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The total engineering geology approach applied to railways in the Pilbara, Western Australia

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Abstract The application of the *total engineering geology approach* to the investigation, design, construction and operation of several major iron ore railways in the ancient cratonic Pilbara region of Western Australia is described. The approach is based on developing a thorough understanding of the geological and geomorphological history of the area and adopting strategies such as staged investigations, an emphasis on geo-mapping, establishing reference conditions, the development of models and applying the observational method. The role of engineering geologists in such projects, their objectives and responsibilities, and the range of issues that have to be dealt with are reviewed and used to illustrate how inputs from engineering geologists are critical to project implementation. Some conclusions are drawn regarding what is good practice in heavy civil engineering projects.

Keywords Total engineering geology · Investigation · Design · Construction · Railways

Résumé Une approche globale d'engineering geology est mise en oeuvre pour les études de reconnaissance, conception et construction relatives à d'importants projets de voies de chemins de fer destinées au transport de minerai de fer dans la région du craton de Pilbara (Etat d'Australie-Occidentale). La méthode est basée sur un examen approfondi de l'histoire géologique et géomorphologique des sites concernés, incluant des investigations progressives basées sur l'observation, des études cartographiques spécialisées et l'établissement de modèles géologiques. Les responsabilités des spécialistes en engineering geology, les apports spécifiques de cette discipline et les différents problèmes qui doivent être traités dans ces projets sont soulignés. Des conclusions sont établies concernant les conditions d'une bonne mise en œuvre des méthodes et techniques de l'engineering geology dans les projets importants de génie civil.

Mots clés Engineering geology · Reconnaissance des sites · Conception des ouvrages · Construction · Tracés ferroviaires

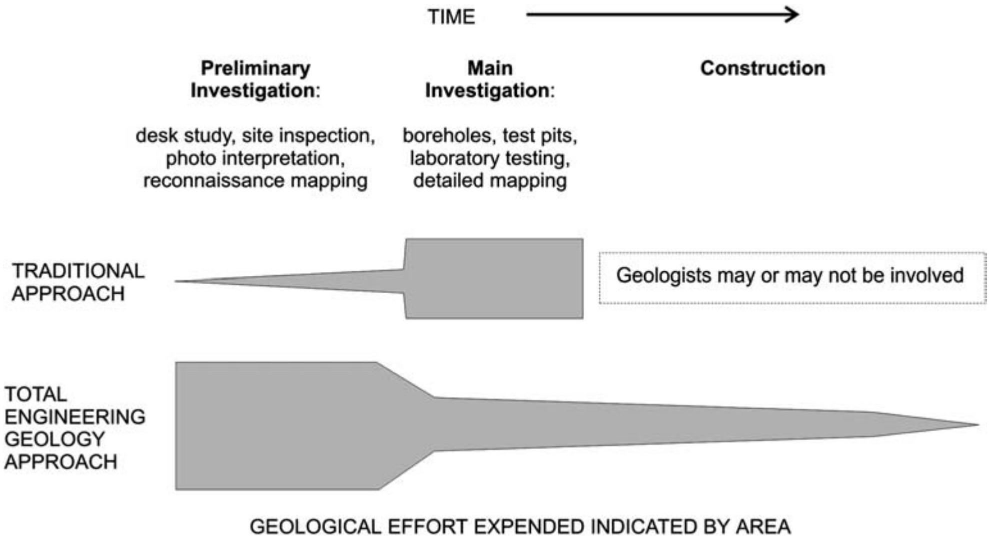

Fig. 1 Contrasting approaches to the application of engineering geology on projects. Although greater geological effort is expended using the *total engineering geology approach* it does not usually cost as much as the *traditional approach* as the latter generally involves more extensive subsurface investigations using expensive plant

Introduction

Unless engineering geologists know how to add value toprojects their contribution will not be sought by project managers and those projects will ultimately suffer. Thus it is important to identify strategies that ensure engineering geologists contribute to projects effectively. However, accounts of the strategies that are intrinsic to effective engineering geology have only recently been published e.g. Fookes (1997) and some are still fearful that the discipline remains poorly defined (Knill 2003).

The *''total engineering geology approach''* is based on the concept that site conditions should be viewed as the result of the complete geological and geomorphological history and that an understanding of that history has to be well developed at the earliest possible opportunity in any project for it to be successfully engineered. The approach has been used intuitively by practitioners for many years but it is only recently that it has been formalised (Fookes et al. 2000, 2001). The way in which this approach differs from the *''traditional approach''*, followed by many engineering organizations, is illustrated in Fig. 1.

The underlying premise of the *total engineering geology approach* is that many of the fundamental decisions required for successful project implementation can only be reasonably made after thoroughly understanding the total geological and geomorphological history of the project area and the associated engineering implications. Recent authoritative guidelines on the management of geotechnical risk (e.g. Clayton 2001) now embody this advice. It follows that adopting this approach is the most effective way for engineering geologists to contribute to the implementation of any ground engineering project.

In this paper, the practical strategies involved in the *total engineering geology approach* are identified by describing its application in the investigation, design, construction and operation of some major railways that have recently been developed to haul iron ore in the Pilbara region of Western Australia.

The paper summarises the engineering geological information that was acquired and the lessons that were learnt during the authors' involvement in a succession of these railway projects and uses this experience base to illustrate the application of the methodology. The paper is divided into three parts that reflect the methodology. In the first part an overview of the development of the Pilbara region and a summary of the geological and geomorphological history is provided, as this must be the starting point for any engineering geological study. In the second part the relationship between the engineering geology and the railway projects is explored, as it is the application of engineering geology in real life engineering projects which provides it with relevance. In the third part the involvement of engineering geologists in the decision making processes associated with a range of ground engineering issues is described to illustrate the effectiveness of the methodology in contributing to project engineering.

Part 1: Overview, geology and geomorphology

Upon arrival at any project site the first task of the engineering geologist is to develop a general appreciation of the development of the region and to understand the entire geological and geomorphological history.

Development of the Pilbara region

The Pilbara region is located in northwestern Australia (Fig. 2). The iron ore in the Pilbara was first noted when European settlers started to move into the area in the late 1800s but systematic exploration of the resource

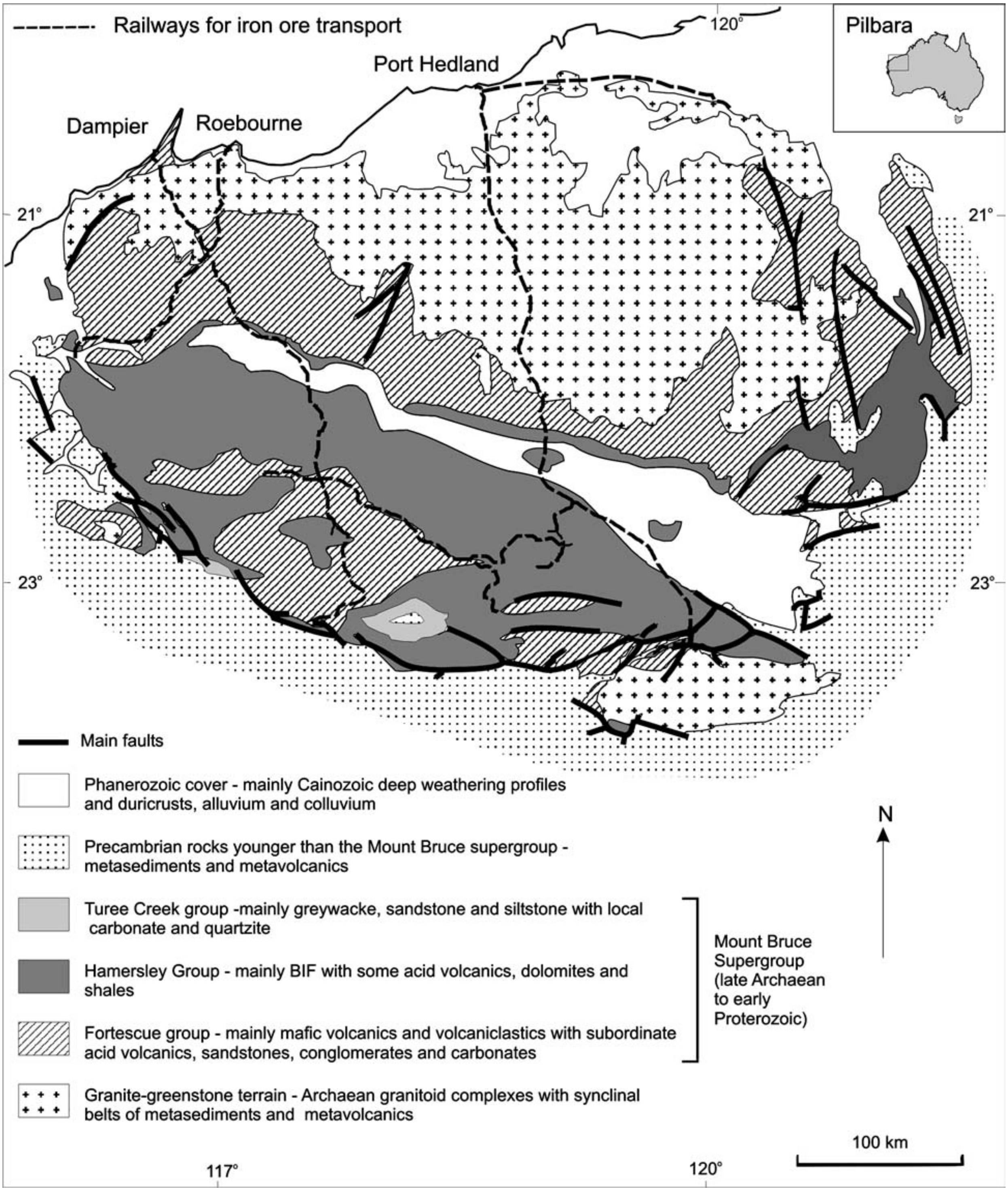

Fig. 2 Pilbara region—regional geology, stratigraphy and railway networks

only started after an embargo on the export of iron ore imposed by the Australian Commonwealth government was lifted in 1960. The area has since become established as one of the world's major iron ore provinces.

Iron ore mining

The economic deposits of iron ore may be differentiated into three types of ore bodies (Kneeshaw 2000):

a. Bedded ores, also known as bedrock or enrichment ores, which consist of martite, haematite and goethite and are mined from enriched banded iron formation (colloquially referred to using the acronym "BIF") in the Proterozoic Hamersley Group.

b. Channel ores (or channel iron deposits—"CIDs"), which consist of cemented goethite and haematite pisolites occurring in mid-Tertiary fluvial palaeochannels.
c. Detrital ores, which occur as late Tertiary colluvial fans derived from adjacent bedded ores.

Since mining commenced in 1966 production of iron ore from the Pilbara totalled about 4 billion tonnes up to 2003. Annual production during 2003 was of the order of 180 million tonnes, which represented about 9% of total world production (including both low and high grade ore) and about 35% of total seaborne trade (which is limited to high-grade production).

The railway systems

The iron ore mined in the Pilbara is destined for export and requires transport to shipping ports on some of the longest, most heavily loaded railway trains in the world. Ore trains typically consist of up to 240 wagons and can be 2.6 km in length. Each wagon carries around 130 tonnes of iron ore, which is usually loaded into the wagons at a loop near the mine where the train turns round. The locomotives can be as powerful as 6000 hp units and up to 4 units are used to move a large train. Each wagon imposes individual axle loads of 35 tonnes onto a railway track that has a gauge of 1435 mm and is supported on pre-cast concrete sleepers 650 mm apart placed on a 200–300 mm thick layer of 40 mm ballast. Ruling grades for loaded trains are typically an absolute maximum of around 0.5%. Development of railways commenced in the 1960s and has continued as iron ore exports grow. The system is currently estimated to consist of about 1400 kms of track and new railways are being planned. The authors have been involved in one form or another in railway developments in the Pilbara since the 1990s.

Geology and geomorphology of the Pilbara region

The development of a detailed understanding of the geological and geomorphological history of an area and how that history influences the project engineering is a fundamental strategy of the *total engineering geology approach*. The understanding has to be very broad and sometimes extends to aspects of geology, such as regional metamorphism or palaeoclimates, that might appear esoteric to engineering managers. This contrasts with the *traditional approach*, which is often limited to the logging of boreholes and test pits and laboratory measurements of strength and index properties.

Bedrock stratigraphy

Figure 2 is a geological map of the Pilbara region, which is a cratonic area underlain by massive Archaean granites and gneisses aged around 3 Ga (i.e. 3 billion years old). The Archaen rocks are overlain in the south of the region by bedded volcanics and sediments which were deposited around 2.5 Ga onto the eroded cratonic surface during late Archaean and early Proterozoic times (Trendall 1990).

At the beginning of the Proterozoic the earth's atmosphere contained little oxygen and consequently ferrous iron derived from weathering could remain in solution in oceanic waters. It is postulated that during the Proterozoic the evolution of photosynthesizing organisms produced oxygen which precipitated iron from the oceanic waters in the ferric state as haematite, to form the iron-rich layers in the BIF (Trendall 2000).

The railways have mainly been built to service the mines developed around ore bodies located in the central Pilbara where rocks of the Hamersley Group occur. The Group has an estimated total thickness of approximately 2500 m and consists of eight formations comprising BIF, "shale" (a term used in the Pilbara region for interbedded fine sandstones, laminated siltstones and mudstones), dolomite, and thick sequences of basic and acidic volcanic rocks. Certain formations are characterized by thick sills of basic intrusive rocks such as dolerite.

A distinctive characteristic of the Hamersley Group is the lateral stratigraphic continuity of the BIF units, which can extend over hundreds of kilometres (Trendall 1990). During regional geological mapping the stratigraphic continuity allows the recognition of individual marker horizons and conspicuous landform patterns associated with specific formations. The alternating formations, which have been gently folded, control the landscape development, with the more resistant BIF formations forming ranges of hills with distinctive cuesta or mesa shapes. Many of the deep broad valleys are associated with the Wittenoom Formation and Bee Gorge shales, the former having been subject to karst development and the latter being more easily eroded.

The late Archaean and early Proterozoic volcanics and sediments were deformed during the Capricorn orogeny between 2.0 Ga and 1.6 Ga, intruded by thick dolerite sills and subject to medium-grade regional metamorphism. A significant mineralogical consequence of the metamorphism was the growth of asbestiform minerals in certain parts of the rock mass (Trendall and Blockley 1970). The presence of such minerals creates a geohazard that can be a significant health and safety issue in the field.

The BIF consists of alternating laminae or layers of chert, siltstone, mudstone and haematite in varying proportions. Within the BIF sequences there are often beds of massive siliceous rock which are of very high strength and abrasive. The abrasive siliceous rocks can reduce production rates for both diamond coring and blast-hole drilling, cause excessive bit wear and can also produce significant wear on earthmoving and processing machinery.

Most bedrock types in the region have high uniaxial compressive strength values. However, the engineering characteristics of the bedrock reflect both the rock material properties and the presence of throughgoing discontinuities of all types. For instance, the BIFs can contain siliceous beds with uniaxial compressive strengths of 150 MPa (and values up to 450 MPa have been measured), but can also contain beds of "shales" which have been sheared during folding, are weaker and more easily weathered, and can have bedding planes with residual shear strengths as low as $\phi'_r = 15°$, $c'_r = 0$. The wide range of engineering characteristics is further accentuated by the influence of geological structures such as faults and joints and, in particular, by the development of deep weathering profiles. The bedrock geology fundamentally controls the distribution and engineering performance of many of the materials in which the deeper railway cuts are excavated and from which the thicker fills are constructed.

Bedrock structure

The degree of development and orientation of geological structures within the bedrock, particularly bedding planes, are the key concerns in cut slope design. The bedrock in the central Pilbara was folded during the Capricorn orogeny in a regional scale foreland fold and thrust tectonic setting (Tyler and Thorne 1990). Up to five different fold phases have been identified by structural geologists working in the Pilbara region (Tyler 1991). In the bedded rocks of the central Pilbara the typical fold styles fall into two main categories of engineering significance, which are described below:

a. There are open large-scale regional fold styles leading to dips of the order of 10–30°. As these folds can result in persistent uniform bedding planes dipping at angles that can be greater than the angle of friction, the dip of the strata can contribute to the development of rock slope instability. Such instability is observed in the steeper natural rock slopes throughout the Pilbara.
b. There are tighter localized folds that are restricted to structural corridors possibly associated with regional faults or intrusions. These structures tend to provide interlock across bedding planes which reduces the potential for large scale and medium scale instability, but can lead to small scale local instability due to adversely dipping bedding planes occurring at outcrop or in cut slopes.

Fault styles are mainly low angle thrusts associated with the regional compression and are rarely encountered in railway excavations. Jointing largely reflects the structural attitude of the adjacent folding and faulting systems. At least three distinct sub-vertical joint sets occur in most BIF units but these sets are usually less developed in other bedrock types. Well-developed master joints on gently dipping BIF fold limbs often extend several hundreds of metres. Steeply dipping persistent master joints typically exert a fundamental control on cliff line stability, especially where the rock mass is prone to toppling failure, and characteristically form a "saw-tooth" pattern on cliff lines.

Landform evolution

Landform evolution governs the distribution of superficial deposits, weathering profiles and slope processes and thus exerts a profound influence on the engineering characteristics of the near surface materials in which the railway earthworks are constructed. Understanding the landform evolution requires an understanding of the regional tectonic evolution of the area, as this has controlled palaeo-latitudes and rates of uplift and hence past climates, weathering processes and cycles of erosion.

The Pilbara was probably glaciated during the Permian, when the region was part of the polar supercontinent Gondwana, as glaciogenic sediments have been found further south preserved in basins in the ancient Western Australian cratonic land surface (Anand and Paine 2002). The supercontinent started to rift during the Jurassic to form the continent of Australia (Fig. 3). During the Mesozoic, progressive erosion produced extensive relatively planar land surfaces cutting across the craton. At the end of the Mesozoic the climate is believed to have been warmer and more uniform globally in comparison with the present, due to restricted oceanic circulation (Summerfield 1991). Thus despite being so far south at this time, the craton was subject to several cycles of deep chemical weathering and the formation of duricrusts that eventually formed the prominent "Hamersley surface", remnants of which can now be seen across the Pilbara (Campana et al. 1964; Twidale 1994).

During the Cainozoic progressive uplift and minor warping, weathering and duricrust formation and erosion during periods of renewed incision produced a complex series of slopes, colluvial and alluvial deposits and duricrusts. A typical Pilbara landscape reflecting the effects of all of these processes is shown in Fig. 4.

Cainozoic changes in climate

Since the break up of Gondwana, the Australian continental plate has moved north through more than 30° of latitude (see Fig. 3) whilst the global climatic system has fluctuated significantly (Bowler 1982). Studies of Cainozoic climate change and regolith development based on sequence stratigraphy around Australia suggest that there may have been at least four distinct periods of

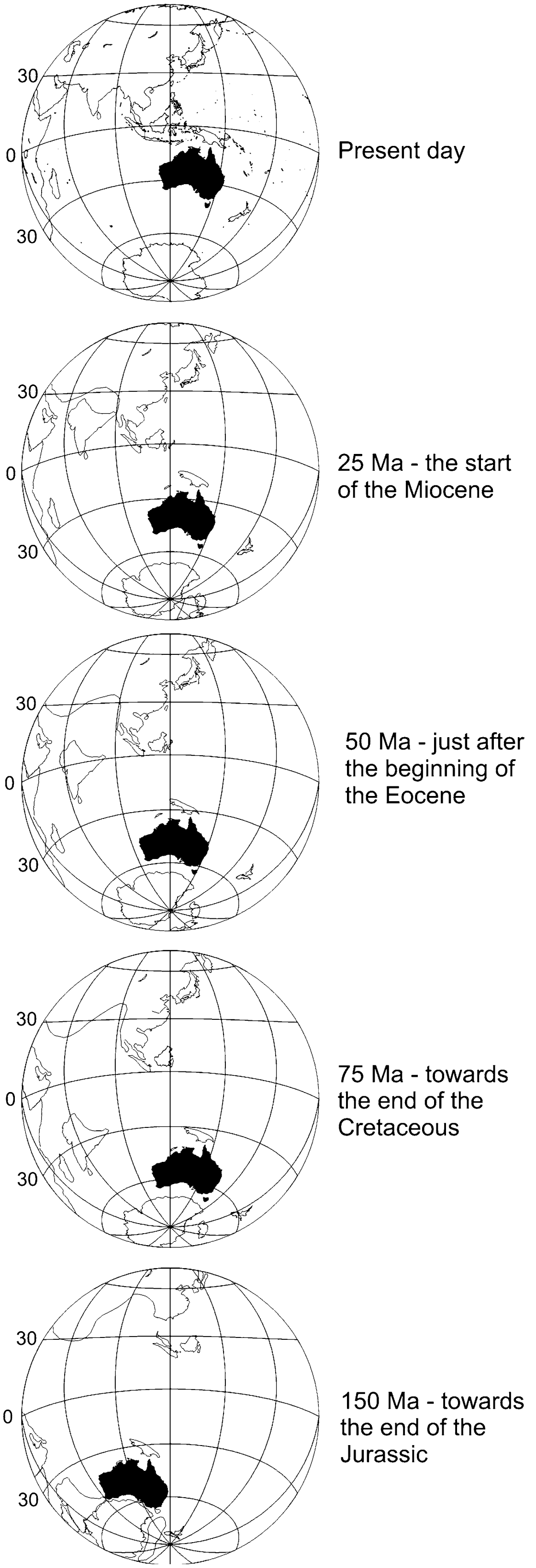

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Fig. 3 Tectonic movements of the Australian Plate. The reconstructions were made by S. A. Pisarevsky (Tectonics Special Research Centre, The University of Western Australia), using the spherical rotation software of the Visual Paleomagnetic Database (Pisarevsky and McElhinny 2003), PLATES software of the University of Texas in Austin, and GMT software of Wessel and Smith

more intense weathering during the Tertiary (McGowran and Li 1998). A simpler view is that most of the deep weathering profiles that are preserved in the Pilbara developed successively between the Late Cretaceous and the mid-Miocene (Killick et al. 2001).

Although the Pilbara has moved from a latitude of about 55°S to a latitude of about 25°S, it appears that during most of the Tertiary the climate was "tropical" or "sub-tropical" i.e. warm with a heavy rainfall. It seems probable that for much of the time the area was heavily forested, there was deep weathering of the erosion surfaces and there was a high degree of mobility of iron in the landscape. Between late Oligocene and mid-Miocene times erosion of duricrusts, fluvial deposition and iron enrichment led to the formation of the CIDs (Ramanaidou et al. 2003).

During the Pliocene there was incision, erosion and deposition of alluvial/colluvial fans. This may have resulted from regional tectonic uplift and increasing aridity, coupled with loss of vegetation cover and periodic extreme storm events. The gently sloping distal portions of the Pliocene alluvial/colluvial fans currently provide optimal railway route corridors and usually excellent construction materials.

The Quaternary climate is thought to have been generally semi-arid with a monsoonal hot wet summer. It

Fig. 4 Typical Pilbara landscape including rolling spinifex covered hills, broad valleys, BIF outcropping as cliff lines and concordant summits forming the Hamersley Surface on the skyline

is likely that the region was subject to considerable variations in the amount and intensity of rainfall during the Quaternary associated with global climatic fluctuations related to glacial and interglacial periods. There may be similarities with the nearby Kimberley region where marked climatic fluctuations during the Quaternary have been documented (Wende et al. 1997). However, research is yet to be carried out in the Pilbara region into past periods of increased aridity or the recurrence intervals of extreme flood events associated with monsoonal activity.

Superficial deposits

The superficial deposits that accumulated during the different climatic regimes vary in age from early Tertiary to Recent and form deposits on or close to the surface of the bedrock. Four main processes have formed the superficial deposits:

a. Deposition of colluvial and taluvial sands, gravels and boulders on slopes.
b. Deposition of alluvial and colluvial gravels, sands, silts and clays in fans, channels or on flood plains. The finer sediments tend to be deposited in the more distal parts of the fans and the clays tend to be deposited in the low-lying floodplains.
d. The development of weathering profiles on both bedrock and unconsolidated sediments involving solution and decomposition of mineral species.
d. The growth of mineral species in the superficial deposits or at the top of weathering profiles developed on bedrock, which in places have cemented unconsolidated materials to form rock or gravelly materials and become duricrusts (Thomas 1994).

The dominance of duricrust development (Hocking and Cockbain 1990; Killick et al. 2001) and deep weathering has resulted in the formation of a series of cemented surfaces within the landscape. Any surface process capable of transforming soil to rock is clearly important from an engineering viewpoint. Depending upon the cementing agent the materials may be described as: a. Ferricrete—cemented by iron oxide, typically brown or red, often with a nodular appearance, sometimes forming fine gravels, or irregular rock material.b. Calcrete—cemented by calcium carbonate, typically a red pink or white gravely material, sometimes forming tabular rock material.c. Silcrete—cemented by silica, typically a white cherty, gravely material sometimes forming a tabular rock material.

Where reactive i.e. moisture-sensitive clay species have been deposited or developed on the flatter more distal colluvial slopes and flood plains, areas known as "gilgai" have developed (Beckman et al. 1970; Cooke and Warren 1973; Maxwell 1994). Gilgai have a characteristic hummocky appearance with cracks and "crab holes". The surface features are produced by marked seasonal volume changes due to the wetting and drying of reactive clay species that form a significant proportion of the soils. Gilgai are a significant geohazard.

Current topography, climate and vegetation

Currently the central Pilbara is a semi-arid upland with a base elevation some 700 m above sea level and with ranges of hills that extend up to 1000 m in height. The topographic relief leads to the development of a variety of active slope processes that can impact upon railways, such as debris flow and rockfall.

Summer daytime temperatures range well into the 40s and winter frosts can occur. Annual evaporation is well in excess of annual rainfall, which on average is between 180 mm and 350 mm, but it is highly irregular due to periodic cyclonic events and thunderstorm cells that produce localized intense falls. There may be no rain for several months, or even years, in a particular area, then a large part of the yearly rainfall will occur in a short time, leading to flooding along the water courses and movement of debris down slopes and along drainage lines. Rainfalls of up to 200 mm in 24 hours can occur during the rainy season. This type of irregular intense rainfall pattern exerts a major control over current slope process rates and the occurrence of damaging floods.

Due to the semi-arid environment the vegetation cover consists of scrub and spinifex grass with isolated gum trees along drainage lines. The region has been subject to pastoral grazing since European settlement, but this has not led to significant impacts to the vegetation cover. However, the naturally sparse vegetation cover increases the rapidity of the runoff and does little to impede the movement of sediment downslope and thus contributes to the active slope processes and flood impacts.

The outstanding scenery of the Pilbara, which is typified by the ranges of hills and dramatic gorges and the contrast between the green vegetation cover and the red and brown tones of the underlying geology, has resulted in much of the area having National Park status.

Current natural slopes

Slopes in the Pilbara reflect the underlying lithology and structure and the overprinting of different phases of weathering, duricrust formation, erosion and deposition (Joyce and Ollier 2003). The upper parts of slopes are often remnants of former erosion surfaces and usually include rounded duricrusted portions or flat surfaces sub-parallel to the bedding. Below the upper slopes steep cliff lines controlled by persistent sub-vertical joints have often developed due to rejuvenation of the landscape by uplift and incision (Fig. 5).

The cliff lines are usually actively degrading with aprons of rockfall debris forming transportational mid-slopes (Fig. 6).

Below the cliffs and rockfall aprons and at the exit points of gullies and canyons there are widespread alluvial/colluvial fans and slopes mantled with such deposits. Both alluvial deposits and channelised debris flows form low angle fans towards the base of the slopes. Within the broad valleys there are alluvial flats and intermittent flood-prone river systems (Fig. 7).

Total engineering geology history

The entire geological and geomorphological history of the Pilbara region that is described above needs to be understood as part of the *total engineering geology approach*. This history, and the consequences for railway engineering, are summarized in Table 1.

Part 2: Project strategies for total engineering geology

A high level of geological and geomorphological understanding was not in itself sufficient to successfully support project implementation for the various railways in which the authors were involved. Various strategies had to be developed to efficiently acquire and effectively communicate that knowledge. Geological information had to be delivered to the right people in the project team at the right time in an easily understandable manner and with an explanation of the significance of the information.

Project stages

To effectively contribute to the railway projects in the Pilbara using the *total engineering geology approach* different types of information were collected and communicated at each of the typical engineering project stages. Figure 8 summarises the range of engineering geological activities that were found to be most effective in achieving the objectives of each of the idealised project stages.

Finance is generally limited at the pre-feasibility, feasibility or initial design stage in any project and the collection of low-cost information that will support very broad decisions has to be the main objective. Hence, the investigations during these stages usually involved desk studies, studies of aerial photographs, site reconnaissance, ground truthing of aerial photographic interpretations by site visits, general mapping and inspection. Investigations involving detailed mapping, test pitting, drilling of boreholes to obtain information for deep cuts, laboratory testing etc are far more expensive and were only carried out as the alignments became more fixed and greater detail was required for design and costing.

Fig. 5 Composite landscape including rounded upper slopes, cliff lines and colluvium covered slopes

Fig. 6 A typical cliff line controlled by joints which form a characteristic “saw-tooth” pattern. A taluvial apron has accumulated on the slope below the cliff line, which is about 10 m high

Fig. 7 Lower slopes formed by coalescing distal portions of alluvial/colluvial fans, which merge into alluvial flats forming extensive floodplains. The optimal railway route corridor is on the lower slopes

Table 1 Pilbara total engineering geology

Episode and age	Geological events	Geological environments	Engineering consequences
Quaternary 0–2 Ma			
Holocene 0–0.01 Ma	Current interglacial and highstand, Australian craton moving north at 10 mm/year, latitude 23°	Hot, semi-arid, monsoonal, misfit alluvial tracts subject to periodic flood events, minor colluvial, alluvial, aeolian, lacustrine deposits and rockfall aprons.	Flash flood, debris flows, rock fall, insolation weathering, shrink/swell of clays, low seismic risk
Pleistocene 0.01–2 Ma	Oscillations in temperature leading to worldwide glacial/interglacial cycles	Semi-arid monsoonal environment with imposed cycles of both increased aridity and heightened monsoonal rainfall, substantial colluvial, alluvial, aeolian, lacustrine deposits and rockfall aprons.	Troublesome superficial deposits such as windblown sands, gilgai clays, loose alluvium etc
Tertiary 2–65 Ma			
Pliocene 2–5 Ma	Increasing rate of global cooling and dropping sea levels. Palaeolatitude 27°	Increasing aridity, loss of vegetation, extreme rainfalls produce massive erosion, large alluvial/colluvial fans, coarse proximal and fine distal facies, up to 50 m of clayey sandy gravels and cobbles with local ferricretes. Possible early Pliocene intense weathering event	Formation of deep colluvial fans which provide excellent construction materials and rail corridor
Miocene 5–25 Ma	Growth of polar ice, reduced sea levels, global cooling offset by increased temperature associated with reduced latitude. Palaeolatitude 30°	Late Miocene aridityWarm, wet climate, mature landscape, deep weathering profiles, duricrusts, lacustrine or meandering mature alluvial deposition, up to 50 m of clays, clayey sands, goethitic clays, lacustrine limestone, some fine gravels, and pisolitic haematite enriched alluvium—correlates of CID. Mid Miocene intense weathering event and tectonic uplift Early Miocene sea levels 200 m above present levels	Extensive weathering profile and duricrust development, karst development, gentle rounded slopes develop
Oligocene (24–34)	Opening of southern oceans, Antarctic ice sheet established. Palaeolatitude 35°	Continuing high rainfall, warm, "tropical" weathering	Continuing weathering and erosion
Eocene 34–55 Ma Palaeocene 55–65 Ma	Uniformly warm phase produced "tropical" weathering to 45° latitude, restricted oceanic circulation, anoxic ocean basins. Palaeolatitude 45°	Late Eocene intense weathering event followed by aridity. Generally high rainfall, warm, "tropical" weathering and duricrusts developed on planation surface, alluvial sheet wash or braided alluvial deposits, residual soils locally preserved in dolomite karst, 10–100 m of silty sands and fine gravels, manganiferous goethitic clays developed on weathered dolomite surfacesEarly Eocene intense weathering event	Deep weathering, duricrusts, development of karst, early surfaces and initial slopes
Mesozoic 65–241 Ma			
Cretaceous 65–141 Ma	Faunal extinctions at end of Cretaceous continuing break-up of Gondwana. Palaeolatitude 60°	Late Cretaceous climate generally high rainfall, warm, "sub-tropical" and equitable with no polar ice, deep weathering profiles and duricrusts develop, long term sea levels 250 m above present levels	Weathering and erosion produces surfaces which form concordant summits after incision
Palaeozoic 545–251 Ma	Formation of Gondwana	Continental crustal plates coalesce to form a supercontinent, mountain chains formed between the plates are progressive eroded	Future Australian cratonic area fused together and eroded
Proterozoic 1.6–2.5 Ga	Capricornia orogen	Folding, faulting and jointingDeposition of sediments, BIFs, volcanics, intrusives	Bedded bedrock, dips, most discontinuities
Archean 2.5–3 Ga	Formation of crust	Granites and gneisses solidify close to earth's surface	Massive bedrock

Investigation reporting objectives

From an engineering perspective most investigation reports prepared for the railways had a dual function:

a. To provide sufficient information to support the design of the railway and the generation of an engineer's estimate of the cost of the project, so that project finance could be sought. Engineers' estimates typically aimed to be accurate to ±20% at feasibility level.
b. To provide ground engineering information to prospective tenderers for the contract works in the form of site-investigation reports. As such reports would ultimately have contractual significance it was important to control their style and content.

As a consequence of this dual function, investigation reports for the railways were prepared with the following objectives in mind:

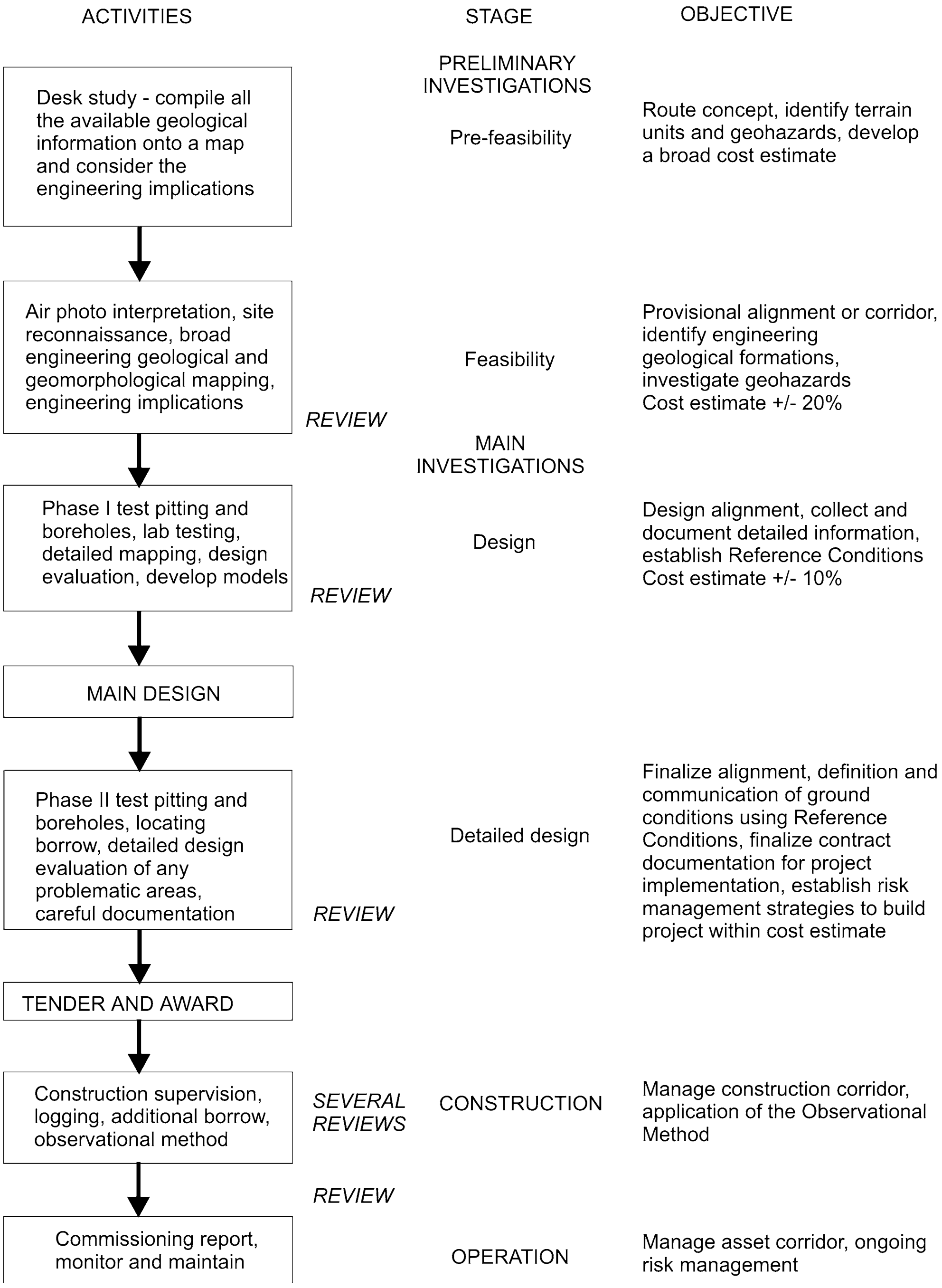


Fig. 8 Idealised project stages, engineering geological activities and strategic objectives

a. The overall aim of the investigation was to characterise the ground to the level where project scale unforeseen ground conditions were unlikely to be encountered. Some balance had to be established between expenditure on the investigations and the resulting benefit of the information obtained (Stapledon 1982). For these railways a reasonable balance between cost and benefit was considered to have been met when the following questions were answered in the affirmative:

i. Is the geology mapped at a scale of about 1:5000, reasonably well documented and sufficiently well understood to be able to generate reliable geological models (sketch maps and sections) for all cuts?
ii. Have all embankment foundation conditions been characterized?
iii. Have all sources of construction materials been located and their performance characterized?
iv. Have all geohazards been identified?
v. Is it reasonable to confidently complete the geometric design and then request tenders for construction?

b. All of the observations were presented using a standardised descriptive system to minimise confusion amongst design or construction engineers about the geological and geotechnical descriptions of the materials. In the Pilbara the Australian Standard for Site Investigations, AS1726 (1993), formed the basis of the descriptive system.
c. There was an emphasis on non-written communication i.e. colour photographs, maps and drawings, so that those with little or no understanding of the engineering geological descriptive terms could gain an appreciation of the ground conditions by looking at the photographs, especially where the information related to machine performance such as ripping trials and backhoe excavations.
d. All information relevant to the project was assembled and made available either as reports provided to prospective tenderers or assembled in a room for viewing by prospective tenderers (c.f. the guidelines of the Construction Industry Committee 1987).
e. A clear distinction was drawn in the reports between observations, interpretations and opinions to minimize confusion as to the nature of information being provided. All of the site-investigation information was compiled into a ''factual report'', which consisted of observations but not interpretations, and a separate ''interpretation/evaluation report'' in which the interpretations and opinions were documented. Both kinds of report were provided to prospective tenderers.

From the Owner's perspective, the more that carefully presented information could be provided to prospective tenderers, the less was their uncertainty during the brief period when they prepared their bids. As uncertainty can only be allowed for in a bid price by an increase in the cost estimate, these strategies were specifically directed at obtaining the most competitive bids for building the project.

Importance of geo-mapping

Mapping was not a significant component of the investigations of the earlier (i.e. pre 1990s) Pilbara railways, and efforts were instead directed immediately to more costly sub-surface investigations. This proved to be ineffective and is typical of the *traditional approach* (Fig. 1) that is adopted in many heavy civil engineering projects throughout the world. It has been caustically described as *''drilling first and asking questions later''* and is the antithesis of the *total engineering geology approach*. The *traditional approach* is a particularly ineffective way of investigating long linear structures such as railways because carrying out subsurface investigations too early in such projects almost inevitably results in having to carry out additional expensive subsurface investigations due to changes in the alignment required by ongoing design. In contrast, early engineering geological and geomorphological mapping of a route corridor is far less expensive and far more productive because it involves no expensive plant and is more likely to provide information relevant to whatever final alignment is chosen.

More importantly, mapping of the route corridor requires careful observations of the geology and geomorphology, interpretation of the near surface ground conditions, reporting and the generation of a ''model'' into which all of the information is incorporated for future analysis. Thus geo-mapping can be regarded as the essential and defining strategy of the *total engineering geological approach*.

Where this approach was adopted, considerable reliance was ultimately placed on detailed engineering geological and geomorphological mapping of the routes at various scales as the primary method of investigation. Using mapping as a primary investigation tool also allowed the subsurface investigations that were subsequently required, such as drilling and ripping trials, to be planned and targeted to investigate the engineering geological formations in a more systematic fashion. The alternative *traditional approach* often locates subsurface investigations without regard for the geology; for instance, planning boreholes at the highest point of the deepest cuttings, where the existing access tracks cross the centre line or, possibly worst of all, exactly every 5 km along the centre line!

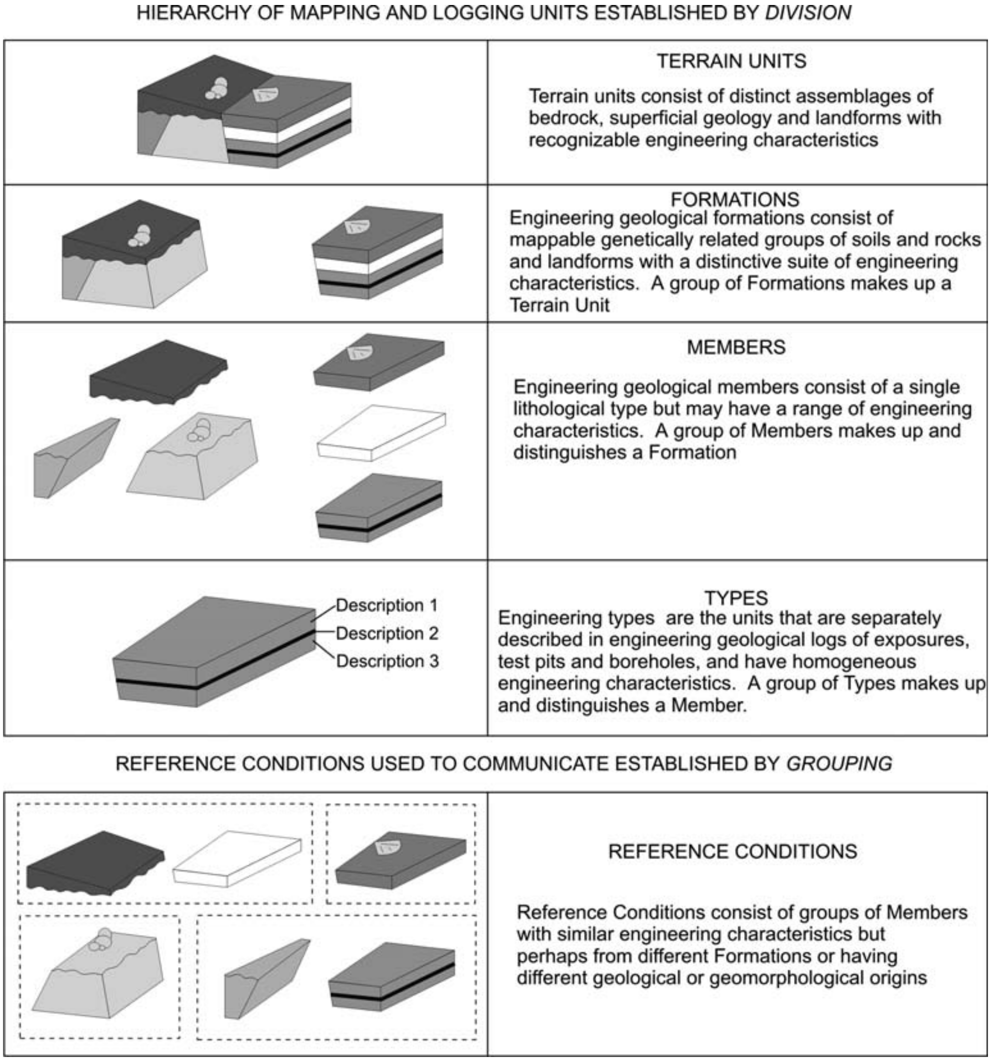
The engineering geological maps were produced with the objective of differentiating geological units with characteristic engineering behaviour (Fookes 1969; Dearman 1991). In practice it was found that the *total engineering geological approach* required the identification of mapping units at four different scales for which the following terminology was adopted:

a. *Terrain Units*, which consist of distinct assemblages of bedrock, superficial deposits and landforms with recognizable engineering characteristics and which were mapped at a scale of about 1:50000 to 1:250000. Terrain systems mapping has recently been reviewed by Phipps (2001).
b. *Engineering Geological Formations*, which consist of genetically related groups of soils and rocks and landforms with a distinctive suite of engineering characteristics and which were mapped at a scale of between 1:5000 and 1:50000. These units were termed ‘‘engineering formations’’ by Dearman (ibid).
c. *Engineering Geological Members*, which consist of a single lithological type but which might have a range of engineering characteristics. Variations in engineering characteristics within *members* often result from the influence of tectonics and surface processes upon lithology and thus reflect the total geological and geomorphological history. They were usually mapped at a scale of 1:5000 to 1:1000 for the detailed design of specific project elements. These units were termed ‘‘lithological types’’ by Dearman (ibid).
d. *Engineering Geological Types*, which are units that have effectively homogenous engineering characteristics and were described using standard descriptive systems, usually in logs of boreholes, test pits and exposures.

The different mapping units were logically differentiated in the field, on the map legend or on logs using the processes of *division* described by Varnes (1974). The mapping units provided a framework for systematically making observations and collecting information.

Definition of Reference Conditions

The definition of Reference Conditions was another essential strategy of the *total engineering geology approach*. Reference Conditions (CIRIA Report 1978) consist of groups of geological materials with similar



Terrain units consist of distinct assemblages of bedrock, superficial geology and landforms with recognizable engineering characteristics

Engineering geological formations consist of mappable genetically related groups of soils and rocks and landforms with a distinctive suite of engineering characteristics. A group of Formations makes up a Terrain Unit

Engineering geological members consist of a single lithological type but may have a range of engineering characteristics. A group of Members makes up and distinguishes a Formation

Engineering types are the units that are separately described in engineering geological logs of exposures, test pits and boreholes, and have homogeneous engineering characteristics. A group of Types makes up and distinguishes a Member.

Reference Conditions consist of groups of Members with similar engineering characteristics but perhaps from different Formations or having different geological or geomorphological origins

Fig. 9 Logical relationships between the mapping units and the Reference Conditions engineering characteristics, and depict the range of geological conditions that can reasonably be anticipated or foreseen (Essex 1997; Knill 2003). They were used to describe and communicate the geological conditions to project engineers. In contrast to the process of *division* used to establish the mapping units, the process of *grouping* (Varnes 1974) was used to establish Reference Conditions. The relationships between the different levels of mapping units and the Reference Conditions are illustrated in Fig. 9

The definition of Reference Conditions was also a part of developing the models that were central to the understanding and communication process. In most projects, the geological model is based upon observing or sampling only a small part of the ground, and alternative interpretations are possible. Where a project is to be constructed under contract and where there is uncertainty in the level of understanding of particular features of the ground, which could have had a significant influence on the Contractor's choice of method or cost, the use of Reference Conditions indicates the assumptions that have been made for the basis of the contract (Muir Wood 2000).

In the case of the central Pilbara, all of the lithostratigraphic units are essentially different successions of BIF and shale, with dolerite intruded to varying degrees. The strata have all been subject to folding, faulting, deep weathering and duricrust formation. Thus the large number of different geological formations (with a stratigraphic nomenclature that varies from map sheet to map sheet and has been revised on various occasions) can be reduced to a smaller number of Reference Conditions, which can be communicated using as few esoteric geological terms as possible.

The important functions of Reference Conditions may be summarized as follows:

a. To formally define and describe the components of the engineering geological formations and the geological models.
b. To simplify the geology by grouping together the geological units with similar engineering characteristics, which eases communication to engineers.
c. Most importantly, to document the conditions that can be reasonably foreseen for contract purposes.
d. To allow a reduction of overall laboratory testing schedules - only representative samples from each Reference Condition have to be tested rather than testing all geological units encountered.
e. To allow the incorporation of knowledge from similar geological units that occur outside the project area and that may be correlated with the Reference Conditions.
f. To be of practical help during construction in matters such as predicting equipment performance and capability.

Examples of some typical Reference Conditions used in the central Pilbara are provided in Table 2 and the suite of geological and engineering characteristics of one typical Reference Condition are provided in Table 3.

The use of models

The use of geological models in project engineering has been described in detail by Fookes (1997), the strategic application of geological modelling on a specific project has been described by Newman et al. (2003), and the more general use of models in ground investigations has been discussed by Harding (2004). The *total engineering geology approach* relies heavily on the use of engineering geological models (Fookes et al. 2000) to:

a. Assemble and collate a disparate information base;
b. Interpret, present and communicate the observed or inferred conditions;
c. Indicate conditions that might be reasonably anticipated and might require further investigation.

In order to be useful any model must satisfy three criteria (Moores and Twiss 1995):

a. The model must be *powerful*, that is capable of explaining a large number of disparate observations.
b. The model must be *parsimonious* and must use a minimum number of assumptions compared to the range of observations that it explains.
c. The model must be *testable*, which means that it must anticipate conditions that at least in principle can be verified by observation.

The models that were developed for the railway projects in the Pilbara took the form of simple geological and geomorphological maps and sections, combinations of geological, geomorphological and geotechnical information in engineering geological maps and sections, evolutionary diagrams and 3D block models. These models presented three different kinds of information:

a. *Conceptual models*, which indicated the geological relationships between mapping units, their likely geometry, and anticipated distribution e.g. Fig. 10. These kinds of conceptual models were used to conveniently represent the nature of different Terrain Units and Engineering Geological Formations.
b. *Observational models*, which presented the observed and interpreted distribution of Reference Conditions in 2D models such as maps and sections and in 3D models such as block diagrams, and were constrained by subsurface data or by extrapolation from the surface e.g. Fig. 11.
c. *Evolutionary models*, which illustrated the way in which the Terrain units, Engineering Geological Formations or Reference Conditions developed in time using a series of sketch maps, sections or block

models e.g. Fig. 12. Block models depicting the geological and geomorphological development with time become 4D (i.e. 3D plus the dimension of time).

The models were used to develop an understanding of the *total engineering geology*, to target areas for subsurface investigations, or for detailed mapping investigations (especially for potential borrow sources or geohazards such as landslides, unstable soils and flooding), to relate sites within the railway route corridors to the local and regional geological stratigraphy and structure, to assess cutting excavatability, embankment foundation conditions and the location of construction materials, and to engineer controls on the occurrence of selected geohazards. Very importantly, the models were used as graphic tools to communicate the interpreted and anticipated conditions to project engineers. Such relatively simple models helped project engineers to understand the engineering implications of the geology

Table 2 An outline of selected Pilbara Reference Conditions

Reference condition	Geological origin	Engineering characteristics	Engineering performance
Fine grained soils	Alluvial sands and silts, distal alluvial/colluvial deposits, aeolian silts, gilgai (high plasticity clay deposits), clayey residual soils developed over dolerites, basalts and some granites, mangrove muds, supratidal flats.	Uncemented soil deposits with > 50% of particle sizes < 2.36 mm and a significant clay or silt content.	Unsuitable as fill, potentially troublesome embankment foundation, erodable, low cut slope angles.
Coarse grained soils	Alluvial gravels, proximal alluvial/colluvial deposits, colluvium and taluvium, gravelly weathering profiles developed over some granites.	Uncemented soil deposits with > 50% of particle sizes > 2.36 mm, low clay and silt content, significant gravel content, often some cobbles.	Good source of borrow for general and select fill, generally good embankment foundation
Duricrusts	Gravels, cobbles and rock materials developed in-situ by cementation of superficial deposits and weathering profiles due to: accumulation of calcium carbonate (calcrete - also developed on freshwater and aeolian coastal limestones); iron enrichment by haematite/goethite during weathering (ferricrete); or accumulation of silica (silcrete).	Ranges from gravely soil deposits to irregular variable masses of rock material with dimensions > 1000 mm, rock material formed in-situ with low to high strength. Characteristics vary rapidly over short distances.	May break down upon handling or exposure, not necessarily rock in contract terms, source of general fill but may require blasting, variable embankment foundation conditions
Extremely weathered bedrock	Deep clayey or silty weathering profiles developed over Weeli Wolli Dolerite, Mt McRae Shale, Mt Sylvia Formation shales, Bee Gorge Member shales, some weathered granites and basalts.	Soils developed by weathering of bedrock, generally with a significant clay and silt content, corestones and relict structures common,	Erodable if exposed in cuts or fills, prone to shrink swell and requires encapsulation if used as fill
Shaley BIF	Parts of Weeli Wolli BIF, Yandicoogina Shale, Joffre unit, Whaleback Shale, Dales Gorge Member.	Fresh or slightly weathered high strength BIF with bedding planes spaced at 5–25 mm, BIF with > 30% of weak siltstones, distinctly weathered low strength BIF with bedding planes spaced at < 100 mm,	Often excavated as common, potential source of select fill but can be too platey, may break down on handling.
Blocky BIF	Parts of Weeli Wolli BIF, parts of Joffre unit, parts of Dales Gorge Member, Mt Sylvia Formation Brunos Band and BIF Twins, shale poor or mineralized BIF sequences	Fresh or slightly weathered high strength BIF with bedding planes spaced at 50–300 mm	Requires blasting, provides good rockfill but can be slabby, steep cut slopes
Blocky bedrock	Relatively unweathered parts of Weeli Wolli Dolerite, Archaen granites and gneisses, Fortesque Group basalts, sandstones and quartzites.	Fresh or slightly weathered high strength rock with joints spaced at 50–3000 mm, equidimensional blocks, no pervasive fabric	Requires blasting, provides good rockfill, rip-rap, steep cut slopes
CID	CIDs within Tertiary palaeochannels	Fresh or slightly weathered low to high strength flat bedded rock with joints spaced at 50–300 mm, equidimensional blocks, no pervasive fabric.	Some rippable but mostly requires blasting, provides good general fill, steep cut slopes

and to appreciate the importance of collecting geological evidence and the power of geological observation, interpretation and anticipation.

Effective subsurface investigations

Subsurface investigations were an essential part of the studies for the railways, but wherever possible the scope of the subsurface works was limited in order to minimize expenditure. The objectives of the subsurface investigations were to provide additional data in areas of geological uncertainty defined by the geo-mapping, and to provide representative data to document the Reference Conditions. Test pits dug by rubber-tyred backhoes were often used to characterize the mapped units within the corridor. Boreholes were used at the location of some of the deeper cuts to confirm the surface mapping. In the

Table 3 Example of a Reference Condition in detail

Reference condition	Blocky BIF
Stratigraphic origin	Weeli Wolli BIF, Joffre unit, Dales Gorge Member and Mt Sylvia Formation, Brunos Band and BIF Twins
Lithological description	Finely bedded BIF with occasional shale beds. BIF comprises interbedded shale, chert and hematite and is typically red-brown to red-purple and grey in colour. Units commonly silica/chert (jaspilite) rich, red grey striped with chert pods. Duricrust development has resulted in cementation at the surface in places. Locally haematite enriched to ore, or altered by a duricrust. Fibrous mineralisation may be encountered
Structural geological characteristics	Pervasive bedding fabric throughout, orientation varies due to folding, bedding spacing typically 2–5 mm, bedding partings 50–300 mm. Bedding commonly more widely spaced in silica/chert rich (jaspilitic)) units. At least two orthogonal sub-vertical joint sets typically present, spaced 0.5–4 m, discontinuous to continuous, slightly rough to rough. Up to 2 other joint sets can occur. Jointing tends to be less well developed as shale content increases. Many joints open near surface and in-filled with clay gravel and rootlets.
Degree of weathering	Variable. For engineering applications at relatively shallow depths expect rock mass to be Distinctly Weathered. Weathering often concentrated preferentially along bedding planes or joints, where wall rocks may be more weathered than the general rock mass.
Material strength	Estimated strength ranges from Low to Very High. UCS indicates materials can have Extremely High Strength (Note an extremely high UCS value 447 MPa has been reported). UCS indicates that Very High strength materials common in the upper 10 m, suggesting increased strength due to development of a duricrust. Anisotropic, weaker parallel to bedding, higher strength perpendicular/across bedding.
Rock quality/defect spacing	Depends on degree of weathering. Rock quality increases as weathering decreases. Typically expect RQD less than 50% and often less than 25% due to pervasive bedding fabric.
Design slope angles	1 v:1 h for extremely weathered rock or shallow cuts to 2 v:1 h for Distinctly Weathered to Fresh rock and deeper cuttings. If slopes undercut bedding careful mapping and monitoring is required to assess potential for failure. Slopes may be required to be cut back to dip of bedding if bedding under-cut.
Embankment foundation suitability	Suitable.
Expected excavation techniques	Predominantly rock requiring blasting, minor common (typically expect less than 5%). depending on degree of weathering, development of bedding and secondary cementation.Abrasive.
Expected excavated material types	Predominantly Type 3 coarse fill, some Type 3 graded fill.
Comments	Often a relatively open rock mass (along bedding planes and joints that may be infilled with soil materials). Some caves and overhangs to 5 m deep developed in cliffs. Most likely variations: • Degree of weathering and/or shale content increases and bedding parting spacing increases or duricrust development results in materials become Shaley BIF. • Bedding parting spacing increases such that materials become blocky bedrock.

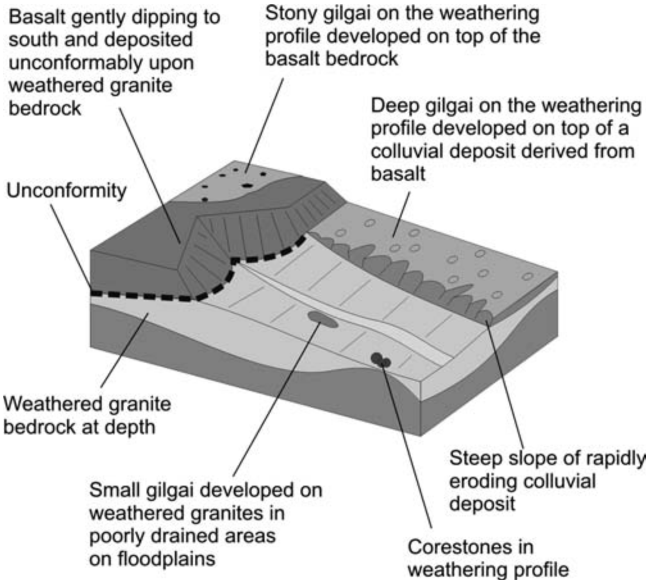


Fig. 10 Conceptual model used to explain the genesis and distribution of different types of Pilbara Gilgai. The model includes two conspicuous Terrain Units (basalt hills and pediplains) and several mappable Engineering Geological Formations (granites with weathering profiles, basalts with weathering profiles, stoney gilgai, deep gilgai, colluvial deposits and floodplains)

sparsely vegetated rolling country of the Pilbara, the use of large bulldozers (typically Caterpillar D10s) to excavate deep wide trenches (locally called "costeans") to expose the ground conditions was a particularly successful and cost-effective subsurface investigation technique. Information collected from such costeans was used to assess excavatability based on the techniques described in Pettifer and Fookes (1994).

Attempts have been made to assess rippability using geophysical techniques in the form of seismic refraction traverses. However, there were difficulties in reliably interpreting the information and it was not found to be a useful technique for investigating railways in the Pilbara.

A limited number of boreholes were also required simply to support the letting of the construction contracts. It was considered important to provide prospective tenderers with "traditional" types of information (i.e. boxes of core for viewing during the tender preparation) to counter any later claim that the information provided was somehow unusual. Selected boreholes also ideally documented each Reference Condition and, as part of the project information base, formed an essential part of the understanding of the ground.

Established design objectives

The design of the ground engineering–related aspects of the railway mainly involved:

a. Optimization of the horizontal and vertical alignment, and the associated excavation volumes and earthworks volumes, as these represent the principal cost variable;
b. The definition of construction materials, both from cuttings and borrow;
c. The design of cut and fill slopes, bridge foundations and drainage to achieve a certain performance.

Inputs from engineering geologists into ground engineering design included the choice of cut batter angles, excavatability assessments and assessments of any geohazards that had been identified.

At the Design stage (sometimes called a Definitive Engineering Study in the Pilbara), both the Owner and the Engineer desire to refine the cost estimate, perhaps to ± 10%. This was seldom achievable for the ground engineering components because of the large degree of uncertainty that still existed. However, because cost uncertainties associated with other non-geological aspects of the project such as steel, concrete, sleepers and many of the fixed costs were often less than ± 10%, inaccuracies in the cost estimates of the ground engineering components that exceeded ± 10% were balanced by the other components. This often resulted in a net cost estimate that went some way towards meeting the aim of ± 10%.

Detailed design occurred towards the end of the main investigation phases and included the finalization of the documentation for the contractors. At this stage, the engineering geological information was generally summarized into two kinds of report:

a. An "interpretive report", which included the details of the design and which was made available to the prospective tenderers.
b. An internal "basis of design report" in which detailed information relative to the design process and assumptions was documented. As such information had no bearing upon the activities of the Contractor, and it was not made available to prospective tenderers.

The detailed design phase was not always clearly defined as a separate activity because it was intimately tied to the final stages of project financing and was often influenced by the developing contractual relationships between the Owner and the Engineer.

The observational method

It was not possible to completely investigate every detail of the geology and geomorphology of any of the railway routes prior to construction for logistic and financial reasons and hence the design and attached Engineer's cost estimate were always necessarily based on limited information. In order to overcome the inherent uncertainty that will always be present in any ground engineering the Observational Method was routinely adopted during railway construction.

The Observational Method involves more than just observing geological conditions during construction and responding to failures, although it is this view of the method that prevails in many projects. To properly apply the Observational Method the engineering implications of a range of conditions that can be reasonably anticipated from the Geological Models must be overtly considered before construction starts and the project managed with these implications in mind. (Peck 1969; Fookes et al. 2000). The uncertainty can best be dealt with by conceiving a range of designs and allowing for them in the cost estimate as a contingency. During construction, if changes in the as-encountered ground conditions are observed, the designs may be modified accordingly. Providing the contract contains sufficient flexibility, variations will not cause undue concern to either the Contractor or the designer.

The method was found to be particularly useful in the railway construction in the Pilbara because of the following reasons:

a. The *short time frame* within which many of the projects had to be implemented. In some projects it was planned to construct several hundred kilometres of heavy-duty railway track within 3 years from commencement of a feasibility study.
b. The *cost benefit* of carrying out investigations prior to project approval. To investigate many tens of deep cuttings with boreholes in rugged country would have taken a long time and cost several million Australian dollars—time and money that were not necessarily available.
c. An awareness of the *relative ineffectiveness* of any subsurface investigation technique when compared to full-scale excavations in finding what is actually in the ground. Whilst 20 m of good quality 83.1 mm diameter oriented PQ3 core from one location can be extremely useful, it is very expensive to acquire and it can never provide as much geological detail as a 20 m deep 100 m long cutting at the same location.

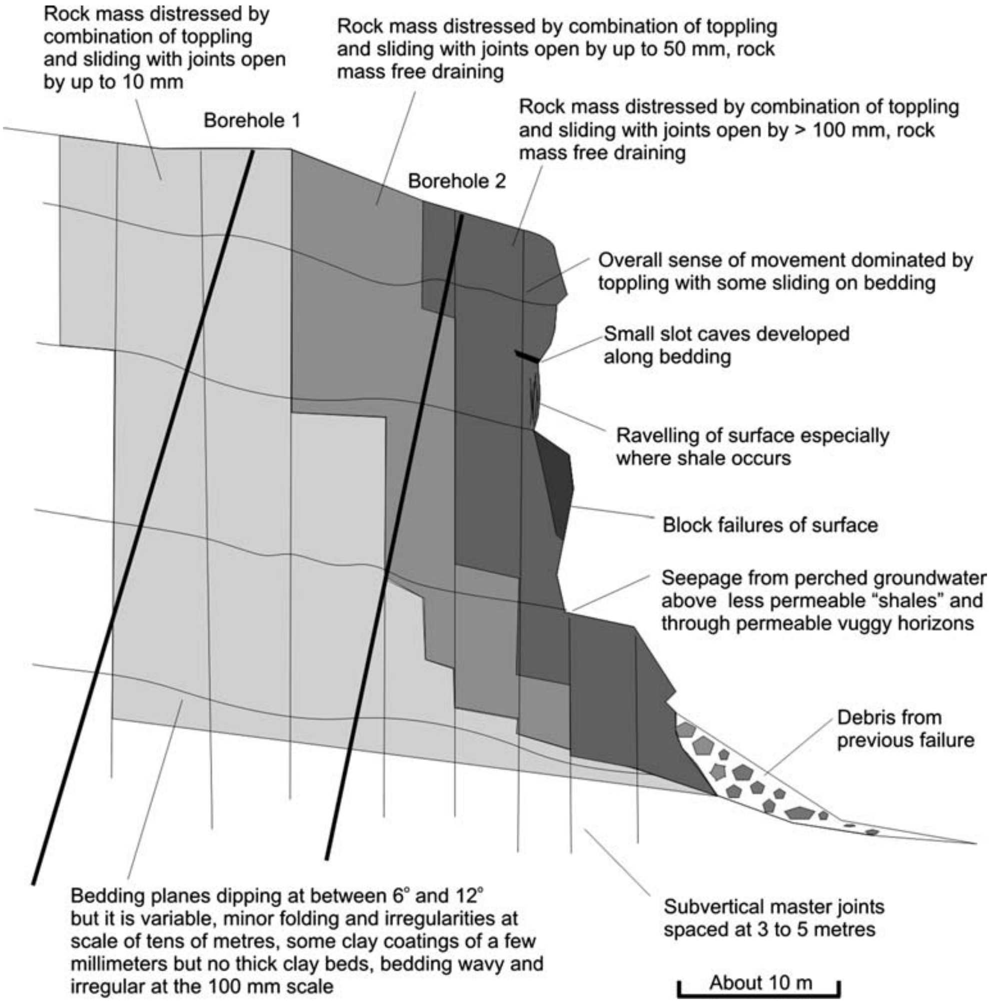


Fig. 11 Observational model of a steep Pilbara BIF slope that was investigated by boreholes to assess stability. The model indicates the factors that control stability—the geometry and characteristics of geological structures, the distribution of Engineering Geological Members with different proportions of BIF and shale, and the groundwater conditions

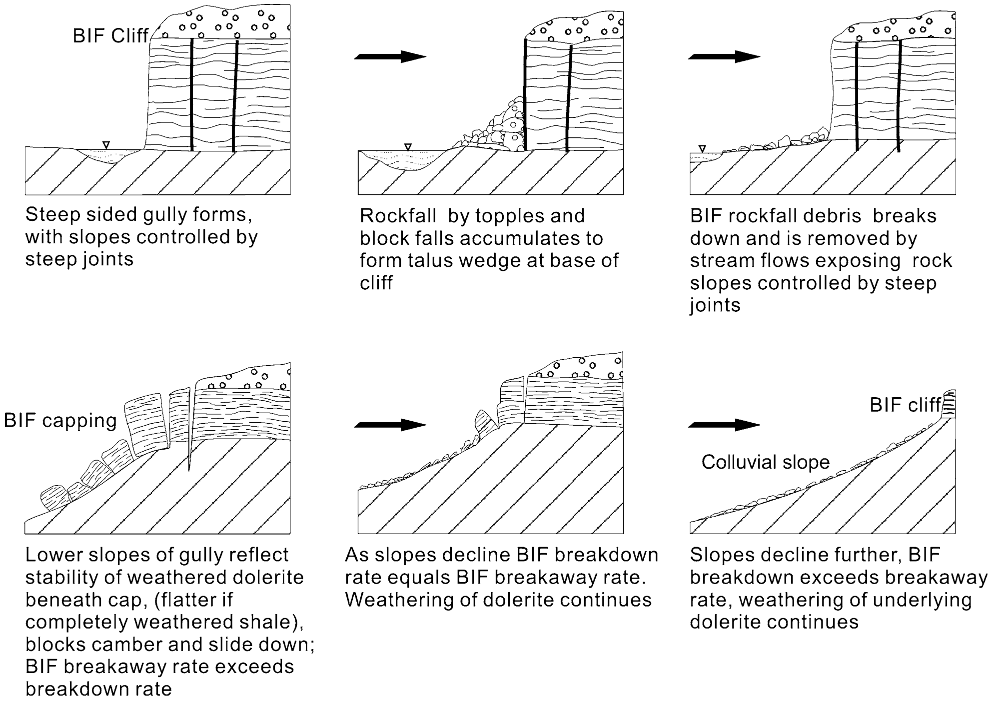


Fig. 12 Evolutionary model of Pilbara slopes underlain by BIF and dolerite used to anticipate excavation conditions. The model describes landform development controlled by juxtaposed Engineering Geological Members

Responsibilities during construction and operation

Adoption of the Observational Method during construction required engineering geologists to be on site and to form part of the construction team. The responsibilities of those engineering geologists included the following:

a. The application of the Observational Method.
b. The redesign of cut slopes if required.
c. Earthworks materials management including classification of fill materials and the nomination of adequate borrow areas.
d. The location and identification of further borrow if required.
e. Geohazard identification, especially of asbestiform minerals.
f. The documentation of as-encountered conditions for contract management purposes.
g. The confirmation of the nominated Reference Conditions.

Upon completion of construction an as-built report and maintenance manual was generally produced to:

a. Document the as-built conditions, particularly excavation stability, fill batter slopes, the finishing and detailing of the works and surface drainage.
b. Identify any risks that the Owner should be aware of when taking over the works e.g. areas where rockfalls may occur or where culverts may be damaged by floods.
c. Outline any maintenance and monitoring that was likely to be required over the operating life of the railways.

Required resources

It is always difficult to estimate how long it will take to carry out the type of studies that have been described in this paper. Table 4 is based on a number of different projects and indicates in very broad terms the typical number of experienced engineering geologists and the approximate time taken for each of the different project stages involved in building about 50–100 km of railway track across relatively flat ground. Similar resources were required for about 10–30 km of track across more deeply incised hilly country. Each of the engineering geologists

Table 4 Typical resource requirements for 50–100 km of railway across relatively flat country or 10–30 km of railway across deeply incised hilly country

Stage	Resources	Comments
Pre-feasibility	Two engineering geologists	40 man days (2×20)
Feasibility	Two engineering geologists	100 man days (2×50)
Design	One engineering geologist	60 man days (1×60)
Construction	One engineering geologist	Duration of construction—300 man days (1×300)
Operation	One engineering geologist	20 man days for commissioning report (1×20)

concerned had a minimum of 10 years experience and had worked in the Pilbara on a number of occasions i.e. they were equivalent to someone who had attained Chartered Geologist status and had worked in a variety of engineering projects in remote locations for over 10 years.

In addition to these resources, the periodic involvement of other specialists was arranged to ensure the required breadth of technical knowledge that was applied to the project. At various times the geo-team included:

a. A very experienced engineering geologist to provide technical reviews of the engineering geology studies.
b. A specialist blasting consultant.
c. A specialist earthworks consultant.
d. A specialist asbestiform minerals consultant.
e. A specialist regional geology consultant.

All of these resources were brought together to generate high-quality geological knowledge and to present and communicate that knowledge to the engineers involved in the design, construction and operation of the railway. Figure 13 is an assessment of the rate at which geological knowledge was accumulated in several Pilbara railway projects using the resource levels indicated in Table 4 and adopting the *total engineering geology approach*.

Independent review

Independent formal review by experienced practitioners is generally acknowledged as being one of the most effective ways of ensuring the quality of studies relating to ground engineering (Fookes 1997). The use of a formal review was found to be extremely beneficial on these railway projects, with two levels of review on some, one at a local level and the other at an international level. By incorporating these levels of review the quality of the engineering geological studies was maintained. The international reviewer often reported directly to the Owner even though retained by the Engineer. This encouraged frank, objective discussions of the issues and avoided any commercial interests influencing review findings.

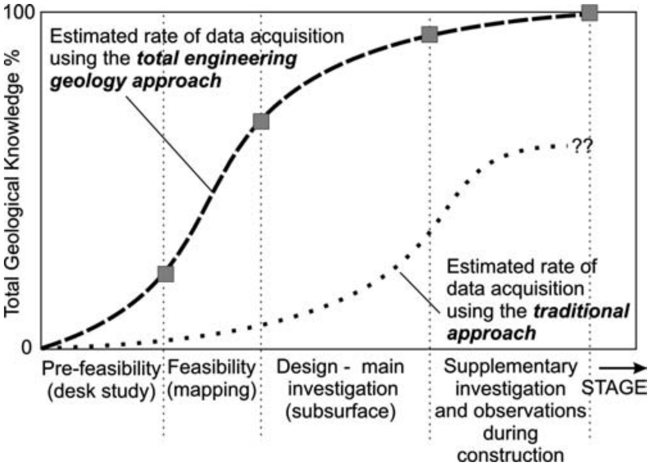


Fig. 13 Comparison of knowledge acquisition using the *total engineering geology approach* and the typical geotechnical engineering *traditional approach* for several railway projects in the Pilbara. The assessed rates of knowledge acquisition are based on the pooled judgement of the authors, who were intimately involved in projects that used both approaches

Part 3: Engineering geology issues

The *total engineering geology approach* requires the involvement of engineering geologists in many different aspects of investigation, risk management, design and construction supervision that relate to ground engineering. Tasks involving routine data collection such as logging test pits and boreholes are generally recognized as being necessary by civil engineers managing projects. However, certain engineering geology issues requiring specialized studies such as detailed aerial photo interpretation or observations of particularly relevant geofeatures that were a considerable distance from the railway line were sometimes well outside the experience of the engineering management. In such cases approval to undertake the necessary studies was obtained once the cost benefit or potential for risk reduction were demonstrated to the engineering management. As engineering managers were exposed to the benefits of the approach they gradually began to appreciate the contribution that engineering geologists could make to projects.

Geohazards

Identification and assessment of geohazards that could impact upon the construction and/or operation of any project is always a key investigation activity. Geohazards that have been identified in the Pilbara include large rockslides, karst, asbestiform minerals, collapsing soils, reactive clays, seismicity, flooding, concrete aggregate soundness and settlement due to dewatering.

Rockslides

The occurrence of substantial rockslides in the Pilbara may be anticipated because of the steep slopes, incised topography and gently folded bedrock containing weak layers along bedding. A large rockslide has been documented (Wyrwoll 1986) and several large rockslides (estimated volumes of the order of 50 million m^3) have been identified in aerial photographs associated with one particular stratigraphic unit known as the MacCrae Shale. Some of the rockslides have developed where the bedding planes daylight with dip angles as low as 9°.

During feasibility level investigations for one railway the possibility of initiating large scale instability by excavating deep cuts in certain parts of the stratigraphic succession containing shale was identified. The highest risk occurred where cuts ran parallel to strike and excavations across dip slopes could undermine dipping strata. With these very large rockslide risks a strategy of avoidance was adopted due to the time and likely cost of developing engineered solutions and the residual levels of uncertainty that would remain regarding the effectiveness of the proposed stabilization measures.

Karst

Karst landforms (Waltham and Fookes 2003) are neither well developed nor particularly common in the Pilbara but the presence of sinkholes may be anticipated in particular geological settings and karst features have been documented (Waterhouse and Howe 1994). Hazard zones are typically associated with many of the broad valleys that are underlain by the Wittenoom Formation (which consists of metamorphosed dolomite, dolomitic pelite, chert and volcaniclastic sandstone) and which contain thick infills of Tertiary detritals, including lacustrine limestones and associated calcretes. In these areas individual sinkholes could sometimes be seen on 1:40000 aerial photographs and were identifiable on low-level 1:5000 aerial photographs and during helicopter inspections. In one karst hazard zone, where groundwater had been pumped from a karst aquifer, several sinkholes tens of metres in diameter have formed within the last few decades.

Where individual sinkholes were identified during investigations they were avoided by the railways during early route-selection studies. However, there remained a risk that sinkholes could develop in the future within karst-hazard zones and impact on a railway crossing the zone, although this was considered rather unlikely as the rate of development of sinkholes was thought to be currently very low. The hazard was engineered using risk management techniques originally developed for landslide risk assessment (Anon 2000). The risks were quantitatively assessed as the mathematical product of hazard and consequence and expressed in terms of annual probabilities of death, loss of property and loss of earnings. The hazard was considered as the annual probability of the process occurring and the consequences were related to a series of conditional probabilities that the elements at risk would be impacted, thus:

$$R_{(\mathrm{D/P})} = P_{(\mathrm{H})} \times P_{(\mathrm{S:H})} \times P_{(\mathrm{T:S})} \times V \times E$$

where

$R_{(\mathrm{D/P})}$ is the risk, which is the annual probability of death *or* the annual loss of property value, annual loss of life expressed in dollar terms, or the annual loss of earnings due to downtime.

$P_{(\mathrm{H})}$ is the annual probability of the process occurring (expressed as a rate of sinkhole formation of a certain size per unit area)

$P_{(\mathrm{S:H})}$ is the probability of spatial impact of the process on the elements at risk, given the event i.e. the probability that the zone of influence of the process, which is the sinkhole development, coincides with the area or footprint occupied by the element at risk.

$P_{(\mathrm{T:S})}$ is the temporal probability that an element at risk is in the footprint at the time of impact e.g. the probability of a train (that may be occupied by people) being present in the footprint.

V is the vulnerability, which is the probability of loss of life of the individual given the impact or the proportion of property value lost or damaged or the proportion of time lost.

E is the element at risk e.g. the value of the property, probable number of people present or profit from continuous production.

This information was used to calculate the risk for various scenarios to make informed decisions about the cost benefit of engineering options. Those options ranged from relocation of elements at risk away from hazard zones to managing activities that could trigger karst collapse such as groundwater extraction or concentrated infiltration. The engineering options included monitoring, to detect early signs of subsidence developing.

Fibrous materials

Due to the regional metamorphism, fibrous amphiboles occur within both the BIF and dolerite, usually as actinolite. At some stratigraphic horizons the particular chemistry of the volcaniclastic host sequences and the presence of inter-bed shearing associated with regional folding has produced fibrous amphiboles such as crocidolite (blue asbestos). Inhalation of blue asbestos fibres during mining and processing has caused the deaths of many workers in Western Australia and one of the world's most notorious crocidolite mines was developed in the BIF sequences at Wittenoom Gorge in the central Pilbara (Trendall and Blockley 1970; Fetherston and Brown 1990; Western Australia Mining Operations Division Pamphlet undated).

Due to the potential for risk to the workforce stringent protocols were established in order to manage the hazard. The protocols involved the identification of the hazard and the adoption of various levels of protective clothing together with construction procedures such as watering to keep down dust, covering spoil and working in sealed cabs, in order to reduce any exposure to harmful fibrous minerals to acceptable levels. Regular, open communication of the nature and occurrence of the hazard to the workforce was found to be a particularly effective way of managing the risk.

Collapsing soils

The presence of recent deposits of loose fine alluvium and loose wind-blown silts associated with flash floods and aeolian transport processes is to be anticipated from the cyclonic semi-arid environment and limited vegetation cover. Such materials can collapse upon inundation after loading (Cooke 1986; Waltham 1994) and could cause embankments to settle; they are also difficult to wet and compact. The materials were recognized by a combination of mapping and test pitting and were usually less than about 300 mm deep. During construction these fine dusty surface materials were removed from below the embankment footprint. Where loose silts and sands occurred as lenses within deeper soil profiles they could not be economically removed. In such cases settlements were estimated to be neither catastrophic nor excessive i.e. perhaps a maximum of a few hundreds of millimetres. The possibility of such settlements occurring was generally taken into account in design by planning for re-ballasting of the track.

Reactive clays

The presence of reactive clays, i.e. moisture-sensitive clays, is to be anticipated in soils forming part of, or derived from, deep weathering profiles developed on basic rocks such as metabasalts and dolerites (Anon 1997); the presence of reactive clays should also be anticipated in soil profiles developed in arid and semi-arid environments (Cooke and Warren 1973). Reactive clays in the soil profile cause large volume changes during the annual cycle of extreme wetting and drying in the Pilbara and create characteristic landforms. These areas are known as gilgai and may be identified by their distinctive surface forms (mounds several tens of centimetres high, deep polygonal desiccation cracks and “crabholes”) during aerial photo interpretation and surface mapping. Figure 10 illustrates different types of gilgai developed in certain geomorphological settings.

Deep gilgai were generally avoided by rail alignments as the problems associated with crossing them can be quite severe. Where older railway lines have crossed such areas, progressive re-ballasting of formation that has “disappeared” into soft surface materials has led to an accumulated ballast thickness of over one metre.

Flood

The typical location of the railway corridor within the wide valleys of the central Pilbara is on the large colluvial/alluvial fan systems. The fans have developed where drainage lines that cut through the strike ridges of bedrock debouch (see Figure 14) and the distal portions often coalesce to form a relatively uniform surface that slopes gently down to the flood plain. Railways constructed across this sloping surface can minimise earthworks and avoid the major flood hazard and the reactive clays within the floodplain deposits. However the semi-arid environment coupled with the propensity for cyclonic rainfall events provides potential for large-scale flash flooding in the channels incised into the fan systems. During the time that there have been railways in the Pilbara, floods have washed out many sections of embankment and levees have been constructed to protect certain sections of railway threatened by mobile channels within fan complexes. Within the design lives of the existing railways there is the possibility of massive destructive events and channel avulsion (a sudden change in the course of a river), when many culverts would be blocked by the movement of gravels and overwhelmed. The paucity of hydrographic data means that flood recurrence intervals are difficult to assess and a general appreciation of the geomorphological setting and channel widths of the various drainage systems could be of use in design. However, the economics of railway construction are such that culverts are generally designed simply to cater for 25 year floods and the potential effects of larger events and general uncertainty in the design are treated as an acceptable risk by the Owners.

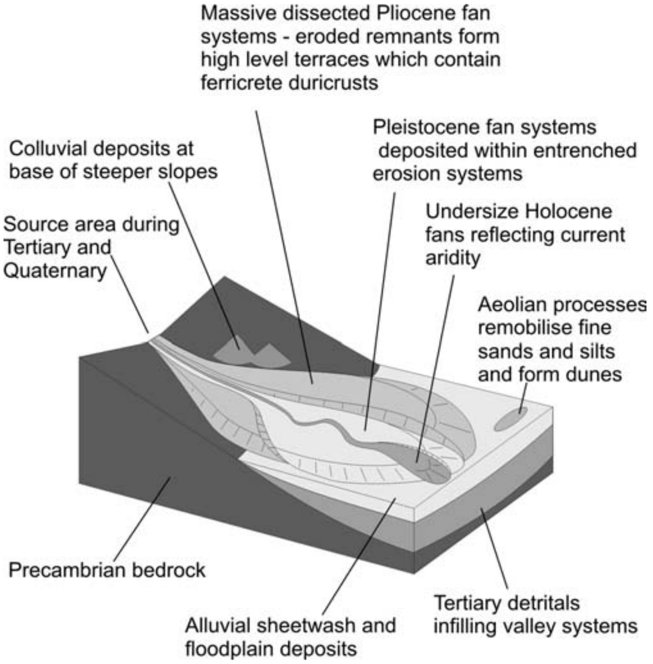


Fig. 14 Conceptual model of alluvial/colluvial fan systems in the Pilbara. The model describes the relationships between different Engineering Geological Formations in terms of their relative age and depositional environment and may be used to understand the spatial distribution of flood hazard zones

Settlement due to dewatering

The need for construction water in this semi-arid environment has led to groundwater extraction. The most prospective areas for groundwater extraction are valleys with a thick alluvial infill containing cavernous calcrete, which are often underlain by cavernous dolomite bedrock. Dewatering such areas can lead to sinkhole formation, which has been discussed earlier, but dewatering of thick sequences of superficial deposits can also lead to general settlement. The settlements have been estimated to be a maximum of a few hundreds of millimetres and are probably a lot less. On one railway line the potential impact of such settlements was taken into account in the design by planning for re-ballasting of the track.

Concrete aggregate soundness

The presence of cryptocrystalline silica within the silcrete duricrusts and the BIF bedrock provides potential for alkali silica reactivity. The deep weathering profiles can result in the presence of clay minerals and micro-cracks within apparently sound rock at considerable depths below the surface. As a consequence, the aggregate for concrete was carefully selected to avoid incorporating such materials and generally was quarried from fresh dolerites, which have performed well in concrete.

Seismic hazard

The stable cratonic area of the Pilbara is subject to relatively low levels of seismic hazard typically with 500-year return events of 0.16 g. Seismicity is not a threat to railway formations but it is relevant to the design of high bridges where the railways cross deeply incised creek lines.

Design of cuts and fills

Railways involve many cuts and fills within linear corridors and the ground engineering component of the design largely relates to the performance of those cuts and fills.

Cut stability

With the exception of those areas where large-scale rock slope stability had been identified, the cut batters for these railways were all designed on the basis of "precedent" using knowledge of the geological conditions derived from a geological model of the excavation. Table 5 indicates the precedent designs that were prescribed for soil and rock masses of varying quality. The precedent designs were based on experience of the past performance of railway cuts in the Pilbara and similar cuts on other projects throughout the world.

In Table 5 the rock quality descriptors were not derived using rock mass classifications systems (e.g. Bieniawski 1989) but instead were related in a more holistic manner to the Reference Conditions e.g. fresh massive dolerite is typically a good quality rock mass whereas weathered shaley BIF is generally a poor quality rock mass. Where adversely oriented defects were encountered that had not been identified prior to construction, local modifications were made to the precedent slope designs using the Observational Method. A great deal of attention was paid to the presence of specific geological conditions identified by mapping during excavation and there was little reliance on the collection of discontinuity statistics, because it is usually the presence or absence of specific geological structures that will determine stability. Some of the conceptual failure mechanisms associated with different Reference Conditions are illustrated in Fig. 15.

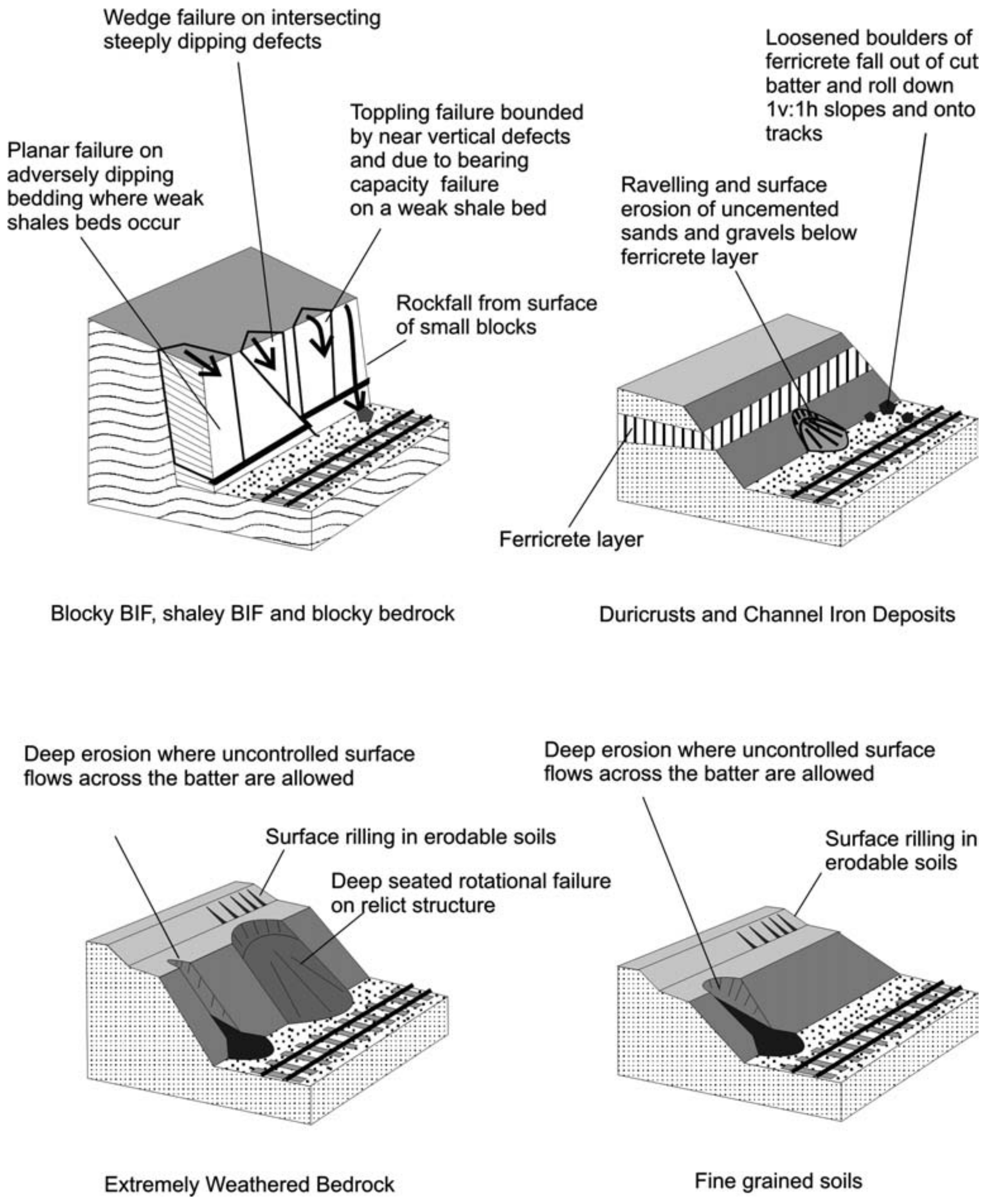
Table 5 Precedent designs for cut batters

Mass descriptor, *Reference Condition*	Design batter (for cuts up to 5 m high in superficial deposits and up to 20 m high in bedrock)
Loose sands, silts, clays, *fine grained soils, some extremely weathered bedrock*	1 v:1.5 h
Dense sands and gravels, *coarse grained soils, duricrusts, some extremely weathered bedrock*	1 v:1 h
Weathered rock with some soil zones, jointed poorer quality rock, *duricrusts, some shaley BIF, some extremely weathered bedrock*	1.5 v:1 h
Jointed medium quality rock, *some shaley BIF, CIDs, some blocky BIF, some blocky bedrock*	2 v:1 h
Massive good quality rock, *some blocky bedrock, some blocky BIF*	3 v:1 h to 4 v:1 h

Blasting

Blast designs were developed by a blasting specialist working with the engineering geologists. The objectives of the designs were to maximize safety and minimize the overall cost to the project. Particular emphasis was placed on producing stable cuts and developing sufficient comminution of the material from excavations for use where appropriate as fill. Precise ground conditions were difficult to anticipate in detail owing to varying rock material strength and rock mass properties. However the geological models of each excavation developed during the investigations were supplemented by mapping during construction and used to anticipate the conditions for individual blasts. This directly affected the blast design with, for instance, the adoption of pre-split blasts in the more massive dolerite, CIDs and blocky BIF rocks and

Fig. 15 Observed and anticipated failure mechanisms for cut batters related to selected Reference Conditions



production blasts with post-blast trimming in the shaley BIF.

Accurate setting out, drilling, loading and detonation were critical to the success of any blast and therefore the preferred drill rigs were track-mounted high performance hydraulic rigs with good angled drilling capacity. Ideally, the collars of blastholes were surveyed prior to charging in order to make sure that they were exactly in the right position and the amount of charge introduced to each hole was carefully monitored. Experienced drill and blast crews were essential.

In addition, the early blasts on projects were generally reviewed to ensure that good practices were being followed, as considerable damage can occur in the early stages of a project before blasting crews gain experience with the local site conditions. In some of the locations, blasts were close to sensitive infrastructure and devices such as blast mats were employed.

Embankments

Some of the larger railway embankments were up to 45 m high and were constructed of rockfill. The rockfill complied with the typical grading specification for rockfill as used in embankment dams (Fell et al. 1992) and were constructed in compacted lifts of 750–1000 mm thickness with about 10% by weight of water added during placement. A stable construction surface after watering and successful trafficking by heavy trucks demonstrated that the wheel loads were being carried by a free draining, structural skeleton of rock-to-rock contacts.

The design slopes of high rockfill embankments were also based on precedent with angles of 1.5 horizontal to 1 vertical or 34°. A settlement value of 1% for the embankment height was considered appropriate (ibid). With large embankments this settlement was allowed for by cambering and by increasing the crest width so that an increased thickness of ballast could be built if it was necessary to compensate for any long-term settlement.

Environmental issues

Engineering geologists were generally not responsible for environmental matters but typically interacted with environmental managers providing them with information and advice, particularly with respect to borrow management.

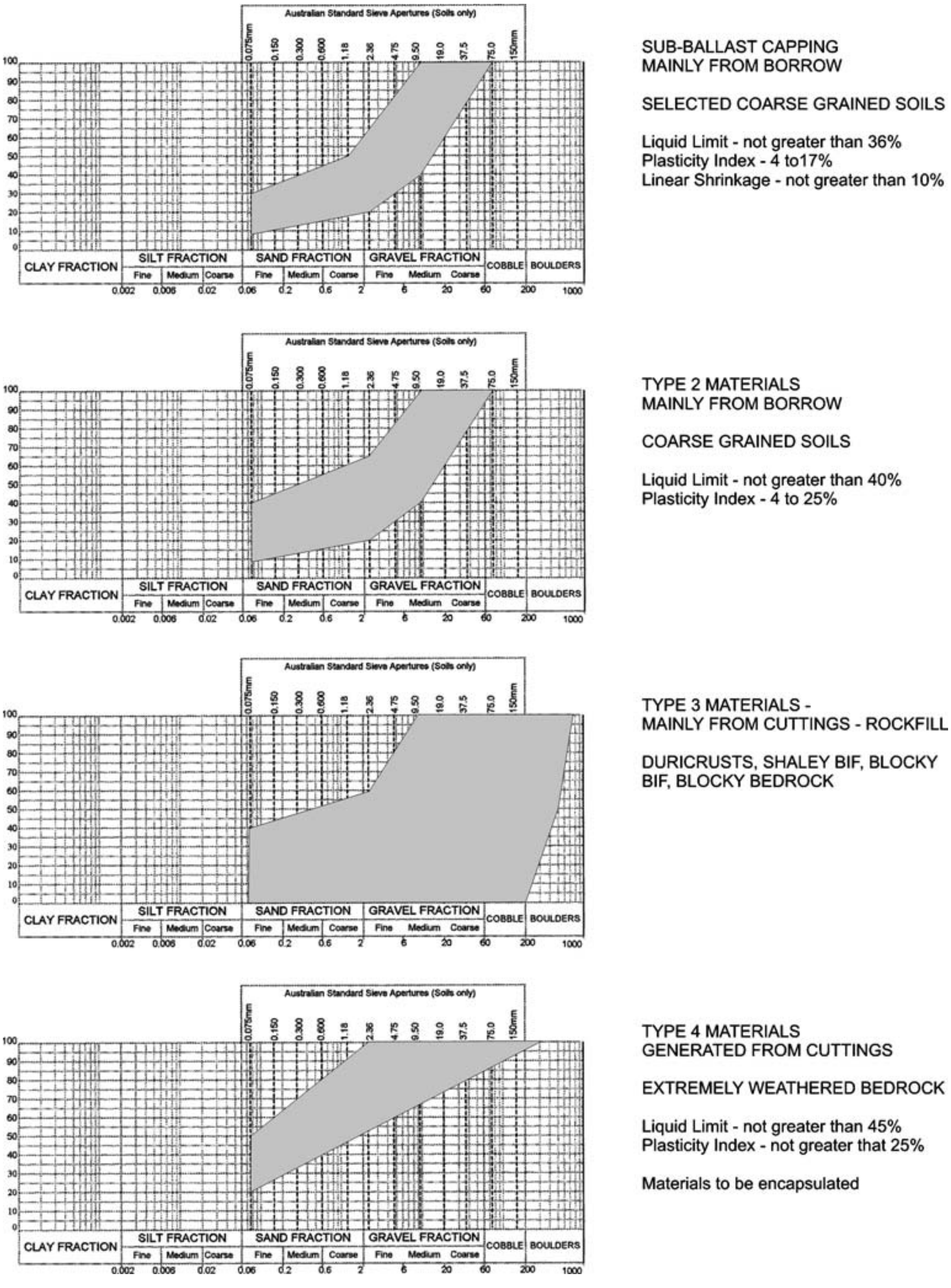


Fig. 16 Specified grading envelopes for the main construction material types related to the typical Reference Conditions detailed in Table 2

Construction materials

The identification and systematic management of construction materials was one of the most important activities of engineering geologists on these rail projects.

Borrow investigations

The overall aim of the borrow investigations was to ensure that sufficient borrow was identified to allow the Contractor to carry out his works unhindered by any restrictions on the availability of borrow material. A large proportion of the borrow materials were located prior to construction and during construction additional borrow materials were located, usually by the engineering geologists in conjunction with earthworks supervisors. The quantities of the borrow materials were described using carefully chosen reporting terminology (Berkman 1989):

a. When only one or two test pits had been excavated in a borrow area of several thousand square metres *probable reserves* were defined. This was considered sufficient information for contractors to tender on. As a rule of thumb, *probable reserves* of about double the estimated fill requirements were identified prior to construction.
b. At the start of construction borrow areas were investigated further, usually with a grid of test pits at 50–100 m centres and *proven reserves* were defined.

Despite this cautious approach once the borrow pits were worked it was usual for shortfalls in borrow to be identified. This was due to variations in overburden depth, incursions of unsuitable materials and environmental constraints such as a need to keep borrow pits shallow to allow drainage and prevent water ponding. Borrow pits were especially prone to extraction difficulties due to the large size of much of the typical plant e.g. Caterpillar bulldozers (D10 and D11) and Caterpillar open bowl (631) and elevating (633) scrapers, and the need to extract borrow economically. Consequently, during construction a large proportion of the engineering geologist's time was spent in identifying additional borrow. This was essential to allow the work to proceed as quickly as possible and to minimise any opportunities for contract claims.

Material quality

Four main types of construction materials were used for railways in the Pilbara. Figure 16 provides their specified grading envelopes and indicates the typical Reference Conditions from which the specified materials were won.

Sub-ballast capping

The embankments were capped with a thin layer of relatively fine-grained granular material (see Fig. 16) called "sub-ballast capping" that could be rolled to a smooth finish to seal the embankment against water ingress and to allow the concrete sleepers to be placed on a surface with minimal protuberances, prior to ballasting, to avoid damage. The sub-ballast was generally compacted to a modified dry density of 95%. A slight fines content was required to allow satisfactory compaction and to develop a cohesive non-erodable surface. Sub-ballast capping was carefully selected and generally came from the distal portions of alluvial and colluvial fan systems.

Type 2 fill

"Type 2 fill" was bulk-engineered fill obtained from borrow for embankment construction and was generally compacted according to a performance specification, i.e. a modified dry density of 95% was achieved by the use of controlled amounts of water and sufficient passes of compacting equipment. Type 2 fill materials were obtained from colluvial or alluvial gravels from nominated borrow pits. Usually this material was a sandy gravel with some clay and was obtained from the mid-sections of the alluvial and colluvial fan systems.

Type 3 fill

"Type 3 fill" was typically a rockfill that was obtained from cuttings and was placed according to a method specification with a maximum allowable particle dimension of 750 mm. The water was added during construction at a prescribed amount, not to sluice the rock nor to wash the fines, but to soften the rock–rock contacts to a degree and allow good compaction. Compaction trials on rockfill were carried out to assess the particular performance of different stratigraphic units. Very little of the rockfill suffered from problems of durability and the suitability of the materials in this respect was assessed by visual inspection. Some variations on type 3 fill were:

a. "Fine Type 3 fill" which was generally derived from closely bedded shaley BIF and could be placed with a performance specification, i.e. to a modified dry density of 95% at ±2% of optimum moisture content.
b. "Graded Type 3 fill" material which was a dirty rockfill that was placed according to a method specification.

Type 4 fill

"Type 4 fill" was generated from cuttings in extremely weathered shale or dolerite bedrock and was a material that might be prone to erosion or be expansive. This material was encapsulated so that it was not within 2 m of any of the embankment surfaces. It was generally placed with a performance specification.

Ballast

During the construction of the earlier railways granites and gneisses were used for ballast and these rock types have not performed well due to excessive abrasion, and in some cases breakdown of the clasts. The poor performance seems to be associated with a variety of geological factors such as a slight foliation, the presence of significant amounts of mica in the rock material, the very coarse grain size and resultant persistent feldspar cleavage planes, and, importantly, penetrative weathering with associated clay mineral growth, micro-crack development and rock strength reduction. In contrast, ballast sourced from unweathered metabasalts and metadolerites has performed well, as such rock types have produced very high strength, equidimensional fragments which are resistant to abrasion.

Contract setting

Most of the projects that the authors were involved in were constructed using the traditional engineering contract i.e. involving an Owner, an Engineer and a Contractor. A schedule of rates contract was found to be the best way of constructing the railways as it led to an equitable sharing of the relatively high risks associated with the large ground engineering component (see Fig. 17). A schedule of rates contract also provided the greater flexibility that was required when design changes needed to be made during construction due to the adoption of the Observational Method.

The contracts were designed to ensure that the location of borrow materials was the responsibility of the Engineer. By making the Engineer responsible for locating the materials to be used to construct the railway, rather than the Contractor, the opportunity for a claim against the Owner for unforeseen conditions by the Contractor was reduced.

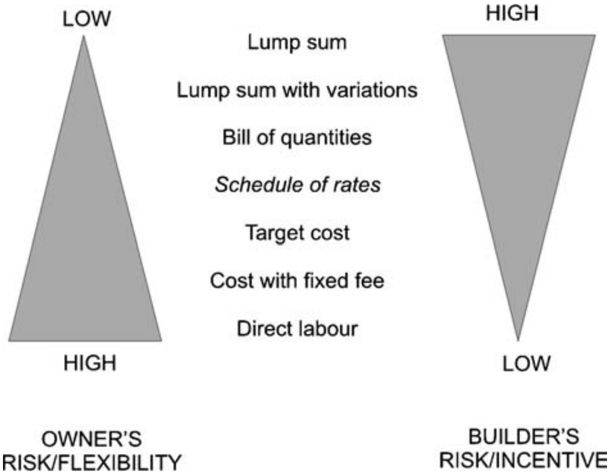


Fig. 17 The relative risks associated with different types of contract, based on Eddleston et al. (1995) and originally presented in CIRIA (1978)

Payment for "rock" versus "common" excavation, which is another traditional potential source of claims, was related to production criteria for standard heavy excavation machinery. The details of the clauses varied, but in essence common excavation was specified as material that could be excavated by a nominated machine at greater than a certain rate and rock excavation was specified as any material not classed as common. This approach was found to be an effective basis for payment and there were minimal disputes associated with predictions of excavatability.

Discussion and conclusions

The *total engineering geology approach* described in this paper is based on a series of practical strategies that were developed on real life heavy civil engineering projects to meet demands for high quality information and to support well informed, considered engineering decisions. The strategies were also developed in response to the sobering observation that many projects that suffer implementation failure, and end up in litigation, do so because of a lack of investment in geological understanding.

The approach is based on developing a thorough understanding of the geology and geomorphology of the project area at a very early stage in the project and places great emphasis on strategies such as:

a. Staged investigations,
b. The definition of investigation objectives,
c. Investigating to answer questions,
d. Geo-mapping,
e. Establishing Reference Conditions,
f. The development of different types of Geological Models, and
g. The application of the Observational Method.

Application of the approach requires the involvement of engineering geologists in decision making throughout the project life and the examples provided illustrate the important nature of those decisions. Observation, interpretation and anticipation allow information to be generated that is relevant to a wide range of the fundamental components of project implementation such as feasibility assessment, design functionality, cost estimates, contract documentation, construction productivity and operational performance. The effectiveness with which these components of the project are engineered can all be related to the adequacy of geological information, which is thus absolutely critical to the success of the project. The requirement that engineering geologists should form part of the engineering team throughout the project life makes it essential that adequate numbers of experienced individuals should be employed on any project and it is this expenditure on people and thinking time that represents the investment in geology that is advocated.

For the approach to be most successful it must be adopted at the beginning of a project. If, for instance, the Observational Method is implemented in response to some disaster then it is unlikely that the other necessary management structures, such as a flexible contract, will exist, and the situation is unlikely to be improved. Above all else, good communication is fundamental to the approach. This requires engineering geologists who are knowledgeable of the engineering issues and engineering managers who can appreciate the worth of geological advice.

The advantages of the approach advocated in this paper are that geological knowledge is acquired more quickly and more cost effectively and thus better decisions can be made about ground engineering issues, which are often a principal source of project risk. Additionally, there is a more equitable and transparent sharing of ground engineering risks between the parties involved in the project, which leads to less conflict and easier project implementation. A disadvantage of the approach is that greater flexibility and management effort is required as the engineering manager must take overall responsibility for not only implementing the project but for ensuring that the complex geological implications of the project are overtly considered. Training of engineering management in the application of the approach is usually necessary for it to be successful as it is often outside their experience, and some inexperienced project managers will be uncomfortable with the greater involvement of engineering geologists that is required.

In general, the approach is not restricted to the railways. Other linear structures that can traverse wide-ranging geological conditions such as roads and pipelines, and projects involving extensive ground engineering such as hydro-electric schemes, have been built efficiently using this approach. It is suggested that the *total engineering geology approach* could be used to great effect in all ground engineering, if only it was appreciated that it is a practical philosophy that aids and promotes successful engineering in the face of geological uncertainty.

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