

CHAPTER 3. SUB-SURFACE ASPECTS: SEISMICS AND RADON

- 3.1 Introduction
 - 3.2 A high resolution seismic reflection study
 - 3.2.1 Methodology
 - 3.2.2 Application
 - 3.3 A gas-geochemical study
 - 3.3.1 Radon as a fault tracer
 - 3.3.2 Methods
 - 3.3.3 Limitations
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The previous chapter showed how remote sensing in mountainous regions can only be used as a first step in the characterisation of fault structures. This chapter discusses a different approach, where the sub-surface expression of fault structures are studied. This is used as a second step in characterising fault structures. We will use two different methods for gaining sub-surface information of faults, namely reflection seismics and radon and mercury activity. In some cases, a relative timing or an estimation of the age of fault activity can be deduced using these methods.

3.1 Introduction

As a second step in the identification of active faulting and structural investigation of deformed continental basement areas, we will discuss the specific geophysical and geochemical studies applied in the Lake Teletskoye area with the aim of further identifying active faults on the one hand, and complementing and specifying the remotely sensed structures and zones on the other hand. Where the morphological study gives information only about the surface expression of tectonic deformation, no direct information can be obtained concerning the evolution with depth of the studied structures. The complementing studies will provide information about the sub-surface aspects of the studied structures.

In continental mountainous terrains, little information about the recent tectonic activity is generally available, due to the absence of a well developed Cenozoic stratigraphy. The zones of Cenozoic sedimentation are generally limited to local basins, and often it are those basins that are filled with water to form lakes. In the latter case, seismic reflection profiling provides a relatively cheap method for studying the sedimentological and structural characteristics at depth, leading to a tectonic interpretation with a relative timing constraint.

In the other case, where all structures cut basement rocks and no reliable direct time-related investigations can be carried out, a way to characterise the investigated structure is by analysing the characteristics of the gases formed at depth and escaping to the atmosphere along the fractures. In certain cases, the characteristics of the emanated gases could give information about the fault activity. The technical and theoretical aspects of both methods will

be treated in this chapter, and the application to the study area, the results and conclusions will be discussed in Part II of this study.

3.2 A high resolution seismic reflection study

3.2.1 Methodology

A detailed seismic survey of the sedimentary fill of the Teletsk basin was performed over the last few years, using different techniques and resolutions. A first seismic reflection study was carried out by Victor Seleznev and his team (Seismological Survey SB RAS, Novosibirsk). In total 120 km one-channel seismic reflection profiles penetrating about 900 ms were used to study the structure of the sediment load inside the basin. Preliminary interpretation of these sections was done by Seleznev et al. [1995]. High resolution one-channel seismic reflection profiling was carried out in 1996 by M. De Batist (Renard Centre of Marine Geology, RUG, Ghent). These profiles have a higher resolution but penetrate less deep in the sediments.

Both methods use one-channel continuous seismo-acoustic profiling. The Seleznev equipment used signals from IMPULSE and PI-250 airguns (30 l) with main excited frequencies of 70-80 and 175 Hz, recorded by a 30-m long seismic piezo-streamer towed behind the same ship on which the pneumo-source was mounted. Airguns were shot every 25 m. The source control and signal recording were monitored by an onboard computer system (for locations of the profiles see fig. 3.1). The signal penetrated the bottom sediments more than 800 ms in the southern part and more than 700 ms (variable) in the northern part of the basin.

The high resolution image of the uppermost section was obtained through high resolution one-channel reflection profiling in which higher-frequency (150-1500 Hz) signals of a CENTIPEDE multi-electrode sparker were received by a 3.2 m one-channel streamer. The streamer included eight serial hydrophones spaced at 40 cm. It was dragged near the water surface and collected a high-resolution response. The incoming signal was band pass-filtered with 400 Hz low-cut and 3000 Hz high-cut. The observations were performed on a grid of 91 profiles with a total length of 340 km (fig. 3.2). In the southernmost extremity of the basin, penetration reaches 750 ms. Some regions of the lake showed no seismic penetration at all, probably because of interstitial biogenic gas.

3.2.2 Application

The aim of the high resolution profiling was to study in more detail the top few hundred metres of sediments. The relatively dense profile net (fig. 3.2) allowed correlation between the most important observed faults and construction of a structural map of the sediments. It are basically the latter high resolution reflection profiles that have been used in the present study, combined with the (re-interpreted) more penetrating reflection profiles of Seleznev.

A structural interpretation was performed on the profiles, identifying fault trends, and the segments of the sedimentary column they affect (a compilation is presented in appendix D). By this, relative timing could be determined and basin architecture was analysed. Faults affecting the uppermost sediments and breaking through to the surface are considered as Holocene active. They have been correlated with the bathymetric and topographic morphology

discussed in the previous chapter, and are used as a basis for the structural interpretation of the active and recent tectonics for the Lake Teletskoye graben, presented in the second part of this study.

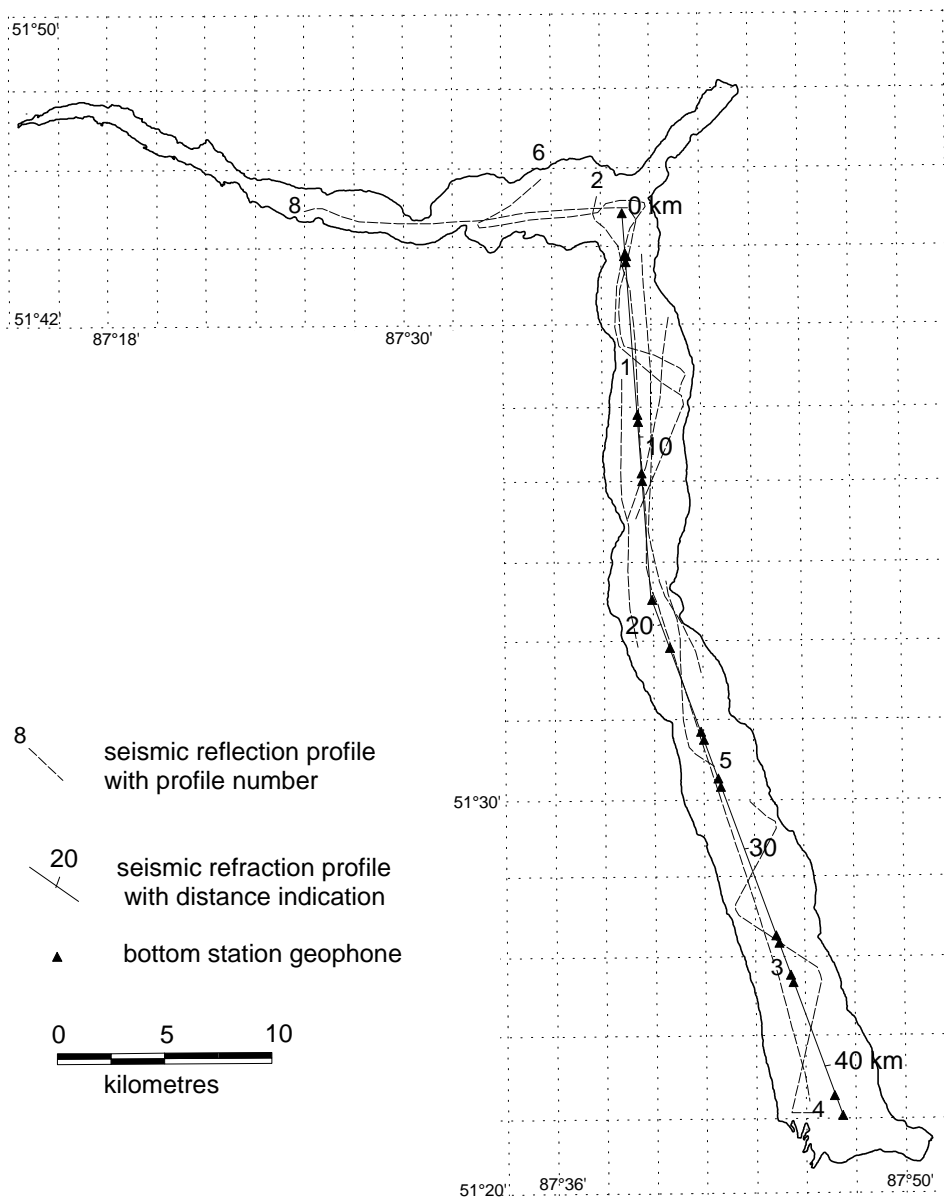


fig. 3.1 Location of refraction and reflection profiles obtained by V. Seleznev [Seleznev et al. 1995], and partly reinterpreted in the present study [Dehandschutter et al., submitted; Seleznev et al, in press].

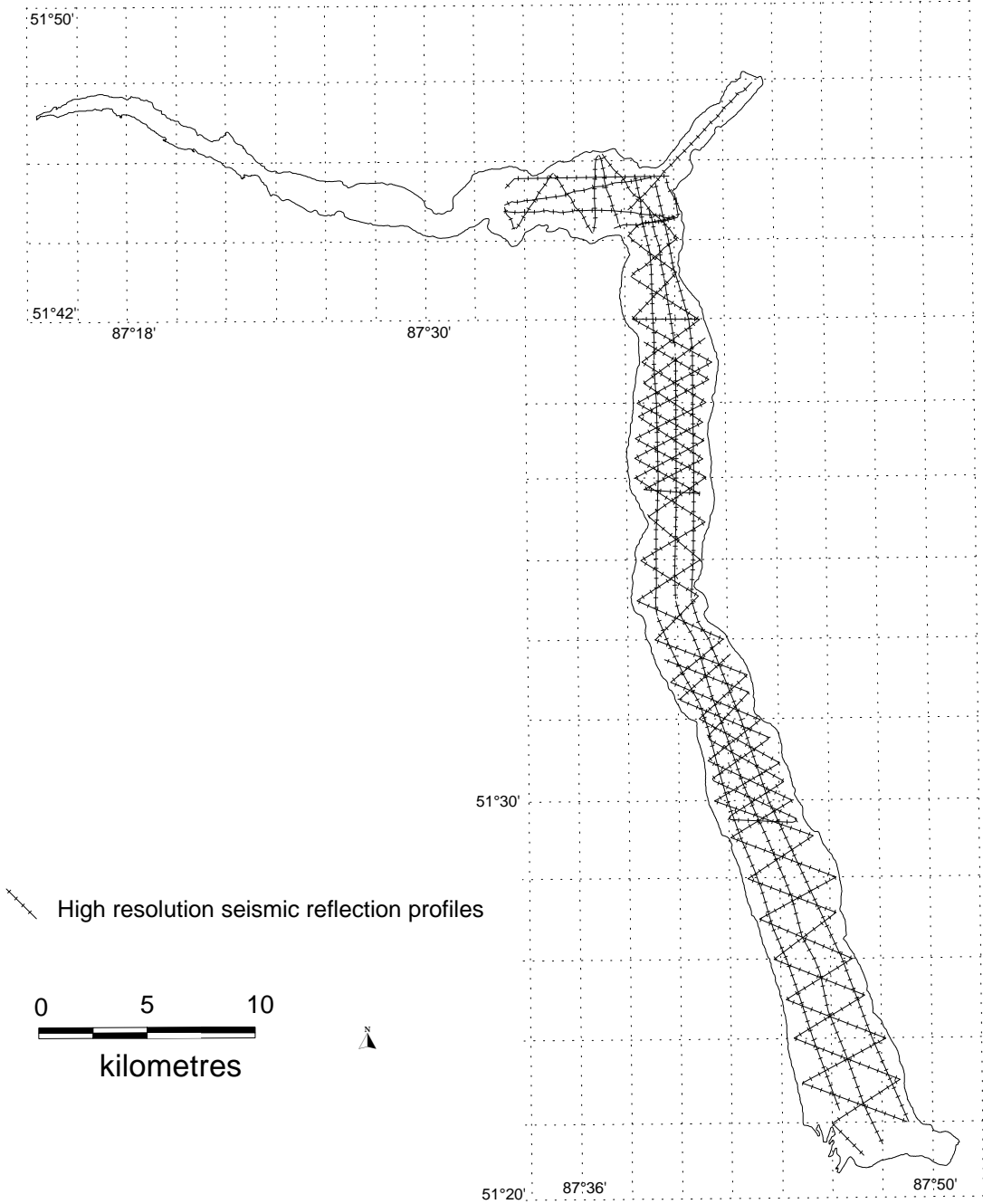


Fig. 3.2 Location of high resolution seismic reflection profiles obtained by M. De Batist and interpreted in the frame of the present study [Dehandschutter et al., submitted].

3.3 A gas-geochemical study

3.3.1 Radon as a fault tracer

Fault zones often exhibit a high permeability compared to the surrounding country rock. The difference generally is up to several orders of magnitude [Pedersen et al., 1997]. This property can turn fault zones into preferential pathways for advective gas-carrying fluid transport. During their way to the surface, pressure decrease allows the gases to escape from the fluids into soil-gas and eventually into the atmosphere. This allows to define a 'geochemical active fault' [Lombardi et al., 1998], when increased gas concentrations (methane, CO₂, He, Hg, Rn, ...) are measured in the soil gas above the fault.

Radon is a radioactive gas that is formed in the decay series of uranium and thorium, which occur in virtually all kinds of rocks, in small concentrations. Two radon isotopes are important in geological studies: ²²²Rn (normally referred to as radon, Rn) is formed by the decay of ²²⁶Ra (and ²³⁸U) and has a half life of 3.82 days; ²²⁰Rn (also called thoron, Tn) is formed by the decay of ²²⁴Ra (and ²³²Th) and has a half life of 55.6 seconds. Although uranium and thorium have largely similar geochemical behaviour, in oxidizing environments oxidized uranium (uranyl) is soluble in water, and can be enriched in certain rocks, whereas thorium has no differentiating mechanism. Thus, the Th/U ratio in metamorphic and sedimentary rocks is variable.

Because of its inert gas geochemistry (that allows radon to accumulate and to be transported in the pore fluid) and its radioactivity (that makes it detectable in small concentrations), radon is a suitable gas for tracing geochemical active faults. Radon existing in rock forming minerals can escape from that rock by recoil into air¹- or fluid filled cracks. This can be quantified by the emanation coefficient, being the ratio of Rn escaping from the minerals to the Rn formed in the minerals. This ratio obviously depends on the availability of U and Th, porosity, moisture content and temperature, and lays between 1 and 20 % [Nazaroff, 1992].

Subsequent transport from the place of escape into the gas/fluid phase towards the earth surface occurs mainly by advection, where the radon is carried by fluids or other gasses [Lombardi et al., 1998]. Darcy's law describes the velocity v of the fluid (in m/s), driven by a pressure gradient P

$$v = -k / \mu \nabla P$$

where k is the permeability of the medium and μ the viscosity of the fluid. The permeability on itself depends on the porosity and the diameter of the particles. This relation also shows the influence of changing atmospheric pressure conditions on the radon transport.

The partitioning of Rn between the water- and the gas-phase can be estimated by Henry's law

¹ Relative to the recoil-distances ($\sim 10^{-8}$ m), diffusion lengths ($\sim 10^{-30}$ m) are negligible in the process of freeing Rn from the rock or soil grains, and diffusion therefore doesn't contribute in this process [Nazaroff, 1992].

$$I_w = kI_g$$

introducing a P and T dependent partitioning coefficient k (Ostwald coefficient) ranging from 0.5 (at 1 atm and 0°C) to 0.2 (at 25°C). I_w is the Rn concentration in water, I_g in gas, both expressed in Bq/m³.

Transport from radon through the soil occurs by combined molecular diffusion and advection. The diffusive flux density in soil (J_{ds} in Bqm⁻²s⁻¹), described by Fick's law, depends on the radon activity gradient in the soil and on the diffusion coefficient:

$$J_{ds} = -D_e \nabla I_g$$

With I_g the radon concentration in the soil gas (in Bqm⁻³) and D_e the effective diffusion coefficient (in m²/s), which is corrected for soil (reduced free surface area and increased travel distance) and reduced relative to the molecular diffusion coefficient in open air by a typical factor 4 [Nazaroff, 1992]. D_e is also strongly dependent of the moist content, where water (blocking the available pore space) can reduce D_e by 10⁴ times.

It can be supposed that active faults induce higher radon emanations and exhalations along their gauge than inactive faults [De la Cruz et al., 1986; Steinitz et al., 1992]. This is acceptable, since crack formation and propagation (increased by active faulting) allows radon trapped in rock pores to be transported to the surface [Schery et al., 1982; Banwall and Parizek, 1988; Reimer, 1990; Kemski et al., 1992]. This principle was already successfully applied in several studies accurately localizing faults and determining fault activity [Israel and Björnsson, 1966; King, 1980; Varley and Flowers, 1992; Clamp and Pritchard, 1998; Ciotoli et al., 1999].

The present study uses radon activity measurements to characterise the investigated potentially active fault zones, and to try to distinguish active faults. We choose to test the application of the method in an area for which a wide variety of information, derived from field mapping, micro-structural analysis, remote sensing on various scales and seismic reflection profiling has been accumulated in the frame of this study. This information led to the determination of active fault segments and of other fault segments supposed to be not active in the current tectonic regime. A comparison of the radon behaviour between these different fault segments (active and non-active) was used as a test of the method for the local area. The radon concentrations outside the fault zone are compared to the values inside the zone, resulting in the detection of relative anomalies.

3.3.2 Methods

Radon concentrations were determined along traverses running perpendicular to the investigated fault zones. The radon activity (emanation) was measured in soil-gas extracted by a syringe through a probe that was inserted about 80 cm into the ground. This depth seems to be a realistic balance between theory and practical circumstances. On the one hand, the influence of short term meteorological fluctuations on radon concentration diminish rapidly

with sampling depth [Varley and Flowers, 1992]. On the other hand the thickness of a soil layer is often less than 1 m, and the presence of boulders inside the soil can hamper penetration. However, a constant measurement depth is important to make the different points in a profile comparable. Experience showed that an 80 cm sampling depth could be maintained throughout a profile. Sample distance was generally 20 m to 80 m, depending on the location.

Two different measurement methods were used. Radon concentrations were determined by injecting the soil-gas in an electret-ionization chamber (E-PERM) where the ^{222}Rn activity is deduced from the reduction of surface potential (measured by the voltage difference just before and one hour after injection of the soil gas) of a charged synthetic layer (electret) inside the ionization chamber. Discharge of the electret occurs due to the formation of ions by α -particle emission during decay of ^{222}Rn to ^{218}Po [Kotrappa et al., 1988]. Ten minutes of sample equilibration before injection into the electret cell brought the thoron (^{220}Rn) concentration to a negligible level ($T_{1/2} = 56$ s).

Radon concentration was also measured by an α -scintillation radon counter. For this, another soil-gas sample was extracted through the same probe (where possible). The soil gas was directly pumped into a scintillation chamber. When the α -particles, produced during radon decay, impact the scintillator's ZnS(Ag) layer, an energy pulse is created in the form of photons, measurable by a photo-multiplier and a counter. Because both radon and thoron decay by means of α -emission, counting was performed during four intervals of 100 seconds each. The concentration of both isotopes could be determined by solving a set of equations.

Additionally to the soil gas concentration measurements, radon concentrations in spring-waters were determined by an E-PERM electret device for water sample measurements, and by a SARAD scintillation counter for water samples [Dehandschutter et al., in press].

The radon flux (exhalation) was measured along profiles perpendicular to the fault trend, by absorption on active charcoal that retains radon by Van der Waal absorption [Gustafsson and Hildingsson, 1984]. The charcoal was buried in the ground at 15 cm depth for 12-24 hours. Sample distance was 20 m. The absorbed radon was measured by the ^{214}Bi concentration determined using a γ -spectrometer with a NaI detection crystal. The radon flux can be calculated knowing the surface of the lid, the absorption time and the absorbed radon concentration. The method is described in detail by Cohen and Cohen [1983].

Background γ -radiation was monitored and mapped, using a portable γ -spectrometer, in order to control the influence of possible shallow and local uranium-thorium sources on the radon content. 13 soil samples, taken in the vicinity of the radon measurements, were analysed in the laboratory for their U and Th concentrations by γ -spectrometry [Dehandschutter et al., in press]. This allowed to determine the existence and location of possible local radon sources.

Another way to estimate the occurrence of local radon producing U-Th ore sources is the evaluation of the Tn/Rn ratio along the profile. This ratio evaluation is allowed, since U and Th have a similar geochemical behaviour, and generally occur together. As thoron has a short half-life time, it can not move over large distances, and its presence in the soil gas, reflected

by a high Tn/Rn ratio, indicates the presence of a local radioactive source. Radon anomalies are thought to have a relatively deep origin only if they are accompanied by a low Tn/Rn ratio [Hus et al., 1999].

In parallel with the radon measurements, mercury was measured in several soil and water samples. For the determination of Hg in soil, samples were taken at two levels. The upper 5 cm of turf and the underlying 35 cm of soil. Water samples were carried in 33 cc glass bottles. 3 ml of strong nitrogen-acid was added as a preserver. Mercury concentrations were determined by 'cold vapour' atomic absorption [Dehandschutter et al., in press].

3.3.3 Limitations

Although a '*geochemical active*' fault is not necessarily '*tectonically active*', high radon concentrations over fault zones can give information about fault activity complementary to geological information.

Although the detection of local geological anomalies and their characteristics using radon activity measurements is aimed by this study, several other parameters also influence the occurrence of radon inside soil-gas and in underground and surface waters. The most important factors are briefly discussed here, in order of importance. In the discussion of the results, the actual effects of the influences are examined in detail.

The **uranium content** in the sub-surface rocks can act as a primary ore source for radon emanation. The influence of this parameter on the measurement can be controlled by soil sample geochemical analysis [Dehandschutter et al., in press] and by monitoring the ratio of thoron to radon [Hus et al., 1999]. The **soil permeability** influences the retainment of radon in the soil gas, and thus has a major influence on the measurements. Measurement of radon exhalation is preferable over emanation in cases where a high soil-gas permeability causes fast escape of radon to the atmosphere. In such cases the emanation values are low, but the escaping radon is captured by the exhalation device. Parallel measurements of emanation and flux can give an estimation of the influence of soil permeability on the radon behaviour. **Moisture content** in the soil, and more general the sense of vertical moist transport, influences the concentration of radon in the soil as well as its flux to the atmosphere. Generally, wet soil gives a higher emanation due to a decreased permeability (and increased emanation coefficient; e.g. [Nazaroff, 1992]). Local variations in this parameter thus influence and complicate the results, and detailed estimation and evaluation has to be carried out on site. For advective transport, atmospheric circumstances and changes in **atmospheric conditions** (air pressure, temperature, wind speed) can change the emanation and exhalation values by influencing the emanation coefficient [Kraner et al., 1964; Duenas et al., 1997]. The availability of radon in soil gas is also controlled by the temperature dependent partitioning of radon between the gas-phase and the fluid-phase [Washington and Rose, 1990]. For the above mentioned reasons, stable atmospheric conditions are preferable for measuring radon.