CHAPTER 2. MORPHOLOGICAL ASPECTS: RELIEF ELEMENTS

2.1 Introduction

This first chapter discusses the role of morphologic analysis of landscape elements in the process of fault recognition by means of remote sensing observations. It is our aim to shortly outline the reasons why remote sensing takes an essential part in the presented study. However, we will not go into great detail about the theoretical aspects of data acquisition and processing as it is the main interest of this study to apply methodology developed elsewhere, sometimes modifying the techniques for our purposes, rather than to contribute to new developments in this field of science.

This chapter presents the use of optic image analysis and digital terrain models in structural analysis. An integration of remote sensing in structural modelling combining structural geology and tectonic theory with field observations and micro-tectonics will be presented in chapter 5.

The aim of using remotely sensed observations in the present study is to determine the geometrical relations of structural discontinuities at the earth surface, which are used as a first step in analysing and interpreting their tectonic meaning. The geometrical and geological relations between structures can allow a first relative timing of the structures. It has to be emphasized that space image and topographic analysis is used as a first and generally non-exclusive tool for tectonic interpretation, to be completed with field analysis or geophysical data. Analysis of satellite images, aerial photographs and small-scale digital terrain models was applied to the whole study area of northeast Altai-Sayan. High resolution detailed-scale digital terrain models have been developed only for the Lake Teletskoye area.

Since the introduction of computer-aided data processing, the use of digital remotely sensed data in geology has been intensively developed, and remote sensing has become a very useful
and widely applied tool in tectonic analysis of geological structures [e.g. Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Sankov et al., 2000; Bayasgalan et al., 1999a,...]. Information derived from remote sensing data at proper scale of the investigated features is the first and essential tool for constructing structural geological models and guides the choice of fieldwork location. The key purpose is to extrapolate remote sensing responses into meaningful models useful for kinematic and dynamic analysis. While constructing such a model, it is important to start from small scale data, covering large area’s, gradually zooming in to large scale data of high resolution, in order to evaluate, detail and confirm the morphological observations and come to a model. Table 2.1 shows the different scene systems used in the present study for structure analysis and model construction.

<table>
<thead>
<tr>
<th>approximate scale of analysis</th>
<th>feature size order of magnitude (m)</th>
<th>morphotectonic elements</th>
<th>types of data</th>
<th>ground resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:10 000 000 to 1:200 000</td>
<td>10^6 to 10^4</td>
<td>topography of terranes, mega-lineaments, ridges, hydro-nets, basin shape, domes...</td>
<td>NOAA DEM</td>
<td>800</td>
</tr>
<tr>
<td>1:5000 000 to 1:200 000</td>
<td>10^6 to 10^3</td>
<td>... ridges, lithological zones, alluvial fans, river valleys, basin borders...</td>
<td>RESURS and LANDSAT MSS</td>
<td>160</td>
</tr>
<tr>
<td>1:50 000</td>
<td>up to 10^1</td>
<td>... lineaments, folds, dikes, bedding, cleavage ...</td>
<td>SPOT</td>
<td>20</td>
</tr>
<tr>
<td>1:50 000</td>
<td>up to 10^1</td>
<td>... blocks, lineaments, divides, ....</td>
<td>DEM 1:50000 scale map</td>
<td>5-50</td>
</tr>
<tr>
<td>1:35 000</td>
<td>up to 20</td>
<td>... small faults, river valleys, glacial features...</td>
<td>CORONA</td>
<td>41</td>
</tr>
<tr>
<td>1:25 000</td>
<td>up to 10</td>
<td>... joints, cleavage, scarps, alluvium,...</td>
<td>aerial photo’s</td>
<td>2-variable</td>
</tr>
</tbody>
</table>

Table 2.1 Remote sensing source data

Table 2.1 shows (from top to bottom) the scale enlarging applied in the present study. The analysis started on small scale images, gradually enlarging the resolution of the images, up to aerial photograph resolution. The digital topography from NOAA data with a spatial resolution of 1 arc-second (approximately 800 metres) provided the basic topographic information. Low resolution RESURS and LANDSAT MSS images, covering a wide area, have been analysed. For the intermediate scale, SPOT images have been used. High resolution CORONA satellite images formed the link with aerial photographs.

### 2.2 Digital Terrain Models

As tectonic deformation modifies the relief of the affected region, topography gives a first and indispensable indication of the distribution and arrangement of morphological structures within a studied region. This statement holds particularly for actively deforming terrains. Three-dimensional visualisation is therefore crucial to the study of structural geology. The visualisation of a three-dimensional structure from two-dimensional maps is greatly complicated by topographic relief. The analysis of the topography is done by constructing Digital Elevation Models (DEM) or Digital Terrain Models (DTM). The term DEM refers to a model of a featureless surface that contains only \{x, y, z\} co-ordinates and no accompanying attributes. It can represent any continually varying surface, both real or conceptual. For
geological surfaces, $x$ and $y$ are generally the geographic coordinates, where $z$ can be elevation above sea-level, but also geochemical concentrations or geophysical information such as magnetic susceptibility, gravity-anomalies... A DTM on the other hand is specifically a model of topography, and usually has additional attributes such as drainage, geology,... [Spark and Williams, 1996]. In practice, we will talk about DEM in the general discussion about model generation and geostatistics, applicable to any $\{x, y, z\}$ data, whereas we use the term DTM for the discussion of specifically topographic models.

Digital Terrain Models within a Geographic Information System (GIS) can significantly enhance the visual impact of a complexly deformed terrain. The flow-chart in figure 2.1 presents the relations between source data and application, the tasks associated with - and the reasons for undertaking digital terrain analysis. The flow chart shows the DTM to be at the centre of the interactions between source data capture and applications. Visualisation techniques support and facilitate interpretations as well as evaluation of data quality, and thus enhancement of the model itself. The interpretation of the data depends and influences the projection of the DTM. The mode of visualisation clearly has a great influence on the interpretation. An important factor in the DTM generation process is the issue of spatial scale. The resolution of the source data determines the resolution of the final DTM, and the scales and resolutions of the visualisations should match the natural scales of the investigated structures. The interpolation method is crucial for the production of a reliable DTM usable for correct structural interpretations. It depends on the source data type and on the resolution and scale of the end product. As a source for geographically correct (projected) topographic information, various data were used, all appropriate to the envisioned analysis scale.

![Fig. 2.1 Main tasks associated with digital terrain modelling. After Hutchinson and Gallant [1999].](image-url)
**Source data**

**Topography**
NOAA data of digital raster topography with a consistent 30 arc-second grid spacing (GTOPO30) were used for the production of small scale documents (covering large areas) on which several morphologic analyses were applied. The nature of the data implies that pixel ground resolution of the source data varies with latitude. Therefore, processing of the source data, especially projecting the data from geographic coordinates to an equal area or equal angle projection, depending on the purpose, is necessary. Derivative products, such as slope maps, drainage basin areas and stream channel length will be more reliable in equal area projection, so that each cell, regardless of latitude, represents the same ground dimensions and area as every other cell. We used DTM’s to create B&W and colour relief maps, analytical hills-shading, slope- and aspect maps, with the purpose of lineament and morphologic analysis. Also, these kinds of maps are found very useful as a background for presenting the results of the tectonic analysis. On small scale overview images of such kind, it is important to choose an appropriate projection for the maps, minimising directional distortions. Lambert Conformal projections are optimal in such cases.

For more detailed analysis on larger scale, digitised topographic maps of scale 1:200 000, 1:100 000 and 1:50 000 were used. The digitised contour lines of these maps show the following characteristics: the contour intervals digitised are respectively 100, 40 and 20 metres. The distance between the contour lines evidently depends the steepness of the slopes, and generalities are difficult to make. Along a specific contour line, the distance between two points is also irregular. The point density along a contour is low for straight lines, and gets higher as curvature of the contour increases.

**Bathymetry**
In the study of active faulting, surface deformations are the main starting point for identification and specification of active faults. Where in free air conditions air-borne remote sensing data provide the basis for such investigations (table 1), the morphology of under water regions can be analysed using bathymetric maps. Detailed information about the bathymetric features of lake basins is therefore of high scientific importance. Not only does the absolute depth variation and trend give information about sedimentological characteristics of the deposition environment, but also can subtle underwater slope trends be related to tectonic activity and discover active faults inside the basin. The continuation of on-shore graben delimiting border faults under water further characterises the graben morphology, otherwise limited to the air-free region. Additionally, bathymetric surface maps resulting from high-density profiling can facilitate the interpretation of- and correlation between less dense seismic profiles. A methodology of bathymetric mapping was elaborated for the presented study. \{x, y, z\} depth points resulting from echo-sounding bathymetric profiling were used as source data for the construction of a DEM of lake bottom morphology. Unlike the topographic contours, these points are located along more or less orthogonal profile grids. The technical aspects are discussed in appendix A.
DEM generation

Important for the quality of the results is the use of the best fitted interpolation technique and resolution of the interpolated grid, depending on the source data. The main problems to conceive are the characteristics of the terrain surface anisotropy, typical for many topographic regions. For the specific problem, three main classes of interpolation methods are proposed [Hutchinson and Gallant, 1999]: triangulation, local surface patches and locally adaptive gridding. It is the middle technique that is applied in this study.

The results of any DEM construction from third-party initial data depends mainly on the characteristics of the initial data, and the used interpolation method. Both parameters should be thoroughly analysed and evaluated. The data used in this study, digitised contour lines of topographic maps and depth points from echo-sounding surveys, both result in irregular spaced point data. The elevation data can be combined into a DEM by creating a grid (raster) of regularly spaced elevation points (or pixels) by filling empty places between the fixed points, i.e. estimating the value of the studied properties at unsampled sites within the area covered by existing observations. This is done by spatial interpolation. There exist a wide variety of interpolation methods, all accommodating specific requirements of calculation speed, memory limitations, and desired result. The choice of the interpolation method depends also on the initial data characteristics. To evaluate the spatial variation, interdependency and anisotropy of the initial data, geostatistical analysis can be applied. Geostatistics estimates the spatial variability of data points (elevation), and the directional interdependency of these points.

Interpolation based on triangulation uses the actual data points as the vertices of the constructed triangles, and then fit the local polynomial functions across each triangle. Because the original data are used to define the triangles, the data are honoured very closely. The method has difficulties interpolating contour data, which generate many flat triangles. Also, the resulting contour lines have generally not a smooth, but rather an angular shape. It is a relatively fast and exact method, though.

Among the different interpolation methods, Kriging has become the most favourable during the last few years, as computer calculating speed and capacity increased greatly. For the (universal) Kriging interpolation method, the semivariogram model of a given data set, characterising the degree of spatial dependency between the heights of adjacent terrain points, is used as a basis for estimating the altitude value between different observation points. For a dense set of data points, this method gives generally good results, minimising the error for the interpolated points. Until recently, a disadvantage of the Kriging method was that it disregarded the hydrographic features of the region as well as the vertical slopes formed by cliffs and faults. This problem has been solved in the latest versions of the software used for interpolations in this study (PCI and Surfer) that use break-lines and river nets defining the stream-lines inside valleys to obtain drainage enforcement.

Kriging has problems estimating values at areas with sparse control points, in the case of topographic map derived data this means in relatively flat regions. To solve this problem, Vysotsky and Dobretsov [Vysotsky, 1999], proposed a procedure for adding contour lines (or points) to relatively flat zones where the distance between existing contours is large. This is
done on the basis of a TIN (triangulated irregular network) surface (as opposed to a square grid network), constructed for the investigated area. The specificity of a TIN surface is that it does not interpolate between points, but creates a set of triangular surfaces, connecting the existing points. By this, a 3D surface is created, from which a slope map can be easily derived. Slope classes with inclinations less than 12° are isolated, because the flatter surfaces have less control points and therefore cause the interpolation problems. These areas were supplied with new control points, assuming linear evolution from one contour line to the other.

The main difficulties encountered in classical interpolations are variations in anisotropy and DTM errors along ridges, vertical cliffs and streamline pathways. Several procedures were proposed to minimise the errors created in a DTM by those complications. Local Surface Patches is a procedure proposed to overcome the computational problems, and to permit a degree of local anisotropy [Mitasova and Mitas, 1993]. A global interpolation method (Kriging, spline, ...) is applied to overlapping regions (patches). The regions are then smoothly blended. The patches can be chosen according to local anisotropy.

Another methodology producing high-accuracy DTM is the so called Locally Adaptive Gridding technology. It uses a combination of a universal interpolation method with local algorithms such as drainage enforcement (eliminating artificial sinks in model valley’s) and ridge calculating (determining ridge lines from points of locally maximum curvature of contour lines).

Optimisation of DEM resolution
For DEM construction based on digitised topography of 1:50,000 scale topographic maps, two different scales of digitalisations were used. For the general map of the Lake Teletskoye surroundings contours were, for memory reasons, digitised with a 100 m altitude interval. The resulting ‘low resolution grids’ have pixel sizes of 25 m. Several detail zones were chosen, for geological reasons, where all the contours were digitised, with an altitude difference between two contour lines of 20 metres. In the present study, we speak of ‘high resolution grids’ in the case of a DEM with spatial pixel resolution of 10 metres. In the case where all contours of the topographic map have been digitised (20 m altitude intervals), the spacing between the contour lines and the spacing between 2 points along a digitised line are comparable for moderately sloped zones of the study area (a 45° slope for 2 contour lines horizontally separated by 20 m). Flat slopes have a larger plane distance between the contour lines (50 m for a 20° slope).

For such irregularly spaced data points, the choice of the most accurate DTM resolution is not obvious and depends on the source data. Comparison between initial data and resulting contours showed that, for the highest resolution of topographic data, 10 m resolution is optimal mediation between accuracy and reality. A method for evaluating DEM accuracies developed by Hutchinson comes to similar conclusions [Hutchinson, 1996].

Integration of terrain models from combined topography and bathymetry
An integrated model of (on-shore) digital topography and (off-shore) bathymetry forms a first step to a time-delimiting analysis of structural deformation of a basin and its surroundings. Structures traceable both on- and off-shore allow to classify them as potentially active structures. An off-shore structure affecting top layer sediments that can be traced and followed in the on-shore morphology is classified as such. However, in many cases it could be an erosional feature or a sedimentation feature rather than an active fault. Thus, the step between
observing and mapping potentially active structures, generally lineaments, and identifying them as active faults demands an additional discriminating factor. In the present study, this is provided by additional information obtained from seismics (chapter 3) and/or structural field investigations (chapters 4 and 6). Figure 2.1 shows a DTM of the combined bathymetry and topography of Lake Teletskoye with a pixel resolution of 25 m, elaborated in the frame of the present work. Higher resolution sub-regions were isolated and a 10 m resolution DTM was constructed, as shown (as a 3D grid) on figure 2.2.

**Visualisation**

There are several ways in which a DEM or DTM can be represented. Triangulated networks, contour maps, grid maps, ... Usually, DTM’s are represented as raster files composed of pixels with physical dimensions. Each pixel has a constant elevation value. The smaller the pixel size, the more accurate the model, as the physical earth surface is not composed of horizontal rectangles with equal elevation, but of slopes with a varying inclination. Therefore, depending on the DEM resolution, a DTM will represent a approximated stepped morphological surface as a raster or grid file, or a set of inclined triangles in a TIN representation.

The large scale 3D images derived from topographic maps proved to be very useful in combination with satellite images to envision and highlight large scale structures recognised by photo-geology and field observations. Presentation of structural terrain features by draping a satellite image over a DTM was used for analysing and presentation purposes.

Analytical hill shading (shaded relief e.g. fig. 2.1) maps accentuate the structural grain or discontinuity in the topography in function of the chosen ‘sun’ elevation and orientation. This can be an advantage for presentation of the data and highlighting of the structures. However, structural analysis of such shaded relief images should account for this characteristic, and several different light direction orientations should be chosen subsequently while investigating the imagery. In fact, ordinary satellite images also suffer from his limitation which cannot be accounted for. Therefore, different satellite images displaying different light directions should be investigated for the same region, in order not to miss structural features obscured by certain light directions.
Fig. 2.1 Shaded Relief DTM of the Teletsk basin area. Topography and bathymetry have been combined in order to get a general DTM. Projection in UTM, zone 45N, WGS 84.
Fig. 2.2
2.3 Satellite imagery and photo-geology

The use of digital technology for remote sensed image processing has greatly facilitated the possibilities, accuracy and speed of digital data processing during the last decade. The quality of the available images as well as the development of software has made great advances the last five years, allowing the application of colour-composite analysis of IR-and visible spectral bands for structural geology. The image processing techniques applied in this study such as georeferencing, colour-composite image generation and mosaicing are supposed to be routine processes and will not be discussed here. As stated in the introduction (table 2.1), the present study uses several available satellite scenes at different resolutions of the studied region as a starting point for the structural analysis. We will now present examples of the different scenes, all representing a same patch of sensed terrain. This allows us to show the differences in characteristics and possibilities of the different scenes, and to highlight the compatibility of the different source data.

Figure 2.3 shows a fragment of a Russian RESURS satellite image recorded in March 1998. The RESURS satellite records reflectance in the visible and near IR frequency’s (0.4-1 μm), and has three spectral bands. The maximal ground resolution is 160 m for RESURS-MSU-SK images. The images consist of narrow (~50 km) and long (~400 km) patches striking in N-S to NE-SW direction. The large scan-bands have the disadvantage that they produce high angular
distortions, and ortho-rectification and warping of the scenes is obligatory for correct image interpretations. For the whole study area about 10 such images have been used.

Figure 2.4 shows a fragment of a LANDSAT MSS (taken in April 1977) image covering the southern part of Lake Teletskoye. The LANDSAT 2 satellite was equipped with a four channel multi-spectral scanner (MSS) with band 1 and 2 recording reflections in the visible spectra (0.5-0.6 and 0.6-0.7 μm) and band 3 and 4 in the near IR (0.7-0.8 and 0.8-1.1 μm). The sensor produces scenes of approx. 185x185 km, resulting in ground resolutions of approx. 80 m. Six of such images, covering most of the study area, have been analysed in the present study.

Fig. 2.4 False colour composite of a LANDSAT MSS image of the southern Teletskoye area.
Figure 2.5 shows a SPOT 1 scene of southern Lake Teletskoye, recorded in June 1986. This satellite was equipped with a three band multi-spectral scanner operating in frequencies comparable to LANDSAT MSS, namely 0.5-0.6, 0.6-0.7 and 0.8-0.9 µm. The images have a pixel size (ground resolution) of 20 m and record 3000 pixels a line. This results in image scenes of 60x60 km. Eight SPOT images have been used for analysis of northeastern Altai.
Figure 2.6 shows a CORONA satellite image of southern Lake Teletskoye. The CORONA satellites form part of a reconnaissance program developed by the CIA (United States), which started in 1959. The program and the scenes have been kept secret for four decades, until they were declassified in 1995 [Wheelon, 1997]. The high resolution black-and-white images of the CORONA satellites form a valuable (and low-cost) source for structural-geological investigations. The example on figure 2.5 comes from the KH-4A mission from September 1964, and has a ground resolution of 9 feet (2.7 m). The CORONA images of such type consist of long (~300 km) and narrow (~20 km) negative black-and-white films. Both photoprints and direct high-resolution scans of the negatives were used for interpretation. The whole investigated zone in northeastern Altai and parts of Tuva and West-Sayan (chapter 8) are covered by the 20 images used in the present study.

![CORONA Satellite Image](image1.png)

**Fig. 2.6** Fragment of a CORONA satellite image covering the southern Teletsk area, represented at two different resolutions.
Figure 2.7 shows an aerial photograph of the southern segment of Lake Teletskoye. The photographs have a scale of about 1:30,000, and cover areas of typical 6x6 km. Detailed analysis of aerial photographs has been conducted for the Teletsk basin area and for local zones along the Shapshal fault (chapter 7).

Fig. 2.7 Aerial photograph of the southern Teletsk region.
2.4 Remote sensing as a tool for tectonic analysis and interpretation: structural relations

Introduction

This chapter briefly recapitulates the theoretical restrictions related to the interpretation of sensed data. The concept and application of morphotectonic analysis is explained. As remote sensing is used in this study to analyse structural phenomena and interpret kinematics, tectonic histories and evolutions, some terms are briefly explained here, in order to keep nomenclature cohesive and clear throughout the study.

Graben-Rift

Distinction is made between a graben and a rift, in the descriptive-structural versus geodynamic sense of the terms. Graben is a term describing the structural phenomenon of a down-dropped trough framed by faults [e.g. Olsen and Morgan, 1995]. It has a morphological meaning, although a tectonic origin in intrinsic. It can vary in scale from several metres to hundreds of kilometres.

A rift is an extensional structure, affecting at least the whole crust and the upper lithospheric mantle [Olsen and Morgan, 1995]. So a rift structure has always a scale order of several tens to hundreds of kilometres. Continental extension, mantle anomalies and intraplate volcanism are highly associated to the term. Rifts can, though not exclusively, have a graben morphology.

Active fault

The question whether a fault is ‘active’ or not is difficult to address, and definitions of active faults are therefore various and depending on the interpreter’s speciality and aim. On geological basis, it has been proposed that an active fault could be defined as a fault which moved in the current (active) tectonic (faulting) regime. A fault which has not moved during the current regime of prevailing regional stress and strain may be termed ‘extinct’ [Wood and Mallard, 1992]. In place of proposing a universal time-scale for classifying active faults, those authors propose that geologists should preferably use time-scales derived from the regional tectonic information on displacement recurrence and the duration of the current tectonic regime. However, this approach suffers from the disadvantage of the vagueness in terms of age constraint of the ‘current tectonic regime’, and the wide variation of its absolute age in different parts of the world.

Neotectonics, defined as the tectonics occurring in the current tectonic regime [Wood and Mallard, 1992], or as the period controlled by the last and prevailing geodynamic mechanism [Angelier, 1989] thus has a timing varying with the studied region, as the current tectonic regime started at different times in different places. Thus, neotectonic structures, such as

---

1 Measured on the base of active (historical) geodynamic phenomena, such as earthquakes, creep, volcanic activity, etc.
active faults in this definition would be faults that moved during the last 700 ka in Italy, <500 ka for the Western USA, and >2Ma for the Basin and Range province.

Also, tectonic regimes seem to be able to change rapidly in both time and space [e.g. Bergerat et al., 2000], resulting in a complicated relation in adjoining regions between the ‘active faults’ following the above definition. Note also that active tectonics and neotectonics are not always interpreted in the same way. The former has got historical time connotation (tectonic movements that are expected to occur within a future time span of concern to society [e.g. Steward and Hancock, 1994]), while the latter became related to the current tectonic regime.

A recent attempt to classify fault activity on a paleoseismic base was done by M.N. Machette. He proposes a subdivision of fault activity based on an absolute time-scale. When surface displacement along the fault during the last 10,000 years is evidenced, the fault is a Holocene active fault. A fault that has moved during the last 130,000 years is a Late Quaternary active fault, and a fault that moved during the last 1.6 Ma is a Quaternary active fault [Machette, 2000]. Capable active faults and potentially active faults are rather ill-defined terms used in seismic risk assessment studies, interpreted differently by different organisations.

The problem of this absolute time scale based classification is that it is strongly influenced by the amount and type of data available for the studied objects indicating their activity, and absolute dating of active faults is still suffering from great errors and uncertainties.

In the whole discussion about fault activity, it has become important to define the recurrence intervals of the seismic cycle for each studied region when talking about active faulting. Those recurrence intervals range from several tens of years to >10 ka and even >100 ka [Machette, 2000 and references therein]. For paleoseismic applications and seismic-hazards analysis, fault maps showing potentially active faults should encompass a time interval that includes several earthquake cycles. Also slip rate should be used as a proxy for fault activity and fault risk, with low (< 2 mm/yr) slip rates faults distinguished from high (>5 mm/yr) slip-rate faults.

The present study inherently will make use of terms related to this topic. Because of the specific nature of the investigated region (instability of the current tectonic regime and absence of well defined stratigraphic markers), we will talk about recent faults for structures showing evidences of late Cenozoic movements, corresponding to the onset of the uplift of the region and related to the current tectonic regime in general terms of $S_{\text{Hmax}}$ direction (see part II). They may, though not necessarily, be active in the Holocene. Where dated, active faults will be treated on the absolute scale of Holocene active faults, Late Quaternary active faults and Quaternary Active faults. Potentially active faults throughout this study are structures mapped using remote sensing on their morphological characteristics of possible recent movements and which are used as a basis for further (field) analysis.

---

2 According to the US Regulatory commission, capable faults are faults having one displacement during the last 50 ka or multiple movements during the last 500 ka. Others define it as faults having the ability for future movement. The state of California defines potentially active faults as all faults associated with surface-rupturing earthquakes during the Quaternary, whereas others define them as ‘faults which are suitable oriented to become activated in the present tectonic regime, but which have not yet moved’ [Machette, 2000; Stewart and Hancock, 1994, and references therein].
Morphotectonics

A basic tool in the structural interpretation of remote sensing data is morphotectonic analysis. It relates specific landforms to the tectonic movements causing them. Inferences from morphotectonics are directly related to dynamic and/or kinematic processes. At the smallest scale, the starting point of the morphotectonic analysis is the outline of the major topographic units, such as mountain ranges, basins, river drainage, large lineaments, ...

Lineaments generally don’t give as much information concerning the type of structure as they do about the trend and extend of the structure. In some cases, however, the adjacent blocks on both sides of the lineament have specific features allowing to estimate or qualify the type of structure. Difference in lithology and/or relief at both sides of the lineaments can indicates a fault. Secondary structures, such as pinnate joints and Riedel shears can also indicate movement zones. Active faults can be recognised by the nature of the alluvial fans, their relation with topography, displacements of river valleys and of other geomorphological elements.

Lineament analysis

Lineaments are traced in accordance with the definition given by Dennis [Dennis, 1967] who follows Hobbs' early statement [Hobbs 1911] that lineaments are "rectilinear or gently curved alignments of topographic features on a regional scale, generally judged to reflect crustal structures". Structural and morphological elements are combined into lineaments of composite nature. Lineaments are long and linear alignments of relatively short morphologic structures occurring in a restricted number of trends. Morphologic structures out of one of the groups of azimuths may become linked together and appear as a lineament. On tabular terranes covered by recent alluvium, the interpretation of lineaments is based on more subtle criteria, e.g. tonal differences.

There is only limited three-dimensional control on the attitude of the sensed structures and lineaments. It is tentatively assumed that the straight lineaments which are independent of topography, extent sub-vertically [e.g. Wise et al., 1985]. This assumption is confirmed for the near-surface by field observations and seismic reflection studies (see further). Curvilinear structures are generally supposed to dip less steep. However, exclusions about dip directions and angles are not to be made on the basis of remote sensing alone.

Lineaments are, but for a few, not treated as individually distinct structural elements. Rather have they been attributed a statistical significance on the level of a set of parallel linear elements and grouped in lineament swarms. Essential in the analysis is the model of vertical superposition of sets of surficial lineaments in the brittle uppermost parts of the crust upon a limited number of individual crustal discontinuities in lower crustal layers having the properties of an elastic continuum. The latter may recur in various geodynamic cycles, the former are mostly (secondary) effects of neotectonics, related to lateral movements, rifting, uplift and crustal arching. Some of the deeper lineaments break through to the surface. These fundamental structures can sometimes be links to the mantle [Sykes, 1978; Dobretsov et al., 1996]. We follow Holdsworth [Holdsworth et al., 1997] in accepting the presence of perennial crustal discontinuities [see also e.g. McConnell, 1972; Theunissen et al., 1994; Cunningham...
et al., 1996; Klerkx et al., 1998; ...]. The genesis and (type of) reactivation of many of them, however, depend on the regional and local rheology and stress field [Wise et al. 1985; Sassi et al., 1993; Brun and Nalpas, 1996; Delvaux et al., 1997].

The interpretation procedure followed is entirely visual. A clear and straight segment is picked out and traced. The interpreter then looks for any significant cross-cutting linear structure at both ends of the traced segment, thus looking for a possible causative relationship between each pair of lines. This routine analysis is repeated under different viewing angles. Aligned segments are subjectively interconnected in accordance with the former definition. Tightly disposed parallel lines are replaced by one main lineament. In areas of horizontal cover rocks and alluvia, straight river segments, abrupt tonal changes and contrasting tonal corridors are treated in the same way as lineaments recognised in dissected terrains with hard rock lithology. The physical meaning of a class of lineament directions is taken for granted if an identical or parallel set of lineaments is detected on various occasions. No systematic multi-temporal analysis has been carried out, but scenes taken at different times of the day and the year have been used in the course of the work. These precautions should allow for a sufficient degree of confidence in the physical reality of the recognised lineament classes.

Lineament schemes and available geological maps are then combined and the results interpreted. The photo-interpretation of selected areas may be repeated in the light of the ongoing interpretation. This non-automatic approach emphasizes all geologically significant structural directions. In most cases it discerns at once between bedding and tectonic features. The final result of the survey is a re-interpretation of the available geological map on a suitable scale, assigning importance to relative age and possible activity of the investigated structures. The structures and trends suspected from controlling the active tectonics of the investigated region are then used as a basis for further investigations of geological and/or geophysical nature (see further).

The geodynamic interpretation of the structural elements delimited by lineaments is treated in the last chapter of part 1 and applied in part 2 of this study.