Proceedings

Second Meeting of the Tectonics and Structural Geology Studies Group of NGF on 'Dating of structural events'

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Gabrielsen, R. H. & Koestler, A. G.: Second meeting of the Tectonics and Structural Geology Studies Group of NGF on 'Dating of structural events'. *Norsk Geologisk Tidsskrift,* Vol. 65, pp. 321–324. ISSN 0029-196X.

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The second meeting of the Tectonics and Structural Geology Studies Group of NGF was held in Bergen, 4th to 5th of October 1984. The topic of the meeting, which gathered eleven speakers and about 60 participants, was 'Dating of structural events'.

The possibility for both absolute and relative dating is essential for all geological modelling, and the aim of the meeting was to focus upon methods for age determinations which can be used in dating structural events. The meeting included presentations which treated relative dating by the use of traditional geological methods (structural correlation, identification of unconformities, palaeontological data) as well as absolute dating of structural events by the use of isotope studies (Rb/Sr and $^{40}Ar/^{39}Ar$).

The present report is an attempt to summarize the main conclusions drawn during the meeting. The summaries are mainly shortened versions of abstracts submitted before the meeting, but oral presentations and discussions during the meeting have in some cases been taken into account. The present authors are responsible for any misunderstandings in this process, and also for the general comments and conclusions.

Timing of tectono-metamorphic events in the Norwegian Caledonides

Information on timing in mountain belts obtained by correlation of tectonic and metamorphic events was discussed by several speakers.

D. Roberts, who presented a review of tectonometamorphism in the Norwegian Caledonides, stated that the traditional view that there has been one single, ubiquitous, tectonothermal event during which the Norwegian Caledonide mountain chain was raised in Silurian time has come under fierce assault over the last decade. Based on recognition of post-hiatus conglomerates, biostratigraphy and isotope age-determination, two principal events and a third less intense event are now recognized:

1. The early or Finnmarkian phase (late Cambrian to early Ordovician).
2. The main or Scandian phase (mid-Silurian to earliest Devonian).
3. The late phase (probably late Devonian). Local names such as 'Røragenian' and 'Solundian' have been applied to this latter event.

An important point is that each of these principal orogenic events was diachronous. Differences in timing are discernible both along and across the orogen. In northern Norway for example, the Finnmarkian deformation and nappe accretion proceeded from west to east – from Cambrian in the higher nappes to early Ordovician in the lowest tectonic units and the parautochthon. Similarly, the Scandian event in southern districts shows evidence of first affecting the higher nappes of the orogenic interior and then gradually progressing diachronously southeastwards onto the Baltoscandian margin, ultimately deforming the sediments of the Oslo Region.

The role of unconformities in the dating of structural events in the Scandinavian Caledonides was also addressed by *B. A. Sturt.* He referred to 1st- and 2nd-order stratigraphic unconformities. A 1st-order unconformity is one which post-dates an orogenic cycle and where the unconformity and succeeding sedimentary sequences may represent a major uplift and erosional stripping. Such unconformities may be *rooted* (in the autochthon) or *transported* (in the allochthon), and hence the patterns of basement/cover relation and their former extent can be traced through the tectono-stratigraphic stack. One such unconformity can be traced in the Kalak nappe complex in Finnmark, and defines not only the start of the Finnmarkian cycle but also indicates the former extent of the continental rise prism.

Another of the 1st-order unconformities in the Norwegian Caledonides defines the end of the Finnmarkian Orogeny and the succeeding coarse clastics record part of the morphogenic expression of that orogenic event. This unconformity has a special significance in that the overlap deposits now link together the rocks of the deformed continental rise prism/miogeocline and those of sea-board accreted ophiolitic terranes – thus its status is raised to that of a *terrane-linking unconformity*. The unconformity naturally also marks the start of the Scandian cycle. The Ordovician was further characterized by tectonic instability and a number of unconformities of 2nd-order are present within the belt.

The end of the Scandian Orogeny is marked by another 1st-order unconformity which is covered by the Old Red Sandstone molasse of Western Norway. The latter has been involved in a post-lower middle Devonian orogenic cycle (Solundian) though the 1st-order unconformity marking the end of this cycle must be sought in the North Sea.

The structural evolution of the Kalak nappe complex was elaborated by *C. Townsend* who demonstrated that it has undergone a five-fold polyphase deformation. He suggested that the D_1 and D_2 deformational phases are Finnmarkian in age, whereas the D_3-folds both pre- and post-date formation of the Kalak thrust zone. Accordingly, correlations of the D_3 event throughout the Kalak nappe are invalid, demonstrating the danger in correlation of structural events on structural styles alone.

Also in western Spitsbergen indications of an early Caledonian structural and metamorphic event are recorded. *Y. Ohta* showed that an unconformity, which has been found at the base of the (?)Ordovician–Silurian succession implies that high-P metamorphism (1) is definitely older than (?)Ordovician–Silurian, and (2) provides evidence of a progressive high-P metamorphic facies series. The combination of oceanic basic rocks and sediments of shallow marine reef facies is explained in terms of a change of tectonic domain, i.e., from that of a continental shelf during sedimentation, to an active oceanic condition at the time of basic intrusion. This change implies an active plate boundary which is responsible for the high-P metamorphism in an early Caledonian phase.

Late Caledonian influence on basement of the North Sea was addressed by *A. Le Marrec, J. P. Richert & F. Walgenwitz*. They presented data from Well 2/6-3, which is situated at the western flank of the Mandal High. The well encountered red and black phyllites, which have been cored. They concluded that polyphase tectonic events are depicted in the basement of the Southern Norwegian North Sea. The first phase with incipient metamorphism could be related to a major thrust event (376 ± 5 ma). A partial rejuvenation occurring at about 315 ma demonstrates that the main basement events were not concluded by the Silurian, but continued further in post-middle Devonian and pre-Carboniferous times.

Radiometric dating and mylonite zones

In general, geochronoligcal data from deformation zones is difficult to interpret. Often, insufficient structural control and/or lack of enough isotopic data makes it impossible to decide whether the result represents the primary or the metamorphic age of a rock complex, or corresponds to a deformational phase, or a mixture of those. These problems were addressed in three papers.

A. G. Koestler described Caledonian ductile shear zones in the Jotun nappe complex. These cut pyroxene-granulites and amphibolites which are their retrograded products. The mylonitic zones must be of Caledonian age because they cut the Valdres Sparagmite sequence of Eocambrian age as well. The retrogression of the pyroxene-granulites to amphibolites belong to the Sveconorwegian event. Geochronological investigations of small samples from profiles across a shear zone in pyroxene-granulites give a whole-rock isochron indicating a Precambrian age, similar to undeformed pyroxene-granulites. However, the same type of investigation across a shear zone in the amphibolites clearly indicates a partial reequilibration of the isotopic system. A Caledonian reference line fits best with the data points on the Rb-Sr plot.

R. H. Gabrielsen, S. Solheim, A. Råheim and H. Austrheim demonstrated disturbance of Rb–Sr systems during deformation. Mylonites cutting the Precambrian (c. 1500 ma) Dyrskard Group of the Hardangervidda–Ryfylke nappe complex have yielded data indicating a significant disturbance of the isotopic systems associated with tectonization and mylonitization during Caledonian thrusting. Calculated 'ages' are within the range 483 ± 68 ma to 705 ±59 ma. The presented 'ages', however, cannot be used for the dating of the thrust episode.

Both Koestler and Gabrielsen et al. stressed the importance of water for resetting isotope systems during deformation.

A. Andresen gave an introduction to the use of the $^{40}Ar/^{39}Ar$ method and its usefulness in studying the thermal evolution of polymetamorphic terranes. Data from both the Alta Window and the basement terranes of Tysfjord–Lofoten–West Troms were presented. Mineral release patterns on amphibole and biotite from the latter area are in general internally discordant and with excess argon in most of the biotite samples. $^{40}Ar/^{39}Ar$ release patterns from (?) Karelian slates in the Alta Window give high temperature plateau ages of approximately 1830 Ma, becoming gradually younger with lower temperatures and ending at 420 Ma. The ages are interpreted as the age of the slate formation and the superimposed Scandian thermal event, respectively.

Dating by combined biostratigraphic, structural and sedimentological methods

D. Guy-Ohlsen used a sedimentological sequence at Kullemölle, Sweden, to demonstrate how palynological evidence can be used to date structural events. Using palynological zonation, it has been possible to divide the sediments in the Kullemölle well into three zones of Liassic to Aptian age. If the biostratigraphical ages based upon the palynological evidence are accepted, this would suggest that the tilting of the strata must have occurred towards the end of, or shortly after, what has been determined as the Berriasian–Hauterivian.

Evidence of synsedimentary tectonism in the lowermost Silurian strata of Brumunddalen, Norway, was given by *N. Møller*. She attempted to distinguish between sea-level changes caused by crustal movements and those caused by changes in climate. Three sections have been studied in the Brumunddal area in the northern part of the Oslo Region. Here the lowermost Silurian contains a thin intraformational breccia of tectonic origin, genetically related to erosional unconformities and synsedimentary slump structures in an early cemented calcareous sandstone. Differences in the style of deformation of the overlying limestone and overthrusted shale are significant, as is the multiphase (syn- and post-lithification) fracture deformation of the uppermost limestone bed.

An integrated study using structural, biostratigraphic and sedimentological evidence was presented by *J. Indrehaug*. The eastern flank of the Statfjord Field is limited by a fault zone. Within this zone the combined Dunlin/Brent Groups average thickness of 450 m thins to 150–200 m. The dominant thinning mechanism is tectonic, namely shale flowage within the Dunlin Group combined with low angle listric faulting manifested by variable formation thicknesses and frequent repetitions of the Dunlin/Brent sections observed in the wells. Secondarily, depositional thinning and unconformities also contribute to this rapid loss of section.

Biostratigraphic evidence shows that the early/mid-Bathonian Heather shale is deposited conformably on the Brent Group. Shales of Callovian/Oxfordian age are found only along the western flank of the Statfjord Field, indicating either non-deposition or removal of these sediments over the crest of the structure.

Also major faulting was going on by late Kimmeridge/early Portlandian time when the central part of the structure started to fault down to the east, forming an apparent collapse zone. Within this zone, a relatively thick shale sequence ranging in age from late Kimmeridge/early Portlandian to Ryazanian is preserved, suggesting that growth faulting started by late Kimmeridgian/early Portlandian times. Sediments of late Kimmeridgian/early Portlandian age have not been discovered elsewhere on the structure, probably as a result of a regional Portlandian regression.

Following the regression, a condensed section of shales was draped over most of the structure. Due to lack of age diagnostic biostratigraphic data, these shales are tentatively dated as Portlandian/Ryazanian. To the west there are indications of an age range from late Portlandian to late Ryazanian. The late Ryazanian/Valanginian was most likely a period of uplift, with possible erosion of the Portlandian/Ryazanian Draupne shales.

The lower Cretaceous is represented by Hauterivian/Valanginian to lower Barremian limestones and marls. These shallow water, sublittoral sediments indicate a period of relative tectonic stability. Tectonic movements probably did not begin again until late Barremian/early Aptian when marine shales were deposited unconformably on sediments as young as early Barremian. Tectonic activity continued throughout the rest of the early Cretaceous, reactivating late Jurassic faults to form the present-day structural configuration.

Conclusions

The presentations during the meeting demonstrated different approaches to the essential problem of giving fixed dates to tectonic events in geological modelling. Naturally, the methods preferred will depend upon the general geology of the area considered, and the resources available for the study.

Nevertheless, the discussions pointed to the need for use of more than one method of dating of any structural event. A combination of different dating methods will increase the level of confidence in absolute or relative dating, and give valuable data which can be used in general geological modelling.

Radiometric dating of heavily deformed rocks may be considered as a major problem in radiometric geochronology. However, experiments in the Norwegian Caledonides indicate that meaningful ages may be obtained if careful studies are carried out, even though the present attempts have given no firm datings for time of thrusting.

Acknowledgements. – We wish to thank David Worsley and Alan Krill, who corrected the English text.