, wrench, transcurrent or transform faults but transform generally used when associated with sea floor spreading. Sites of major earthquakes. Associated with ancient crustal fractures.

EXAMPLES: Philippine fault; San Andreas fault in California; Alpine fault in New Zealand; Atacama fault in Chile.

Figure 3.9 : Geological model - structural - strike slip faults
(based on Park 1997)



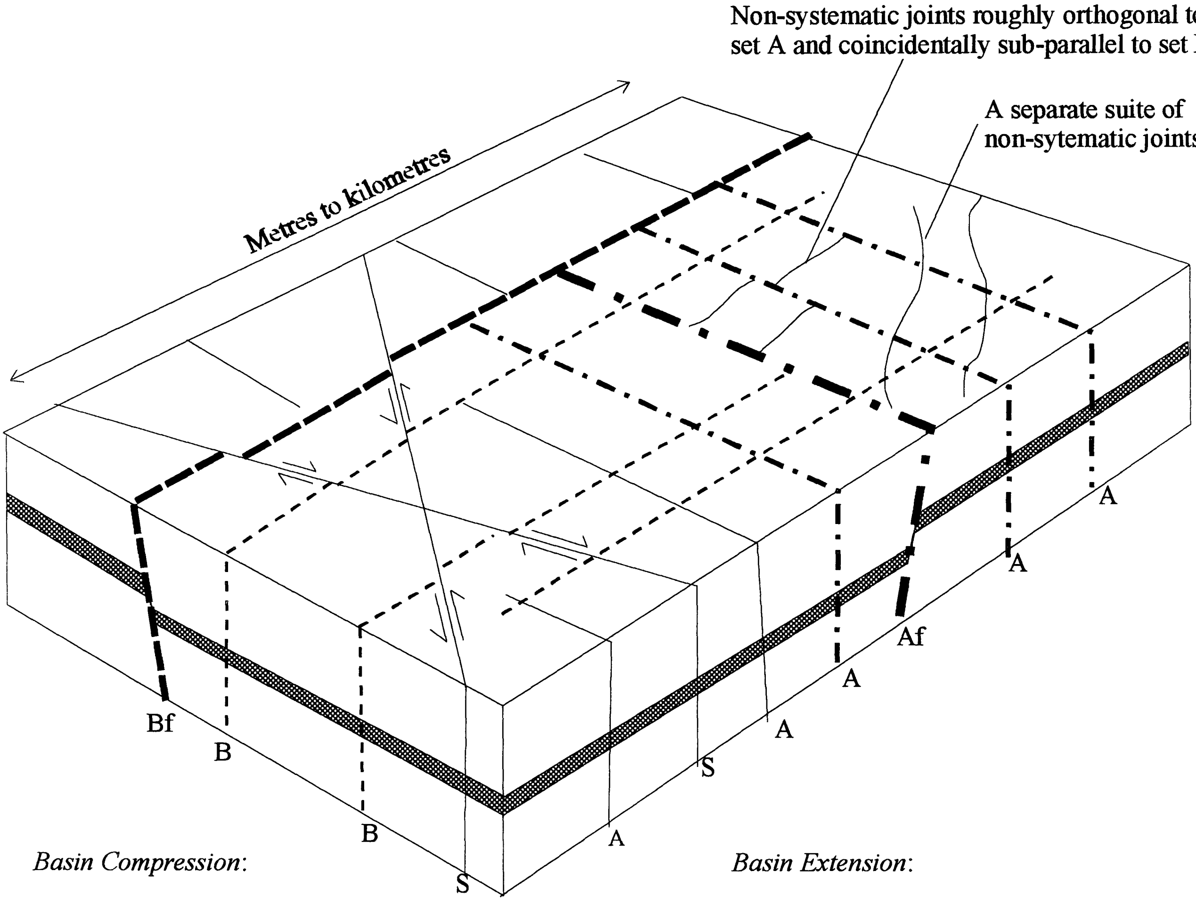
ANTICIPATE:

Associations: folding, orogenesis, movements of many tens or hundreds of kilometres on the floor thrust or sole or decollement, thrust climbs through stratigraphy on flats and ramps defining a staircase, ramps may be frontal (in thrust direction) or lateral/oblique (at an angle to thrust direction), numerous frontal thrust planes form a stack of imbricate or schuppen structures, a block bounded by thrusts is a horse and a series of horses form a duplex.

General: Large scale thrust form nappes. A window or fenster is an exposure of the rock below the thrust, a klippe is an exposure of rock from below the thrust surrounded by rock from above the thrust.

EXAMPLES: Moine thrust in Scotland; Glarus thrust in the Alps; McConnell thrust in eastern Canadian Rockies; Hindenberg mountain range Papua New Guinea.

Figure 3.10 : Geological model - structural - thrust faults
(based on Park 1997)



Basin Compression:

Set S - persistent conjugate shears

Basin Extension:

Set A - in response to normal fault Af

Set B - in response to normal fault Bf

ANTICIPATE:

Lithology: bedded sediments, with the more systematic joint systems developed in relatively strong uniform fine grained sediments such as siltstones and fine sandstones interbedded with thin shales.

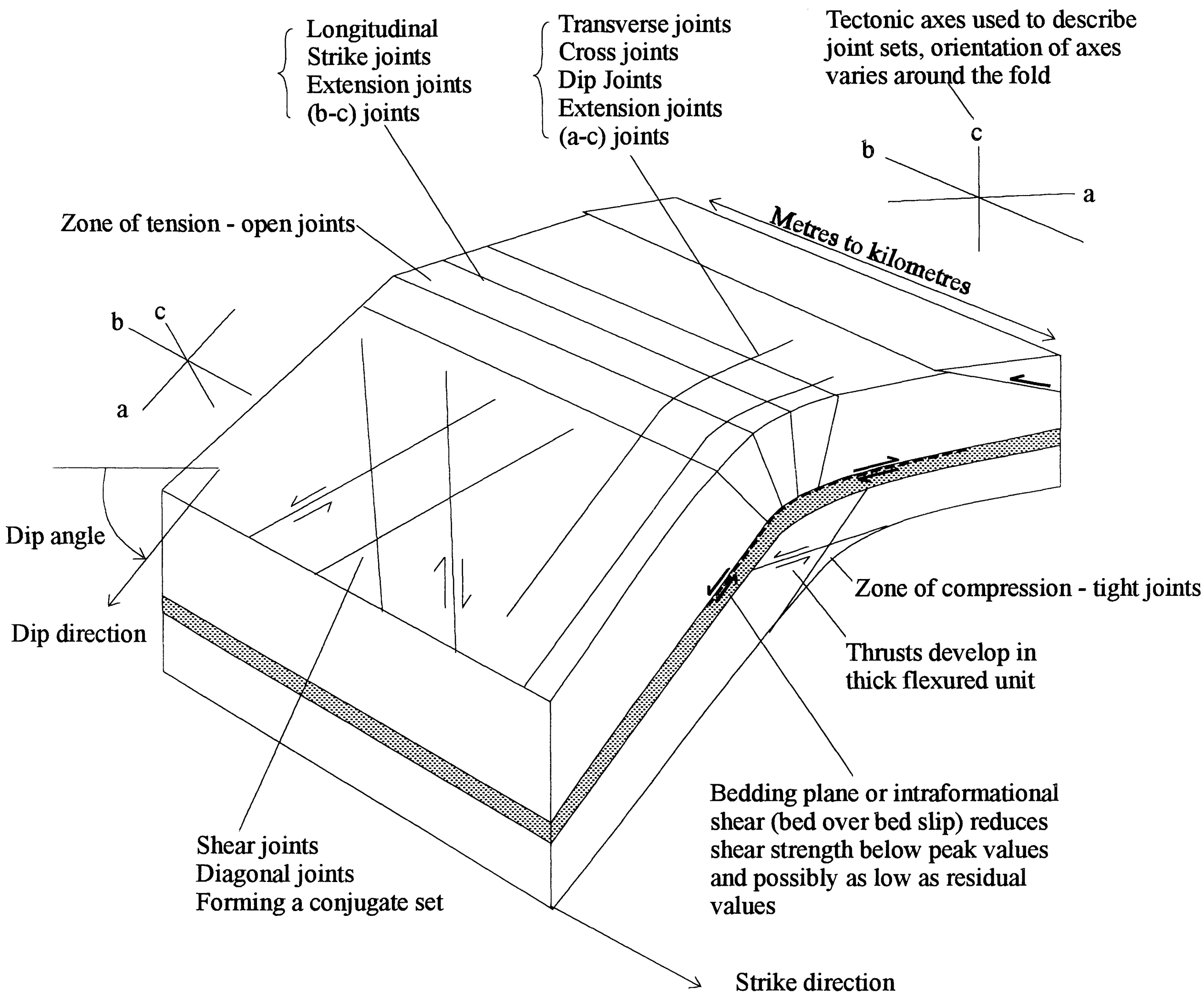
Setting: basin and platform sediments of any age, recent sediments subject to slight tectonic warping, pore pressures during tectonism can play a significant role in fracture formation.

General: shear joints tend to be planar and persistent, dilational joints tend to be curved and irregular and less persistent. It is often the case that even flat lying undeformed sediments exhibit jointing patterns that are the result of more than one episode of tectonism. The different tectonic episodes may have stress fields with coincident axes (controlled by basin morphology which remains constant) but different relative stresses (controlled by basin tectonic evolution which might include periods of compression, tension, high fluid pressures etc).

Discontinuity description: type (bedding, foliation, cleavage, joint, fault, shear zone, crush zone, decomposed zone infilled zone), genesis/phase (from geological history), orientation (dip and direction), shape and amplitude at scales >1 m , shape at 100m mm scale (planar, curved, undulose, irregular, stepped), surface roughness (polished, smooth, rough, very rough) infill (mineral type and thickness), persistence (length and nature of termination), spacing (average and extremes).

EXAMPLES: Cambrian to Cretaceous flat lying sediments in the Grand Canyon USA; Cretaceous flat lying sediments in the Cotswolds UK.

Figure 3.11 : Geological model - structural - joints in undeformed sediments
(based on Price and Cosgrove, 1990)



ANTICIPATE:

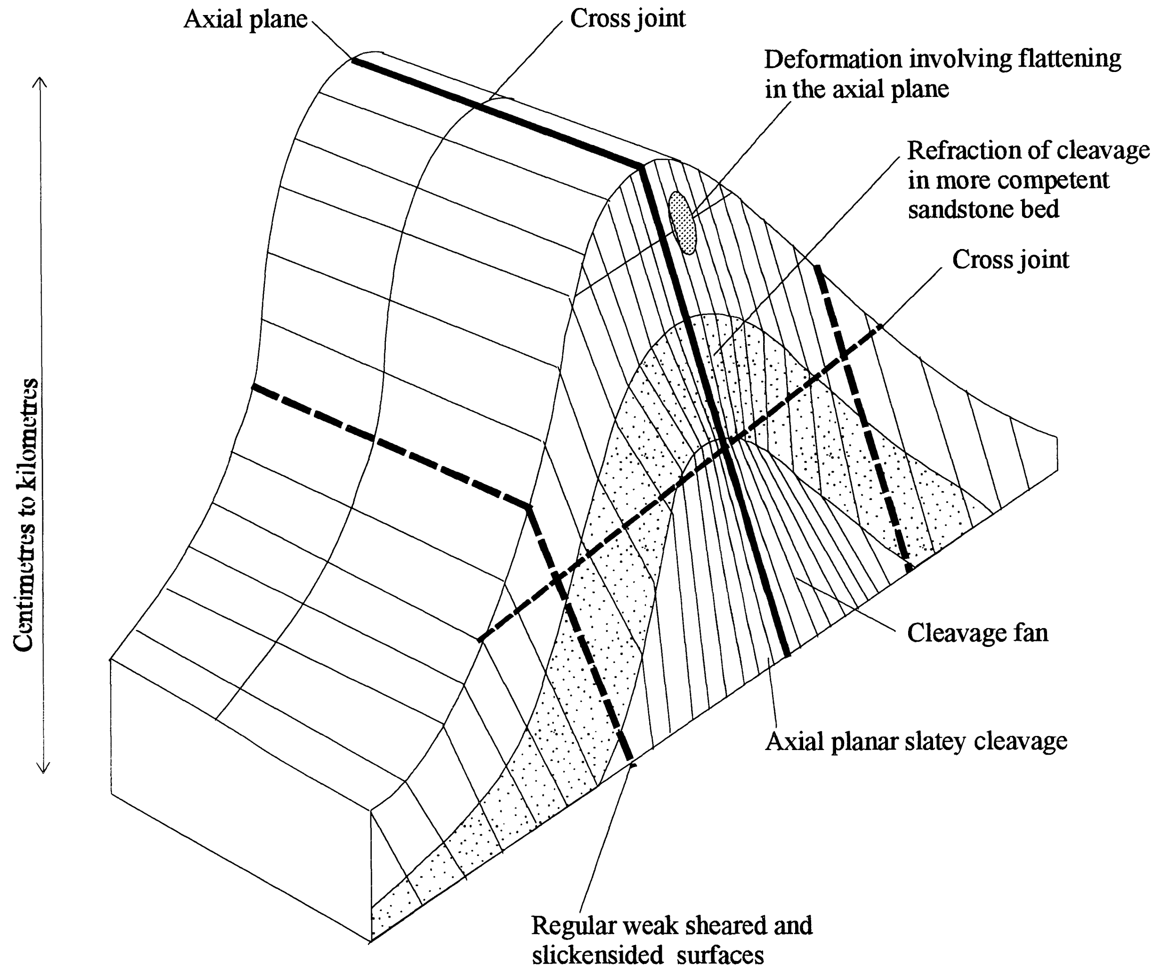
Lithologies: bedded sediments, often with interbedded weak lithologies such as mudstone, fracture sets develop in beds at various scales, neutral surface may separate extension from compression within one bed.

Settings: fold belts especially foreland basins and distal parts of fold and thrust belts, typically Class 1b or parallel folds, folds initiated by buckling.

General: associated faulting tends to follow the same pattern, actual fracture pattern that is developed is dependent on local stress system and pore pressure, history of stress system development often exhibits complex evolution, many fracture systems display a complex interrelated development between types of fractures.

EXAMPLES: Siwaliks at Mangla damsite; Teton anticline northwest Montana.

Figure 3.12 : Geological model - structural - open folds and joints
(based on Price and Cosgrove 1990)



ANTICIPATE:

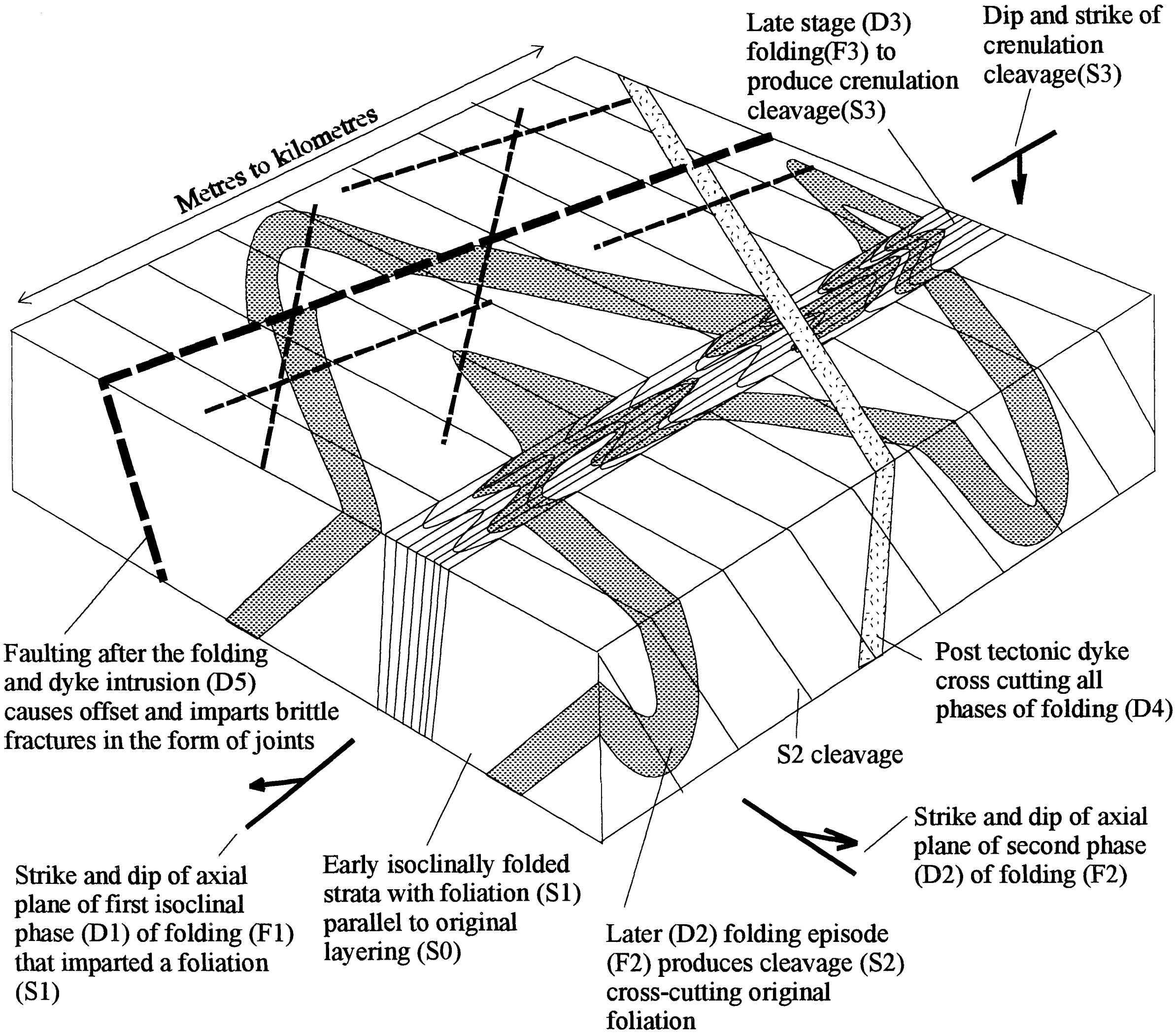
Lithologies: plastic folding with cleavage develops particularly well in uniform mudstones to form high quality slates, but can develop in most rocks, particularly those with a high content of phyllosilicates and/or if subject to high temperatures and pressures (ie. within a metamorphic regime). Thick mudstones are often associated with immature greywacke sandstones and/or volcaniclastics in deep marine sediment sequences. Cleavage is a fissility due to mineral orientation. Crenulation cleavage forms from the folding of a pre-existing cleavage, fracture cleavage is non-penetrative, pressure solution cleavage forms mineral segregations.

Setting: fold belts, forearc and backarc basins, thick sequences of deep marine sediments.

General: cleavage bedding relationships may be used to deduce the position of the fold axial plane, highly anisotropic strength properties, unfavourable for stability if cleavage or sets of shears are adversely oriented with respect to an excavation. Poor aggregates and rockfill can be difficult to compact due to particle shape.

EXAMPLES: Slate belt of north Wales; Ordovician slates of Victoria Australia (which contain gold-bearing quartz reefs).

Figure 3.13 : Geological model - structural - plastic folds with cleavage
(based on Price and Cosgrove 1990)



ANTICIPATE:

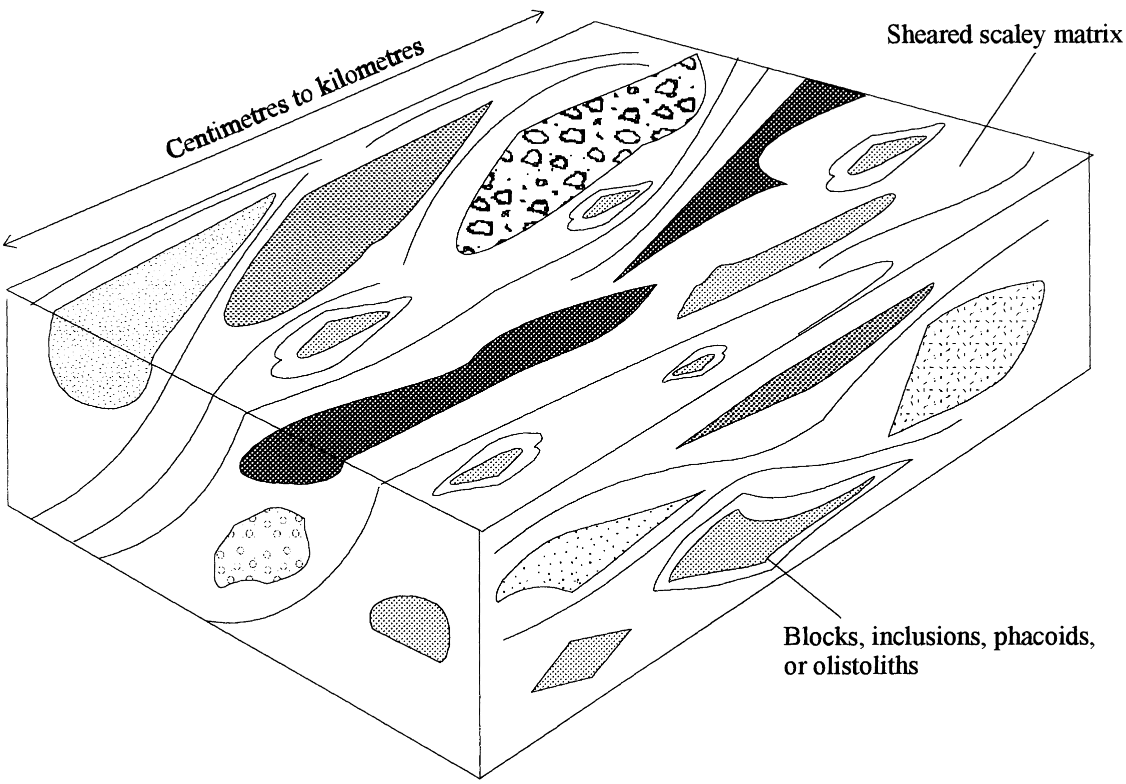
Lithologies: multiple folding and faulting can occur in any lithology but will be most clearly observed in bedded or foliated lithologies. Generally the folding and faulting occurs ubiquitously, and not separately as in the block diagram above, consequently complex rock mass conditions develop. The interfering fold and fault patterns occur at scales from small outcrops to extensive regional settings and can lead to complex outcrop patterns with dome and basin structures. This level of tectonism is usually, but not always, associated with some slight level of metamorphism (ie greenschist facies and higher).

Setting: fold belts, orogenic belts, tectonic corridors, or wide fault zones subject to repeated movements in different directions, major portions of most of the world's fold mountain belts.

General: prediction of rock mass conditions difficult due to complex structures Several more phases of folding may often be discerned by detailed structural analysis but this level of detail may not be important for project engineering, which is often controlled by the later stage brittle structures.

EXAMPLES: Palaeozoics of north Corwall in UK; Archaen greenstone belts of western Australia; Palaeozoics from Soroy in northern Norway; Palaeozoics from Parrsboro in Novia Scotia Canada.

Figure 3.14 : Geological model - structural - multiple folds and shears



ANTICIPATE:

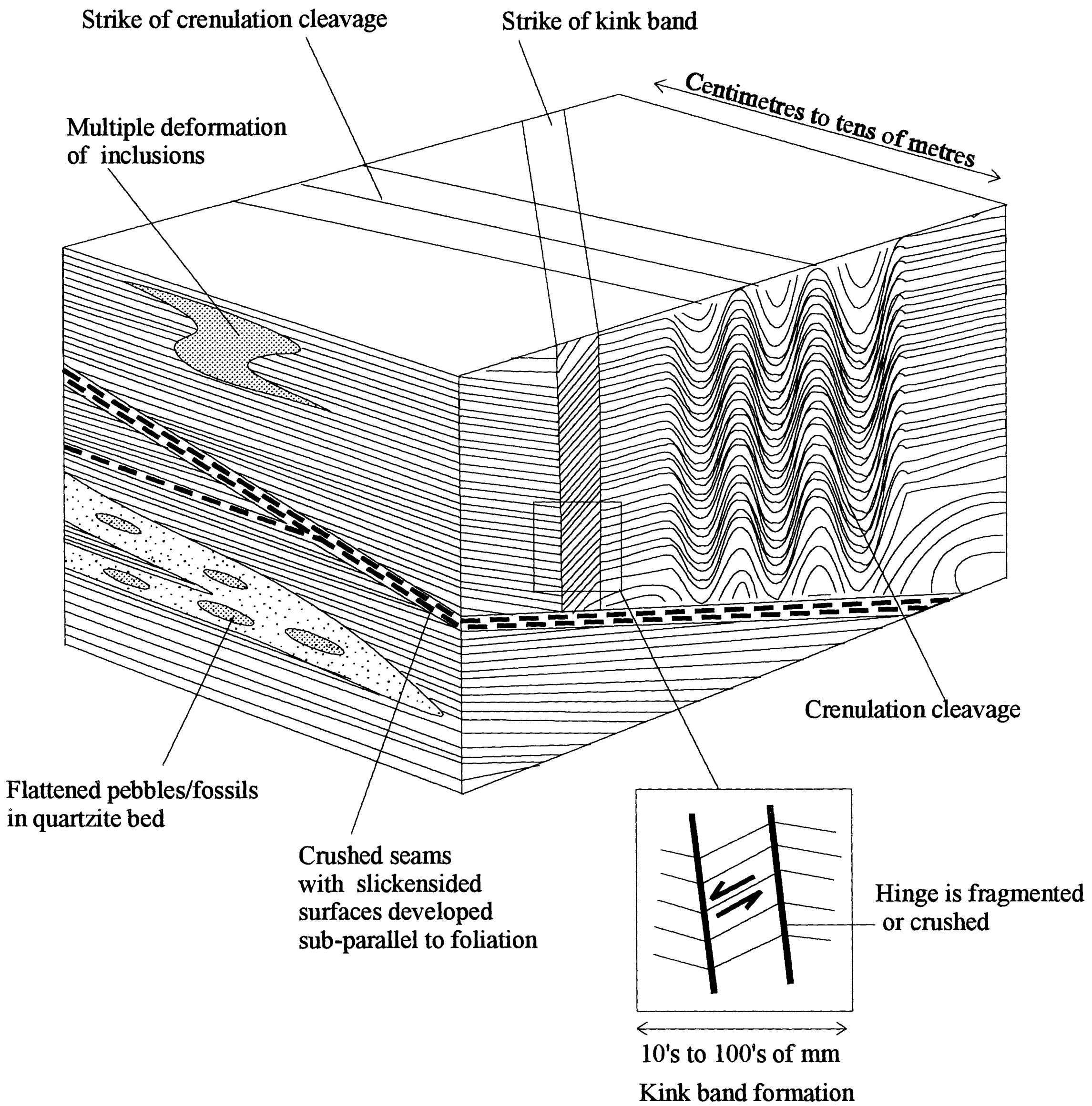
Lithologies: melange or olistostrome consisting of blocks of sediments (shallow and deep water deposits juxtaposed), metamorphics or volcanics, especially ophiolite, in a matrix of sheared clay, sand clay mixture or serpentinite. Matrix may have a characteristic anastomising foliation along which it breaks down to form small scale-like fragments, hence the names scaley clay, scaley argillite and "argile scagliose".

Setting: trench slopes, thick sediment sequences adjacent to major fault zones at plate boundaries, accretionary prisms.

General: chaotic nature makes them difficult to map and interpret. Individual melange blocks may be kilometres across and form mappable units. Surprising juxtaposition of different rock types.

EXAMPLES: scaly clays of the Italian Apennines; Anglesey in North Wales; Damaran belt in Namibia; San Franciscan rocks in the Coast Ranges of California USA.

Figure 3.15 : Geological model - structural - tectonised melange
(based on Moores and Twiss 1995)



ANTICIPATE:

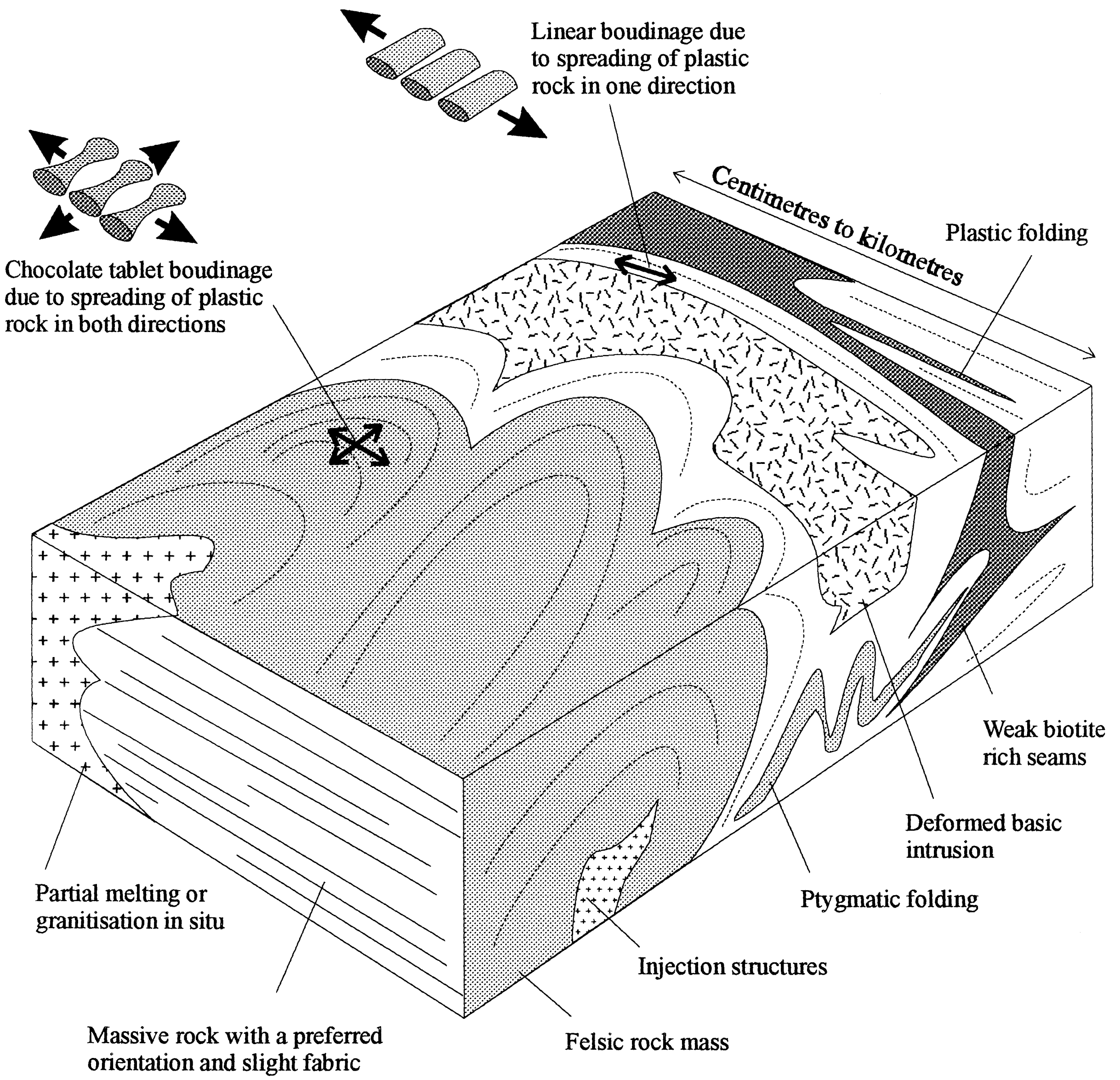
Lithologies: rock types dominated by micas, schists, phyllites. Interbedded marbles, quartzites and deformed pebble beds form if rocks were originally sediments, greenstones form if originally volcanics etc. Differentiated layering and segregation of quartzo-feldspathic material develops with more intense metamorphism, injection or partial melting to form igneous rock types is possible.

Setting: metamorphic rocks, shear zones, mobile belts, extensive belts of flat lying schistose rocks associated with the sole of major thrusts and recumbent folds, "schistes lustres" in the cores of nappes.

General: platey clasts, anisotropic and low shear strengths, high mica contents, low durability, schists exhibit reduced shear and compressive strength when wet, schist formations show a tendency to attract regional tectonic strain during orogenesis because they are weak and this generally manifests itself in the form of numerous conjugate kink bands and shears throughout the formation. Landslides are common, schists can be poor aggregates, rockfill etc. due to shape and low strength.

EXAMPLES: Otago schists of New Zealand; Lewisian of Scotland; Sanbagawa terrain of Japan.

Figure 3.16 : Geological model - metamorphic - schists and phyllites



ANTICIPATE:

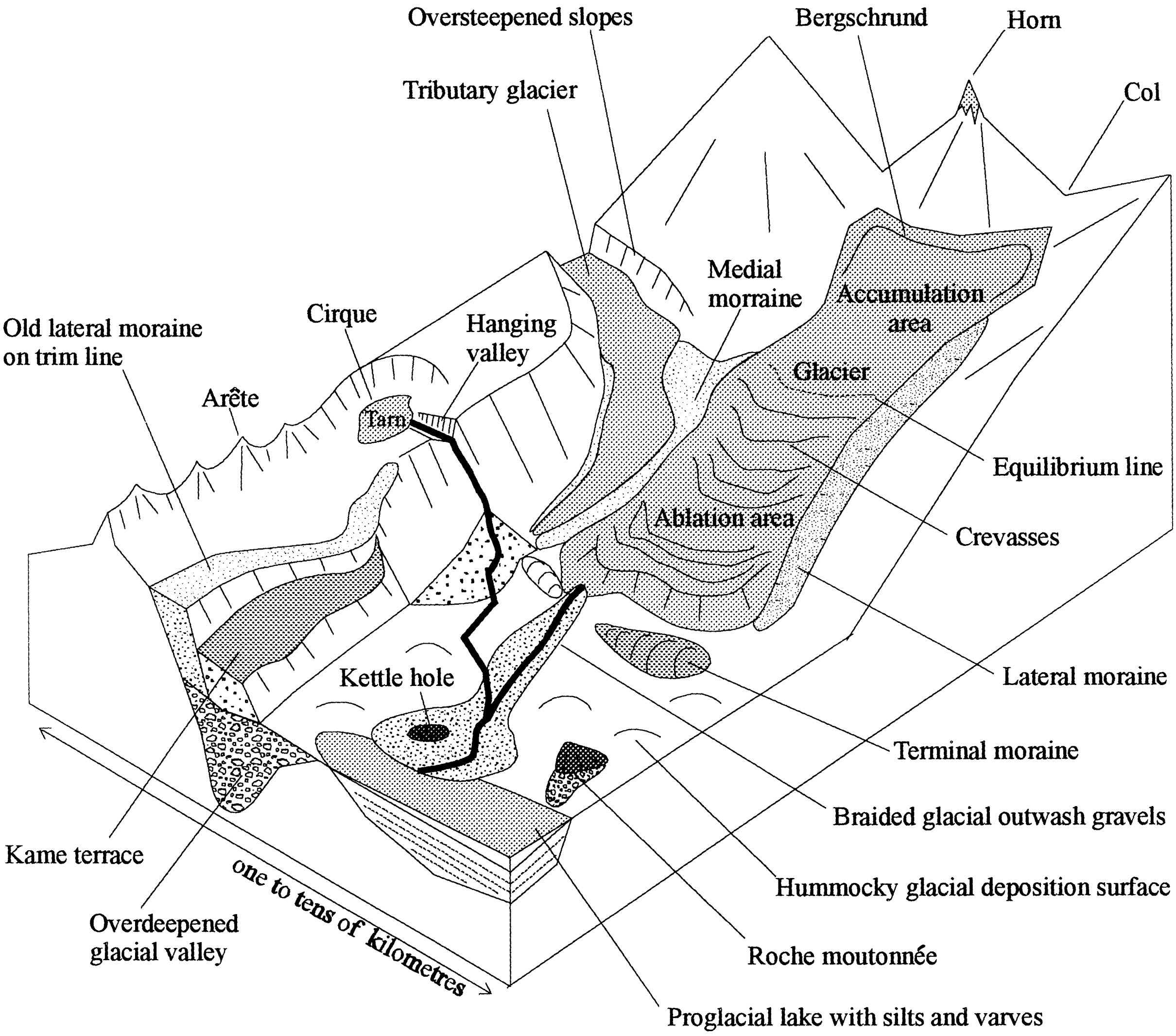
Lithologies: gneiss, migmatite, granites, schists seams, granulites with no obvious foliations, basic eclogites.

Setting: high grade metamorphic zones, cratons, root zones of orogenic belts, mantled gneiss domes consisting of a core of gneiss and migmatite diapirically intruded into a cover of metavolcanic or metasedimentary rock.

General: massive rock system but with weak foliation and seams of micaceous material, deep weathering profiles retain weak foliation and seams and often instability is associated with the relict structure, flaky aggregates, strained quartz alkali silica reactivity.

EXAMPLES: cratonic areas of most large continents - Africa, Australia, Canada.

Figure 3.17 : Geological model - metamorphic - gneisses and migmatites



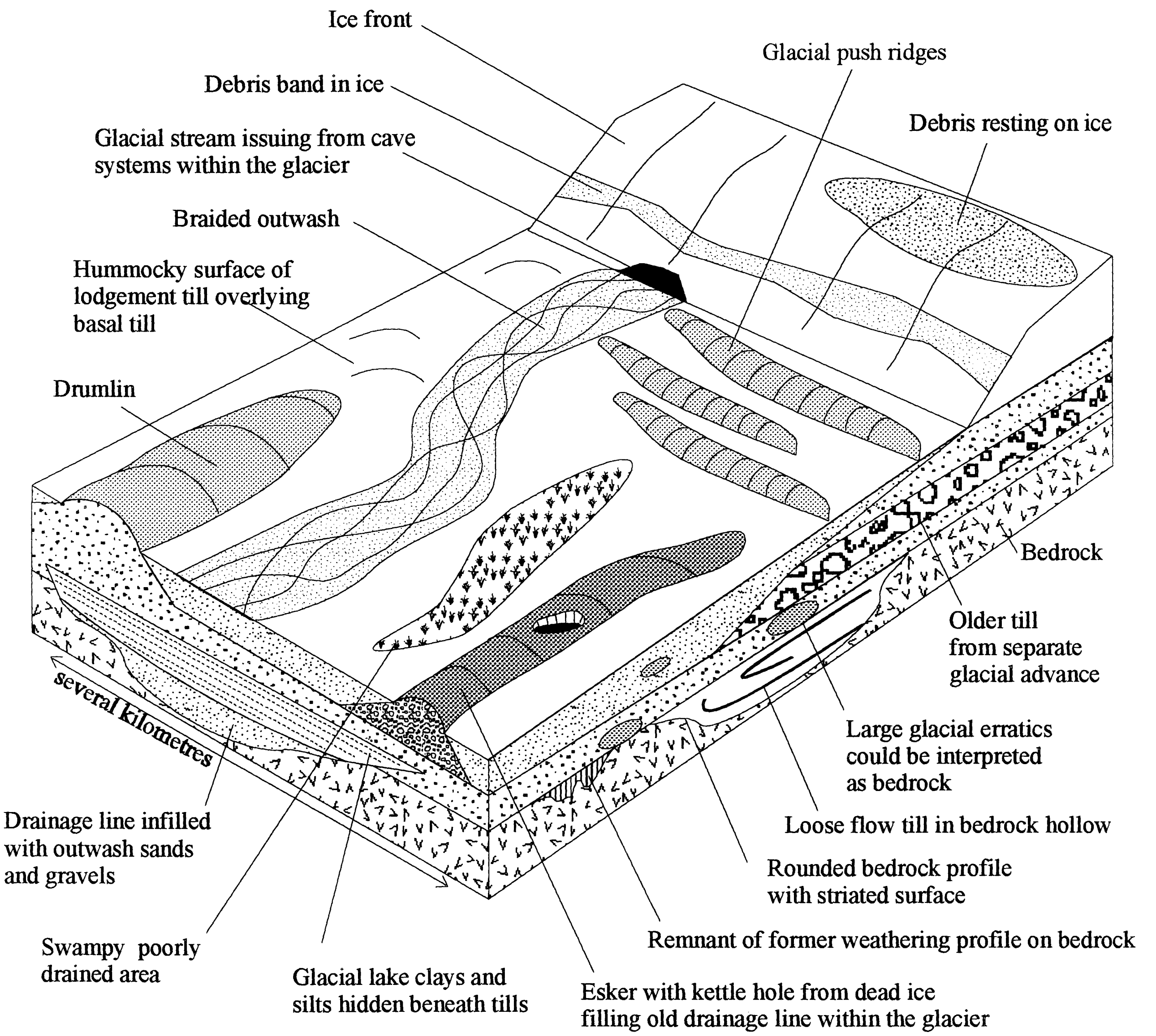
ANTICIPATE:

Superficial deposits: tills or boulder clays (*formation*: comminution, deformation, *transport:* supraglacial, englacial, basal, *depositional:* ablation, meltout, lodgement, flow, waterlain), rock flour, varved silts with low shear strengths, glacial erratics with boulders up to many metres in size, outwash sands and gravels, chaotic and often unpredictable distribution of different superficial deposits, innate heterogeneity.

Processes: powerful erosion and swift transport and deposition of bedrock fragments, deformation and shear in superficial deposits and bedrock at the base of the glacier, striation of bedrock, deep subglacial erosion (overdeepening) and later infill leads to irregular rockhead, overconsolidation of boulder clays, transport of debris results in terminal moraines many kilometres away from existing glaciers that have been deposited before glacial retreat, numerous phases of advance and retreat including the "Little Ice Age" during the 16th Century, stress release phenomena in swiftly eroded bedrock. Proglacial lakes dammed by ice cored moraines may present a hazard.

EXAMPLES: Switzerland; Scotland; New Zealand; Canadian Rockies; ie. all mountainous areas

Figure 3.18 : Geomorphological model - valley glaciation features



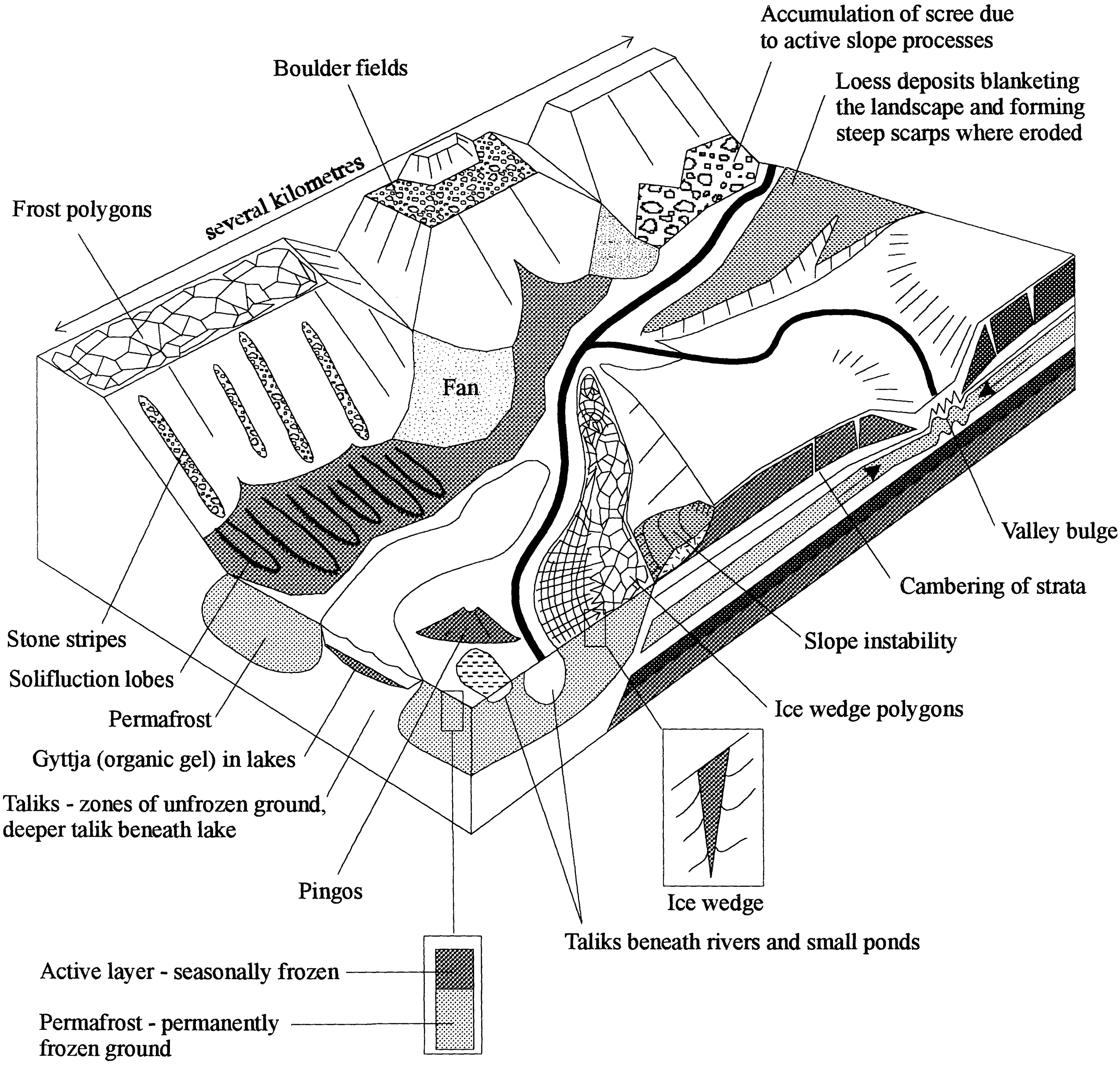
ANTICIPATE:

Superficial deposits: tills or boulder clays (*formation*: comminution, deformation, *transport:* supraglacial, englacial, basal, *depositional:* ablation, meltout, lodgement, flow, waterlain), rock flour, varved silts with low shear strengths, glacial erratics with boulders up to many metres in size, drumlins, eskers, outwash sands and gravels, chaotic and often unpredictable distribution of different superficial deposits, innate heterogeneity.

Processes: deposition of bedrock fragments derived from distant provenances, blanketing of sub-glacial topography with superficial deposits, deformation and shear in superficial deposits and bedrock at the base of the glacier, deep subglacial erosion and later infill leads to irregular rockhead, overconsolidation of tills due to weight of ice, numerous phases of advance and retreat, isostatic rebound due to the removal of up to kilometres depth of ice.

EXAMPLES: Laurentian shield Canada; Baltic region of northern Europe.

Figure 3.19 : Geomorphological model - continental glaciation features



NOTE: This is both an existing active assemblage of landforms in present day periglacial environments and a commonly occurring assemblage of fossil landforms encountered in vast areas that were subject to periglacial environments during the Pleistocene, but which today are subject to temperate climates.

ANTICIPATE:

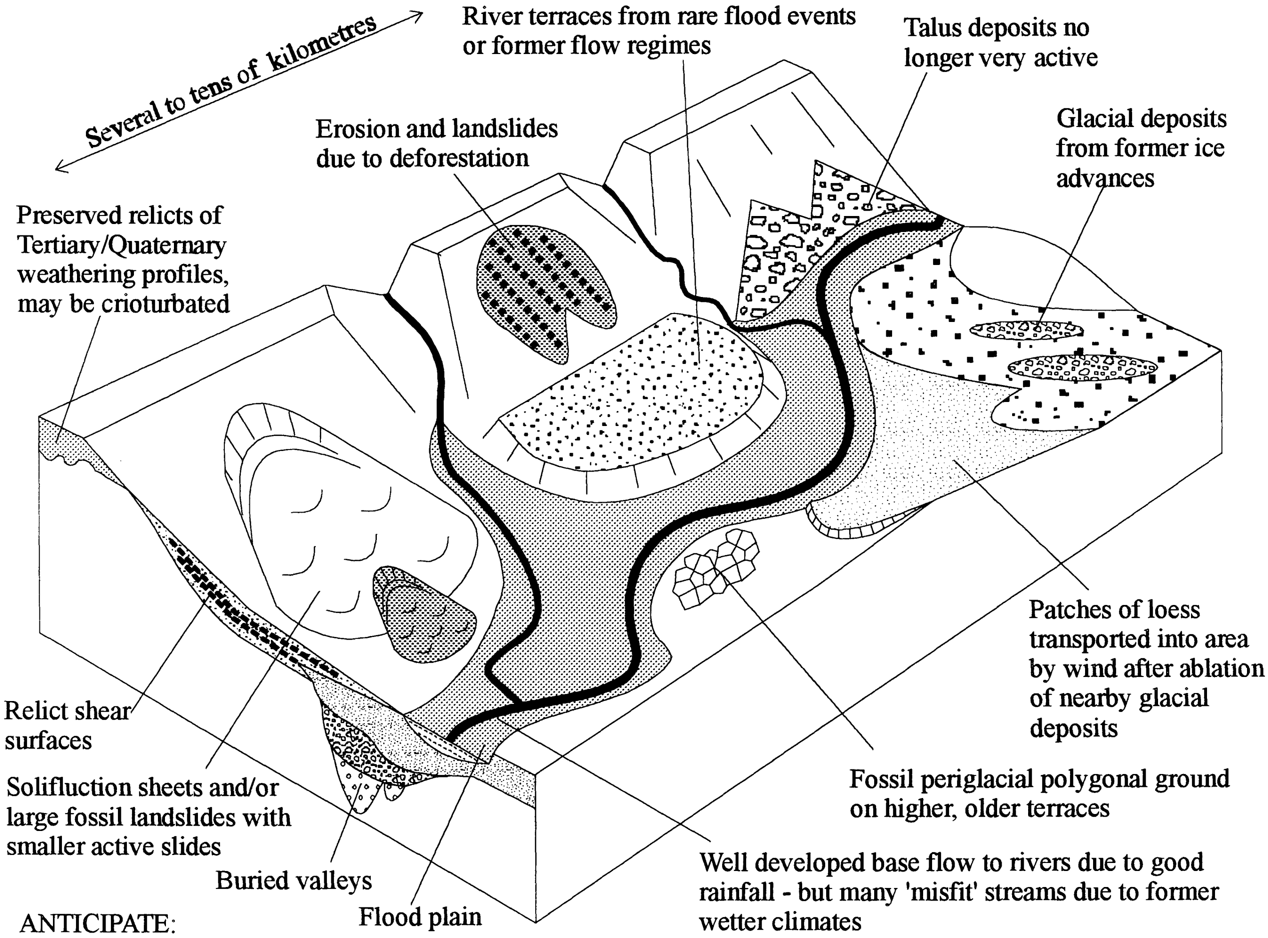
Superficial deposits: altiplanation terraces, block fields, rock glaciers, patterned ground, frost mounds, pingos, thermokarst, loess, talus.

Processes: frost wedging, nivation, frost heaving/creep/sorting, deflocculation, gelifluction/solifluction, permafrost, ice heave, mass movement.

Major engineering problems are associated with permafrost.

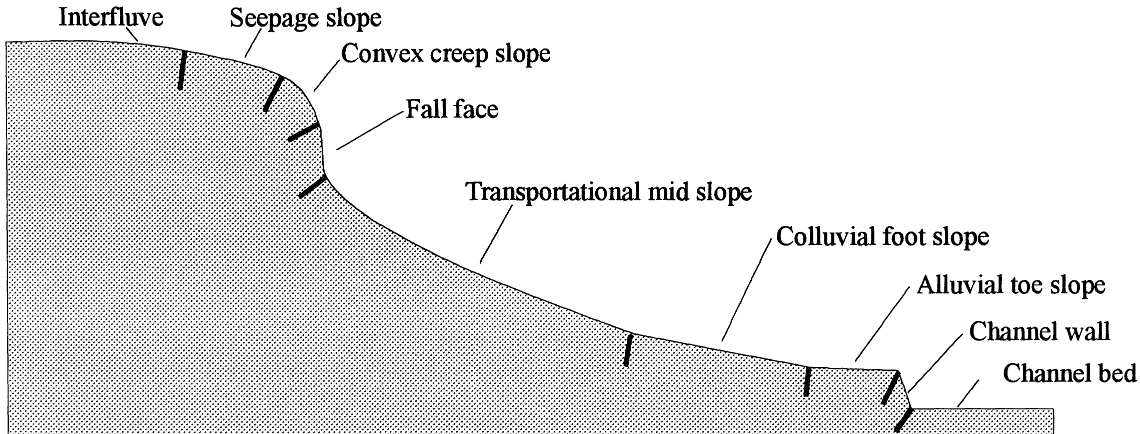
EXAMPLES: *Active* - Alaska, Siberia. *Fossil features* - northern Europe, United Kingdom, northern U.S.A..

Figure 3.20 : Geomorphological model - periglacial features (based on Ritter 1986)



ANTICIPATE:

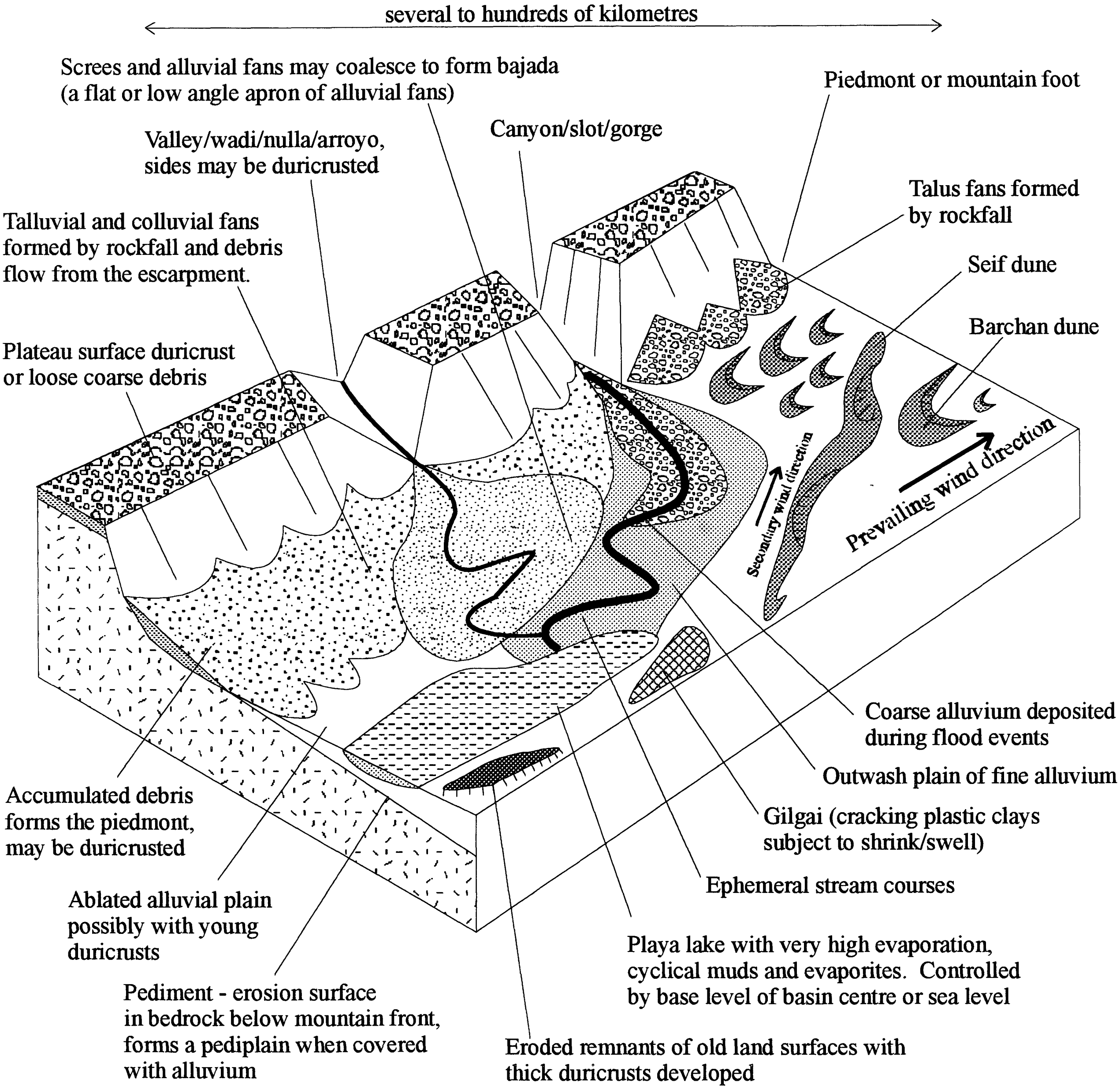
Superficial deposits : features are the least distinctive of all the geomorphological models, they generally include much evidence of landscape change during former climates. Deposits tend to be thinner and less well developed in comparison with other systems. Landforms may often be subdivided into upper planation surface remnants, valley slopes with various colluvial deposits and alluvial systems infilling the valley floor (see also Figure 3.4). Slope systems may be conveniently subdivided into a nine unit landform model (but note that this model also applies to other geomorphological regimes such as hot wet, hot dry, coastal etc.):



Processes: fluvial, also colluvial and talluvial, active where slopes are responding to relatively recent incision, many formerly active processes are represented as relicts produced by earlier climate systems.

Examples: Southern UK; northern France; south eastern seaboard of Australia.

Figure 3.21 : Geomorphology - temperate climate features (based on Ritter 1986)



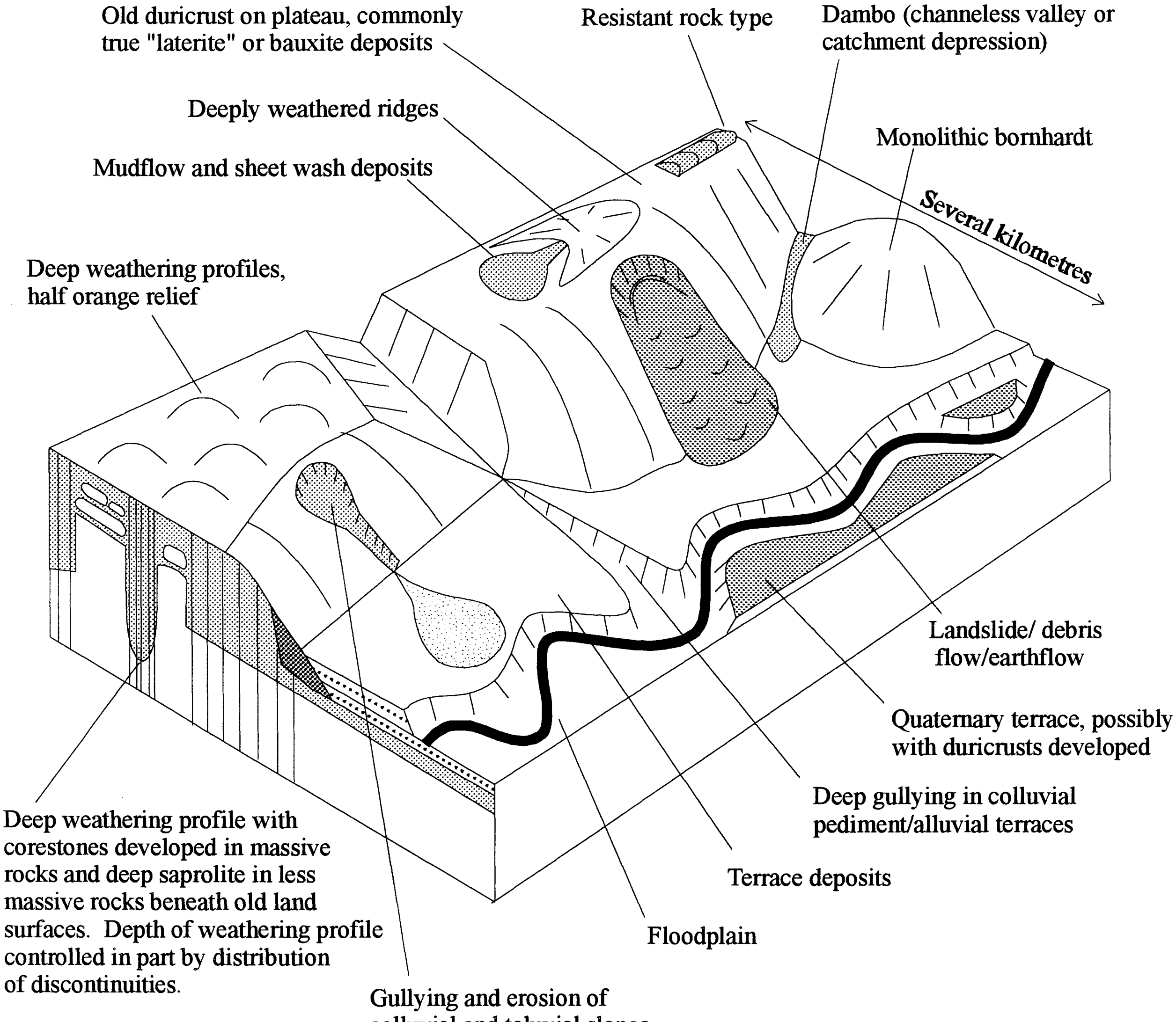
ANTICIPATE:

Superficial deposits: colluvial, taluvial and alluvial sands and gravels, deposited close to slopes or by ephemeral water courses; wind blown sands winnowed from deposits leaving ablated surfaces; active and quiescent sand seas silts, clays and evaporites, aggressive salty groundwaters, salinas (salt pans) in center of basins; metastable fine soils; aggregations of silts and clays by chemical cements; duricrusts of different ages (Mesozoic, Tertiary, Quaternary and Recent), variable thickness (up to a few metres) and type (eg. gypcrust, gypcrete, calcrete, silcrete, ferricrete) depending on bedrock geology and age of the desert surface. "Crusts" are weak, "cretes" are strong.

Processes: minimal vegetation cover to bind superficial deposits, sheet and channel flash floods, mobile dune sands, sand blasting, extremes of temperature and thermal stresses.

EXAMPLE: arid parts of Middle East, north Africa, parts of Arizona, inland parts of the Pilbara region and the Great Sandy Desert of Australia

Figure 3.22 : Geomorphological model - hot dry climate features



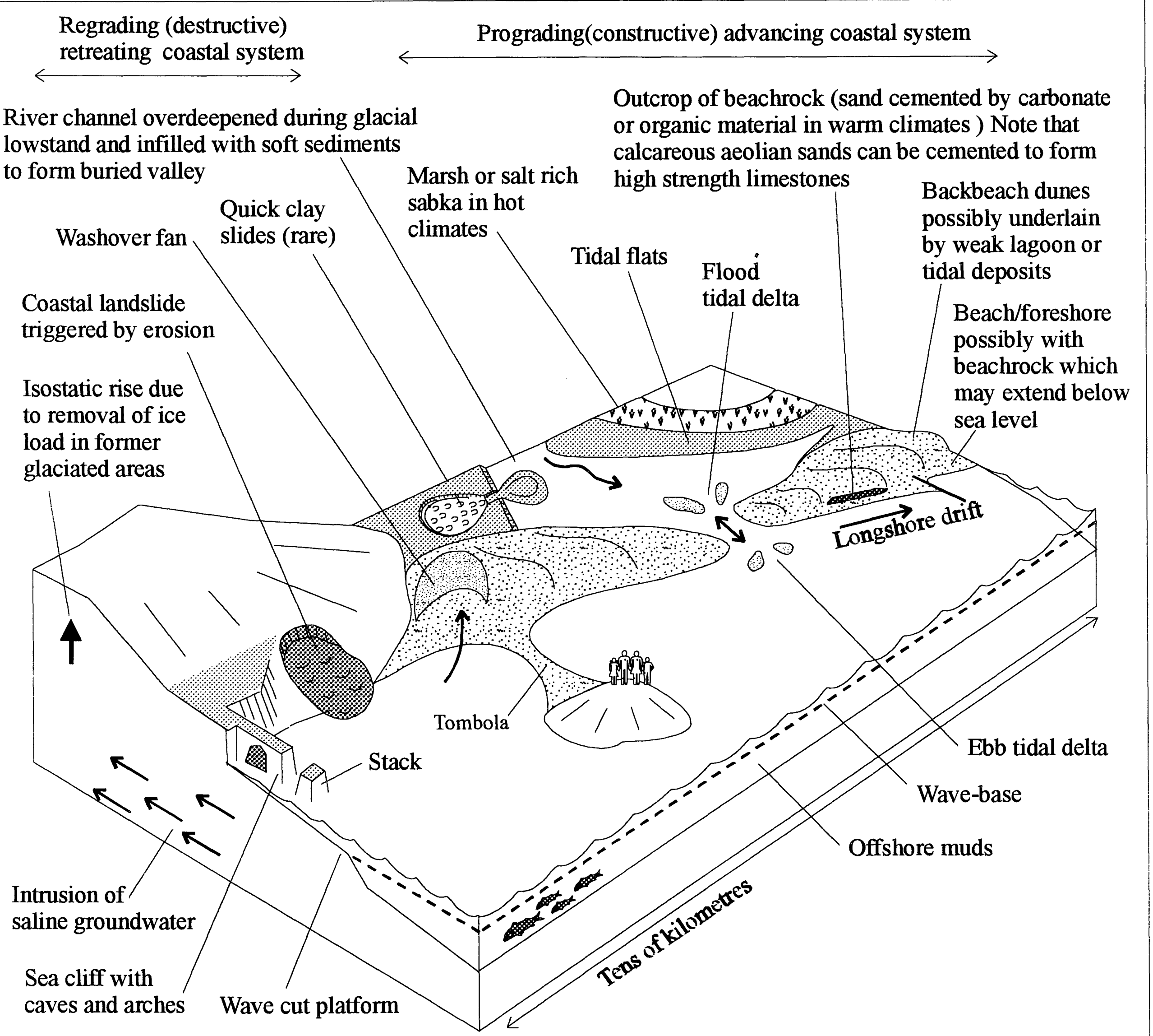
ANTICIPATE:

Superficial deposits: existing or former cover of thick rain forest, deep weathering profiles, depth of weathering related to climate, geomorphological history and geological rock type and structure but can be many tens of metres. Duricrusts where groundwater concentrates soluble weathering products, collapsing soils where there are porous extremely weathered rocks, relict discontinuities in weathering profile control stability, profiles range from older, leached, kaolinite and gibbsite dominated soils, to poorly drained, younger, montmorillonite (smectite) rich soils. Deeply weathered colluvial soils often difficult to distinguish from in-situ weathering profiles. Permeability contrasts often control slope stability with highly permeable zones at bedrock/weathing profile interface and in the zone of piping failure where silty soils form from extremely weathered rock below residual soils. Volcanic ashes tend to develop moisture susceptible andosols. Use weathering grades and duricrust terminology and avoid "laterite profile" terms because many different interpretations.

Processes: active weathering sometimes proceeding at startling rates where rock types are susceptible, mass movement associated with incision of deep weak weathering profiles includes gully erosion, landslide, mudflows etc. System may also be responding to recent land clearing by man and extensive soil erosion may result. Characteristic intense rainfall leads to saturation of surface layers and instability, also movement of high pressure water along soil pipes. Silty soils characteristic of deep weathering profiles susceptible to internal erosion and piping failure.

EXAMPLES: Hong Kong; central Malay Penisula; Udzungwa scarp in central Tanzania; south-west coastal ranges of western Australia.

Figure 3.23 : Geomorphological model - hot wet climate features (based on Thomas 1994)



ANTICIPATE

Superficial deposits: sands and gravels sorted by wind and wave actions, offshore sand and gravel bars, foreshore sands and gravels, dune sands, quartz and carbonate sands, shell components, organic deposits and clays preserved in lagoons behind dunes, muds and fine sands, shell banks, mangrove muds, chenier sands and plains in more sheltered tidal flats, constructive features, destructive features.

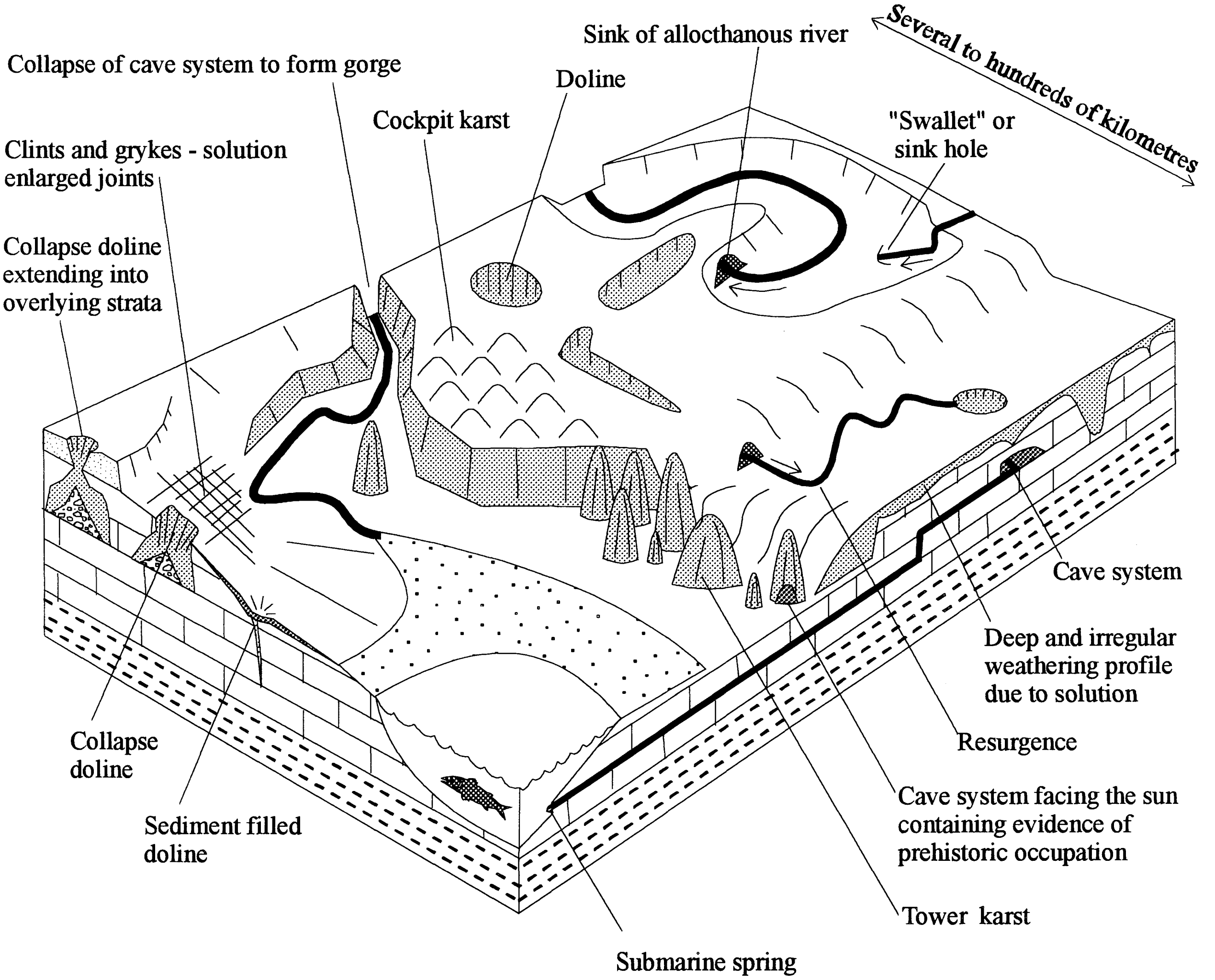
Processes: reflect sediment budgets, sediment cells, delivery of sand by post glacial transgression and subsequent erosion, coastal erosion, rising and falling sea levels, landslides, progradation, regradation.

Some key instances of eustatic (world wide) sea level change associated with the Pleistocene (but note that isotatic rises and falls of sea level associated with tectonics or ice unloading are locally important):

Flandrian maximum, c. 6,000 years BP, when sea levels c. 2 m higher than today.
Onset of Holocene, 10,000 years BP, sea level c.40 m lower than today
Onset of Post glacial (Flandrian) transgression <20,000 years BP
Last glacial maximum, c. 20,000 years BP, sea level around 150 m lower than today
Various glacial maxima between 20,000 and 120,000 BP with associated sea level falls
Last interglacial, say, 120,000 years BP sea level 2 or 3 m higher (various interpretations).

EXAMPLES: south coast UK; east and south coast USA; all coastlines will display combinations of these features.

Figure 3.24 : Geomorphological model - coastal features



ANTICIPATE:

Associated lithologies: limestone, dolomite, halite, gypsum, (and documented examples of impure quartzite if exposed for long enough periods on the tropics). Thick limestones give rise to most of the world's karst topography. Karst systems usually relate to former water tables and often structurally controlled with fissures, conduits and caves initially developing along faults and joints. Controls on karst development are usually complex and difficult to evaluate.

Superficial deposits: terra rosa, insoluble bedrock components, collapse breccias, tufa, windblown infills, alluvial infills, skeletal remains of animals that have become trapped.

Processes: active solution, enlargement of joints, surface collapse, deposition of speleothems and tufa.

General : significant hazards to engineered works due to subsidence, collapse, gross permeabilities, complex and locally flat water tables due to high permeability, complex flow paths etc. Processes may be active, or renewed activity may be triggered by engineering works. Karst best developed in areas of high rainfall with hot wet climates producing some spectacular forms. Solution occurs in both the vadose (unsaturated) zone and the phreatic zone (below the water table). Larger dolines called uvalas and poljes. Active solution of halite and gypsum very possible. Relict karst can occur in arid climates.

EXAMPLES: classical description of karst ("a bleak waterless place") from a high plateau near the Adriatic sea between north-west Italy and Yugoslavia; central Florida in USA; east-central Missouri in USA; Ordovician limestones belts of Tasmania, Australia; Mendip Hills in UK; Jamaica; parts of Malaysia.

Figure 3.25 : Geomorphological model - soluble rocks features (landform scale)