EUG XI

Symposium LS05

The Dynamics of Basin Inversion: Observations and Numerical Modelling

Convenors

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LS05
The Dynamics of Basin Inversion

Sunday PM Session

LS05 : SUpm25 : F2
Modelling the Process of Basin Inversion

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In the process of basin inversion sedimentary basins are reactivated in regional compression. This general observation implies that sedimentary basins represent relatively weak zones of the continental lithosphere even long after basin formation. An explanation for this phenomenon is not easily found since standard rheological models, due to crustal thinning, predict a cold and relatively strong upper mantle beneath thermally equilibrated basins.

Results from dynamic thermo-mechanical models are presented. The models are based on large strain theory and include history dependent rheologies relating the 2nd Piola Kirchoff stress to the Lagrangian Green strain tensor. The rheological laws comprise elastic, viscous and plastic deformation. The formation and evolution of faults and shear zones formed in extension and compression are tracked during model evolution. Yielding and plastic flow are simulated through the use of non-associated plasticity models with pressure sensitive yield criteria. The consequences of inherited weakness and strain softening are studied in scenarios of extension followed by compression.

The modelling results show that reactivation of sedimentary basins in compression produces shortening and thickening of the crust and uplift followed by erosion in the basin centre. In response to the loading by the thickened sediments and crust, the upper mantle subsides in the central parts of the basins. Flexural strength in the upper mantle transfers this subsidence to the former rift flanks where marginal troughs are created (Nielsen & Hansen, 2000). The topography of the system can be understood as the superposition of two opposite topographic effects: The smooth, long-wavelength, downward flexure of the upper mantle caused by loading, and the rugged short-wavelength topography related to shortening and thickening of sediments and crust in the central inversion zone. The system relaxes after cessation of the compressional forces and inverts a second time, now regionally, involving both the central inversion zone and the marginal troughs.

Results are presented from integrated modelling studies of the post-Triassic evolution of the Sorgenfrei-Tornquist Zone in the eastern North Sea (Hansen et al., 2001)

Nielsen SB & Hansen DL, *Geology*, **28**, 875-878, (2000).
Hansen DL, Nielsen SB & Lykke-Andersen H, *Tectonophysics*, **in press**, (2001).

LS05 : SUpm26 : F2
3-D Thermo-Mechanical Modelling of Inversion Tectonics

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Several areas in northern Europe were subjected to tectonic inversion in the Late Cretaceous - Early Cenozoic. The inversion happened as a response to the compressional stress field caused by the collision of Europe and Africa and by ridge push forces from the opening of the North Atlantic.

A 3-D thermo-mechanical model is used to study the behaviour of a heterogeneous lithosphere when subjected to a compressional stress field. The lithosphere is modelled as an elasto-visco-plastic continuum. The model includes the thermal evolution, surface processes, variations in eustatic sea level and variations of stress in time and space.

The model has been applied to two areas characterised by Late Cretaceous - Early Cenozoic inversion: The Sorgenfrei-Tornquist Zone in the north-eastern part of the Norwegian-Danish Basin marking the transition from the proterozoic Baltic Shield to tectonically younger areas, and the North German Basin.

In both areas the inversion structures are characterised by surface uplift in the inverted zones and surface subsidence of the areas bordering the inverted zones, leaving room for sedimentation in marginal troughs.

Modelling results show that deformation of the lithosphere under compression is controlled by the stress field and the lateral variations in lithospheric strength.

The inverted structures are zones of prominent crustal structural weakness. Under compression the lithosphere in these zones is thickened producing uplift and erosion of the surface of the weak zone. The thickened crust acts as a load and pulls down the margins of the weak zone developing marginal depositional troughs.

The Moho topography is of significant importance to the lateral variations in lithospheric strength and thereby the deformation properties of the lithosphere. Thus the geometries of the inverted structures and marginal basins are controlled by the lateral variations in Moho depth.

The modelled sediment thicknesses and paleo-geography are in agreement with the observations, e.g. the predicted paleo-geography in the Paleocene corresponds closely to observed patterns of erosion and deposition of chalk in the eastern North Sea area. This verifies the importance of the mechanisms dealt with in this paper on the deformation patterns and the evolution of intra cratonic sedimentary basins.

LS05 : SUpm27 : F2
Analysis of Vertical and Horizontal Lithospheric Movements in Northern Europe, from the North Sea to Germany: Results from Dynamic Modelling

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Predictions from dynamic modelling of the lithospheric deformation are presented for Northern Europe, where several basins underwent inversion during the Late Cretaceous and Early Tertiary and contemporary uplift and erosion of sediments occurred. In order to analyse the evolution of the continental lithosphere the equations for the deformation of a continuum and for the energy conservation are solved numerically for a layered lithospheric structure, with a temperature dependence of the rheological parameters for each layer. The most important stress sources is assumed to be associated with the Alpine tectonics, but additional stress sources are also incorporated into the modelling, such as pre-existing fault systems and localized weak or strong zones that affect mainly the local deformation pattern. Present-day observations available in the studied region and coming from seismic structural interpretations, stress measurements and geodetic strain data have constrained the model. In order to compare the modelled deformation with the observed geodetic strain, inferred from GPS and VLBI data, and to interpret correctly the modelled stress pattern, the analysis has been completed with the modelling of the Glacial Isostatic Adjustment (GIA) due to deglaciation in Fennoscandia. The region under study is in fact peripheral with respect to the major uplifting area centred in the Gulf of Bothnia, where crustal deformation rates (both horizontal and vertical components) at the millimetre per year level are expected, thus comparable with those due to tectonics. The GIA models are based on an analytical approach that accounts for the visco-elastic behaviour of a stratified Earth.

LS05 : SUpm28 : F2
Salt Redistribution during Extension and Inversion Inferred from Observations and Modelling

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We investigate the role of salt as a decoupling horizon between its basement and its cover during the Mesozoic deformation processes by integration of 3D structural modelling, backstripping and seismic interpretation in the North-East German Basin (NEGB). Our results indicate, that temporal and spatial variations of salt movements are related to changes in regional stress field.

A major indication for thin-skinned deformation is the fact that the salt basement is not faulted in the basin area but only at the north-eastern and southern basin margins. In contrast, the salt cover is folded and faulted. The onset of salt diapirism is observed as synchronous with regional extension during Late Triassic and affected mainly the southern part of the basin till Late Cretaceous times. During Late Cretaceous, diapirism was associated with compressive deformation and progressed farther north and west. WNW-trending salt structures are associated with WNW striking inversion structures. Late Cretaceous-Early Cenozoic compressive deformation caused partial inversion of older rim synclines and reverse reactivation of some Late Triassic to Jurassic normal faults in the salt cover. An erosional event took place during Late Cretaceous-Early Tertiary compression affecting the pre-Cenozoic layers in the entire basin. Regional subsidence in the Cenozoic was also accompanied by salt tectonic deformation but Cenozoic salt structures have a larger wavelength and are overstepping older structures.

Results from a 3D backstripping approach considering salt flow as a consequence of spatially and temporally changing overburden load distribution, isostatic rebound and sedimentary compaction suggest that salt motion partially balanced Late Cretaceous-Early Tertiary compression as well as Late Triassic extension. Within this approach, salt is considered to behave like a viscous fluid and it is assumed that it is always almost in hydrostatic equilibrium with the overburden. We stripped back all cover layers down to top of salt. After salt redistribution according to the change in load, isostatic compensation and decompaction we got the hydrostatically equilibrated salt distribution at the end of each backstripping step. Major observations from backstripping are: (1) Lateral salt flow can partially explain the observed structural setting in the basin; (2) Salt diapirism was weakest in the area of highest initial salt thickness and thickest overburden. (3) Initially, there was more salt present in the basin centre than today.

LS05 : SUpm29 : F2
Post Mortem Simulation Study of Hydrocarbon Generation and Migration on the Inverted South-Western Rim of the North German Basin- A 2D Basin Modelling Study

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The Northwest German Basin belongs to well developed basins in Europe with ca.75,000 exploration and production wells (dating back to 1874) and with ca.750,000 km to 1 Million km of seismic lines.

The focus of the research was to perform a post mortem simulation study of the mature Palaeozoic and Mesozoic Petroleum Systems in the Emsland region and to verify the outcome against established concepts utilising 2D forward basin modelling software, PetroMod. The underlying conceptual model used in the simulation study was constrained by the extensive data base comprised of tectonic reconstructions, organic and isotope geochemistry, geothermics as well as sedimentological and petrophysical studies.

The Coniacian-Santonian inversion plays a particular part in the study as it has an impact on the present status quo in the Apeldorn Gas and Bramberge Oil Fields. With the associated basic to intermediate intrusion of the Bramsche-Vlotho Massif in the Lower Saxony Basin at ca. 89 Ma ago, particular attention is drawn to its offshoot in the study area. It is the anomalous amount of ca. 75% of gaseous nitrogen at Apeldorn in the Middle Triassic reservoir, that leads us to think of an additional involvement of inorganic nitrogen, i.e. sourced most likely from the lower crust-upper mantle region during the structural reconfiguration from the Coniacian to Santonian period. A further aspect regards the abnormal signature of carbon isotopes of oil associated gases within the Valanginian oil reservoir in the Bramberge field. Based on the simulation results it can be inferred that prior to the Coniacian-Santonian inversion, Wealden oil mixed not only with gas formed by secondary cracking and sourced from Posidonia Shale, but at the same time also with oil supplied directly from Posidonia Shale source rock itself. The structural complexity of the geological framework along the studied section might explain the temporal as well as lateral differences in the timing of mixing, influencing the mode and behaviour of three phase fluid flow in the area.

Another critical aspect of the Coniacian-Santonian inversion relates to the “turn on” and “turn off” of the HC generation in the source rocks of the Posidonia Shale and the Wealden. With respect to both Mesozoic source rocks, the inversion-related uplift together with the Bramberge intrusion accounted for considerable thermal changes leading to disturbances in HC generation, migration and desorption potential between 89 Ma and 84 Ma ago. It was subsequently followed by a second stage of HC generation in the Mesozoic Petroleum System during the Tertiary regional subsidence. As a result, a range of sensitivity studies has been applied to the established model in order to firstly, asses error margins for a variety of defined parameters and secondly, to identify the limitations of the numerical modelling.

LS05 : SUpm30 : F2
The Tectonic Evolution of the Southern Dutch North Sea during the Paleogene

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We present a quantitative Paleogene subsidence analysis study of the southern Dutch North Sea. Basic data for the subsidence analysis are newly constructed depth and thickness maps, based on two high-resolution 2D-seismic surveys constrained by well logs.

The compiled thickness maps clearly show the complex structural development of the area with strong temporal and spatial variations in the evolution of accommodation space and erosion. The Paleogene sedimentary succession covers different Mesozoic basin structures including the Broad Fourteens Basin, which developed in response to multiple rifting events, of which the most important was the Late Jurassic-Early Cretaceous extension phase. During the Late Cretaceous the basins were inverted, mainly as a result of Subhercynean compression tectonics (van Wijhe, 1987b). The resulting differential compaction trends of the Mesozoic sediments underlying the Paleogene succession had potentially a large influence on the evolution of Paleogene accommodation space. Furthermore, the Mesozoic structural grain had a strong influence on tectonically induced Paleogene subsidence and uplift patterns. During the Paleogene, inversion continued in several pulses. Two uplift phases associated with the Paleocene Laramide and the Late Eocene to Early Oligocene Pyrenean orogenic phases (Letsch & Sissingh, 1983; van Wijhe, 1987a; 1987b) have resulted in regional uplift and erosion of large quantities of sediment. After the Pyrenean phase, increased local subsidence occurred in the centre of the uplifted area. A relative sea level lowstand associated with the Savian phase terminated deposition and resulted in erosion once again. Neogene sediments disconformably overlie the Paleogene section.

Backstrip analysis and forward modelling of basin subsidence allows a quantitative assessment of the tectonic evolution of the area. It provides valuable information about the timing and magnitude of Late Eocene uplift and erosion. It also allows differentiating between different factors contributing to subsidence and uplift of the area.

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van Wijhe DH, *in: Petroleum Geology of North West Europe (Publ. : Graham & Trotman)*, 315-323, (1987a).
van Wijhe DH, *Tectonophysics*, **137**, 171-219, (1987b).

LS05 : SUpm31 : F2
Mid-Paleocene Evolution of the Eastern North Sea Basin: Does Quantitative Basin Modelling Improve Geological Models?

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The eastern part of the North Sea Basin is underlain by a number of Mesozoic structures such as the Central and Horn Grabens, which dissect the E-W striking Ringkøbing-Fyn High (RFH); and the NW-SE striking Sorgenfrei-Tornquist Zone (STZ), which separates the North Sea Basin from the Fennoscandian Shield. Upper Cretaceous and Danian deposits in the North Sea Basin consist mainly of chalk, calcarenite and bryozoan limestone. The various limestone facies recognizable in wells, outcrops and in high-resolution seismic data allow for an assessment of depositional water depths during the Danian. The Lower Selandian North Sea Marl (and its equivalents) that overlies the Danian deposits covers large parts of the North Sea Basin. In the easternmost parts of the basin the coeval Lellinge Greensand, consisting of eroded chalk and glauconite, has been found. Thickness and facies changes of the marl and greensand (and sub units identified on well logs) allow for an assessment of depositional water depths during the early Selandian. The thickness and facies distribution of the limestones, marls and greensands show that the mid-Paleocene development of the eastern North Sea basin was dominated by inversion of the STZ and the Central Graben and by relatively shallow water depths at the RFH. The inversion of the STZ and the long-term sea level lowering of ~200 m during the Cenozoic interacted to remove all Cenozoic sediments from the area around the STZ, thus leaving the evolution of this area open to interpretation. The geological observations were used to verify the output of a three-dimensional numerical model. The model incorporates deviatoric stresses, vertical and lateral variations in lithospheric rheology and temperatures, surface processes and eustasy. The observed Paleocene sediment thicknesses and paleo-geographies are modelled as a consequence of a compressive stress field, a weak zone in the STZ and the lateral variations in lithospheric strength due to variations in Moho depth. The modelling results indicate that inversion of the STZ was associated with development of troughs on both sides of the inversion zone, thus possibly trapping any supply of coarse sediments towards the Danish area. Correlation between modelling results and geological observations, where these are available, indicates that basin modelling provides accurate quantitative information on basin development, also of areas where stratigraphic data are presently absent due to erosion.

LS05 : SUpm34 : F2
Inversion Tectonics in Central Alborz Range; Evidences from Geometry and Kinematics of Thrust Sheets

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Geometry and kinematics analysis of thrust sheets in fold-thrust system provides key understanding to unravel structural evolution of external parts of orogeny (Mitra & Fischer 1992). Alborz mountain Range, situated in central portion of Alpine-Himalayan System, forms a composite polly orogenic belt and suffered shortening from late Triassic (Cimmerian event) up to Oligo-Miocene (Late Alpide event) (Alavi 1994). Almost all the shortening in the belt were governed by reverse movement towards both north and south and along major thrust. In central Alborz, these differences in movement direction of the sheets caused the heights region and harsh topography in the belt. Structural investigation and analysis of thrust sheets demonstrates that in southern parts of the range, they are thin and their spacing varies and is up to few kilometers, and all moving towards south. Geometry of thrust sheets based on balanced sections is quite similar to geometry of leading imbricate fans (McClay 1992). Within the sheets small imbricate which form rejoining and diverging imbricate are also seen. In northern parts, however, thrust sheets are thicker and are also more spaced. Their movement directions are almost all to north. In central parts, evidences of thrust sheets with movement directions both to south and north were accommodated. Along one of these major thrusts which show characteristics of basin-bounding faults, Eocene volcano-sedimentary rocks of Karaj Formation are exposed only to south. Evidences of back-thrusts on the hangingwall of the thrust were seen. These backthrusts rejoin main thrust and cause thrusting of older Permian rocks in a pop-up structure fashion on top of Jurassic and Eocene rocks to north and south respectively. The amount of reactivation along these basin-bound faults is less than the amount of thrusting on back thrusts. This characteristic which is common on inverted basins (Coney et al. 1996) demonstrate that these backthrusts were developed during contractional phase in an inversion tectonic regime. It seems that major thrust faults in central part of the range which act as basin-bounding faults of Paleozoic-Mesozoic basin to south were deformed and inverted, possibly in late Cimmerian event, along major dip-slip normal faults. Such inversion provides major pop-up structures in central parts where evidence of late Cambrian rocks were deposited. Further imbrication of the faults, more likely in late Alpide event, and as footwall short-cut thrusts caused development of imbricate thrust sheets in southern parts. This event can also be consider being responsible for further deformation of central pop-up structure by development of Nemours steeper dip backthrusts to north. These regional assessment of inversion tectonics in central Alborz that have been placed here and based on geometry and kinematics of thrust sheets are of course, preliminary and much more works need to be done.

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LS05 : SUpm35 : F2
Inversion Related Features along the Southern Margin of the Northeast German Basin

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The North German Basin is bounded to the SW by the Elbe-Fault-System (EFS), which is believed to be a basement controlled weakness zone. It is suspected that the EFS has been active/reactivated several times since the Upper Carboniferous/Lower Permian. During the Late Cretaceous/Early Tertiary Alpine compressional event the EFS was an area where deformation localized. Based on results from a prelimanary 3D structural model of the southern margin of the Northeast German Basin, we show the Flechtingen High (FH) - as a part of the EFS - to be the main area affected by inversion. A first-order quantification of the amounts of erosion is provided by comparing the strata thickness on top of the FH with the surrounding basinal areas as deduced from seismic sections and from well data. Assuming the entire Triassic-Jurassic succession to have been deposited on the FH, we estimate that the uplift led to the erosion of sediments in a range of 1500 m to 3000 m. Whereas beneath the FH the basement was uplifted, to the N of it the compression is expressed by folding of the Mesozoic strata over the Late Paleozoic Zechstein salt layer, which acted as decollement. Folds generally display NE vergence indicating therewith compression from the SW.

From the end of the Early Tertiary onward, wide spread subsidence is observed throughout the North German Basin. Also the FH is truncated by the base Cenozoic unconformity. Taking this strongly differing deformation style as well as the still maintained compressional state into account, it is hypothesized that the NE part of the EFS has acted as a hinge zone between a flexural basin in the NE and a flexural bulge in the SW.

By integrating well data in the seismostragraphic interpretation of the seismic sections, we further attempt to date the timing of both the inversion and the following subsidence phase.

LS05
The Dynamics of Basin Inversion

LS05 : SUpm36 : F2
A Major Stage of Convergence in the Issyk-Kul Basin (Northern Tien-Shan) at the end of the Neogene

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The structural features the northern Tien-Shan mountain belt in Kyrgyzstan, including the Issyk-Kul basin, indicate a complex Cenozoic deformation, associated to the Indian-Eurasian collision. The collision caused deformation to propagate inside the continent, resulting in crustal thickening and mountain growth. The present-day shortening occurs at a rate of about 10-15 mm/yr and is oriented roughly N-S in the southern Tien-Shan and up to 2-6 mm/yr and variably oriented in the northern Tien-Shan. Different rate values and orientation could be related to the presence of a Precambrian microcontinent in the northern Tien-Shan. That microcontinent could affect the formation of the Neogene-Quaternary structure of the Issyk-Kul basin.

In the Paleogene, more then 3 km of lacustrine sediments was deposited in the subsiding basin. The onset of uplift of the southern Tien-Shan started in the Neogene, when clastic and proluvial sediments, transported from the rising southern ranges were deposited in the basin. In this stage, the basin was much larger and more elongated than at present. It was probably controlled by ENE trending faults.

Starting in the late Neogene, clastic material was deposited in a moderately subsiding basin. This indicates the onset of uplift in the Northern Tien-Shan, reaching a peak at the end of the Pliocene-early Pleistocene. In this period, strong N-S oriented contractions caused rigorous deformations inside the Issyk-Kul Cenozoic deposits. The southern and northern edges of the basin were intensely deformed. They are presently exposed and exhibit two major trends of tectonic lineaments, that correspond to transpressive zones, oriented ENE and NW. Pop-up and transpressive flower structures indicate oblique convergence in these zones. Ramp structures developed at the latitudinal edges of the basin and the thrusting of the basement over the basin is accompanied by late Neogene molasse deposition. E-W striking faults controlled the late Neogene structure of the basin.

The deformed Neogene sediments are often unconformably overlain by undeformed Quaternary terraces. The Quaternary tectonics in the uplifted parts of the basin is expressed by reverse reactivation of preexisting faults. The border faults shifted toward the internal parts of the basin which was further narrowing in north-south direction, and the borders of the basin were further uplifted. Within the lake, active deformation has been recorded in its southern part, expressed by upright folding with NE trending axis.

A major stage of convergence is consequently evidenced, dating from the end of the Neogene, mainly expressed by transpressive movements along a conjugate set of strike-slip zones. This stage of strong deformation is contrasting with the Quaternary tectonic stage of moderate basin inversion. We investigate the relations between the tectonic history of the Himalaya and of the Tibet plateau, and the deformation stages observed for the Issyk-Kul basin.

LS05 : SUpm37 : F2
Lower Lithosphere Reflectors and Inhomogeneities of the Lithospheric Structure beneath the Central and Northern Europe

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Over last two decades big international seismic experiments were made in the central and northern Europe to investigate lithospheric structure, particularly beneath the Precambrian East European Craton (EEC) and the Trans-European Suture Zone (TESZ). The new results from the POLONAISE'97 will be presented. The thickness of the crust changes in this area from about 30 km under the Palaeozoic Platform to about 40-50 under the EEC. The TESZ is associated with a crustal root of about 50 km thickness, and the velocity of the sub-Moho uppermost mantle is high (8.2-8.3 km/s). Besides very good intracrustal and Moho phases, correlated phases from the lower lithosphere, beneath the Moho were recorded. Within the Palaeozoic Platform strong arrivals just after Pn phases were interpreted as reflections from the upper mantle at a depth of 43 km. In the EEC phase behind the Pn wave is interpreted as a week reflection from a low-contrast (about 0.1 km/s) discontinuity at depth 56 km. Another lower lithosphere reflector was found within EEC beneath profile P5. To explain its amplitude, it is necessary to assume a contrast of P-wave velocity of about 0.5 km/s, however are not able to distinguish between "negative" and "positive" velocity contrast. Strong reflections from the lower lithosphere were correlated in TESZ, and interpreted as reflectors in the depth range 60-90 km.

Results from the POLONAISE'97 will be discussed with results from surrounding profiles FENNOLORA, Baltic Sea - Black Sea, EUGENO-S, EUROBRIDGE, Baltic Sea, Sylen - Porvoo. Good quality seismic records obtained up to about 600 - 1000 km from the shot points permit to investigate structure up to about 100 km depth. The models of the lower lithosphere differ in the character of velocity distribution, the number of layers, and the presence of the low velocity layers. This is the consequence of inhomogeneity of the lower lithosphere, but also follows from the differing accuracy and quality of data.

LS05 : SUpm38 : F2
CELEBRATION 2000: An International Seismic Experiment Crossing the Main Geoelogical Units in Central Europe

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A large consortium of institutions (28 in all) from Europe and North America has just completed a huge active source seismic experiment focused on Central Europe. This experiment is called CELEBRATION 2000 (Central Eurpean Lithospheric Experiment Based on Refraction 2000), and it targeted the structure and evolution of the complex collage of major tectonic features in the TESZ region, as well as, the southwestern portion of the East European Craton, the Carpathian Mts., the Pannonian basin, and the Bohemian Massif. The primary scientific goals of CELEBRATION 2000 are: 1) investigate the deep structure of southwestern Baltica and its relationships to younger terranes, 2) delineate the major terranes and crustal blocks in the TESZ region (e.g., Bohemian Massif, Upper Silesian Massif, and blocks exposed in the Holy Cross Mountains), 3) investigate the origin and structural framework of the Pannonian basin and its subbasins, 4) investigate the nature and extent of thrust faulting along the northern front of the Carpathian Mountains, 5) construct a 3-D model of the lithospheric structure in the study area, 6) evaluate and develop geodynamic models for the tectonic evolution of the region. The layout of the experiment was a network of interloking profiles whose total length was about 9000 km. The total number was 1200 seismic stations and 147 shot points located along seismic lines in Poland, Hungary, the Slovak Republic, The Czech Republic, Austria, Germany as well as in Russia and Belarus. First results are present.

CELEBRATION 2000 Working Group: K.C. Miller, S. Harder (USA); A. Hegedus (Hungary); P. Hrubcova (Czech Republic); K. Aric, F. Kohlbeck (Austria); I. Asudeh, R. Clowes (Canada); P. Joergensen (Denmark); S. L. Kostiuchenko (Russia); G. Jentzsch, D. Kracke (Germany); J. Yliniemi, T. Tiira (Finland); A. A. Belinsky (Belarus).

Sunday PO Session

LS05 : SUpo01 : PO
The Inverted Donbas Basin (Ukraine)– First Results from *DOBREflection* in 2000

DOBREflection* Working Group

The Donbas Foldbelt (DF), in the south-eastern part of the Dniepr-Donets Basin (Ukraine and southern Russia), displays exceptional characteristics for the study of processes involved in the destabilisation of cratonic interiors. This includes the evolution (destruction/replacement or deformation) of the Moho as well as other lower crustal/upper mantle processes that occurr during rifting and rift reactivation and basin uplift and inversion. The DF is also a key feature related to the deep structure and tectonic history of the southern margin of the East European Craton, and its juncture with accreted terranes to the south, and its evolutionary connection to middle Europe. *DOBREflection* comprises 133 km of deep seismic reflection data recorded during the summer of 2000 coincident with the previously acquired refraction/wide-angle reflection seismic profile *DOBREfraction'99*, from the Ukrainian Shield (UkS) in the south towards the Voronezh Massif in the north. Both seismic surveys were done in the framework of the Ukrainian National Programme on regional investigations in sedimentary basins and the European Science Foundation EUROPROBE programme. Participating institutions in *DOBREflection* are: Ukrgeofisika, Kyiv, Institute of Geophysics (National Academy of Sciences of Ukraine), Kyiv, Ukraine; GeoForschungsZentrum, Potsdam, University of Hamburg, University of Kiel, Germany; Vrije Universiteit, Amsterdam, Utrecht University, Netherlands; and the University of Copenhagen, Denmark.

DOBREflection provides detailed resolution of both basin infill and deep crustal structures. The base of Devonian to Carboniferous sediments is well resolved from the UkS to the axial part of the DF, where the thickness of sediments reaches some 20-km. The top of basement dips 15 degrees from the UkS beneath the basin, disrupted by faults with offsets up to 2 km. Inversion is mainly displayed as folding within the Carboniferous succession while the Devonian sediments appear not to have been affected. This pattern is perhaps related to the decoupling effect of Upper Devonian salt-rich sediments. From the preliminary interpretation of the near vertical reflection data, the thickness of the crust decreases continuously from ~44-km beneath the UkS to only some 11-km beneath the basin centre.

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LS05 : SUpo02 : PO
Dynamic Modelling of Faults in Geological Environments

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The presence of faults and shear zones influence the rheology of geomaterials and geological systems in general. The fact that deformation often is controlled by pre-existing faults, as in the case of basin inversion, motivate the use of history dependent rheologies in dynamic thermo-mechanical models.

Presented are results from a newly developed finite element code. The code is build on finite strain continuum mechanics incorporating visco-elastic-plastic rheologies and thermo-mechanical coupling in a fully Lagrangian formulation. Shear zones are formed using non-associated plasticity models including dependence of strain history through strain softening/hardening and pressure sensitive yield criteria. The theoretical foundation is discussed.

The presented applications range from modelling of small scale sedimentary structures to large scale lithospheric shear zones. Situations in extension, compression and tectonic reactivation are considered.

LS05 : SUpo03 : PO
The Folded Antiatlas of Morocco- An Inverted Paleozoic Basin rather than a Foreland Fold-Thrust Belt?

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In southwestern Morocco, a late Proterozoic - early Carboniferous passive margin series of up to 10 km thickness is involved in Variscan continent-continent collision between Africa and N-America. In contrast to the well developed foreland fold-thrust-belts seen on the American side of the Appalachians, the African side of this orogen in the Antiatlas shows no obvious signs of any thin skinned basal décollement, minor thrust faults, imbrications or duplexing. Shortening is entirely accomodated by intense polyharmonic buckle folding of the sedimentary cover. Amplitudes and wavelengths of folds are directly controlled by the thickness of a few competent marker beds. They decrease systematically from the bottom (Cambrian carbonates, Ordovician Sandstones Bani) to the top (Devonian "Rich" and Carboniferous limestone-sandstone series). Structural observations and balanced cross sections indicate a total shortening on the order of 15 to 25% regardless of stratigraphic horizon. A similar amount of shortening in the pre-Cambrian (pre-PIII) basement could be responsible for the formation of even larger scale inlyers the so called "plis de fond" of Argand (1924). We interpret these "basement folds" as strongly inverted former graben and/or half-graben floors. This interpretation is compatible with structural observations, subsidence - curves derived from the Palozoic sedimentary pile, the degree of incipient metamorphism and the large scale map pattern of basement inlyers. Erosion has removed up to 15 km of sediments from above the present day basement inlyers. Horizontal distance between the most external (SE) basement culminations and the Variscan deformation front in the Jbel Ouarkziz toward the Tindouf basin further SE varies between 40 and 70 km. Despite some uncertainties in the present day Moho depth, and associated freedom in crustal scale balanced cross section construction, all these numbers add up to a very steep taper angle for the SE front of the Appalachian - Antiatlas orogen in the middle to late Carboniferous times.

key words : Antiatlas of Morocco, Variscan Orogeny, Basin inversion, Fold-and-Thrust-Belt, Folding, Thin skinned vs. Thick skinned Tectonics, Paleozoic Basin evolution, Tindouf basin - Antiatlas basin.

Argand, E, *La Tectonique de l'Asie, 13th Int. Geol. Congress conf. proceedings, Brussels*, 171p, (1924).

LS05 : SUpo04 : PO
Heterogeneous Tectonic Inversion of the Mid-Polish Basin Related to Crustal Architecture, Sedimentary Patterns and Structural Inheritance

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The Mid-Polish Swell (MPS) is an inverted Permo-Mesozoic basin trending NW-SE from the Baltic Sea to southeastern Poland. The swell is located at the boundary between the East and the West European Platforms. Up to 6-7 km of Rotliegend (Lower Permian) to Maastrichtian (Upper Cretaceous) sediments accumulated in the axial zone of the basin and were partially eroded after tectonic inversion. Tectonic inversion took place during the Maastrichtian-Palaeocene interval and was the result of NE-SW intra-continental compression, perpendicular to the basin elongation, leading to the formation of the MPS. To analyse the vertical displacements due to the tectonic inversion, we constructed a 3D structural model of the MPS based on tectonic and thickness maps of Poland. A comparison of the subsidence and inversion rates revealed that the axial part of the basin was squeezed upward during inversion while the marginal parts were almost not uplifted. Thus, the uplifted area is narrower than the former basin and the most uplifted areas correspond to the zones of strongest subsidence prior to inversion. The swell appears segmented into a NW part and SE part, separated by a transversal boundary. The two parts are characterized by different tectonic, sedimentary and geophysical properties. The NW part, was less uplifted during the tectonic inversion, it was the area of Zechstein salt (Upper Permian) deposition and the Moho depth attain 35-39 km. The SE part, show a tectonic uplift of some km, Zechstein salt was not sedimented there, the Moho is deeper with a high velocity layer at the bottom of the crust. The inversion related displacement in the SE part of the basin was large enough that the Palaeozoic basement crops out. We observed that no décollement developped between the Palaeozoic basement and the Permo-Triassic sediments during inversion. In contrast, in the NW part of the basin the basement-cover relationships are less clear due to the presence of Zechstein salt, which probably acted as a décollement during the inversion. The localization of the deformation through time along the narrow NW-SE striking zone can be linked with the crustal structure of this area. The Mid-Polish Basin was located above an important crustal boundary: the Teisseyre-Tornquist Zone (TTZ). Seismic refraction data revealed differencies in crustal properties showing very deep-seated roots of the TTZ expressed as variable Moho depth and change in shear wave velocity structure of the Mantle. The NE-SW transversal boundary deduced from the basin characteristics is also present in the Moho structure. To investigate the present day state of the crust, we compared isostatic crustal models based on the 3D structural model with the geophysical data.

LS05 : SUpo05 : PO
Structural Development of the Inverted Northeast German Basin

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The Northeast German Basin (NEGB) is one of a series of related intracontinental basins extending from the North Sea to Poland. Basin formation began following Permo-Carboniferous magmatic activity with a period of thermal subsidence extending from Early Permian to Triassic times. The long-term subsidence was interrupted by two phases of inversion-related deformation and uplift in Late Jurassic and Late Cretaceous times. Extensive salt migration occurred within the basin masking regional geological processes and thus, complicated the quantitative evaluation of subsidence rates after salt mobilisation, the magnitude of shortening during inversion and the amount of associated uplift and erosion. Interpretation of the seismic reflection profile DEKORP 9601 together with unpublished industrial data has facilitated the structural analysis of the sedimentary succession in the NEGB. The data were used to compile a basinwide geological profile across the entire NEGB. Stepwise restoration of this profile allowed the evolution of the basin geometry during Mesozoic basin inversions to be studied. Furthermore the role of structural key elements and the development of structures at different stratigraphic levels could be evaluated in a more quantitative manner.

The study reveals that two distinct periods of inversion can be distinguished in the NEGB. A first phase of inversion occurred in the Late Jurassic to Early Cretaceous when a basinwide growth of salt-cored anticlines is observed. The magnitude of accompanied uplift and erosion rises towards the south where it may be more than 1 km. These facts, together with the absence of major faults below most salt structures, suggests a compressional component in formation of these structures with less than 1 km of shortening being required to produce this structural pattern. A second inversion period took place in the Late Cretaceous. Upthrusting of 3.5 km along the intrabasinal Gardelegen Fault exerted a north-directed compression on the post-Zechstein sequence. As a result, the suprasalt sediments were shortened by about 10 km and this was accompanied by strong uplift and thrusting near the fault. During shortening the Zechstein evaporites acted as a detachment horizon and facilitated the transmission of the deformation across the entire NEGB up to 200 km distant from the zone of crustal shortening. While Alpine tectonics is thought to be responsible for the Late Cretaceous inversion, the Late Jurassic deformation is interpreted as a local intra-plate transpressional phenomenon.

LS05 : SUpo06 : PO

Bangasil Anticlinorium and NW-SE Trends within the Hinge Zone Near Ogcheon-Up, South Korea

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The NE-SW-trending Bangasil Anticlinorium exists in the southern part of the Ogcheon Supergroup between Ogcheon and Taejeon, southern Korea. The hinge of this folding is preserved in pebble-bearing phyllites, namely Hwanggangri Formation. The pebbles are variable in size, lithology, roundness and shape from place to place, mainly consisting of granite, quartzite, limestone, gneiss, slate. The matrix is generally calcareous and made up of quartz, calcite, graphite, muscovite and biotite. Limestone and slate clasts are stretched and flattened, and reveal a strong preference in orientation. In microscopic scale, the matrix consists of quartz, biotite, muscovite, iron oxides and calcite. Some of these pebbles have pressure shadows, symmetric or asymmetric, or sometimes complex, along a schistosity. In this particular pebble-bearing phyllites preserve a planar structure having a NW-SE strike and NE-ward dip, defined by flatten or stretched pebbles, contrasting to the feature from the typical Ogcheon Orogen style structures where general trend is approximately NE-SW only. These pebbles, or planar structure, are crenulated around differentiated cleavages steeply dipping towards NW. These pebbles appear to be flattened by some other deformations before the NE-SW crenulation cleavage event. Two mechanisms can interpret the origin of these particular structural features. Firstly, a progressive noncoaxial shortening through NW-SE produced the regional NE-SW trend and partly, but progressively rotated it into the NW-SE trend around the hinge area. The very portion of the fold were then likely to be exposed to be overprinted by younger NE-SW-striking foliation would develope at the late stage of the same deformation event..Alternatively, these NW-SE-trending fabrics in the hinge part can be interpreted to be preserved from the intense strain, and/or rotation, that the later NW-SE shortening provided, keeping the NW-SE trend. Indeed, this study has found a critical evidence for the latter. That is, the hinge area of the Bangasil Anticlinorium preserves the partitioning of lower strain occurred during the regional NW-SE shortening. This is consistent with recent studies that provide evidence of NW-SE-trending structures along the Ogcheon Orogen and, furthermore, this NE-SW shortening may be related to the North and South China Block Collision.

LS05 : SUpo07 : PO

Models of Intra-Plate Compressional Structures of the Pechora Basin

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The Pechora Basin is characterized by a great variety of compressional platform structures. Their formation is closely associated with the collision processes in the Urals. The morphology of these structures is controlled by the distance from the source of deformation as well as by the structure and dislocation types of the preceding stages of development.

The collision processes started in the eastern part of the Pechora Basin in the Early Carboniferous. They were caused by the collision of the Tagil island arc with the Euroamerican continent. Tangential stresses spread all over the area of the Pechora basin. In the areas with extension structures (Pechora-Kolva Aulokogen, Michayu-Pashnya paleorift and others) the compression led to the formation of inversion swells. Within the Khoreyver and Izhma depressions compressional structures were confined to the re-activated basement faults. Within the Varandey-Adzva zone many of the swell-like structures were formed under the conditions of transpression. Within the eastern part of the Pechora Basin (pre-Urals foredeep) compressinal structures were confined to detachment faults.