R-01-25

Dating methods and geochronology of fractures and movements in bedrock: a review

Eva-Lena Tullborg
Terralogica AB

Sven Åke Larson
Göteborgs universitet

Sadoon Morad
Uppsala universitet

June 2001

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1402-3091
SKB Rapport R-01-25

Dating methods and geochronology of fractures and movements in bedrock: a review

Eva-Lena Tullborg
Terralogica AB

Sven Åke Larson
Göteborgs universitet

Sadoon Morad
Uppsala universitet

June 2001

Abstract

Constraining the absolute and relative ages of crustal movements is of fundamental importance in evaluating the potentials of a site as a repository for spent radioactive fuel.

In this report a review summary of up to date absolute and relative dating methods is presented with specific attention to those methods most amenable for dating of fractures. A review of major fracture- and shear zones in the Swedish part of the Baltic Shield is also given.

Since the shield has suffered a long and complicated history, geochronologists are faced with the problem of reactivated zones when attempting to date these. It is important to get structural control in order to make the choice of dating method since different methods may give answer to completely different questions. An integration of all geological background data is necessary in order to make the proper chose to fit the raised question.

Sammanfattning

Vid bedömningen av potentiella lägen för förvar av använt kärnbränsle är kunskapen om absoluta och relativa åldrar hos rörelser i berget av stor vikt.

Denna rapport innehåller ett sammandrag av vanligare dateringsmetoder för åldersbestämning av mineral och bergarter med speciell vikt på metoder lämpliga till att datera rörelser längs sprickor. En översikt ges även över viktigare sprick-/skjuvzoner i framförallt den svenska delen av Baltiska skölden.

Sammanfattningsvis kan sägas att vid datering av sprick- och skjuvzoner i Baltiska skölden ställs man inför problemet med reaktivering av zoner då skölden haft en lång och komplicerad tektonisk historia. En noggrann strukturell kontroll är nödvändig vid val av metod då de olika metoderna kan ge svar på helt olika frågor. Viktigt är därför att integrera all geologisk bakgrundkunskap i syfte att välja rätt metod och därmed besvara önskad frågeställning.

Contents

1 Introduction

The relative and absolute dating of fractures in bedrock help constraining the frequency and extent of crustal movements, and should thus be considered seriously prior to the selection of an appropriate site as a repository for spent radioactive fuel. In most cases, geochronology of crustal fracturing and movement is approximated by dating a variety of associated fracture minerals. The formation of these fracture minerals, in turn, records variations in the physico-chemical conditions. Therefore, to properly constrain the suitability of a site, it is of fundamental importance to employ an integrated approach that takes into consideration three parameters:

- origin of fractures,
- fluid types that circulate in the bedrock during the geological evolution of the area,
- type(s) of minerals in the fractures and their conditions of precipitation.

1.1 Origin of fractures

Fractures are structures that vary widely in length (< 1 mm to 1000 km) and develop by brittle failure of rigid bedrock that are subjected to stress (force per unit area). However, brittle deformation of the bedrock, which occurs at shallow depths in the crust, may have deep (i.e. high temperature and pressure) ductile or semi-ductile precursors. If displacement occurs along the plane of bedrock rupture, fractures are then generally referred to as faults. If no displacement is involved, the fractures are called joints, cracks or fissures. Fractures are extremely common in the uppermost 10 km of the Earth's crust where low temperatures (<=300°C) and pressures (<=4 kb) are encountered (Ramsay and Huber, 1987). Although major fracture zones can be avoided when a repository is constructed at depths of several hundred meters below the surface, it is extremely difficult to avoid small fracture zones and solitary fractures in the bedrock.

Forces that induce stress and fracturing to bedrock include gravitation, plate-motions, loading and unloading of the crust, emplacements of magmas, changes in temperature and humidity, increase in fluid pressure and impacts by asteroids (e.g. Ramsay and Huber, 1987).

As the direction and intensity of stress regimes change locally and regionally with time, bedrock fracturing is usually recursive but not continuous over geological time scale. Repeated fracturing may occur along older rupture planes or result in new fractures. The intensity and frequency of crustal deformation (fracturing and folding) due to plate motion are greatest particularly in settings at or close to active plate margins, resulting, for example, from the collision of two continental plates, subduction of oceanic plate beneath a continental plate, and transform faulting. This means that dating of fracturing and faulting events should be performed within the context of a tectonic model of the study site.

Sweden is located mostly in a continental shield, and is thus in a stable area in terms of plate tectonics. Therefore, dramatic changes in the direction and magnitude of stress regimes due only to plate motion is not expected to occur over a foreseeable time, perhaps not even over the time scenario covered by the storage of radioactive waste (i.e. 100 000 yrs). However, crustal fracturing in this region occurred also due to the loading and removal of the latest ice sheet(s). Fracturing and faulting induced are mainly by deglaciation, being enhanced by an increase in the differential stress caused by a decrease in vertical stress relative to the horizontal stress (Boulton et al, 1995; Mörner, 1995; Talbot, 1999). Local compositional, textural and structural heterogeneities of crystalline continental crust may lead to local variations in the style and magnitude of deformation. For instance, crustal movement commonly involves the reactivation of palaeo-tectonic faults rather than the initiation of new faults (Fenton, 1991). It is further believed that crustal deformation in Scandinavia is probably due to the combined effects of both plate tectonics and glacio-isostatic rebound. It is thus likely that post-glacial crustal raptures occur as chaotic fracture belts in which tensional and compressional features co-exist (e.g. Stewart and Hancock, 1994).

1.2 Fluid types

Fractures act as pathways for fluid flow as well as for heat- and mass transfer (e.g. Deming, 1993 and the references therein). Fluids play an important role in nearly all geological processes and are ubiquitous in the oceanic and continental crusts to maximum depths of at least 10–15 km (Nur and Walder, 1990). Fluids in the Earth's crust vary widely in origin (Figure 1-1) as well as in chemical and isotopic compositions, but can be broadly classified into:

- high-temperature magmatic and metamorphic fluids,
- hydrothermal fluids,
- low-temperature fluids.

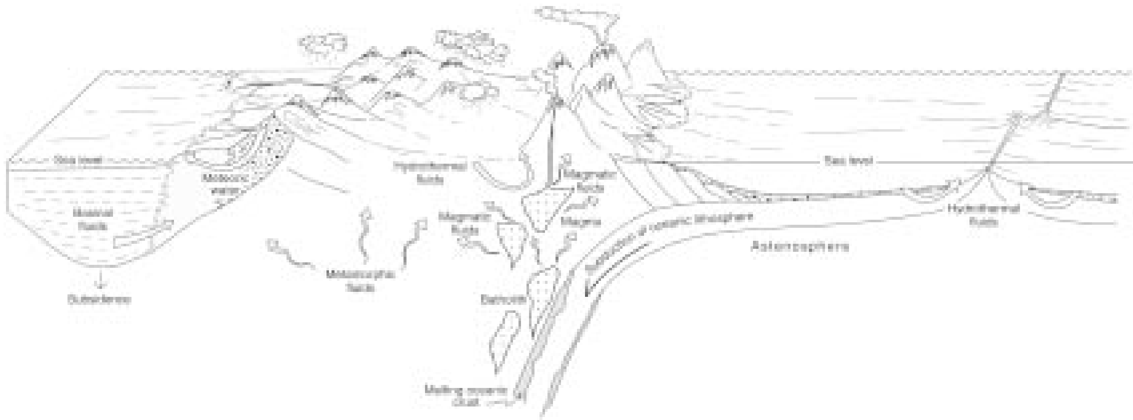

__Figure 1-1.__ A cross section of the upper parts of Earth's crust illustrating schematically the origin of various types of fluids in a plate tectonic context.

High-temperature, magmatic fluids are related to the expulsion of fluids from magma prior to and during crystallisation. High-temperature, metamorphic fluids (initially CO_2-rich, low-salinity water) are related to dehydration reactions that occur during prograde metamorphism to amphibolite facies (e.g. Phillips et al, 1993). Hydrothermal fluids are formed by the incursion and convection of meteoric and marine waters in the vicinity of magmatic bodies seated in continental and oceanic crusts. Basinal fluids are derived by compactional dewatering and thermal dehydration of hydrous minerals in sedimentary basins.

Low-temperature groundwater in crystalline bedrock is largely of meteoric, brackish and marine origins and at larger depths, brines of marine and meteoric origin occur (Stober and Bucher, 2000).

All of these fluids often have chemical compositions reflecting elemental and isotopic evolution due mainly to water-mineral interactions and/or mixing with other fluid types.

1.3 Fracture mineralisation

Various types of minerals (Table 1-1) may precipitate from fluids (liquid and/or gases) and partially or completely fill the fractures (i.e. brittle failure of host rocks). In some cases, the formation of fracture mineralisation is associated with brecciation of the host rock (i.e. rupturing into angular rock fragments) along fault planes. The formation of fracture mineralisation may also occur during semi-ductile deformation of bedrock. The type(s) of fracture minerals formed is controlled by several parameters including:

- pressure-temperature conditions (i.e. depth below surface and proximity to magmatic bodies),
- chemical composition of the fluids in the fractures,
- mineralogy, chemistry and texture of the host rocks,
- patterns of fluid circulation.

Various generations of fracture minerals result from changes in these parameters, which may or may not be related to recursive activation of fractures. Nevertheless, changes in stress regimes often have a profound influence upon the pattern of fluid flow in bedrock (Sibson, 1993). In addition to fracture filling, mineralisation may occur within the host rock in the immediate vicinity of the fractures. Surficial cracks and fissures that are located above the groundwater table in crystalline bedrock may be filled with sediments and weathering products of the host rock.

1.4 Aims

This report is written at the request of Swedish Nuclear Fuel and Waste Management Co (SKB) and represents a review of the current available knowledge of relative and absolute geological dating methods. A special emphasis is made on dating of fractures and movements in bedrock of a wide variety in type and age range. It also includes a brief presentation of the major Swedish shear zones.

Table 1-1. A list over main types of vein minerals, their formulae and most common host bedrock.

Mineral[1]	Formula	Host rock[2]	Temperature[3]
actinolite	Ca2 (MgFe)5Si8O22(OH)2	crystalline	≥ 200°C
adularia	KAlSi3O8	crystalline	≥ 100°C
albite	NaAlSi3O8	crystalline	≥ 100°C
analcime	Na16(Al16Si32O96).16H2O	volcanic	≥ 150°C
anhydrite	CaSO4	•	≥ 0°C
ankerite	Ca(Fe,Mg)(CO3)2	sedimentary	≥ 50°C
barite	BaSO4	•	≥ 0°C
calcite (c)	CaCO3	•	≥ 0°C
chalcedony	SiO2	•	≥ 0°C
chalcopyrite	CuFeS2	•	≥ 0°C
chlorite	(Fe, Mg, Al)5(Al,Si)4O10(OH)8	crystalline	≥ 100°C
clinoptiolite	(Na4K4)(Al8Si40O96).24H2O	volcanic	≥ 50°C
dickite	Al2Si2O5(OH)4	•	≥ 80°C
dolomite (r)	CaMg(CO3)2	sedimentary	≥ 50°C
epidote	Ca2(AlFe)3Si3O12(OH)	crystalline	≥ 200°C
Fe-crust	FeO(OH)	•	≥ 0°C
fluorite	CaF2	•	≥ 100°C
galena	PbS	•	≥ 0°C
heulandite	Ca4(Al8Si28O72)24H2O	volcanic	≥ 100°C
illite/sericite corrensite	KAl3Si3O10(OH)2	•	≥ 100°C
kaolinite	Al2Si2O5(OH)4	•	≤ 80°C
laumontite	Ca4(Al8Si16O48).16H2O	crystalline	≥ 50°C
magnesite	MgCO3	mafic	≥ 50°C
Mn-crust	MnO(OH)	•	≥ 0°C
monazite	(CeLaYTh)PO4	crystalline	≥ 200°C
opal	SiO2	volcanic	≥ 0°C
phillipsite	(K,Na)10(Al10Si22O62).20H2O	volcanic	≥ 50°C
prehnite	Ca2Al(AlSi3)O10(OH)2	crystalline	≥ 200°C
pyrite	FeS2	•	≥ 0°C
pyrrhotite	FeS	•	≥ 25°C
quartz	SiO2	•	≥ 70°C
serpentine	Mg6Si4O10(OH)8	mafic	≥ 100°C
smectite	Al2Si4O10(OH)2.xH2O	•	≥ 0°C
sphalerite	ZnS	•	≥ 0°C
talc	Mg3 Si4O10(OH)2	mafic	≥ 100°C
titanite	CaTiSiO3	crystalline	≥ 150°C
tourmaline	Na(MgFe)3Al6Si6O18(OH)4	crystalline	≥ 200°C
wairakite	Ca8(Al16 Si32 O96).16H2O	volcanic	≥ 100°C

1 (r) = rare; (c) = common.

2 • common in more than one rock type.

3 precipitation temperature may vary widely depending on the mineralogical composition of host rocks, chemical composition of the fluids and pressure.

2 Absolute and relative dating methods in geochronology

Dating of geological material and events can be relative to other objects (i.e. younger or older within a sequence of events), or absolute (precise age expressed in number of years). The dating method selected depends on the availability and age of suitable materials in the fracture (Figure 2-1).

The fracture fillings are usually used for dating fractures and movements in bedrock by employing a wide range of methods. Some of the methods may date actual movements (e.g. palaeomagnetic dating and electron spin resonance), whereas others record the time required to precipitate vein minerals or time elapsed since a section of fault emerged at the ground surface (e.g. thermoluminescence of scarp-derived colluvium) (Forman et al, 1991). Generally, fracturing and faulting are, in a geological perspective, instantaneous processes whereas the process of fracture mineralisation is, at least during low temperature conditions, likely to be very slow and conducted over a prolonged period of time. This underlines the problems in dating movements by the use of mineralisation in fractures. Further, the age of fracture minerals always yields a minimum of the age of fracturing. Additional complexities in accurate dating of crustal movements stem from:

- The formation of fracture minerals may occur during several episodes of fracture reactivation and fluid flow.
- Re-setting of the isotopic systems or palaeomagnetic poles at elevated temperatures.

Usually, geologists constrain the geological evolution of an area by reconstructing the sequence of events based on relative- and/or absolute dating. However, relative dating of geological objects both on micro- and macro-scales is important prior to the selection of targets to be used for absolute dating. A complete reconstruction of the relative geological history for an area may not be fully achieved due, for example, to the lack of suitable exposures of key features, complex metamorphic recycling, limited access to sample material, or the absence of materials that are suitable for dating. Since individual fractures and fracture zones are often reactivated, it is important to be aware of the

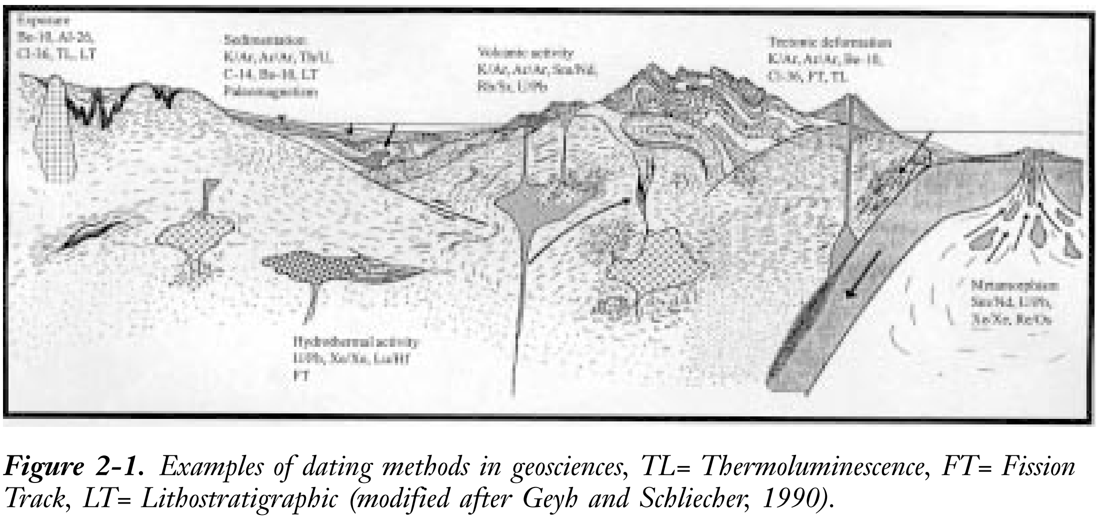

Figure 2-1. *Examples of dating methods in geosciences, TL= Thermoluminescence, FT= Fission Track, LT= Lithostratigraphic (modified after Geyh and Schliecher, 1990).*

specific event selected for absolute dating. Poor separation of recursive events induces the risk of inadequate dating. Thus, mineralogical and textural information should be derived from thin-section studies prior to sampling of material for dating (cf Gromet, 1991). This information can then be linked to the geological evolution of the area.

2.1 Relative geochronology

The relative dating of geological material and events can be achieved at micrometer- to regional scales using a wide variety of techniques, being dependent on the target to be dated and the overall geological setting (Table 2-1). In addition to cross cutting relationships of geological features, relative dating methods include:

- reconstruction of the current and palaeo-hydrogeological conditions,
- structural evolution and tectono-stratigraphy,
- petrology and mineral paragenesis,
- stable oxygen, hydrogen, carbon and sulphur isotopes,
- radiogenic strontium isotopic signatures,
- microthermometry and micro-chemical analyses of fluid inclusion,
- geomorphology,
- lithostratigraphy.

2.1.1 Petrology and mineral paragenesis

Small-scale petrologic (e.g. crystal morphology, micro-fracturing, paragenetic relationships and occurrence habits) and mineral-chemical/isotopic studies (e.g. Blyth et al, 1998) and/or the study of crystal-chemical zonation contribute to the understanding of the hydro-chemical and structural evolution of bedrock (Milodowski et al, 1998 and references therein). For instance, petrographic observations from the Sellafield site for disposal of nuclear waste indicate that changes in calcite morphology correlate well with salinity changes of the groundwater (Milodowski et al, 1998), and may therefore provide information about the relative age of calcite and palaeo-hydrogeology of the area.

Several site investigations show that many minerals were formed recursively (i.e. various generations of a single mineral) at different geological conditions (e.g. Kamineni and Stone, 1983; Kamineni et al, 1987; Milodowski et al, 1998; Tullborg et al, 1999). Relative dating of such features should be complemented by cross-cutting relationships of fracture fillings and mineral phases (cf Maddock et al, 1993; Tullborg et al, 1999). Micro-chemical and isotopic analyses of small-sized fracture minerals can be conducted with great accuracy by application of electron- and ion microprobe as well as by laser ablation ICP-MS technique.

Table 2-1. Common nonbiostratigraphic relative dating methods in geosciences.

Method	Example of materials	Relative age
Radiogenic isotopes[1]		
Tritium (3H)	water, ice	after 1950
Carbon-14 (14C)	water, organic matters, carbonate, C-gases	after 1950
Chlorine-36 (36Cl)	water, salts	after 1950
Krypton-85 (85Kr)	water, ice	after 1950
Strontium-90 (90Sr)	water, organic matter, carbonate	after 1950
Caesium-137 (137Cs)	whole sediment, water	after 1950
Iodine-129 (129I)	whole sediments, water	after 1950
Stable isotopes[2]		
Hydrogen/Hydrogen (2H/H)	whole rock, water, H-gases	relative source & process
Carbon/Carbon (13C/12C)	carbonate, organic matter, water	relative source &process
Nitrogen/Nitrogen (15N/14N)	whole rock, organic matter, water	relative source & process
Oxygen/Oxygen (18O/16O)	carbonate, Si-oxide, water	relative source & event
Sulphur/Sulphur (34S/32S)	sulphides, water, S-gases	relative source & event
Strontium/Strontium (87Sr/86Sr)	carbonate, feldspars, water	relative source & event
Lithostratigraphic[3]		
Tephrochronology	volcanic ash	relative events
Varvechronology	whole sediments	$<10^4$
Sea-level change chronology	geomorphic relationships	relative events
Sequence stratigraphy	fluvial patterns	
Petrologic and mineral paragensis	mineral growth	
Fluid inclusions	Fluid chemitry	
Hydrological	mixing of groundwater	
Stuctural-stratigraphic		
Geomorphic		
Astronomic[4]		
Earth-Sun-Moon-orbital cycles chronology	mathematical models	relative cyclicity

[1] Radioactive isotopes released during nuclear weapon testing, reprocessing of nuclear fuel and nuclear accidents.

[2] These methods are based on, variation in source of isotopic ratio and natural catastrophic or cyclic events.

[3] Based on sedimentological and stratigraphic features.

[4] Related to the earth's orbital forcing.

2.1.2 Fluid inclusions

Small fluid inclusions tend to be entrapped at imperfections on crystal surfaces during crystallisation. These fluids, which were present at the moment of sealing, are called primary, in that they were enclosed during crystal growth, and represent a sample of the fluid responsible for precipitation of a vein mineral. After crystal growth, stress may result in the formation of tiny cracks and intracrystalline deformation along cleavage and twinning planes. These cracks and planes may contain quartz cement that contain small secondary fluid inclusions, and thus provide a record of the fluids present after growth of a crystal. Thus a single crystal may contain primary and secondary inclusions.

Microanalyses and microthermometry of fluid inclusions can thus provide useful information about the temperature, composition, origin and geochemical evolution of a fluid that existed during crystallisation and fracture healing (Roedder, 1984; Shepard et al, 1985; Goldstein, 1994). These data are important for the reconstruction of the regional hydrogeological history of bedrock in response to repeated deformation and fluid flow events.

Cooling and subsequently heating of the inclusions is performed to obtain the melting temperatures of phases present and the homogenisation temperature between liquid and gas phases. These temperatures are used to calculate the composition and salinity of the inclusions, and the minimum temperature at which the mineral formed. Micro-chemical analyses of the liquid and gas phases in the fluid inclusions can also be carried out by Raman microprobe studies or by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Minerals suitable for fluid-inclusion studies include quartz, calcite and fluorite (Potts et al, 1995).

2.1.3 Stable oxygen ($^{18}O/^{16}O$), hydrogen ($^{2}H/^{1}H$), carbon ($^{13}C/^{12}C$) and sulphur ($^{34}S/^{32}S$) isotopes

The stable isotope ratios of oxygen ($^{18}O/^{16}O$), hydrogen (^{2}H (or D)/^{1}H), carbon ($^{13}C/^{12}C$) and sulphur ($^{34}S/^{32}S$), which are measured by means of a mass spectrometer, can be used to constrain interactions with mineral-water-organic systems and to trace the physico-chemical and climatic conditions that prevailed during the formation of a specific mineral generation(s). Stable isotopes are thus useful for the purpose of the relative dating of fracture minerals.

Values of oxygen ($\delta^{18}O$ per mil) and hydrogen (δD per mil) isotopes relative to a standard (commonly Vienna Standard Mean Ocean Water, V-SMOW), relate as follows:

$$\delta^{18}O \text{ per mil} = [(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}] / (^{18}O/^{16}O)_{standard} \times 1000. \qquad \text{Equ. 2-1}$$

This relation may provide valuable information about the origin and the spatial and temporal geochemical evolution of fluids that circulated in fracture systems. The fractionation of hydrogen and oxygen isotopes between water and minerals is strongly related to temperature. Hence, the $\delta^{18}O$ (e.g. in carbonates and silicates) and δD (e.g. in clay minerals) values can be used to calculate the precipitation temperature of fracture minerals in case the $\delta^{18}O$ or δD values of the fluids are known or inferred. These isotopes can also be used to infer the palaeo-climatic conditions in case the fluids involved are of surficial origin (Gascoyne, 1992; Bar-Matthews et al, 1996). The condensation of clouds into rain during movement to higher latitudes or altitudes causes the progressive enrichment of meteoric waters in ^{16}O relative to ^{18}O (i.e. decrease in $\delta^{18}O$), which will be reflected in minerals that precipitate from such waters. Conversely, fluids influenced by evaporation under dry conditions become enriched in the heavy oxygen (^{18}O) and hydrogen (D) isotopes relative the lighter ^{16}O and ^{1}H isotopes, respectively.

There are two main carbon reservoirs in nature: ^{12}C-rich reduced carbon (including organic matter and methane) and ^{13}C-rich inorganic carbon (the carbonate system). Carbon isotopic composition of dissolved CO_2, and hence of carbonate minerals, may be strongly influenced by kinetic factors. For instance, during microbial methanogenesis of organic matter, methane is strongly enriched in ^{12}C (negative $\delta^{13}C_{PDB}$ values), whereas the dissolved CO_2 (i.e. HCO_3^-) becomes enriched in ^{13}C (positive $\delta^{13}C_{PDB}$ values). Dissolution of gaseous carbon (e.g. from the decay of plant remains in soil) into water is associated by enrichment of HCO_3^- in ^{13}C by about 10 per mil at 25°C. Thus, $\delta^{13}C$ values of carbonate fillings can provide useful information about the origin and biogeochemical conditions of formation of dissolved carbon (e.g. Tullborg, 1989; Tullborg et al, 1999; Wallin and Peterman, 1999; Blyth et al, 1998; Pitkänen et al, 1999; Marshall et al, 1992; Paces et al, 1998).

The $^{34}S/^{32}S$ ratio in sulphides (e.g. pyrite, FeS_2) and sulphates (e.g. anhydrite $CaSO_4$) are reported as $\delta^{34}S$ per mil relative to the standard CDT (Canyon Diablo Troilite). Sulphur isotopes are fractionated by kinetic effects, such as the enrichment of sulphide ions in ^{32}S due to bacterial and thermal reduction of sulphate. Thus, in such systems, the remaining sulphate-ion reservoirs become enriched in ^{34}S, which are commonly recorded in associated sulphate minerals like anhydrite and barite ($BaSO_4$). In the absence of sulphate reduction, low-temperature sulphate minerals (formed e.g. by evaporation) inherit the $\delta^{34}S$ signature of the dissolved SO_4^{2-} in the fluid, for example, seawater, i.e. there is no isotopic fractionation encountered. The $\delta^{34}S$ composition of oceanic sulphate, as deduced from the analyses of marine evaporitic sequences, has varied substantially (+10 to +30 per mil) throughout geological times (Claypool et al, 1980). This variation is attributed to variations in the extents of thermal (by seawater cycling through the oceanic crust about the mid-oceanic ridges) and bacterial sulphate reduction versus derivation of sulphate ions by continental weathering. Modern oceanic water has an average $\delta^{34}S$ value of +20.99 per mil. However, microbial activity may seriously affect isotope ratios in marine or brackish pore-water in bottom sediments and in near surface fractures as observed at the Äspö Hardrock Laboratory by Laaksoharju (1995). A proper identification of the percolation of marine waters cannot be based only on $\delta^{34}S$.

Contrary to seawater, the $\delta^{34}S$ values of near-surface water/groundwater vary widely and reflect several parameters, such as concentration of organic matter, the extent of oxidation of sulphide (source of ^{32}S) and dissolution of sulphate (source of ^{34}S) minerals in the bedrock.

2.1.4 Strontium isotopes ($^{87}Sr/^{86}Sr$)

Strontium isotopic ratios ($^{87}Sr/^{86}Sr$) are normalised to a standard with $^{86}Sr/^{88}Sr = 0.1194$ in order to correct for variable mass fractionation in the mass spectrometer. The $^{87}Sr/^{86}Sr$ ratio is not significantly fractionated by natural processes, so it can be used to determine the strontium isotopic composition of fluids from which Sr-bearing minerals precipitate (e.g. limestone and sulphates). All Sr isotopes are stable (non-radioactive), but ^{87}Sr is a radiogenic isotope derived from the decay of radioactive ^{87}Rb isotope. Regional Sr-isotopic composition of fracture minerals may provide useful information about the origin of fluids and the degree of water-rock interaction during the structural evolution of the bedrock.

The $^{87}Sr/^{86}Sr$ ratios of groundwater depends largely on the degree of interaction with and mineral composition of the host bedrock; young volcanic rocks (e.g. oceanic crust at mid-oceanic ridges) have lower average $^{87}Sr/^{86}Sr$ ratios than old continental crystalline basement (averages of 0.7037 and 0.7198, respectively). McNutt et al (1985), concluded that brines that were isolated in fractures for a long time are equilibrated with the host rock and reach a similar $^{87}Sr/^{86}Sr$ ratio as the present-day whole rock. Conversely, it is well-established (e.g. Burke et al, 1982) that the $^{87}Sr/^{86}Sr$ ratio of the oceans at any one geological time is constant, but that this ratio has changed with time due to variations in the relative supply from the two sources above. The reconstruction of seawater Sr-isotopic composition throughout the Phanerozoic is based on analyses of various Phanerozoic limestones. Sr-isotope investigations of groundwater and fracture calcite in the Äspö area, Sweden, show that extensive water-rock interaction has occurred along the flowpaths, thus making dating of fracture mineralisation based on Sr-isotopes hard, although contributing to the separation of high relative to low-temperature calcite formation (Wallin and Peterman, 1999; Peterman and Wallin, 1999; Bath et al, 2000).

2.1.5 Structural evolution and tectono-stratigraphy

Surface and subsurface, regional structural geological history studies allow constraining the relative timing of deformation and evolution of large-scale shear and fracture zones and related phases of metamorphism and magma emplacement events within an area. The structural geological evolution of the SKB, Äspö site was constrained by, for example, Munier (1993) and for the Eastern Segment in the Sveconorwegian Province of Sweden by Larson et al (1986). The deformation and fault reactivation patterns in the subsurface can be revealed by means of reflection seismics, such as in the northern part of the Protogine Zone (Juhlin et al, 2000), which was correlated with surficial structural features (Wahlgren et al, 1994). The relative ordering of structural and metamorphic events are often emphasised within the framework of progressive deformation of a region (i.e. kinematics). Studies such as the one conducted on the southern part of the Mylonite Zone, south-western Sweden (Park et al, 1991; Berglund, 1997), constrained thrusting and faulting events within the Sveconorwegian orogenic events.

Tectono-stratigraphic studies also allow constraining the relative timing of deformation events in a region (cf Axberg, 1980). For instance, studying the Phanerozoic sedimentary strata by e.g. reflection seismics Marek (2000 and references therein) has revealed that major Jurassic inversion took place in the Sorgenfrei-Tornqvist Zone (a transform fault) that delimits the Baltic Shield to the south. Thus, displacements along faults were restricted to specific strata for which the ages are known. A similar approach of studying structurally disturbed and undisturbed strata has been used by Lagerbäck (1979; 1991) to reveal onshore neotectonic movements in northern Scandinavia. Such studies include e.g. measurements of offsets in eskers and drumlins.

Monitoring of distances across a fracture zone using a system with a very high precision (GPS or laser measurements) can confirm orientation of present aseismic movements (Talbot et al, 1998). Precise monitoring of deformations of the Earth's crust can be carried out by using continuous satellite geodetic measurements. Long-term seismic measurements may register movements in the crust along zones of crustal weakness.

2.1.6 Geomorphology

Sedimentation and erosion occur in response to local and regional geomorphic features and drainage, which are in turn controlled by the pattern of crustal deformation and relative changes in sea level. Geomorphologic studies of denudation surfaces may thus allow defining distinct tectonic blocks and ages, and hence the large-scale tectonics of an area (e.g. Lidmar-Bergström, 1995, 1996).

2.1.7 Lithostratigraphy

There is a close link between the patterns of sedimentation and stratigraphic framework in a basin and regional/global tectonism. Hence, the examination of stratigraphic sequences should provide important clues to the relative timing, extent and scale of crustal movements. Evidence of tectonism is recorded within the geometry, texture (e.g. grain size and sorting) and structure (e.g. the occurrence of slumped deposits) of the fill as well as within the sedimentary pile at the basinal scale (e.g. Frostick and Steel, 1993; Mörner, 1996). For instance, successive marine- and lacustrine delta abandonment may be attributed to uplift and migration of faulting activity in the basin margin (Seger and Alexander, 1993). Several studies have demonstrated that the structural relationship between successive alluvial fan and fan delta lobes and their substratum allows the establishment of chronology of deformation in the basin (e.g. Mellere, 1993). Graded till sediment along major fault escarpments in northern Fennoscandia were interpreted to be the result of palaeo-seismicity events during the retreat of ice about 8 thousands years ago (Lagerbäck, 1990; 1997).

Stratigraphic sequences also record evidence of relative sea-level change, which may, in turn, record regional or global tectonic activities. For instance, the presence of abrupt transgressive events can be due to sudden co-seismic subsidence of the basin floor. Conversely, a fall in the relative sea level can be caused by uplift of the basin floor, and the sediment would thus record regressive events characterized by deposition of shallow-water sediments and erosion of earlier-deposited, deeper water marine or lacustrine sediments. An uplift in the hinterland and/or a fall in the relative sea level induce a change in the style of fluvial systems and their siliciclastic deposits from meandering to braided (Shanley and McCabe, 1994).

Disturbance of lamination in varved sediments has, in some cases, been attributed to liquefaction induced by seismic vibration created during early stages of deglaciation 12000–9000 years ago and during the Holocene (Mörner, 2000).

2.2 Absolute dating methods in geochronology

A large number of methods have been applied to determine the absolute age of minerals, rocks, organic matter and fluids (Table 2-2, Table 2-3). These methods can be sub-divided into five major groups:

- radioactive/radiogenic isotopes,
- radiation damage,
- dosimetry,
- palaeomagnetism,
- chemistry.

Many of these methods are applicable to dating of fracture-filling material and related features. The biostratigraphic dating methods, which rely on identification of age-index fossils, will not be covered by this review.

Table 2-2. Common absolute dating methods in geosciences[1].

Method	Example of materials	Dating limit years[2]	% error
Isotopes			
Potassium/Argon (40K/40Ar)	K-feldspars, mica, whole rock	$>10^{4}$	3
Argon/Argon (39Ar/40Ar)	K-feldspars, mica, whole rock, water	$>10^{4}$	2
Potassium/Calcium (40K/40Ca)	K-feldspars, mica, sylvite	$>10^{6}$	3
Rubidium/Strontium (87Rb/87Sr)	K-feldspars, mica, whole rock	$>10^{6}$	3
Lanthanum/Cerium (138La/138Ce)	pyroxene, allanite, apatite, titanite	$>10^{8}$	5
Lanthanum/Barium (138La/138Ba)	epidote, allanite, monazite	$>10^{8}$	5
Samarium/Neodymium (147Sm/143Nd)	palgioclase, pyroxene, garnet, whole rock	$>10^{7}$	5
Lutetium/Hafnium (176Lu/176Hf)	whole rock	$>10^{8}$	5
Rhenium/Osmium (187Re/187Os)	sulphide minerals, whole rock	$>10^{8}$	5
Osmium/Osmium (187Os/186Os and 187Os/188Os)	molybdenite	$>10^{8}$	5
Uranium/Thorium/Lead (238U/206Pb, 235U/207Pb and 232Th/208Pb)[3]	zircon, titanite, monazite, epidote whole rock	$>10^{6}$	3
Uranium/Thorium/Protactinium (230Th/234U, 231Pa/235U, 231Pa/230Th, 234U/238U)[3]	whole rock, carbonates, Mn-Fe oxides	$>10^{3}$	3
Uranium/Helium (U/He)	carbonate, basalt	$>10^{4}$	15
Thorium-excess and Protactinium-excess (231Th, 230Th, 234Th, 228Th and 231Pa)[1]	carbonate, Fe-Mn oxides	$>10^{3}$	5
Common Lead (206Pb/204Pb, 207Pb/204Pb, 208Pb/204Pb)[3]	Pb-sulfides, whole rock	$>10^{8}$	3
Lead/Lead (207Pb/206Pb)	whole rock, K-feldspars, sulfides, zircon	$>10^{8}$	3
Lead/Alpha (Pb/alpha activity of (238U+235U+232Th))	zircone, xenotime, thorite	$>10^{6}$	3
Krypton/Krypton (Krsf/Kn)[4]	zircon, monazite, britholite	$>10^{7}$	3
Xenon/Xenon (Xesf/Xen)	zircon, monazite, xenotime	$>10^{6}$	5
Lead-210 (210Pb)	whole sediment, peat	$<10^{2}$	5
Tritium (3H)	water, ice	$<10^{2}$	5
Tritium/Helium (3H/3He)	water, ice	$<10^{2}$	5
Helium-3 (3He)	quartz, pyroxene	$<10^{5}$	5
Beryllium-10 (10Be)	whole rock, quartz, carbonate	$<10^{7}$	5
Carbon-14 (14C)	whole sediment, carbonate, organics	$<5x10$	3
Neon-21 (21Ne)	whole rock, quartz, pyroxene,	$<10^{7}$	10
Aluminium-26 (26Al)	whole rock, quartz, carbonate	$<5x10^{6}$	5
Chlorine-36 (36Cl)	whole rock, carbonate, water	$<2x10^{6}$	10
Krypton-81 (81Kr)	water, ice	$<10^{6}$	10
Iodine-129 (129I)	whole rock, carbonate water	$>10^{6}$	10
Radiation damage and dosimetry			
Fission track (FT)	apatite, zircon, allanite, mica	$>10^{3}$	10
Thermoluminescence (TL) and Optically Stimulated Luminescence (OSL)	quartz, feldspars, zircon	$<10^{6}$	10
Electron Spin Resonance (ESR)	carbonate, quartz, feldspar	$<3x10^{6}$	10

Method	Example of materials	Dating limit years[2]	% error
Paleomagnetism			
Archeomagnetic (virtual geomagnetic pole) chronology	ceramics, flint, whole sediment	$<10^4$	10
Geomagnetic polarity chronology	whole rock, magnetite	$<10^8$	10
Chemical			
Amino-Acid Racemization (AAR) and degradation (AAD)	fossils, carbonates, bones	$<10^6$	10
Obsidian hydration	natural glasses	$<10^7$	10

[1] Details of the methods are described in Faure (1986); Geyh and Schleicher (1990); Attendom and Bowen (1997); Dickin (1997).

[2] The dating limit refers to the lowest or highest age and may deviate from the number given depending on the material and instrumentation used.

[3] These are several interrelated methods and can be used together.

[4] The sf refers to spontaneous fission of 238U and n to neutron-induced fission of 235U.

Table 2-3. Radiogenic isotopes commonly used for dating fracturing events and related features[1].

Isotope	Half-life (years)	Decay product	Most appropriate target	Lower age limit (years)[2]
^{39}Ar	269	^{39}K	K-bearing minerals (K-feldspars, mica, hornblende) and water	$>10^4$
^{40}K	1.25×10^9	^{40}Ar, ^{40}Ca	K-bearing minerals (K-feldspars, mica, hornblende)	$>10^4$
^{87}Rb	4.88×10^{10}	^{87}Sr	Whole rock sample, K-bearing minerals	$>10^6$
^{230}Th	7.5×10^4	^{206}Pb	Carbonates (calcite, aragonite), organic materials	$>10^3$
^{231}Pa	3.4×10^4	^{207}Pb	Carbonates (calcite, aragonite), organic materials	$>10^3$
^{232}Th	1.4×10^{10}	^{208}Pb	Whole rock sample and a wide variety of minerals, including zircon, titanite, epidote, monazite, rutile, apatite and uranium minerals	$>10^6$
^{234}U	2.47×10^5	^{208}Pb	See ^{232}Th	$>10^3$
^{235}U	7.04×10^8	^{207}Pb	See ^{232}Th	$>10^6$
^{238}U	4.47×10^9	^{206}Pb	See ^{232}Th	$>10^6$
^{10}Be	1.5×10^6	^{10}B	Quartz, whole rock	$>10^3$
^{14}C	5730	^{14}N	Carbonate, organic material,water	$>10^2$
^{26}Al	716×10^3	^{27}Mg	Quartz, whole rock	$>10^3$
^{36}Cl	301×10^3	^{36}Ar	Cl-bearing minerals (NaCl, KCl), water	$>10^3$
^{129}I	15.7×10^6	^{129}Xe	whole rock, water	$>10^4$

[1] For references see Table 2-2.

[2] This refers to lower limit at which dating is generally possible.

2.2.1 Radiometric methods

The principle of radiometric dating is based on the decay of a radioactive atom (parent nuclide) into a stable atom or another radioactive (daughter nuclide) atom during a specific time termed the half-life. The decay process is not influenced by factors such as temperature, pressure or chemical processes. Therefore, the decay law is based on the statistical probability that a specific radioactive atom will decay within a specific unit of time and expressed as:

$$N_t = N_0 e^{-\lambda t} \qquad \text{Equ. 2-2}$$

Where

N_0 = the number of radioisotopes at time zero,

N_t = the number of radioisotopes at remaining time t and

λ (decay constant) = In2/half-life

or

$$t = -\lambda \cdot \ln\left(\frac{N_t}{N_0}\right) \qquad \text{Equ. 2-3}$$

The basic equation above can also be expressed in term of so called parent (radioisotope) and daughter (stable or in some cases also radioactive) isotopes and appears as growth rather than decay equation:

$$N_d = N_p\left(e^{\lambda t} - 1\right) \qquad \text{Equ. 2-4}$$

or

$$t = \frac{1}{\lambda} \cdot \ln\left[\frac{\left(N_d - N_{d0}\right)}{N_p} + 1\right] \qquad \text{Equ. 2-5}$$

where d and p are daughter and parent isotopes respectively.

An important prerequisite for the use of the equations above is that the system (mineral and rock) has been closed without addition or loss of the radioactive isotope and/or its decay product since time t_0 (the start of radioisotope decay). This is seldom encountered in fractured rocks, but can be used to elucidate events that lead to the resetting of the isotopic equilibrium due to changes in for example, formation of new minerals and fluid migration in the fracture environment upon deformation event(s).

Most methods of dating mineralisations in fracture zones require closed system conditions in terms of mass transfer during mineral formation, which, unfortunately, is not always the case. Thus, it is necessary to integrate dating results with structural and geochemical information in order to describe tectonic events more adequately.

Various dating methods are briefly discussed below and the reader is recommended to modern text-books for more extensive information about the specific methods and applications (e.g. Faure,1986; Geyh and Schleicher, 1990; Heaman and Ludden, 1991; Dickin,1997; Parnell, 1998).

The rubidium-strontium (^{87}Rb-^{87}Sr) method

This method is based on the decay of the radioactive ^{87}Rb isotope to the stable ^{87}Sr isotope and is mainly used for dating K-bearing minerals because Rb can replace K. The age is thus calculated through measurement of ^{87}Rb and ^{87}Sr after correction for excess ^{87}Sr by normalisation to ^{86}Sr. Generally measurement of isotopic ratios on at least two co-genetic samples or minerals (e.g. feldspar-mica) is needed in order to calculate the age which is termed isochron age.

The method has been used widely to date deformation events in, for example, the ultramylonites of Middle Allochton in the Scandinavian Caledonides (Claesson, 1980, 1986); fracturing in shear zones (Hickman and Glassly, 1984), hydrothermal fracture mineralisation at about 250–330 million years of the Mississippi Valley Type ore deposits of the central and eastern USA (Nakai et al, 1990; Brannon et al, 1992), mica in fault zones (13–23 Ma) of the northern Greece (Wawrzenitz, 1994), and mica formation (430 Ma) in mylonite zones of the Moine thrust zone, NW Scotland (Freeman et al, 1998). Wickman et al (1983) used the method to constrain alteration events in granitoids of the Swedish Precambrian.

A metamorphic event may reset the isotopic system if temperatures were higher than the closure temperatures of the dated minerals. After the thermal pulse of a metamorphic event has opened the Rb-Sr mineral system, the rock will cool and the mineral system is again closed to element mobility (blocking temperature). For example muscovite will close at 500°C while biotite will close at approximately 300°C. The degree of isotopic homogenisation depends on many variables such as type and grade of metamorphism and mineral content. Usually ^{87}Sr tends to migrate out of the crystal (e.g. biotite and K-feldspar), and be taken up by the nearest Sr sink (e.g. plagioclase, calcite, epidote and apatite). From this follows that a whole-rock sample may be useful in seeing back through a metamorphic event, which disturbs mineral systems, while single minerals (in smaller scale) can be used to date such an event.

The resetting of the Rb-Sr system during deformation is accomplished by homogenisation of the $^{87}Sr/^{86}Sr$ ratio. This homogenisation is mostly due to diffusion of Sr promoted by high temperature, deformation, recrystallisation and mineralisation (Claesson, 1988), although resetting will preferentially take part along major paths for fluids (Hickman and Glassley, 1984). Small grain size and smaller systems govern resetting. Claesson (1980, 1986) dated low grade thrusting in the Middle Allochton of the Scandinavian Caledonides by using thin slices of ultramylonites while coarser (fine-grained) samples with porphyroblasts were incompletely reset. Whole-rock samples yielded intrusion ages similar to that of zircon U-Pb dating ages.

If the host rock to hydrothermal fracture minerals has had a high and relatively homogeneous Rb/Sr ratio since the time of mineralisation, e.g. due to metamorphism, it is possible to date minerals with low Rb/Sr ratio, such as barite, fluorite, calcite and anhydrite (Ruiz et al, 1980). Thus, the initial $^{87}Sr/^{86}Sr$ is believed to represent the ratio of the wall rock at the mineralisation event since hydrothermal solutions tend to adopt the wall rock Sr isotope composition (e.g. Ruiz et al, 1980, 1981; Ruiz, 1983).

Remarks: This method may be used to date thermal events by using minerals that have suffered internal isotopic homogenisation. Movements can be dated by using ultra-mylonites. Dating is not possible in cases where whole-rock samples did not remain closed to Rb and Sr or where the minerals were incompletely homogenised.

The samarium-neodymium (Sm-Nd) method

The radioactive isotope ^{147}Sm decays to the daughter ^{143}Nd. It has a decay constant of 6.54×10^{-12} yr $^{-1}$. By using the decay equation in a similar way as demonstrated for the Rb-Sr system and dividing through with the stable isotope ^{144}Nd, an isochron diagram can be constructed. The $^{147}Nd/^{144}Nd$ initial ratio is represented by the intercept on the y-axis and the slope of the isochron represents the age. The method is mostly used in genetic studies, and in dating crustal deformation, magmatic emplacement and metamorphic events. The resistance of whole-rock Sm-Nd systems to resetting, even during granulite-facies metamorphism was demonstrated by Whitehouse (1988).

Remarks: The method is well suited to reveal original isotope signatures and not to register low temperature events like those persisting during movements and fracturing of rocks, or circulation of fluids in fractures.

The potassium-argon (K-Ar) method

This dating method, which is based on the decay of the ^{40}K to the stable ^{40}Ar isotope, is used as a standard technique for dating potassium-bearing minerals (mainly feldspars, biotite, muscovite, sericite, illite amphibole and feldspathoid). The method is useful when the sample analysed retains radiogenic argon after cooling through the closure temperatures of the mineral. The loss of radiogenic ^{40}Ar at temperatures exceeding the closure temperatures makes the dates useful indicators of thermal histories. Thus, by dating minerals with different closure temperatures the cooling rate can be determined.

The use of this dating method on various K-bearing minerals has allowed reconstruction of the geochronology of deformation (including fracturing) events and of the fluids involved in a wide variety of geological settings (Zwingman et al, 1998). For examples, biotite was used to constrain the age of regional uplift, deformation and hydrothermal events in the Idaho Batholith, USA, dated back to 100 million years (Criss et al, 1982), and feldspars and mica to date fault zones (Kralik and Riedmüller, 1985). Authigenic illite in fracture gouge material from Äspö, SE Sweden, was dated back to about 400 million years (Maddock et al, 1993).

Remarks: This method may be used to date thermal events. By using different minerals, a time/temperature cooling path can be constructed. Some of the limitations of this method are the problems of heterogeneous samples and the need to measure the absolute concentrations of potassium and argon. Moreover, if present, excess radiogenic ^{40}Ar causes too high K-Ar ages.

The argon-argon (^{40}Ar-^{39}Ar) method

This method is based on the production of ^{39}Ar from ^{39}K during artificial neutron irradiation of the sample (most commonly muscovite and hornblende). The method overcomes some of the limitations of conventional K-Ar dating, such as the K and Ar are determined on the same sample, only the isotopic ratios rather than absolute concentrations are required, and it is well suited to date small samples. Additionally, a date can be calculated solely on the basis of the number of radiogenic ^{40}Ar atoms in a sample due to the decay of ^{40}K during its lifetime (^{40}Ar *) divided by ^{39}Ar in the sample. The incremental heating technique yields a series of dates for a single sample by releasing argon in steps during a stepwise increase in temperature. If the sample acted as a closed system during its lifetime, then the ^{40}Ar */^{39}Ar ratios, and hence the dates calculated at each step should be constant. The technique allows the first gas to be released at heating (lowest temperature) to originate from the surface of the grains and from sites that lose argon readily. Ultimately the ^{40}Ar */^{39}Ar ratios of the sample yielded at raised temperature levels will be corresponding to a date that approaches the time elapsed since the original cooling of the mineral. The method has been enhanced by the heating by laser beams to release argon from individual mineral grains and cooling curves can be constructed for rocks that contain several dateable minerals with various closure temperatures.

^{40}Ar-^{39}Ar dates were obtained from mica in shear-related deformation zones in the turbidite-dominated orogenic system of eastern Australia and constrained the faulting events to 440–430 Ma (Gray and Foster, 1998). The evolution of fault and fracture pattern in the central Pilbara Craton, western Australia, was dated to about 2950 Ma with ^{40}Ar-^{39}Ar (Van Kranendonk and Collins, 1998). Metamorphic ages (representing four thermal events) of fracture filling adularia and hornblende, were constrained by Kamineni et al (1987) in an anorthosite-gabbro complex in Canada. The ^{40}Ar-^{39}Ar dating of muscovite and hornblende was used to bracket the tectono-thermal evolution events across the Eastern Segment of Sveconorwegian orogeny and related ductile deformation and movements at 1–0.9 Ga (e.g. Page et al, 1996).

Remarks: A problem with the method is to detect the presence of excess ^{40}Ar if this is uniformly distributed throughout a mineral grain. Loss of ^{39}Ar by recoil during the neutron irradiation is another problem, which makes very fine-grained, potassic minerals unsuitable for dating. The method has the advantage that K and Ar are determined on the same sample and only measurements of the isotope ratios of Ar are required and thus overcome some of the limitations of the conventional K-Ar method.

The uranium-thorium-lead (U-Th-Pb) methods

These methods make use of the natural decay series of ^{238}U, ^{235}U and ^{232}Th into ^{208}Pb, ^{207}Pb and ^{206}Pb, respectively. ^{204}Pb is a stable, and is thus used as reference isotope. This means that three independent decay series ($^{207}Pb/^{238}U$, $^{206}Pb/^{235}U$ and $^{208}Pb/^{232}Th$) can be used for mineral dating. This requires a closed system conditions and knowledge about decay constants for parent isotopes. A concordia diagram ($^{207}Pb/^{235}U$ on the x-axis and $^{206}Pb/^{238}U$ on the y-axis) is used for mineral dating since an undisturbed mineral will yield concordant ages (Figure 2-2). When compositions yielding such concordant ages are plotted graphically in the diagram they define a curve termed the concordia (Wetherill, 1956). Discordant ages may indicate lead loss. If this is ascribed to a distinct event a regression through the discordant points defines a line called discordia that will have lower and upper intercepts on the concordia. These intercepts ideally define the original age of the mineral and a lead loss event, respectively.

The uranium-thorium-lead methods have been applied widely to regional deformation events, such as mylonitisation with shear zones in the Pan-African (650–550 Ma), meteorite impact polymict breccia (65 Ma), and fracture mineralisation based on dating columbite (960 Ma) in the Kibran belt granites, central Africa (Romer and Lehmann, 1995). Since minerals used for dating may be heterogeneous and contain younger overgrowths, ion microprobe technique (SIMS), which allows analysis of targets about 30 μm in diameter, is currently used. For example zircons may be affected by several metamorphic events, represented by small areas of recrystallisation or overgrowths on an older, primary zircon each of which yield a different U-Pb age. The probe technique is obviously useful in shield areas where poly-metamorphism and deformation are common.

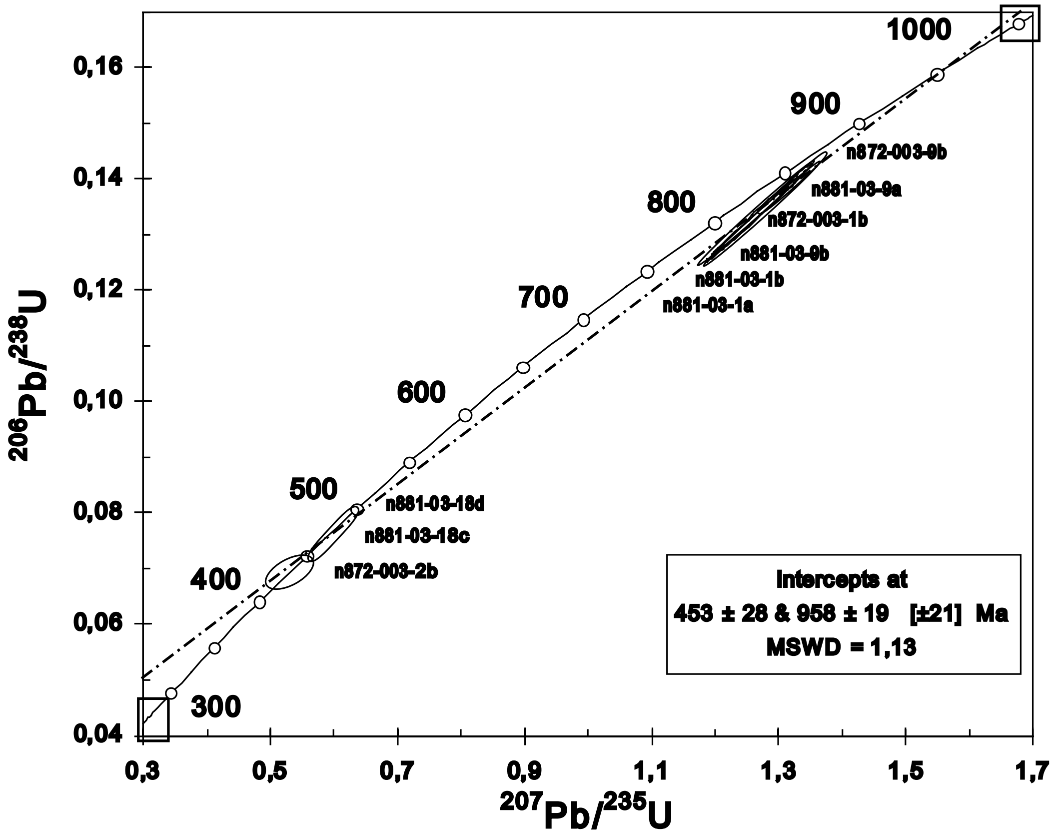

Figure 2-2. *Concordia diagram showing zircons that are discordant due to lead loss and a few zircons that are concordant defining the lower intercept (453 Ma) of the regression line (discordia) on the concordia. The upper intercept (at 958 Ma) indicates a crystallisation age of one zircon generation and the lower intercept crystallisation of another zircon generation at a later event.*

Remarks: The method can be used to date magmatic and metamorphic events by analysis of high U minerals like zircon, titanite and xenotime.

The uranium-thorium-protactinum (U-Th-Pa) disequilibrium methods

These methods are useful for dating minerals and geological events younger than 1 Ma based on the natural radioactive disequilibrium between the parent isotopes ^{238}U, ^{235}U and ^{232}Th and their decay daughter isotopes ^{230}Th and ^{231}Pa induced by geological processes. In closed geological systems the nuclides ^{238}U-^{234}U-^{230}Th attain radioactive equilibrium after ca 1.7 Ma, i.e. the respective activity ratios $^{234}U/^{238}U$, $^{230}Th/^{234}U$, $^{230}Th/^{238}U$ all equal unity. However, if the systems are exposed to weathering and groundwater circulation, and assuming that ^{230}Th is immobile (Langmuir and Herman, 1980), then changes in the physico-chemical conditions result in different isotopic fractionations of ^{238}U and ^{234}U. Thus, disequilibrium may occur by depletion or enrichment of the parent or daughter isotopes. These methods were used for example, to constrain fluid migration in fractured crystalline rocks over the last 1 million years (e.g. Smellie et al, 1986; Landström et al, 1989; Alexander et al, 1990; Suksi et al, 1992). The U-Th dating method has also been used for age determination of calcites based on the assumption that only U and no Th is incorporated into the crystal lattice. However, U-Th dating of fracture calcites is difficult since the amount of U is usually low (< 5 ppm) and excess Th in the calcite needs to be adjusted, to get a reliable age.

Such adjustments are based on the assumption that Th is detrital (derived from external sources), and can be carried out in many different ways leading to quite different results. A significant mobility has also been suggested as an explanation for parts of the Th content found in fracture calcite fillings at 200 m depth at Äspö (Tullborg et al, 1999). Lin et al (1996) experienced similar problems in dating speleotheme calcite. It is thus obvious that the use of U-Th dating of calcite should be considered with caution. One way to improve the dating method is to use a combination of U-Th and ^{235}U-^{231}Pa (e.g. Raisalainen et al, 1994).

The lead isotopes methods

These methods are closely related to or combinations of the U-Th-Pb methods. The most commonly used is the lead-lead method. This is based on the natural variation in ratio of lead isotopes ($^{207}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb$) in relation to $^{235}U/^{238}U$. An age is calculated after measurement of the lead and uranium isotopes in a sample (whole rock and/or co-genetic minerals) and reassessment of radiogenic contribution for the ^{206}Pb and ^{207}Pb isotopes.

Granitic intrusions and related features in the Archean terrain of the eastern India were dated with the Pb-Pb to about 3–3.5 Ga (Ghosh et al, 1996). Fluid movement in the Archean and Proterozoic Craton of Sao Francisco, Brezil, was dated to the last few million years (Iver et al, 1999).

The rhenium-osmium (Re-Os) method

The Re-Os isotopic system, which is a relatively new application in geochronology, can be used to date geological events and to trace the source and subsequent history of rocks and fluids. It is the only system that can date sulphides and oxides, because both Re and Os are accommodated directly into the structure of these mineral groups which commonly precipitate in fractures.

The Re-Os method makes use of the decay of ^{187}Re into ^{187}Os. When the ratio of radiogenic ^{187}Os to the stable ^{186}Os are plotted against $^{187}Re/^{186}Os$, the isochron slope is proportional to the age of the sample (using the decay equation in a similar way as demonstrated for the Rb-Sr system). The half-life of ^{187}Re is slightly less than ten times the age of the Earth. The intercept at $^{187}Re/^{186}Os = 0$ gives the initial $^{187}Os/^{186}Os$ at the time of the last isotopic equilibration or homogenisation.

Re-Os ages were obtained from two molybdenite occurrences (Cu-Mo-W-Au mineralisations) hosted in a shear zone in SE Norway (Stein et al, 1997). They are part of the ore-bearing Mjösa-Vänern Belt (Alm and Sundblad, 1994). This belt occurs within the Mylonite Zone that is dated to ca 915 Ma (Page et al, 1996), and continues south-eastwards into Sweden. The Re-Os dating for the molybdenites surprisingly yielded an age of ca 1700 Ma, which is significantly older than the widely accepted Sveconorwegian (ca 1000 Ma) age for ores in this belt (Alm and Sundblad, 1994). This was the first direct evidence for mineralisations older than the Sveconorwegian in this area. Stein et al (1997) related the molybdenite mineralisation to a magmatic event at ca 1700 Ma, which is the age of shearing. This study shows that the Re-Os chronometer in molybdenite survived regional heating and deformation during the Sveconorwegian orogenic events. A chronometer that will retain primary ages for shear zone deposits in poly-deformed, complex geological terrains permits insight into the original geological setting associated with this type of mineralisations (Stein et al, 1997).

Re-Os dating of pyrite, magnetite, chalcopyrite, galena and sphalerite was carried out by Stein et al (1993). These minerals belong to a highly evolved magmatic system at Mount Emmons in Colorado, USA. A very young age of ca 16.75 Ma (±0.34 Ma)was obtained. These examples demonstrate that Re-Os ages can be obtained within a large time interval.

Remarks: The Re-Os dating of molybdenite (MoS_2) is relatively simple since it contains essentially no initial Os. Therefore, all Os measured is considered as radiogenic daughter ^{187}Os, that was formed by decay of parent ^{187}Re. Typically, one can expect to analyse 25 to 100 milligrams of molybdenite while other sulphides and oxides require several hundred milligrams of mineral separate. The possibility of dating sulphide minerals using Re-Os dating is very interesting as e.g. pyrite is commonly found as a fracture mineral. The use of the Re-Os method is relatively new and the limitations and the optimal use of the method for this purpose have not been established yet.

The cosmogenic nuclides

The interaction of cosmic rays (i.e. secondary cosmic particles such as protons, neutrons and muons) with the Earth's atmosphere and surface produces isotopes, which are referred to as cosmogenic isotopes. Although most of the cosmogenic isotopes production is atmospheric, the production at the earth's surface (*in situ*) in sediments and rocks has been utilised to develop a method termed "exposure dating". The production of some cosmogenic isotopes (e.g. ^{36}Cl, ^{129}I) may also be associated with radioactive decay processes, e.g. spontaneous and neutron-induced fission of ^{238}U, in sediment and rocks. The half-life of most known cosmogenic isotopes is geologically rather short, and thus useful for dating events younger than a few million years. The cosmogenic isotopes ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl have been used in dating fracture-related events. The measurements of cosmogenic isotopes are usually made with the atom counting technique of accelerator mass spectrometry, which has revolutionised the applications of cosmogenic isotopes (for details see Tuniz et al, 1998).

The ^{10}Be and ^{26}Al methods

About 99% of ^{10}Be (half-life 1.5 million years) is produced in the atmosphere by secondary cosmic particles-induced spallation (explosion) of nitrogen, oxygen and carbon molecules. The other path of ^{10}Be production is through interaction of secondary cosmic particles with mineral surfaces in rocks and sediments. Upon exposure to cosmic rays, ^{10}Be is proportional to exposure time and decay constant. The basic concept of calculating an exposure age is based on measuring the amount of ^{10}Be accumulated in quartz. Any change in the exposure conditions of the mineral surface by, for example, erosion or burial causes a change in the ^{10}Be concentration of quartz. Similarly, the production and concentration of the isotope ^{26}Al (half-life 0.72 million years) in quartz follows the same principle for ^{10}Be and the ratio $^{10}Be/^{26}Al$ has been used in exposure time dating.

Exposure dating using the ^{10}Be-^{26}Al method was used for assessment of fracturing and related events including for example dating boulders of fault-induced debris flow fan in the Owen Valley, California to recurrence of earthquakes since about 21 000 years (Bierman et al, 1995). Cosmogenic ^{10}Be measurements on quartz grains from exposed bedrock across the Ghost Dance Fault, Nevada, allowed constraints of whether or not any movements occurred during the last 400 000 years (Taylor et al, 1996). The offset in alluvial fan surfaces was due to faulting between 20 000 to 700 000 years ago (Lionel et al, 1997).

Van der Woerd et al (1998) used ^{26} Al and ^{10} Be in quartz pebbles from alluvial terrace surfaces to constrain late Holocene slip rate on the Kunlun fault in NE Tibet. Their results implied (i) a slip rate of 12.1 ± 2.6 mm/yr and that the landform evolution is modulated by post-glacial climate change and (ii) earthquakes (M≈8) with a recurrence time of 800–1000 yr, rupture the Kunlun fault in the study area. Dating of the maximum highs reached by the Fennoscandian ice sheet in western Norway was carried out by the use of ^{10}Be (Brook et al, 1996), which provided important links between paleoclimate and neotectonism.

The carbon-14 method

More than 99% of natural ^{14}C (half-life 5730 years) is produced in the atmosphere by interaction of secondary cosmic particles with nitrogen molecules. During the last 50 years large amount of ^{14}C has been introduced into the atmosphere by nuclear weapon testing and has spoiled the possibility of decay dating of material younger than 1950 (refereed to as present in ^{14}C dating). The principle of ^{14}C-dating is based on measurement of ^{14}C activity (as atoms or ß particles) and ratio of ^{13}C/^{12}C in a sample. Because of the rather short half-life, the limit of ^{14}C dating is about 50 000 before the present. In spite of the age limitation, the ^{14}C method is widely used because carbon is an abundant element in water, air, organic matters and carbonate minerals.

The ^{14}C dating has been employed to constrain fracture events using fracture fillings such as carbonate and organic matters. Fracture-filling colluvial sediments in Holocene fault zone in Utah, USA (Forman et al, 1991), were precisely dated to three earthquake-generated fault events between 4500–3500, 3200–2500 and 1400–1000 years BP. Fault-related channel filling charcoal at the Lemhi fault, southern Idaho, USA, was dated to 25 000 years (Hemphill-Haley et al, 1998).

There is always a risk for ^{14}C contamination during storage and preparation of small samples of fracture calcites. It is, therefore, important that the cores are protected during storage prior to use for 14C dating. The main problem, however, is to determine the source term, i.e. the ^{14}C content in the recharging groundwater. The different processes influencing the ^{14}C content in the dissolved HCO3$^-$ are clearly demonstrated by samples from the Redox zone, a vertical fracture zone transected by the Äspö tunnel at depth of 70 m (Tullborg and Gustafsson, 1999). Here, HCO_3^- (and in some samples fulvic acid as well) has been analysed in groundwaters and near surface waters which enter the Redox zone at 15, 45 and 70 metres depth. The ^{14}C data indicate that there are three carbon sources, which contribute to the HCO_3^- content in groundwater from the Redox zone, including:

- dissolved CO_2 (dominantly soil CO_2) possibly with some contribution of atmospheric CO_2,
- dissolution of calcite (with low ^{14}C content) which mainly occurs in the near-surface recharge area,
- oxidation of organic material through anaerobic respiration which takes place in the groundwater aquifer.

^{14}C dating of fracture calcite was tried on samples from Klipperås (Possnert and Tullborg, 1989), which showed that the sample volumes were too small and the contamination too large to give reliable results.

A new attempt to date fracture calcite was made at Äspö, SE Sweden. Immediately after the drilling of borehole KAS 05 at the Äspö HRL, open, calcite coated fractures in the depth interval 0–150 metres were sampled and wrapped in plastic film to minimise contamination from the atmosphere. Twenty samples were analysed for ^{14}C at the Svedberg Laboratory, Uppsala University. Extremely low ^{14}C contents were yielded in all of the calcites ranging from 0.43 to 3.38 pmC (43 700 to 27 160 years; Tullborg, 1997). For reference, samples of old calcite from large crystals of "Icelandspar" containing dead carbon only were analysed in order to be able to estimate the ^{14}C uptake during sampling and preparation. Since the $\delta^{18}O$ of the fracture calcites corresponds to equilibrium with the present-day groundwater, it was suggested that these fractures are, or have recently been water-conducting, although, based on results from the geophysical logging, their conductivity seems to be low (Sehlstedt and Stråhle, 1989). The $\delta^{13}C$ values were in accordance with an atmospheric rather than a biogenic origin of carbon. The low ^{14}C content was attributed to drilling of the borehole (KAS 05) in a part of the Äspö Island with low hydraulic conductivity that is dominated by outcrops, which means that the addition of organic CO_2 is very low. The ^{14}C added from the HCO_3^- in precipitation is only a few mg/l. Thus, it is possible that parts of these fracture-calcites are young despite their low ^{14}C content. Another possibility is that calcites with stable isotope values in accordance with present-day groundwater composition and temperatures have been precipitated e.g. before the latest glaciation (100 000 years ago) and were preserved due to the low conductivity of the fractures sampled.

The chlorine-36 method

^{36}Cl with a half-life of $301x10^3$ years is produced in the atmosphere by interaction of secondary cosmic particles with argon, potassium, and calcium and at the Earth surface, ^{36}Cl is also produced from ^{35}Cl. Anthropogenic sources have also supplied huge amount of ^{36}Cl, which has been used to date origin of very young ground water. ^{36}Cl dating of chlorine in groundwater makes use of the water-soluble cosmogenic component whereas in situ ^{36}Cl production is used in dating sediments and rocks. In both cases, the ratio of $^{36}Cl/Cl$ is determined and an age is calculated.

Dating of groundwater in fractured rocks has been achieved through the use of the cosmogenic component. The $^{36}Cl/Cl$ generally decreases with the age of water which can be dated to about 2 million years before the present. The same principle used in ^{10}Be exposure time dating is applied when calculating ^{36}Cl ages from *in situ* production in sediments and rocks.

Rate of glacial erosion between 20 000 and 12 000 years and its impact on abrasion rate and hydraulic fracturing of bedrock was evaluated by use of *in situ* ^{36}Cl in rocks of Mount Erie, USA (Briner and Swanson, 1998).

2.2.2 Thermochronological and other dating methods

The fission track (FT) method

The fission track method makes use of the tracks created by the spontaneous fission of ^{238}U in minerals. During spontaneous fission, the unstable nucleus splits into two daughter nuclides of roughly the same size and large amounts of kinematic energy is released. The two heavily charged repelling daughter nuclides create a trail of damage in the mineral lattice. These tracks are 10–20 µm long and a few µm wide. The disordered atomic structure along fission tracks becomes gradually restored with time and is only stable below a certain temperature. This temperature varies from one mineral to another. At high temperatures, the annealing process is more efficient than the production of tracks and no new tracks are formed. The temperature interval, above which total annealing occurs, varies between minerals. In apatite, complete annealing occurs above a temperature range of approximately 105°C–150°C for heating with duration of 100 to 0.1 Ma, while zircon and titanite experience total annealing above approximately 250°C and 300°C, respectively. Fission tracks become partially stable at lower temperatures where the annealing process is less efficient. For apatite, this zone of partial annealing (PAZ) is conventionally defined as a temperature range between 60°C and 150°C, although very slow partial annealing occurs even at room temperature.

The number of fission tracks and the track length distribution is used to define a fission track age and a thermal history of the mineral used. The age represents a cooling age, i.e. the time passed since the grain cooled below the temperature of total annealing.

The method has been applied to restore thermal histories, such as during uplift and exhumation of the bedrock (cf Larson et al, 1999; Cederbom et al, 2000) but also in revealing breaks in thermal histories across tectonic boundaries (cf Hansen 1995). The combination of radiogenic methods (K-Ar and Rb-Sr) and the fission track method allowed Yoshida et al (2000) to reveal the cooling and hydrothermal history of the Kurihashi granodiorite, Japan and to conclude that fractures were formed mainly during the early stages of cooling.

Remarks: The method is well suited to date the latest thermal event (that reached the annealing temperature of the mineral used) in a region. By using different minerals a cooling history may be constructed.

The (U-Th)-He method

Helium is produced from the radioactive decay of U and Th. In the 1980's it was demonstrated that the diffusive loss of helium from apatite appeared systematic at low temperatures. Subsequently it was shown that volume diffusion occurs at whole crystal scale, the closure temperature is 75 ± 5°C for cooling rates of 10°C/Ma and that He is partially retained between 90 and 40°C. This renders the apatite (U-Th)/He-system a unique chronometer of processes operating at low temperatures (< 100°C; Farley, 2000).

The rate of diffusive loss of He from apatite is controlled by temperature and is independent of mineral composition, pressure and crystal age-related factors, e.g. radiation damage.

Recently progress has been made in dating other accessory minerals using the (U-Th)/He technique, such as titanite and zircon, thus extending the chronometer to crustal processes operating below 200°C.

The thermoluminescence (TL) method

Thermoluminescense (TL) and optically simulated luminescence (OSL) are indirect radiometric dating methods based on the energy stored in the minerals as a result of radiometric decay. This energy, preserved as excitation of electrons, can be released when the sample is heated. The energy emitted is dependent on the radioactivity surrounding the sample during a specific period of time. The use of TL method for dating geological material is described by e.g. Marshall (1988) and Duller (1996) and of the OSL method by Zander et al (2000). OSL has proven to be a more appropriate method for dating geological material since the same process of optical resetting of the luminescence signal is used in the laboratory and in nature, and less exposure to daylight is required to reset the OSL signal than TL, Zander et al (2000). Recent major advances in analytical procedures are now allowing the analysis of much smaller amounts of material or even of single mineral grains.

Luminescence age (years) = palaeodose (Gy) / dose rate (Gy/year) Equ. 2-6

where palaeodose is the measurement of radiation dose received by a grain (typically quartz or K-feldspar) since the initiation of burial, and dose rate is the rate at which it has absorbed energy from the natural environment. Gy (gray) is the SI unit of absorbed dose of ionizing radiation which is the energy (joules) absorbed by 1 kg of irradiated material. An essential assumption of the method is that the luminescence signal from the grain can be reset (zeroed) by exposure to daylight at deposition and by prolonged and/or intensive heating process that are referred to as "bleaching" and "annealing", respectively. Thus, in order to obtain an accurate palaeodose, the single-grain selected for analysis should have a fully reset luminescence signal (e.g. Murray and Roberts, 1997). The palaeodose, and hence age, obtained from the analysis of bulk samples containing a fraction of unbleached grains would be overestimated (e.g. Wintle et al, 1995).

The TL method has been used as either signal reset by exposure to light as the material is removed from up-thrown fault wall or as direct dating of fault gouge material that had the signal reset due to friction-induced heat and/or pressure. Examples of the first approach include; fault scarp development at the Lemhi fault, southern Idaho, USA, during 34 000 years (Hemphill-Haley et al, 1998) and Holocene faults in Utah, USA (Forman et al, 1989) and Australia (Hutton et al, 1994). Examples of the second approach include dating of fine-grain fault gouge from Langtang, Nepal (about 70 000 years ago) and from Nainital, Himalayas (about 40 000 years ago).

Remarks: May be used on geologic material that has suffered resetting by exposure to light or has been heated recently in the geological history.

The electron spin resonance (ESR) method

ESR-dating is based on gamma irradiation defects in quartz, apatite, feldspar or carbonate crystals caused by different electron spin resonance (ESR) which can be measured with high precision. By artificially irradiating natural mineral samples using standard measured defects in quartz crystals, and also knowing the intensity of natural gamma radiation in the sample, the age can be calculated. The defects in the crystals can be reset during, for example, high hydrostatic pressure or heating, which makes the method suitable for the study of tectonic activity.

Grün (1989, 1992) has made a detailed description about the method and its applicability to different problems. Four different zeroing processes can be used for ESR-dating:

- precipitation of the mineral (e.g. secondary carbonates, corals etc),
- heating of the mineral (e.g. volcanic material),
- pressure (e.g. shear stress in intrafault material; signals in quartz is of particular use), and 4) sunlight (the Ge-centre in quartz can be reset by sunlight).

The method has been used for dating recent faulting by the analysis of intra-fault quartz grains dating Quaternary fault movements, on the Japanese islands (Kanaori et al, 1985; Kosaka and Sawada, 1985). ESR was applied on samples from mylonites and fracture at Äspö by Maddock et al (1993), who concluded that no resetting is indicated along the fracture zones studied within the past several hundred thousand to one million years below the resolution limit. A sequence of faulting events in the San Gabriel fault zone, California, USA have been dated by Lee and Schwarcz (1995) to be between 1.2 and 0.35 million years. Yu-Guang et al (1998), obtained consistent ^{14}C and ESR ages of debris-flow deposits from Yunnan Province in China.

Remarks: The method seems promising for dating, e.g. Recent major faulting by the analysis of intra-fault quartz grains.

The palaeomagnetic dating method

It is well-known that the direction of local geomagnetic field vector varies with time. Determination of the magnetic field vector can thus provide information on age of the magnetisation. The principle of paleomagnetic method for dating of faults is to compare the direction of the characteristic remnant magnetisation in the fault rock with the predicted direction of the geomagnetic field vector at the sampling site for different geological periods. An established polar wander path for a region makes it possible to roughly pin the age of a rock in which the palaeomagnetic pole position has been determined. In turn, establishing a good polar wander path requires well-established ages of objects from which the palaeomagnetic polar position was determined. An apparent Polar Wander Path (APW) has been established for the Baltic shield, based on palaeomagnetic work by many scientists (Elming et al, 1993; Perroud et al, 1992; Pesonen et al, 1989, 1991; Smethurst, 1992; Torsvik et al, 1990, 1996).

However, re-magnetisation of a rock may occur at temperatures exceeding the Curie temperature, and thus the established pole position may correspond to a thermal event post-dating the formation of the magnetic mineral. Elmore et al (1987) recognised that magnetite may be precipitated within hydrocarbon migration pathways and in the vicinity of hydrocarbon reservoirs. From this follows that the timing of hydrocarbon migration can be constrained.

Also mineralisation processes have been dated, for example Elmore et al (1998) dated magnetite and hematite precipitated during Palaeozoic fluid flow events in sandstone. Symons et al (1998) used palaeomagnetic data from galena and pyrrhotite to deduce mineralisation age and the duration of this mineralisation event. In sedimentology, the reversibility of the poles has been used for relative dating/separation of layers.

Determination of the magnetic field vector in faulted rocks enables the dating of magnetisation which, in turn, can give a minimum age of the fault itself. This approach has been applied by Hailwood et al (1992) who identified the three following assumptions that must be made for paleomagnetic fault dating:

- the fault rocks acquired a component of magnetisation at the time they were formed or through some subsequent hydrothermal event,
- this magnetisation is parallel to the Earth's contemporary magnetic field,
- it is possible to predict the Earth's magnetie field at the site through geological time.

Maddock et al (1993), used palaeomagnetic determinations in order to date mylonites and fracture zones at Äspö. However, this study ended up with several possible interpretations of the data, and that magnetisation of the fault-rocks may be associated with oxidative fluid flow, related to or post-dating fault movements.

Remarks: The method relies on APW-paths that are based on well-constrained ages. Great uncertainty still remains about the construction of APW-paths.

3 Conclusions

In order to use radiometric systems for dating of movements in bedrock two prerequisites have to be full-filled:

- A mineral must be available that is possible to date with the selected method.
- The age of the dated mineral should be matched with the half-life of the radiogenic decay measured.

In reality it can be hard to full-fill both these prerequisites. In the Baltic Shield (and other shield areas as well), many water conducting fracture zones are the result of brittle reactivation of ductile/brittle deformation zones; the latter often created early in the history of the bedrock. It is usually easy to find datable minerals that are formed during the ductile deformation phase/phases but much more difficult to find minerals that corresponds to the brittle reactivation.

The possibility of dating sulphide minerals using Re-Os dating is very promising as e.g. pyrite is commonly found in fracture mineralisations. However, the use of the Re-Os method is relatively new and the limitations and the optimal use of the method for this purpose have not yet been established.

In addition to absolute dating methods, there are a large number of techniques for relative dating that should be considered as they also provide valuable clues to the timing and conditions that prevailed during bedrock fracturing. The tectonic history of the studied bedrock can only be revealed by the application of a broad spectrum of dating methods (e.g. Heaman and Ludden, 1991; Maddock et al, 1993; Tullborg et al, 1996 and references therein;).

4 References

Alexander W R, MacKenzie A B, Scott R D, McKinley I G, 1990. Natural analogue studies in crystalline rock: the influence of water-bearing fractures on radionuclide immobilisation in a granitic rock repository. Baden: National Cooperative for the Disposal of Radioactive Waste. Nagra Technical report 87-08.

Alm E, Sundblad K, 1994. Sveconorwegian polymetallic quartz veins in Sweden. Neues Jahrbuch fur Mineralogie Monatshefte, 1-22.

Andreasson P-G, Rhode A, 1990. The Protogine Zone. Geology and mobility during the last 1.5 Ga. SKB TR 92-21, 1-60.

Attendom H G, Bowen R N C, 1997. Radioactive and stable isotope geology. Chapman & Hall. London, United Kingdom. Pages: 522.

Axberg, 1980. Seismic stratigraphy and bedrock geology of the Bothian Sea, northern Baltic. Stockholm Contribution to Geology, 36, 153-213.

Axelsson, 1996. Fennoscandian earthquakes: whole Crustal Rupturing Related to Postglaical rebound. Science, 274, 744-746.

Bar-Matthews M, Ayalon A, Matthews A, Sass E, Halicz L, 1996. Carbon and oxygen isotope study of the active water-carbonate system in a karstic Mediterrainen cave: implications for palaeoclimate research in semiarid regions. Geochimica et Cosmochimica Acta 60, 337-347.

Bath A, Milodowski A, Ruotsalainen P, Tullborg E-L, Cortés Ruiz A, Aranyossy J-F, 2000. Evidence from mineralogy and geochemistry for the evolution of groundwater systems during the quaternary for use in radioactive waste repository safety assessment (EQUIP project). European Commission, nuclear science and technology, EUR 19613 EN.

Berglund J, 1997. Mid-Proterozoic evolution in South-western Sweden. Thesis, A15, Earth Sciences centre, Göteborg University, Sweden, ISSN 1400-3813.

Berglund J, Larson S Å, Vinnefors A, 1997. Sveconorwegian extension-parallel deformation structures; an example from the Hammarö Shear Zone, SW Sweden. GFF, 119, 169-180.

Bergman S, Sjöström H, 1994. The Storsjön-Edsbyn deformation zone, central Sweden. Unpublished FoU-rapport to SGU, 1-46.

Bergström J, Holland B, Larsson K, Norling E, Sivhed U, 1982. Guide to excursions in Scania. Sveriges Geologiska Undersökning Ca 54, 1-95.

Berthelsen A, 1980. Towards a palinspastic analysis of the Baltic Shield. Int. Geol. Congress, Colloquium C6, Paris, 5-21.

Bierman P, Gillespie A, Caffee M, 1995. Cosmogenic ages for earthquake recurrence intervals and debris flow fan deposits, Owen Valley, California. Science, 270, 447-550.

Bingen B, Boven A, Punzalan L, Wijbrans J R, Demaiffe D, 1998. Hornblende 40Ar/39Ar geochronology across terrane boundaries in the Sveconorwegian Province of S. Norway. Prec. Res. 90, 159-186.

Blyth A, Frape S, Blomqvist R, Nissinen P, McNutt R, 1998. An isotopic and fluid inclusion study of fracture calcite from borehole OL-KR! At the Olkiluoto site, Finland. Posiva report 98-04, ISSN 1239-3096.

Boulton G S, Caban P E, van Gijsell K, 1995. Groundwater flow beneath ice sheets: part 1 – large scale patterns. Quaternary Science Reviews 14, 545-562.

Brannon J, Podosek F, McLimans R, 1992. Alleghenian age of the Upper Mississippi Valley zinc-lead deposits detrmined by Rb-Sr dating of sphalerites, Nature, 356, 509-512.

Briner J P, Swanson T W, 1998. Using inherited cosmogenic ^{36}Cl to constrain glacial erosion rates of the Cordilleran Ice Sheet. Geology, 26, 3-6.

Brook E, Nesje A, Lehman S, Raisbeck G, Yiou F, 1996. Cosmogenic nuclide exposure ages along a vertical transect in western Norway: implicatons for the high of the Fennoscandian ice sheet. Geology, 24, 207-210.

Burke W H, Denison R E, Hetherington E A, Koepnick R B, Nelson H F, Otto J B, 1982. Variations of seawater $^{86}Sr/^{87}Sr$ throughout Phanerozoic time. Geology 10, 516-519.

Cederbom C, Larson S Å, Tullborg E-L, Stiberg J-P, 2000. Fission track thermochronology applied to Phanerozoic thermotectonic events in central and southern Sweden. Tectonophysics, 316, 153-167.

Claesson S, 1980. A Rb-Sr isotope study of granitoids and related mylonites in the Tännäs Augen Gneiss Nappe, southern Swedish Caledonides. Geologiska Föreningens I Stockholm Förhandlingar 102, 403-420.

Claesson S, 1986. Direct dating of thrusts ion Swedish Caledonides with the Rb-Sr thin slab technique. Geologiska Föreningens i Stockholm Förhandlingar 108, 277.

Claesson S, 1988. Isotopic dating of shear zones – a discussion. Geologiska Föreningens i Stockholm Förhandlingar 110, 383-384.

Claypool G E, Holser W T, Kaplan I R, Sakai H, Zak I, 1980. The age curves of sulpher and oxygene isotopes in marine sulphate and their mutual interpretation. Chemical Geology 28, 199-260.

Criss R, Lanphere M, Taylor H, 1982. Effects of regional uplift, deformation and meteoric hydrothermal metamorphism on K-Ar ages of biotite in the southern half of Idaho batholith. Journal of Geophysical Research 87, 7029-7046.

Deming D, 1993. Fluid flow and heat transport in the upper continental crust. In Parnell J (ed), Geofluids: Origin, Migration and Evolution of Fluids in Sedimentary Basins. Geological Society Special Publication, No 78, 27-42.

Dickin A P, 1997. Radiogenic Isotope Geology. Cambridge University Press, Cambridge. ISBN 0-521-43151-4.

Duller G A T, 1996. Recent developments in luminescence dating of Quaternary sediments. Progress in Physical Geography, 20, 127-145.

Elming S Å, Pesonen L J, Leino M, Khramov A N, Michailova N P, Krasnova A F, Mertanen S, Bylund G, Terho M, 1993. The drift of the Fennoscandian and Ukraina shields during the Precambrian: a palaeomagnetic analysis. Tectonophysics 223, 177-198.

Elmore R D, Engel M, Crawford L, Nick K, Imbus S, Sofer Z, 1987. Evidence for a relationship between hydrocarbons and authigenic magnetite. Nature 325, 428-430.

Elmore R D, Campbell T, Banerjee S, Bixler,W G, 1998. Palaeomagnetic dating of ancient fluid-flow events in the Arbuckle Mountains, southern Oklahoma. In: Parnell J (ed) Dating and Duration of Flow and Fluid-Rock Interaction. Geological Society, London, Special Publications, 144, 9-26.

Erlström M, Thomas S A, Deeks N, Sivhed U, 1997. Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the southern Baltic Sea area. Tectonophysics 271, 191-215.

Farley K, 2000. ((U-Th)/He dating: A review of the technique and current applications. Geol. Soc. Australia Abstract Series 58, 77-79.

Faure G, 1986. Principles of Isotope Geology. John Wiley & Sons, New York.

Fenton C H, 1991. Postglacial faulting and paleoseismic activity in North West Scotland. Geological Society of America, annual meeting. Abstracts with Programs, 23, 5, 90-91.

Forman S L, Machette M N, Jackson M E, Maat P, 1989. An evaluation of thermoluminescence dating of paleoearthquakes on the American Fork segment, Wasatch fault zone, Utah. Quaternary International, 1, 47-59.

Forman S L, Nelson A R, McCalpin J P, 1991. Thermoluminescence dating of fault-scarp-derived colluvium: deciphering the timing of paleoearthquakes on the Weber segment of the Wasatch fault zone, north central Utah. Journal of Geophysical Research, 96, 595-605.

Freeman S, Butler R, Cliff R, Rex D, 1998. Direct dating of mylonite evolution: a multi-disciplinary geochronological study from the Moine thrust zone, NW Scotland. Journal of the Geological Society, 155, 745-758.

Frostick L E, Steel R J, 1993. Tectonic signatures in sedimentary basin fills; an overview. In: L E Frostick and R J Steel (eds), In: Tectonic Controls and Signatures in Sedimentary Successions. International Association of Sedimentologists, Special Publication, 20, 1-9.

Gascoyne M, 1992. Palaeoclimate determination from cave calcite deposits. Quaternary Science Reviews, 11, 609-632.

Geyh M, Schleicher H, 1990. Absolute age determination. Springer-Verlag, Berlin, 503 pp.

Ghosh D K, Sarker S N, Saha A K, Ray S L, 1996. New insights on the early Archaean crustal evolution in eastern India: re-evaluation of lead-lead, samarium-neodymium and rubidium-strontium geochronology. Indian Minerals, 50, 175-188.

Goldstein R H, Reynolds T J, 1994. Systematics of Fluid Inclusions in Diagenetic Minerals. Society of Economic Paleontologists and Mineralogists (SEPM), Short Course, 31, 198 pp.

Gray D R, Foster D A, 1998. Character and kinematicsof faults within the turbidite-dominated Lachlan Orogen: Implications for tectonic evolution of eastern Autralia. Journal of Structural Geology, 20, 1691-1720.

Gromet P L, 1991. Direct dating of deformational fabrics. In: Heaman & Ludden (eds), Short course handbook on applications of radiogenic isotope systems to problems in geology. Mineralogical Association of Canada, Toronto, Vol 19, 167-190.

Grün R, 1989. Electron spin resonance (ESR) dating. Quaternary International 1, 65-109.

Grün R, 1992. Some remarks on ESR dating of fault movements. Journal of Geolocial Society of London 149, 261-264.

Hailwood E A, Maddock R H, Fung T, Rutter E H, 1992. Palaeomagnetic analysis of fault gouge and dating fault movement, Anglesey, north Wales. Journal of Geological Society of London, 149, 273-284.

Hansen K, 1995. Fennoscandian Borderzone: thermal and tectonic history of a tuffaceous sandstone and granite from fission track analysis. Bornholm, Denmark. Tectonophysics, 244, 153-160.

Heaman L, Ludden J N, 1991. Short course handbook on applications of radiogenic isotope systems to problems in geology. Mineralogical Association of Canada, Toronto, Vol 19.

Hemphill-Haley M, Sawyer T, Knuepfer, Forman S, Wong I, 1998. Timing of faulting events from thermoluminescence dating of scarp-related deposits, Lemhi fault, southeastern Idaho. In Sowers J and McMullen R (ed) Dating and Earthquakes: Review of Quaternary geochronology and its application to paleoseismicity. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Engineering Technology, California, 3, 97-107.

Hickman M, Glassley W, 1984. The role of metamorphic fluid transport in the Rb-Sr isotopic resetting of shear zones:evidence from Nordre Stromfjord, west Greenland. Contribution to mineralogy and Petrology 87, 265-281.

Hutton J T, Prescott J R, Bowman J R, Dunham M N, Crone A J, Machette M N, Twidale C R, 1994. Thermoluminescence dating of Australian palaeo-earthquakes. Quaternary-Science Reviews, 13, 143-147.

Högdahl K, Lundqvist L, Sjöström H, 1998. Major shear deformation in the post-orogenic Revsund granite in Jämtland, central Sweden. Abstract volume, 23. Nordiske Geologiske Vintermöde, Århus 1998, p 125.

Högdahl K, 2000. Late-orogenic, ductile shear zones and protolith ages in the Svecofennian Domain, central Sweden. Meddelande från Stockholms Universitets institution för Geologi och Geokemi, No 309.

Iver S, Babinski M, Marinho M, Barbosa J, Sato I, Salvador V, 1999. Lead isotope evidence for recent uranium mobility in geologica formation of Brazil. implication for radioactive waste disposal. Applied Geochemistry 14, 197-221.

Japsen P, 1993. Landhävning i Sen Kridt och Tertiär i det nordlige Danmark. Dansk Geologisk Forenings Årsskrift for 1990-1991, 169-182.

Johansson L, Johansson Å, 1993. U-Pb age of titanite in the Mylonite Zone, south-western Sweden. Geologiska Föreningens I Stockholm Förhandlingar 115, 1-8.

Juhlin C, Wahlgren C-H, Stephens M B, 2000. Seismic imaging in the frontal part of the Sveconorwegian orogen, south-western Sweden. Precambrian Research, 102, 135-154.

Kamineni D , Stone D, 1983. The ages of fractures in the Eye-Dashwa Pluton, Atikokan, Canada. Contr. Mineralogy and Petrology 83, 237-246.

Kamineni D, McCranck G F , Stone D, 1987. Multiple alteration events in the East Bull Lake Anorthosite-gabbro layered complex, NE Ontario, Canada: evidence from fracture mineralogy and 40Ar/39Ar dating. Applied Geochemistry 2, 73-80.

Kanaori Y, Tanaka K, Miyakoshi K, 1985. Further studies on the use of quartz grains from fault gouges to establish the age of faulting. Engineering Geology 21, 175-194.

Kosaka K, Sawada S, 1985. Fault gouge analysis and ESR dating of the Tsurukawa fault, west of Tokyo: Significance of minute sampling. In: Ikeya M and Miki T (eds), ESR dating and dosimetry, 257-266. IONICS, Tokyo.

Kralik M, Riedmüller G, 1985. Dating fault by Rb-Sr and K-Ar techniques. Terra Cognita 5, 279.

Kujansuu R, 1972. On landslides in Finnish Lapland. Geol. Surv. Finland Bull. 256, 1-22.

Kärki A, Laajoki K, Luukas J, 1993. Major Palaeoproterozoic shear zones of the central Fennoscandian Shield. Precambrian Research 64, 207-223.

Laaksoharju M (ed), 1995. Sulphate reduction in the Äspö HRL tunnel. SKB TR 95-25.

Lagerbäck R, 1979. Neotectonic structures in northern Sweden. Geol. Fören. Stockholm Förhandl. 100, 263-269.

Lagerbäck R, 1990. Late Quaternary faulting and palaeoseismicity in northern Fennoscandia, with particular reference to the Lansjärv area, northern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 112, 333-354.

Lagerbäck R, 1991. Seismically deformed sediments in the Lansjärv area, Northern Sweden. SKB TR 91-17, 1-58.

Lagerbäck R, 1997. Neotectonic structures in northern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 100, 263-269.

Landström O, Smellie J, Tullborg E-L, 1989. Mineralogical and geochemical studies of fracture-infillings in drillcore KLJ 01. In: Bäckblom G and Stanfors R (eds), Interdisciplinary study of post-glacial faulting in the Lansjärv area northern Sweden 1986-1988. SKB TR 89-31.

Langmuir D, Herman J S, 1980. The mobility of thorium in natural waters at low temperatures. Geochimica et Cosmochimica Acta, 44, 1753-1766.

Larson S Å, Stigh J, Tullborg E-L, 1986. The deformation history of the eastern part of the Southwest Swedish geniss-belt. Precambrian Research, 31, 237-257.

Larson S Å, Berglund J, Stigh J, Tullborg E-L, 1990. The Protogine Zone, Southwest Sweden. A new model – An old issue. In Gower, Rivers and Ryan (eds): Mid-Proterozoic Laurentia-Baltica. Geological Association of Canada, Special Paper 38, 317-33.

Larson S Å, Tullborg E-L, Cederbom C, Stiberg J-P, 1999. Sveconorwegian and Caledonian foreland basins in the Baltic Shield revealed by fission-track thermochronology. Terra Nova 11, 210-215.

Lee H K, Schwarcz H P, 1995. Fractal clustering of fault activity in California. Geology 23, 377-380.

Lidmar-Bergström K, 1995. Relief and saprolites through time on the Baltic Shield. Geomorphology, 12, 45-61.

Lidmar-Bergström K, 1996. Long-term morphotectonic evolution in Sweden. Geomorphology, 16, 33-59.

Lin J C, Broecker W S, Andersson R F, Hemming J L, Rubenstone J L, Bonavi G, 1996. New 230 Th/U and 14C-ages from the Lake Lahontan carbonates, Nevada, USA and a discussion for the origin of initial thorium contents. Geochim. Cosmochim. Acta, 60, 2817-2832.

Lionel L, Bourlés D, Sébrier M, Bellier O, Castano J, Araujo M, Perez M, Raisbeck G, Yiou F, 1997. Cosmogenic dating ranging from 20 to 700 ka of a series of alluvial fan surfaces affected by the El Tigre fault, Argentina. Geology 25, 975-978.

Lundqvist J, Lagerbäck R, 1976. The Pärvie Fault: A late glacial fault in the Precambrian of Swedish Lapland. Geologiska Föreningens i Stockholm Förhandlingar 98, 45-51.

Maddock R H, Muir-Wood R, Hailwood E-A, Rhodes E J, 1993. Direct fault dating trials at Äspö Hard Rock Laboratory. SKB, TR 93-24.

Mansfeld J, Sturkell E F F, 1996. Geological and geophysical investigation of a mjor shear zone in southeastern Sweden. GFF 118, A18-19.

Marek R, 2000. Tectonic modelling of south west Scandinavia based on marine reflection seismic data. Earth Sciences Centre, Göteborg University, A 49.

Marshall J, 1988. Cathodoluminescence of geological materials. Allen & Unwin Inc. USA.

Marshall B, Whelan J F, Peterman Z E, Futa K, Mahan S A, Stuckless J S, 1992. Isotopic studies of fracture coatings at Yucca Montain, Nevada, USA. In Kharaka Y and Maest A (eds) pp 737-740. Balkema Amsterdam.

McNutt R H, Frape S K, Fritz P, 1985. Strontium isotopic studies of brines from crystalline rocks, Precambrian Shield, Canada. AAPG research conference on radiogenic isotopes and sedimentary basin analyses. New Orleans, April 1985.

Mellere D, 1993. Thrust-generated, back-fill stacking of alluvial fan sequences, south-central Pyrenees, Spain (La Pobla de Segur Conglomerates). In Frostick L E and Steel R J (eds), Tectonic Controls and Signatures in Sedimentary Successions, International Association of Sedimentologists Special Publication, No 20, 259-276.

Milodowski A E, Gillespie M R, Naden J, Fortey N J, Shepherd T J, Pearce J M, Metcalfe R, 1998. The petrology and paragenesis of fracture mineralization in the Sellafield area, west Cumbria. Proceedings of the Yorkshire Geological Society 52, 215-241.

Munier R, 1993. Segmentation, fragmentation and jostling of the Baltic Shield with time, Uppsala Dissertation from the Faculty of Science 37. Almquist & Wiksell International, Stockholm.

Murray A S, Roberts R G, 1997. Determining the burial time of single grains of quartz using optically stimulated luminescence. Earth and Planetary Science Letters, 152, 163-180.

Mörner N-A, 1995. Paleoseismicity-the Swedish case. Quaternary International, 25, 75-79.

Mörner N-A, 1996. Liquefaction and varve disturbance as evidence of paleosiesmic events and tsunami; the autom 10,430BP event in Sweden. Quaternary Science Review, 15, 939-948.

Mörner N-A, 2000. In absurdum: long-term prediction and nuclear waste handling. In press.

Nakai S, Halliday A, Kesler S, Jones H, 1990. Rb-Sr dating of sphalerites from Tennessee and the gensis of Mississippi Valley type ore deposits. Nature, 346, 354-357

Norling E, Bergström J, 1987. Mesozoic and Cenozoic tectonic evolution of Scania, southern Sweden. Tectonophysics 137, 7-19.

Nur A, Walder J, 1990. Time-dependent hydraulics of the Earth's crust. In: The Role of Fluids in Crustal Processes. National Academy of Sciences, Washington, DC, 113-127.

Olesen O, 1988. The Stuoragurra Fault, evidence of neotectonics in the Precambrian of Finnmark, northern Norway. Norsk Geologisk Tidssskrift 68, 107-118.

Paces J B, Peterman Z E, Neymark L A, Whelan J F, Marshall B D, 1998. Constraints on Quaternary unsaturated and saturated zone hydrology from geochronological and isotopic studies of calcite and silica, Yacca Mountain, Nevada USA. In Use of Hydrogeochemical Information in testing groundwater floe models, Summary from Workshop, Borgholm, Sweden, NEA/OECD, Paris.

Page L M, Möller C, Johansson L, 1996. 40Ar/39Ar geochronology across the Mylonite Zone and the Southwestern Granulite Province in the Sveconorwegian Orogen of S. Sweden. Precambrian Research 79, 239-259.

Page L M, Stephens M B, Wahlgren C-H, 1996. 40Ar/39Ar geochronological constraints on the tectonothermal evolution of the Eastern Segment of the Sveconorwegian Orogen, south-central Sweden. In: Brewer T S (ed), Precambrian crustal evolution in the North Atlantic Region, 315-330. Geological Society Special Publication No 112.

Park R G, Åhäll K-I, Boland M P, 1991. The Sveconorwegian shear-zone network of Sweden in relation to mid-Proterozoic plate movements. Precambrain Research, 49, 245-260.

Parnell J (ed), 1998. Dating and duration of fluid flow and fluid-rock interaction, Geological Society Special Publication No 144. ISSN 0305-8715.

Perroud H, Rombardet M, Bruton D L, 1992. Palaeomagnetic constraints upon the palaeogeographic position of the Baltic Shield in the Ordovician. Tectonophysics 201, 97-120.

Pesonen L J, Torsvik T H, Elming S-Å, Bylund G, 1989. Crustal evolution of Fennoscandia – palaeomagnetic constraints. Tectonophysics 162, 27-49.

Pesonen L J, Bylund,G, Torsvik T H, Elming S-Å, Mertanen S, 1991. Catalogue of palaeomagnetic directions and poles from Fennoscandia – Archean to Tertiary. Tectonophysics 196.

Peterman Z E, Wallin B, 1999. Synopsis of Sr isotope variation in groundwater at Äspö, southern Sweden. Applied Geochemistry 14, 939-952.

Phillips G N, Williams P J, De Jong G, 1993. The nature of metamorphic fluids and signatures for metal exploration. In Parnell J (ed), Geofluids; Origin, Migration and Evolution of Fluids in Sedimentary Basins. Geological Society Special Publication, No 78, 55-68.

Pitkänen P, Luukonen A, Ruotsalainen P, Leino-Forsman H, Vuorinen U, 1999. Geochemical modelling of groundwater evolution and residence time at the Olkiluoto Site. Posiva Report POSIVA 98-10. Posiva Oy, Helsinki, Finland.

Possnert G, Tullborg E-L, 1989. C-14 analyses of calcite coatings in open fractures from the Klipperås study site, southern Sweden. SKB TR 89-36, ISSN 0284-3757.

Potts J P, Bowles J F W, Reed S J B, Cave M R, 1995. Microprobe Techniques in the Earth Sciences. The Mineralogical Society Series 6, Chapman & Hall, 419 pp.

Raisalainen K, Suksi J, 1994. Modelling prospects for in situ matrix diffusion at Palmottu natural analogue site, SW Finland. Special Issue of Radiochimica Acta 1994, 581-587.

Ramsay J G, Huber M I, 1987. The Techniques of Modern Structural Geology, Volume 1: Strain Analysis. Academic Press, INC.

Rieffe E C, van Lil R, Verweij P M, Beunk F F, 1993. Preliminary data from the Loftahammar Shear Zone, southeastern Sweden. Sveriges Geologiska Undersökning, Rapporter och Meddelanden 76, p 16.

Roedder E, 1984. Fluid inclusions. Mineralogical Society of America, Reviews in Mineralogy 12.

Romer R, Lehmann B, 1995. U-Pb columbite age of Neoproterozoic Ta-Nb mineralization in Burundi. Economic Geology 90, 2303-2309.

Ruiz J, Kesler S E, Sutter J F, Jones L M, 1980. Geology and geochemistry of the Las Cuevas fluorite deposit, central Mexico. Economic Geology 79, 1200-1209.

Ruiz J, Kesler S E, Jones L M, 1981. Strontium isotope geochemistry of fluorite mineralization from northern Mexico. Geological Society of America, Abstracts with Programs 13, 542.

Ruiz J, 1983. Geochemistry of fluorite mineralization and associated rocks from northern Mexico (Ph. D. Thesis), Ann Arbor, University of Michigan, 202 p.

Scherstén A, Larson S Å, Cornell D H, Stigh J, 2000. Ion probe dating of a migmatite and the role of the Mylonite Zone in Sveconorwegian crustal evolution. In A Scherstén, PhD thesis, Mafic intrusions in SW Sweden. Earth Sciences Centre, Göteborg University, A58, 90 pp.

Seger, Alexander J, 1993. Distribution of Plio-Pleistocene and modern coarse-grained deltas south of the Gulf of Corinth, Greece. In: L E Frostick and R Steel (eds), Tectonic Controls and Signatures in Sedimentary Successions. Blackwell Scientific, IAS Special Publication, 20, 37-48.

Sehlstedt S, Stråhle A, 1989. Geological core mapping and geophysical borehole logging in the boreholes KAS 05 – KAS 08 at Äspö. SKB Progress Report 25-89-09.

Shanley K W, McCabe P J, 1994. Perspectives on the sequence stratigraphy of continental strata. American Association of Petroleum Geologists Bulletin, 78, 544-568.

Shepard T J, Rankin A H, Alderton D H, 1985. A practical guide to fluid inclusions studies. Blackie & Son Ltd, Glasgow, 299 pp.

Sibson R H, 1993. Crustal stress, faulting and fluid flow. In Parnell J (ed), Geofluids: Origin, Migration and Evolution of Fluids in Sedimentary Basins. The Geological Society of London, no 78, 69-84.

Sivhed U, 1991. A pre-Quaternary, post-Palaeozoic erosional channel deformed by strike-slip faulting, Scania, southern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 113, 139-143.

Skjernaa L, 1992. Microstructures in the Nyatorp shear zone, southeastern Sweden. Geol. Fören. Stockholm Förhandl. 114, 195-208.

Slunga R, Norrman P, Glans A-C, 1984. Baltic shield seismicity, the results of a regional network. Geophys. Res. Lett. 11, 1247-1250.

Smellie J A T, MacKenzie A B, Scott R D, 1986. An analogue validation study of natural redionuclide migration in crystalline rocks using uranium series disequilibrium studies. Chem. Geol. 55, 233-254.

Smethurst M A, 1992. A practical suggestion regarding the use of Scandinavian and Russian palaeomagnetic data to determine the palaeo-position of Baltica in Ordivician time. Tectonophysics 201, 65.73.

Stein H J, Makey R J, Morgan J W, Hannah J, Zák K, Sundblad K, 1997. Re-Os dating of shear-hosted Au deposits using molybdenite. Min. Deposita, 313-317.

Stein H J, Morgan J W, Walker R J, Horan M F, 1993. A mantle component for Climax-type granite-molybdenum systems or our first glimpse at Re-Os in the lower continental crust. EOS, Transactions, American Geophysical Union 77 (46), F-773-774.

Stephens M, Wahlgren C-H, 1993. Oblique-slip, right-lateral ductile deformation zones in the Svecokarelian orogen, south-central Sweden. Sveriges Geologiska Undersökning, Rapporter och Meddelanden 76, 18-19.

Stephens M, Wahlgren C-H, Cruden A R, 1996. Left-lateral transpressive deformation and its tectonic implications, Sveconorwegian orogen, Baltic Shield, southwestern Sweden. Precambrian Research, 79, 261-279.

Stephens M, Johansson R, 1998. Översiktsstudie av Norbottens län (urbergsdelen). Geologiska förutsättningar. SKB R-98-40.

Stewart I S, Hancock P L, 1994. Neotectonics. In P L Hancock (ed), Continental Deformation. Pergamon Press. Tarrytown, NY, p 370-409.

Stober I, Bucher K, 2000. Hydrogeology of Crystalline rocks. Water Science and Technology Library. Vol 34. Kluwer Academic Publishers, Dordrecht.

Suksi J, Ruskeeniemi T, Rasilainen K, 1992. Matrix diffusion – evidences from natural anlogue studies at Palmottu in SW Finland. Radiochimica Acta 58/59, 385-393.

Sundvoll B, Neumann E-R, Larsen B T, Tuen E, 1990. Age relation among Oslo rift magmatic rocks: implications for tectonic and magmatic modelling. Tectonophysics 178, 67-87.

Symons D T A, Lewchuk M T, Leach D L, 1998. Age and duration of the Missisippi Valley-type mineralising fluid flow event in the Viburnum Trend, Southeast Missouri, USA, determined from palaeomagnetism. In: Parnell J (ed) Dating and Duration of Fluid Flow and Fluid-Rock Interaction. Geological Society, London, Special Publications, 144, 27-40.

Talbot C, Sokoutis D, 1995. Strain ellipsoids from incompetent dykes: application to volume loss during mylonitization in the Singö gneiss zone, central Sweden. Journal of Structural geology 17, 927-948.

Talbot C, Pan M, Sjöberg L E, Asenjo E, 1998. GPS measurements of crustal deformation in Skåne between 1989 and 1996. Abstract volume, 23. Nordiske Geologiske Vintermöde, Århus 1998, p 293.

Talbot C, 1999. Ice ages and nuclear waste isolation. Engineering Geology, 52, 177-192.

Taylor E M, Whitney J W, Menges C M, Buesch D C, 1996. Results of investigations of the potential for Quaternary faulting on the Ghost Dance Fault, central Yucca Mountain, Nye County, Nevada. Abstracts with Programs – Geological Society of America. 28; 7, p 193.

Torsvik T H, Smethurst M A, Briden J C, Sturt B A, 1990. A review of Palaeozoic palaeomagnetic data from Europe and their palaeomagnetic implications. In: W S McKerrow and C R Scotese (eds), Palaeogeography and Biogeography. Geol. Soc. Mem. 12, 25-41

Torsvik T H, Smethurst M A, Meert J G, Van der Voo R, McKerrow W S, Brasier M D, Surt B A, Walderhaug H J, 1996. Continental beak-up and collision in the Neoproterozoic and Palaeozoic: A tail of Baltica and Laurentia. Earth Science Reviews 40, 229-258.

Tullborg E-L, 1989. $\delta^{18}O$ and $\delta^{13}C$ in fracture calcite used for interpretation of recent meteoric water circulation. In: Miles D L (ed), Water-rock interaction, WRI-6. Balkema, Rotterdam, 695-698.

Tullborg E-L, Larson S Å, Stiberg J-P, 1996. Subsidence and uplift of the present land surface in the southeastern part of the Baltic Shield. GFF 118, 126-128.

Tullborg E-L, 1997. Recognition of low temperature processes in the Fennoscandian shield. Ph D thesis, Earthe Science Centre A17, Göteborg University, ISSN 1400-3813.

Tullborg E-L, Gustafsson E, 1999. 14C in bicarbonate and dissolved organics – a useful tracer? Applied Geochemistry 14, 927-938.

Tullborg E-L, Landström O, Wallin B, 1999. Low-temperature trace element mobility influenced by biogenic activity – indications from fracture calcite and pyrite in crystalline basement. Chemical Geology. 157, 199-218.

Tuniz C, Bird J, Fink D, Herzog G, 1998. Accelerator mass spectrometry, ultrasensetive analysis for global science. CRC Press, London, 371pp.

Wahlgren C-H, Cruden A R, Stephens M B, 1994. Kinematics of a fan-like structure in the eastern part of the Sveconorwegian orogen, Baltic shield, south-central Sweden. Precambrian Research, 70, 67-91.

Wallin B, Peterman Z, 1999. Calcite fracture fillings as indicators of palaeohydrology at Laxemar at the hard Rock Laboratory, southern Sweden. Applied Geochemistry, 14, 953-962.

Van der Woerd J, Ryerson F J, Tapponier P, Gaudemer Y, Finkel R, Meriaux A S, Caffee M, Guoguang Z, Qunlu H, 1998. Holocene left-slip rate determined by cosmogenic surface dating on the Xidatan segment of the Kunlun fault (Qinghai, China). Geology, 26, 695-698.

Van-Kranendonk M J, Collins W J, 1998. Timing and tectonic significance of late Archaean, sinistral strike-slip deformation in the central Pilbara structural corridor, Pilbara Craton, Western Australia. Precambrian Research, 88, 207-232.

Wawrzenitz N, 1994. A Miocene metamorphic core complex in northrn Greece (Thassos Island, Rhodope- Massif) Variscan ancient history and Alpine history of the lowering and exhumation of the mid-crustal rocks. Erlanger-Geologische-Abhandlungen 1994, 61-75.

Wetherill G W, 1956. Discordant uranium-lead ages. Trans. Amer. Geophys. Union 37, 320-326.

Whitehouse M J, 1988. Granulite facies Nd-isotopic homogenisation in the Lewisian complex of northwest Scotland. Nature 331, 705-707.

Wickman F E, Åberg G, Levi B, 1983. Rb-Sr dating of alteration events in granitoids, Contrbution to Mineralogy and Petrology, 83, 358-362.

Wijbrans J R, Beunk F F, Pitka S, van Lil R, Boeken W M, Wahlgren C-H, Stephens M B, Verdurmen E A T, 1995. Laser 40Ar/39Ar and U/Pb dating of right-lateral ductile deformation in the Svecokarelian orogen, south-central Sweden. Terra abstracts, Abstract supplement No 1 to Terra Nova 7, EUG 8, Strasbourg, France, 44, 1995.

Wikström A, Skiöld T, Öhlander B, 1996. The relationship between 1.88 Ga old magmatism and the Baltic-Bothnian shear zone in northern Sweden. In: T S Brewer (ed), Precambrian crustal evolution in the north Atlantic region. Geological Survey Special Publication 112, 249-259.

Wikström A, Persson P-O, 1997. U-Pb zircon and monazite dating of a Lina type leucogranite in northern Sweden and its relationship to the Bothnian shear zone. Sveriges Geologiska Undersökning C380, 81-87.

Wintle A G, Li S H, Botha G A, Vogel J C, 1995. Evaluation of luminescence-dating procedures applied to late-Holocene colluvium near St Paul's Mission, Natal, South Africa. Holocene, 5, 97-102.

von Krauss M, Franz K-M, Hammer J, Lindh A, 1996. Zur Geologie der Småland-Blekinge-Störungszone (SE-Schweden). Z. geol. Wiss. 24, 273-282.

Yoshida H, Aoki K, Semba T, Ota K, Amano K, Hama K, Kawamura M, Tsubota K, 2000. Overview of the stability and barrier functions of the granitic geosphere at the Kamaishi mine: relevance to radioactive waste disposal in Japan. Engineering Geology 56, 151-162.

Yu-Guang Y, Shao-Bo D, Jie H, Jun-Cheng G, Xiang-Yi L, 1998. ESR dating studies of palaeo-debris-flow deposits in Dongchuan, Yunnan Province, China. Quaternary Geochronology 17, 1073-1076.

Zander A, Duller G A T, Wintle A G, 2000. Multiple and single aliquot luminescence dating techniques applied to quartz extracted from Middle and Upper Weichselian loess, Zemechy, Czech Republic. Journal of Quaternary Geology, 15, 51-60.

Zwingman H, Clauer N, Gaupp R, 1998. Timing of fluid flow in a sandstone reservoir of the north German Rotliegend (Permian) by K-Ar dating of related hydrothermal illite. In Parnell J (ed): Dating and duration of fluid flow and fluid-rock interaction. Geological Society Special Publication no 144. ISSN 0305-8719.

Appendix

Fracture zone studies in the Baltic Shield

Knowledge about regional deformation zones is important in selecting target areas for deposition of spent nuclear fuel, such that they can easily be avoided. However, local deformation zones have usually not been mapped in the regional mapping programmes. Since these will have shorter extension, they will be site-specific, yet of considerable importance in the context of nuclear waste disposal. Below is a brief summary about a selected number of regional deformation zones. In some cases, attempt was made to date these zones in order to reconstruct the regional deformational histories.

First-order fracture and fault zones

Several major fracture zones have been recognised in the Baltic Shield (Figure A-1), of which some have been known for a long time. Many fracture zones have plastic shear zones as precursors. Such examples are found within the Protogine Zone, the Mylonite Zone and to some extent the Tornqvist Zone of southern Sweden. Below are a few examples of important deformation zones. Except for these, a great number of shear zones of variable orders have been recognised. For a more complete list see numerous compilations by Stephens and Johansson in SKB reports (R-series) printed 1998 and 1999 (available from Swedish Nuclear Fuel and Waste management Co).

In northern Sweden several examples of late- to post-glacial movements (cf Axelsson, 1996) have been documented (Lundqvist and Lagerbäck, 1976; Lagerbäck, 1979; 1991; 1997) but also in adjoining parts of Norway (Olesen, 1988) and Finland (Kujansuu, 1972 and references therein). Special attention has been devoted to the *Lansjärv* (Lagerbäck, 1990) and *Pärvie* (Lundqvist and Lagerbäck, 1976) faults striking parallel to the Caledonian front in a roughly NNE direction.

The Baltica-Bothnian megashear strikes N-S from Kalix at the Bothnian Bay, northern Sweden, northwards to Pajala and further into Finland. This zone was active at ca 1880 to 1800 Ma (Kärki et al, 1993; Wikström and Persson, 1997; Wikström et al, 1996 and references therein).

The Karesuando-Arjeplog shear zone strikes NNE from Arjeplog to Karesuando in northernmost Sweden and further into Finland. Discrete zones can be several km wide (Stephens and Johansson, 1998).

The Hassela Shear Zone (HSZ) and The Storsjön-Edsbyn Deformation Zone (see below) partly join in a ca 50 km wide area of anastomosing shear zones in the eastern part of Jämtland County. HSZ is sub-vertical and strikes in NW-SE. A 1796 Ma U-Pb titanite age was obtained from a sinistral shear zone (Högdahl, 2000).

The Storsjön-Edsbyn Deformation Zone is one of several NW to NNW striking tectonic zones in central Sweden (Bergman and Sjöström, 1994; Högdahl et al, 1998; Högdahl, 2000), the ages of which are uncertain. Fractures are sealed by quartz, calcite, epidote, fluorite and asphaltite.

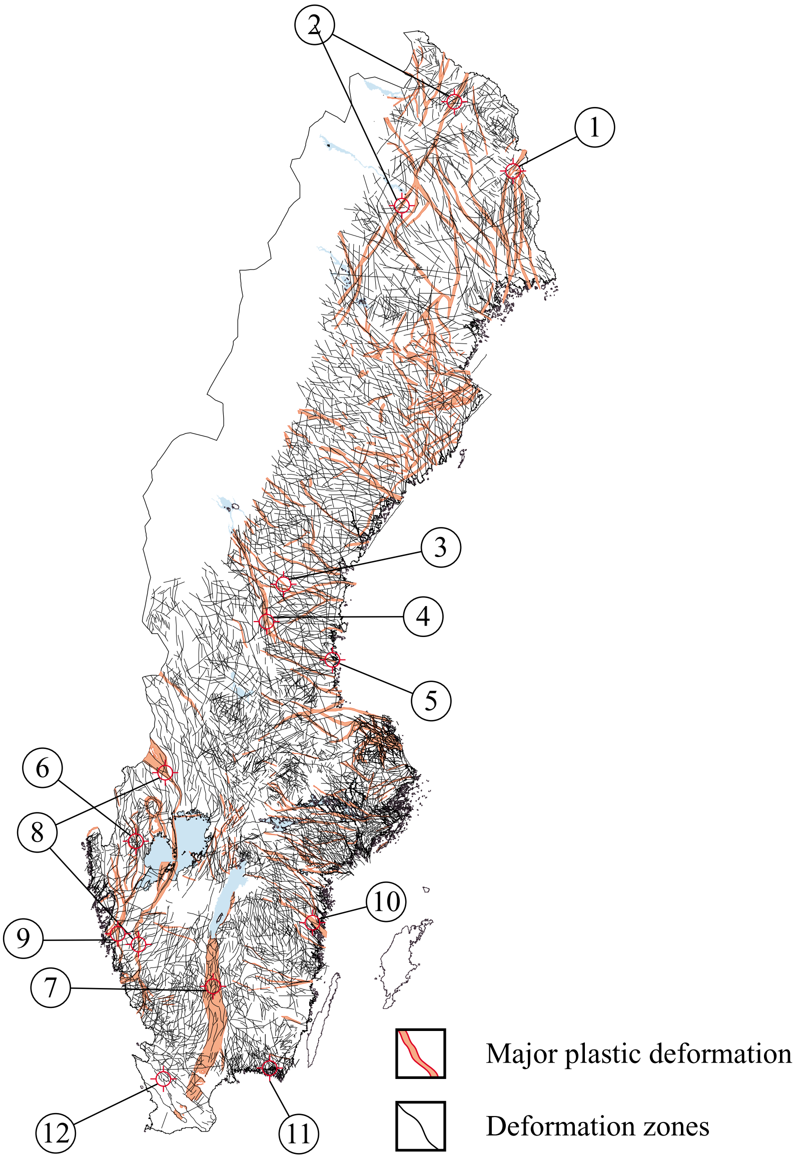

Figure A-1. *First order deformation zones in Sweden mentioned in text: 1) Baltica-Bothnian mega shear, 2) Karesuando-Arjeplog shear zone, 3) Hassela shear zone, 4) Storsjön-Edsbyn deformation zone, 5) Ljusne shear zone, 6) Dalsland boundary thrust, 7) Protogine Zone, 8) Mylonite Zone, 9) Göta Älv Zone, 10) Loftahammar shear zone, 11) Blekinge shear zone, 12) Tornquist Zone.*

The Singö shear zone strikes NW to WNW (Östhammar to Skärplinge) parallel to the coastline of northern Uppland. It is anastomosing and includes less deformed tectonic lenses (cf Talbot and Sokoutis, 1995). Sub-parallel zones are present to the north and to the south of this zone.

The Ljusne shear zone and the *Hagsta gneiss zone* are two dextral, high temperature shear zones in east central Sweden that yield U-Pb titanite ages of 1798 Ma (Högdahl, 2000 and references therein).

The *Hammarö Shear Zone* (Berglund et al, 1997) is an E-W trending several kilometres wide and steep zone comprising a network of individual shear zones that can be easily traced along the northern shoreline of Lake Vänern. It is considered to be related to Sveconorwegian stretching.

The Dalsland boundary thrust was recognised by Berthelsen (1980) and is one of several roughly N-S trending tectonic zones to the west of the Mylonite Zone in Sweden. These were considered as Sveconorwegian thrust zones by, e.g. Park et al (1991) and may have formed during a compressional tectonic regime in beginning of the Sveconorwegian orogeny.

The Protogine Zone (Andreasson and Rhode, 1990; Larson et al, 1990) was earlier given the role of the border zone between rocks of different ages; the Transscandinavian Igneous Belt and gneissic rocks to the west there off. Recent studies reveal that these supposed terrains have overlapping ages and that the zone roughly separates deformed granitoids from less deformed granitoids of the Transscandinavian Igneous Belt. Dating of movements along this zone has been made using Ar-Ar ages from muscovite and hornblende (Page et al, 1996). Thus, it has been concluded that the Protogine Zone is a Sveconorwegian feature although its older history is not obvious.

Relative ages have also been used in constraining the age of the Protogine Zone, showing that foliation related to movements along the zone affects 1.2 Ga old rocks (e.g. Larson et al, 1990). It is evident that parts of the zone were later reactivated since a basin was developed in a rift-like structure in the Vättern area at ca 800–700 Ma. Its importance as a structural feature was pointed out by Slunga et al (1984), who argued that the Protogine Zone is a divider between seismic and aseismic crust.

The Mylonite Zone roughly separates rocks of 1.7 Ga from those of 1.6 Ga. Different roles have been ascribed to this zone, such as a suture, a Sveconorwegian shear zone and a thrust zone. It is evident that both eastward thrusting and normal faulting took place along this zone during the Sveconorwegian (Berglund, 1997; Stephens et al, 1996), although its earlier history remains unclear. Johansson and Johansson (1993) yielded a concordant sphene U-Pb age of ca 920 Ma dating uplift along the Mylonite Zone, and Scherstén et al (2000) recognised igneous zircon at 928 Ma related to uplift of the terrain to the east of the zone.

The Göta Älv Zone strikes sub-parallel and west of to the Protogine Zone. It dips to the west and is one of several N-S striking shear zones in western Sweden formed or reactivated during the Sveconorwegian (cf Park et al, 1991 and references therein).

The Loftahammar shear zone in Southeast Sweden is a NW trending, tectonic zone that branches towards NW. It is several km wide in the coastal area and can be subdivided into discrete zones that have moved obliquely and dextrally (Rieffe et al, 1993; Stephens and Wahlgren, 1993; Wijbrans et al, 1995). A parallel shear zone to the southern part of the Loftahammar Shear Zone can be followed approximately 20 kilometres to southward.

The *Nyatorp Shear Zone* is one of several approximately E-W striking, steeply north-dipping zones in south eastern Sweden. The zone shows shear sense indicators consistent with dip slip movements (Skjernaa, 1992) and can be traced from Oskarshamn westwards to west and south of Virserum (Mansfeld and Sturkell, 1996).

The Blekinge shear zone is a E-W trending steep zone in northern Blekinge (von Krauss et al, 1996). It affects rocks of the Transscandinavian Igneous Belt and is probably younger than ca 1.7 Ga.

The Tornqvist Zone is a prominent tectonic feature cross-cutting southernmost Sweden in a NW-SE direction. It comprises a border zone between the Phanerozoic rocks to the south and the crystalline rocks of the Baltic Shield to the north. This fault zone that can be traced far to the SE (Teisseyre-Tornquist Zone), and NW (Sorgenfrei-Tornquist Zone), has a width of 20 to 50 km has been active during the last 400 million years (Bergström et al, 1982; Norling and Bergström, 1987; Sivhed, 1991; Japsen, 1993; Erlström et al, 1997; Marek, 2000). Faulting along horst structures in the Scania province has been extensive causing serious fracturing of the rocks. Neotectonic movements in the order of 2 to 4 mm/year, were recorded using GPS measurements by Talbot et al (1998).

Proximal to Sweden, in Norway, several tectonic zones are found. Two important examples from south-east Norway are given below.

The Oslo rift is a prominent crustal feature that strikes N-S from north of Oslo into the Skagerrak Sea. It was formed during early Permian (295–275 Ma) and was contemporaneously intruded by magmas, which can be traced along the Swedish west coast (e.g. Sundvoll et al, 1990 and references therein). Coeval rifting and magmatism took place, for example, in Germany.

The Kristiansand -Porsgrund zone is situated in the westernmost part of the Bamble province of south-east Norway. It obviously was active during the Sveconorwegian as several other shear zones in southern Norway and was compressed at 1.13 Ga (Bingen, 1998).