1 *Introduction*

1.1 Objectives

This book is designed as a basic guide to the field mapping and interpretation of geological structures. Emphasis is placed upon the identification of structures and the systematic recording of structural data, as both should be a fundamental part of any mapping programme. The identification and description of structures, together with an understanding of their development, i.e. their movement patterns (*Kinematic analysis*) and an appreciation of the forces and stresses responsible for them (*Dynamic analysis*) are extremely useful for interpreting particular structures, and for knowing what geometry to expect whilst mapping in a particular terrane.

Structural data cannot be recorded or used in a vacuum. They must be accompanied by full lithological, sedimentological, petrological and palaeontological descriptions for their complete interpretation.

The following aspects are emphasised in this Handbook:

1. Recognition of structures.
2. What to measure and what to describe.
3. How to analyse the data collected.
4. How to interpret the data and incorporate it into the stratigraphy, interpretation and regional syntheses for an area.

In all cases emphasis is placed upon systematic field observations, accurate measurements of the orientations of structural elements, careful recording of the data in the field notebook, sketching and photographing the structures, and analysis in the field using the stereographic projection. Above all, structural geology requires the appreciation of the three dimensional nature of structures. Think in 3D and learn to extend your view of structures above and below the map sheet.

1.2 Fieldwork

The importance of careful, accurate and systematic fieldwork cannot be overemphasised. Basic geologic mapping techniques are described in Barnes (1981), and the field descriptions of sedimentary, metamorphic and igneous rocks are outlined in the companion Handbooks by Tucker (1982), Fry (1984), and Thorpe and Brown (1985) respectively.

This Handbook describes the field techniques for mapping geological structures and for the identification and mapping of particular types of structure. It also gives a brief summary of the interpretation and analysis of structures.

Remember the following points:

1 Accurate measurement, observation and recording of all structural elements is essential. Avoid data selection in the field, otherwise you may find that upon further interpretation in the laboratory, you have failed to measure a key structural feature.

2 Carry out an ongoing interpretation whilst in the field (draw sketch cross-sections and maps). This will help you recognise key areas where further work may be necessary. Your interpretation will be governed by your experience and knowledge of regional structure, ***but only accurate and well-recorded data will have a permanent value and permit continuous reinterpretation.***

3 Data should always be plotted on maps and cross-sections whilst in the field. Only in these circumstances can an effective, ongoing interpretation be achieved.

4 Structural data must be collected in conjunction with other lithological, petrological and palaeontological data.

Conduct and safety in the field

Fieldwork frequently puts geologists in hazardous situations. Structural geologists commonly work in rugged and exposed terrain where 3D exposure is good. Be safety conscious and aware of the possible dangers, particularly from loose rock underfoot, and from rock falls. Barnes (1981) outlines fieldwork safety, and in addition to reading this the reader should also consult the safety checklist on p. 16 of this Handbook before commencing fieldwork. Always carry out fieldwork in compliance with the Geologists' Association Code of Conduct (see Barnes, 1981).

1.3 Tectonic and structural regimes

It is beyond the scope of this Handbook to describe regional structural relationships in detail, but it is useful to identify the dominant features associated with particular tectonic settings, as they provide a useful guide to the structures that may be found whilst mapping (Table 1.1). Characteristic families of structures may be expected to occur in a particular environment, e.g. shallow thrust faults and parallel folding in frontal regions of foreland fold and thrust belts, and this knowledge can greatly aid any ongoing interpretation. Table 1.1 is neither exhaustive nor exclusive in its contents and you should always be prepared for other structures to occur and record all the structural information from the outcrops in your mapping area.

Table 1.1 Structures associated with particular tectonic regimes. (Cont'd on p. 4 and p. 5)

	INTRA PLATE REGIMES			
	Passive continental margins (Atlantic type).	**Continental rift zones**	**Intra-plate strike-slip zones**	**Intra-plate fold and fault belts.**
Major structural elements	Extensional (normal) faulting. Syndepositional tectonics, Salt tectonics.	Extensional (normal) faulting. Strike-slip systems linking extensional faults.	Major fault systems, associated en-echelon folding. Secondary extensional and contractional faulting along curved, overlapping fault systems.	Variable folding & thrusting. Extensional faulting associated with regional uplift.
Metamorphism	None to burial metamorphism. Compaction due to burial.	Hydrothermal systems and volcanic activity, elevated heat flow. Dynamic metamorphism associated with faults, cataclasites — mylonites.	Generally low grade.	Variable — to granulite facies. Development of fault rocks, cataclasites mylonites along active fault zones.
Examples	Eastern U.S.A. continental margin, West African continental margin.	North Sea Basin. East African Rift System.	Northern Rocky Mountain Trench — Tintina Fault System, Canada.	Basin and Range, U.S.A.

Table 1.1 (cont'd) Structures associated with particular tectonic regimes.

	ACTIVE PLATE MARGIN REGIMES			
	Constructive	**Conservative**	**Destructive**	**Collision**
	Mid-ocean ridge systems, and marginal basin spreading systems	Major strike-slip fault systems	Island arc or continental margin arc systems	Continent–continent or continent–island arc collison
Major structural elements	Extensional (normal) fault systems, major strike-slip (transform) fault systems	Strike-slip fault systems local extension (normal) and contractional (reverse or thrust) fault systems. Local folding typically en-echelon patterns. Development of pull-apart basins along fault system.	Subduction complexes Fold and thrust belts — uplifted volcanic arcs Fore-arc basins, oblique subduction strike-slip systems. *Subduction complexes* — Contractional (thrust) faulting, Vein systems, penetrative cleavages, melanges. *Fold and thrust belts* — Thrust and fold nappes— *Uplifted volcanic arcs* extensional faults, fracture patterns associated with intrusions and volcanics. *Fore-arc basins* — local extensional tectonics.	Major overthrust sheets, (allochthonous). Major fold nappes. Major strike-slip faults. ***In internal zones*** Fold nappes, contractional (thrust) faults, polyphase deformation. Major strike-slip faults, uplift and late extensional (normal) faults. ***In external zones*** Foreland fold and thrust belts, Minor strike-slip faults (generally simpler geometry than internal zones). Development of foreland basins which may become involved in the thrusting.

Table 1.1 (cont'd) Structures associated with particular tectonic regimes.

	ACTIVE PLATE MARGIN REGIMES (Cont'd)			
	Constructive	**Conservative**	**Destructive**	**Collision**
Metamorphism	Range of Metamorphism from Zeolite, Greenschist, Amphibolite. Hydrothermal alteration and vein systems.	Low-grade – sub greenschist burial metamorphism. Local dynamic metamorphism (cataclasites mylonites) and hydrothermal alteration along major fault zones.	High pressure low temperature metamorphism in subduction complexes. Low pressure high temperature metamorphism in interior of arc (associated with intrusions).	*Internal zones* — high-grade polymetamorphism and igneous intrusions, penetrative foliations. *External zones* — Low-grade or burial metamorphism, one or no penetrative foliation.
Examples	Icelandic Rift System	San Andreas Fault System, Dead Sea Transform System	Japanese Island Arc Systems	Himalayan Collision Zone

1.4 Bedding

In sedimentary and many metamorphic rocks, *bedding surfaces* (surfaces of primary accumulation) are our *principal reference frame* (or datum). There are many possible bedforms in sedimentary sequences (see Tucker, 1982 for details) and the structural geologist must be aware that significant departures from layer-parallel stratigraphy can occur in certain sedimentary environments, e.g. deltas; thus structural data must always be collected in conjunction with sedimentological and stratigraphic data.

Bedding is one of the most important structural elements and the structural data that should be collected for bedding are outlined in Table 1.2. *The spatial distribution of bedding or compositional banding (e.g. in gneissic terranes), will define the major fold and fault structures within your mapping area.*

1.4.1 *Way-up/younging and facing*

Way-up/younging is the direction in which stratigraphically younger beds/units are found. (The term *tops* is also sometimes used in this context.)

The *stratigraphic way-up* is of fundamental importance in determining the structure of an area. It is based upon a knowledge of stratigraphy and of small-scale sedimentary structures which indicate the stratigraphic way-up and the sequence of deposition. Sedimentary structures which indicate way-up are discussed in Tucker, 1982 and are summarised in Fig. 1.1. Always look for and record way-up features when mapping.

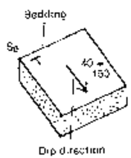
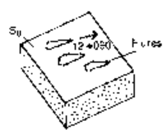
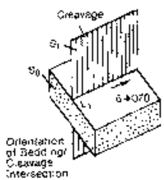
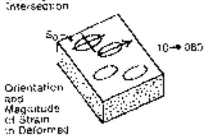
The *structural way-up* refers to the bedding/cleavage relationships that indicate the position within a major fold structure (e.g. on the overturned limb of a recumbent fold). This may have no relationship to stratigraphic way-up. Take care to distinguish the two—see Chapter 3 for greater detail.

Facing is the direction within a structure i.e. along the fold axial plane or cleavage plane, in which younger beds/units are found. This term is generally applied to folds, or cleavage relationships.

1.5 'Synsedimentary' versus tectonic structures

In many areas of deformed sedimentary rocks it is difficult to distinguish between structures formed during deposition or early diagenesis when the sediment was unconsolidated, and those formed after lithification in response to tectonic forces. On cursory examination many 'synsedimentary' structures such as slump folds have superficial geometric similarities to 'tectonic' folds (Fig. 1.2a). Syndepositional faults are also common (Fig. 1.2b) and in some instances syndepositional cleavage fabrics have been observed (Fig. 1.2c). It is therefore extremely important when mapping to distinguish between syndepositional (prelithification)

Table 1.2 Data to be collected from observations on bedding S_0.

Structure	*What to Measure*	*What Observations to Record*	*Results of Analysis*
Bedding 	Dip direction (or strike and dip) (Figs. 2.5,2.6, 2.7).	Lithology, bedding thicknesses Grain-size. Grain shapes, grain fabrics.	
	Orientation of sedimentary structures (Figs. 2.11–2.13).	Sedimentary structures. Geopetal structures.	Depositional surfaces. Palaeocurrent directions. Palaeoenvironments. Way-up – younging.
	Orientation of tectonic structures on bedding plane (particularly the bedding/cleavage intersection) (Figs. 2.11–2.13)	Tectonic structures (cleavage relationships, lineations on bedding plane). (Fig. 4.3b)	Orientation of tectonic structures relative to bedding. (Figs. 4.3b, 5.1b)
	Orientation and magnitude of strain in deformed objects on the bedding plane (Figs. 2.11–2.13 & Appendix III).	Nature of strain relative to bedding. (Fig. 3.12 & Appendix III)	Strain on bedding plane component of layer-parallel shortening. (Fig. 3.12). Relative competencies of units.

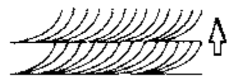
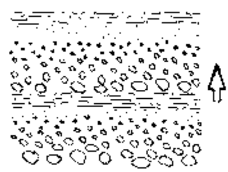
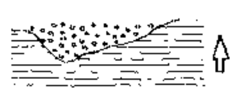
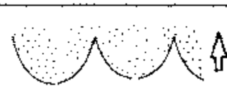
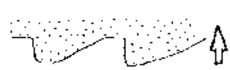
DESCRIPTION	PRIMARY STRUCTURE
CROSS-STRATIFICATION Tabular cross-stratification	
Trough cross–stratification	
NORMAL GRADED BEDDING Coarse grains at the base passing upwards into finer grain sizes; typical of turbidite sequences.	
SCOUR STRUCTURES Scour surface at base of sandstone bed overlying mudrock. Coarse-grained lag deposit may occur in the scour.	
LOAD STRUCTURES Sandstone overlying mudrock Load Casts	
Flame Stuctures Upward injection of mud into the sandstone	
FLUTE CASTS Developed on the underside of Bedding units in Sandstones. Good Palaeocurrent indicators.	Palaeocurrent → 

Fig. 1.1 Primary structures that may be used to determine the stratigraphic way-up of beds. (Cont'd on p. 9)

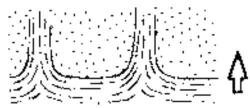
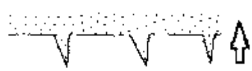
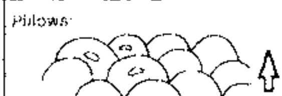
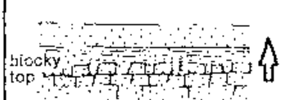
DESCRIPTION	PRIMARY STRUCTURE
Dewatering Structures Pillar structures formed in sandstones and siltstones as water escaped upwards	
Dewatering Structures Sand volcanoes in mudrocks or siltstones. May be underlain by sandstone dykes.	
Shrinkage Structures Mudcracks infilled with overlying sandstone. Dish structures in mudrock that has undergone desiccation	 
Volcanic Structures Lobate Pillow structures in lavas.	
Volcanic Structures Blocky, rubbly and weathered tops to lava flows.	

Fig. 1.2a Synsedimentary (Slump) fold in sandstone. Note the absence of fractures, veins, and cleavage.

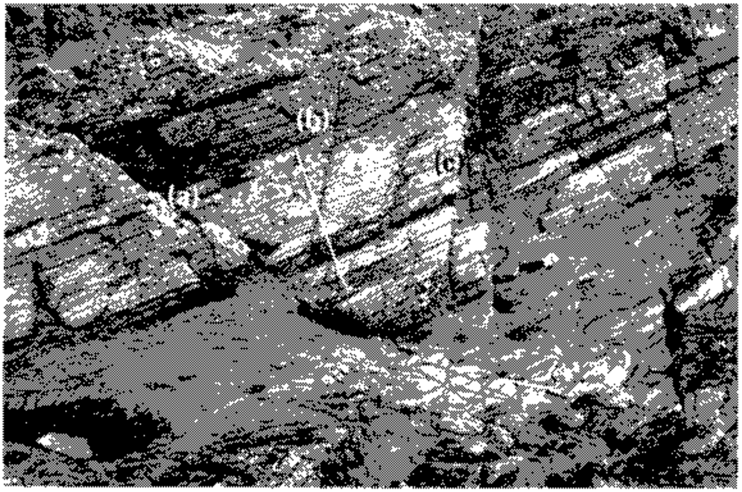


Fig. 1.2b Listric syndepositional extensional fault (a) in siltstones and mudstones. Note the development of left-dipping antithetic faults (b and c). Scale, near (b), is 1 m.

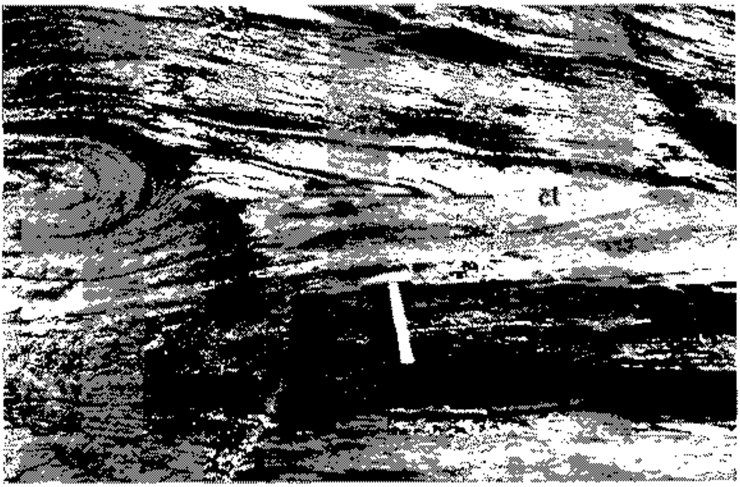


Fig. 1.2c Recumbent Synsedimentary (Slump) fold in siltstones with the development of a weak flat-lying cleavage (cl).

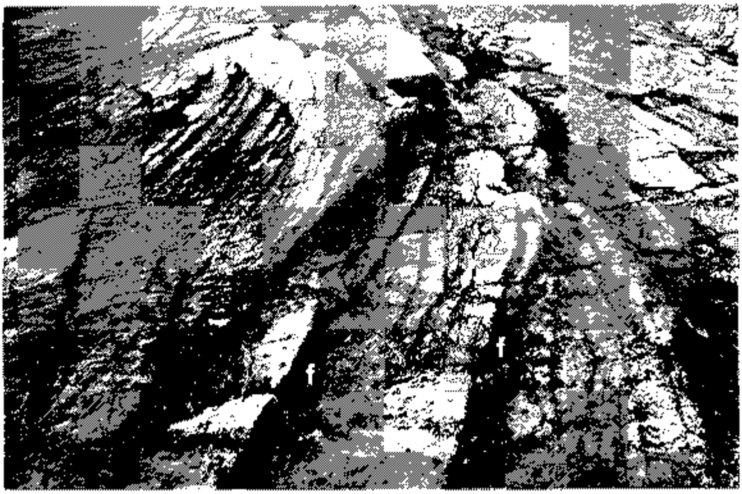


Fig. 1.2d Syndepositional extensional faults (f) in sandstones. Note that the faults are curved in plan and are consistently downthrown to the right. Field of view is 4 m.

structures and post-lithification, 'tectonic' structures. In some situations e.g. active continental margins, sediments are deformed by tectonic forces very soon after deposition, before complete lithification. Hence you may find a complete spectrum of structures, from those formed during deposition to those formed deeper in the crust.

1.5.1 Discrimination of prelithification ('synsedimentary') from post-lithification (tectonic) folds

'Synsedimentary' folds or 'slump' folds have many geometric similarities to the shapes, wavelengths and size distributions of 'tectonic folds'. Slump folds are generally tight to isoclinal with variable shapes at low fold amplitudes. Their fold axes are commonly dispersed in the plane of the slump sheet and recumbent folds are dominant (Fig. 1.2c). The fold axial surfaces may be slightly imbricated (stacked up like shingles) and the folds face and verge down the inferred palaeoslope. Axial-planar cleavages are sometimes developed, particularly in the hinge regions (probably due to later compaction during burial). Lineations and grooving are sometimes produced by the motion of the slump sheet, and these may be refolded along with other minor structures. Slump sheet contacts may be gradational. Their upper boundaries may exhibit sharp erosional truncations. Synsedimentary fractures within slumped sequences are generally not sharp, and fracture openings are not maintained. Veining is absent although the fracture plane may be infilled with mobilised sediment slurry. In general, slump folds have no genetic or geometric relationship to large macroscopic folds.

Syndepositional folding is commonly associated with disturbed sedimentary sequences—synsedimentary extensional faulting, convolute laminations, ball and pillow structures, dewatering structures, sand and mud volcanoes. Remember that slumps are characterised by extensional structures at the rear, whereas the front of the slump sheet will be marked by localised compression, with the development of folds, thrust faults and imbrications. The characteristic features of syndepositional folds are listed in Table 1.3 and are compared with the features of 'tectonic' folds (see Chapter 3).

1.5.2 Discrimination of synsedimentary faulting from tectonic faulting

The attributes of tectonic faults are described in Chapter 6. They are characterised in particular by their geometric relationships with associated structures, folds, fractures and veining, and most importantly, by the development of fault rocks along the fault planes (Chapter 6.6). The presence of faults bounding major basin margins will be revealed by regional mapping, by the associated

Table 1.3 Criteria used to distinguish between synsedimentary folds and 'tectonic folds'. **A** is the most reliable criterion and **C** is the least reliable. Note that several criteria must be used in conjunction in order to determine the origin of a particular fold.

Sedimentary folds	Reliability index	Tectonic folds	Reliability index
Truncation by overlying beds	**A**	Limited spatial distribution — correlated with regional structure	**A**
Burrowing or boring by organisms	**A**	Fold vergences and axial planes symmetrical around large folds	**A**
Cut by synsedimentary dewatering structures	**A**	Symmetrical fracture patterns and veins saddle reefs developed	**A**
Undeformed clasts or fossils.	**A**	Crystallographic fabrics in non-phyllosilicates (possibly associated with fanning axial-planar cleavage in phyllosilicates)	**A**
Folds with no axial planar cleavage — cut by later tectonic cleavage	**B–C**	Slickensides and metamorphic lineations – down fold limbs and around fold hinges	**B**
Fold axes strongly dispersed in plane of sheet	**B–C**	Associated with brittle thrust faults folds generated by ramps	**B**
Dominantly recumbent fold axial planes, may be imbricated (with respect to sheet dip)	**C**	Kink-like folds with upright axial planes (with respect to the sheet dip)	**B**
Both extensional and compressional features with no veins developed	**C**	Continuity of axial planes across several beds	**B**
		Parasitic relationships between major and minor folds	**B**
		Fanning axial plane cleavage in phyllosilicates	**C**

facies distributions of coarse-grained fault derived sediments adjacent to the fault scarp, by increased sediment thicknesses adjacent to the fault, and by associated smaller syndepositional faults and slumps indicating active tectonism during sedimentation. Here, attention is focussed on outcrop scale features indicative of synsedimentary faults.

1 Synsedimentary faults typically do not affect *all* of the stratigraphic sequence and are overlain by unfaulted sediments in depositional contact.
2 The faults are typically listric in shape (Fig. 1.2b).
3 The faults are typically irregular in plan—often curved (Fig. 1.2d).
4 The down-thrown side of the fault is commonly infilled with a triangular wedge of sediments (Fig. 1.3a) which in some cases may be coarser grained than the surrounding sediments.
5 There is an absence of veining and fault rocks typical of brittle deformation (Chapter 6.6).
6 The fault planes are not generally smooth planar fractures, but are often irregular on a small scale (Fig. 1.3b), commonly with injected sediment slurry along the fault plane.
7 The faults are often associated with syndepositional slumping and disturbed sedimentary sequences convolute laminations, dewatering structures and sand volcanoes.

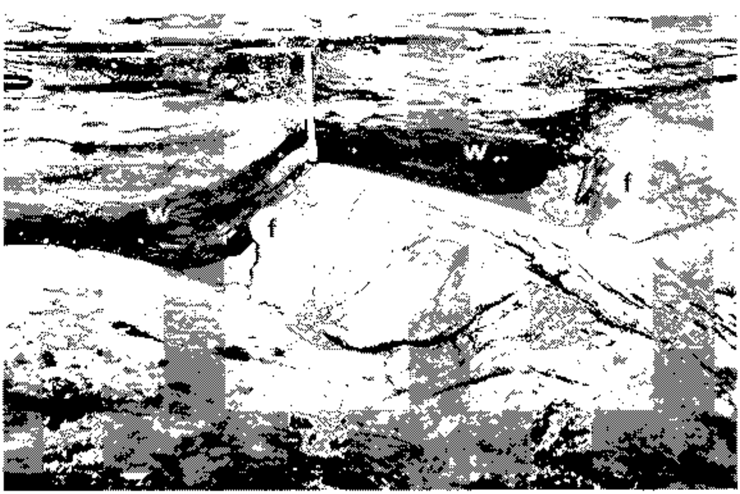


Fig. 1.3a Syndepositional extension faults (f) showing rotation of fault blocks and infilling of the half-graben with a wedge of sediment (w).

Fig. 1.3b Small syndepositional fault in sandstones, showing an irregular fault plane and injection of sediment slurry along the fault plane.

1.5.3 Syndepositional cleavage

This is commonly found in the deformed mudstones of slumped sequences. The foliations are planar and parallel to the sheet dip of the sediments, and typically have the appearance of a slaty cleavage or very closely spaced, fine fracture cleavage (Fig. 1.4). They are axial-planar to recumbent slump folds (Fig. 1.2c) and generally do not penetrate sandstone layers but are restricted to mudstones. Slight fanning of the cleavage may occur but the strong refraction of cleavages commonly found in lithified rocks (Chapter 4.3) does not usually occur.

If there is evidence of synsedimentary deformation, then great care has to be taken in recognising and mapping cleavage features. In such circumstances careful examination of all of the field relationships is required before a cleavage can be ascribed to syndepositional processes or to later tectonism.

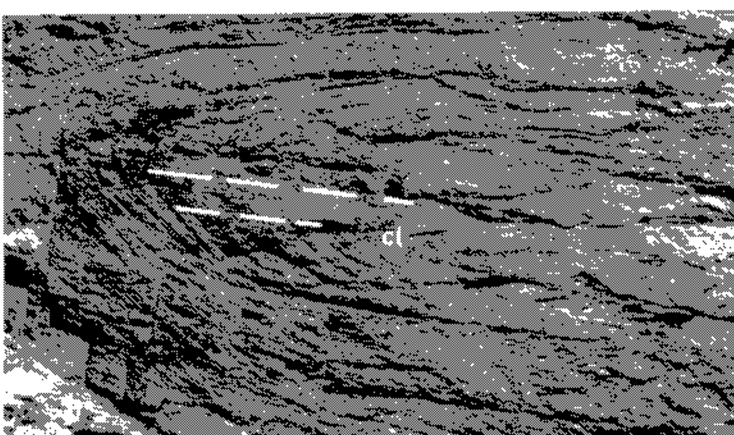


Fig. 1.4 Slump fold with a flat-lying syndepositional axial-planar cleavage (cl). Field of view 2 m.

1.6 Basic References

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1.7 Safety

1. Do not run down hills.
2. Do not climb rock faces unless you are a trained climber and you have a friend present.
3. Do not enter old mine workings or cave systems except by arrangement, and always in company.
4. Wear easily seen clothing.
5. Always wear a safety helmet in quarries, under steep cliffs and scree slopes, and underground, and wear goggles when hammering rocks.
6. Note weather forecasts in mountainous country and if you are going into a remote part of an area leave with a responsible person your route map and the time you expect to return.
7. Keep a first aid kit and manual in camp. Carry a small emergency kit in your rucksack, including dressings for blisters, a whistle and a flashlight for signalling (and a mirror if your compass does not have one). Include, also, matches sealed in a waterproof plastic bag, and an aluminized foil 'space blanket' (it weighs almost nothing). In hot climates, carry a water bottle and a packet of effervescent water sterilizing tablets. Always carry some form of emergency ration in case you have to spend a night on a hillside in mist or snow.
8. The accepted field distress signal is six blasts on a whistle or six flashes with a mirror or flashlight, repeated at minute intervals. Rescuers reply with only three blasts or flashes repeated at minute intervals to prevent rescue parties homing in on each other.