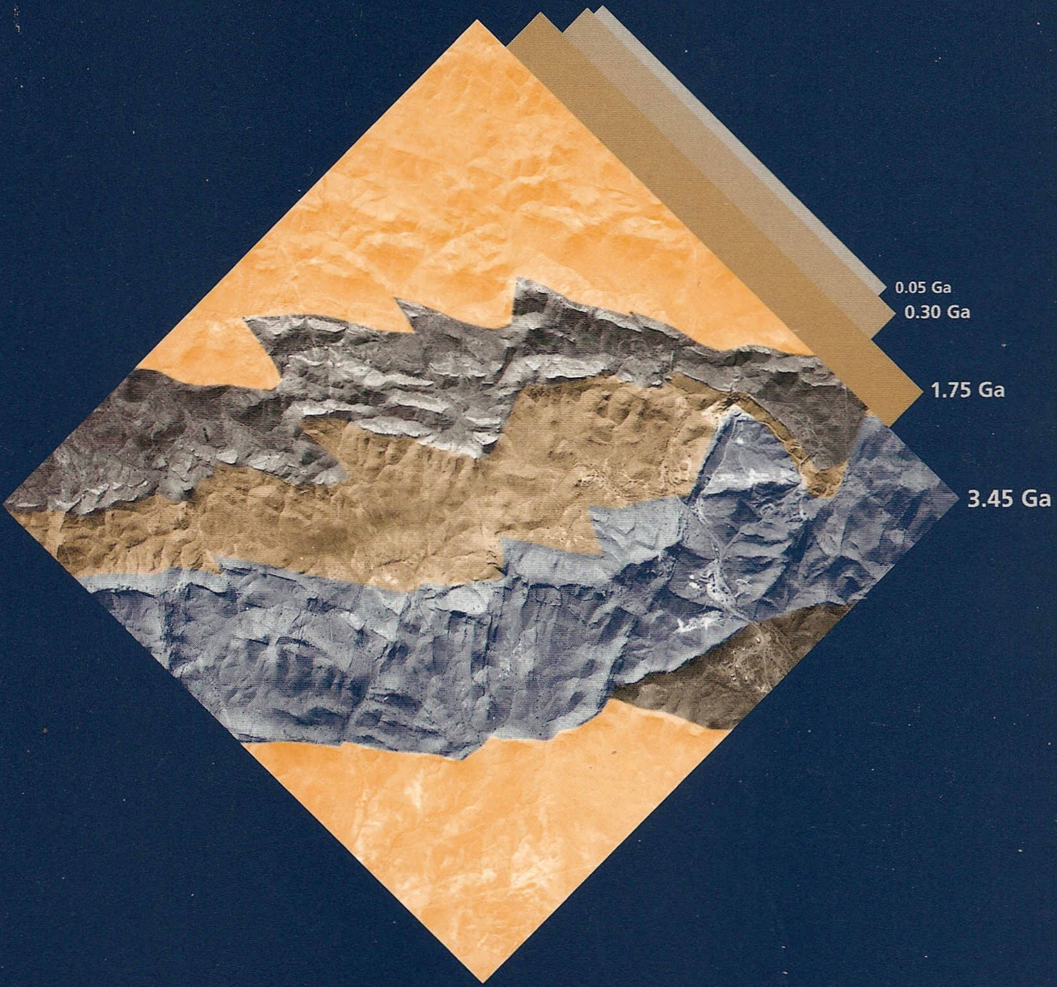
GEOLOGICA ULTRAIECTINA

Mededelingen van de Faculteit Aardwetenschappen
Universiteit Utrecht
No. 173

Growth Structures

Examples of integrated sedimentological and structural-geological basin analysis



W. Nijman

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GROWTH STRUCTURES

EXAMPLES OF INTEGRATED SEDIMENTOLOGICAL AND STRUCTURAL-GEOLOGICAL BASIN ANALYSIS

Wouter Nijman

Cover illustration / Illustratie op omslag

Aerial view of 3500 million year-old North Pole Chert, Early Archaean of the East Pilbara, West Australia, showing listric growth-fault pattern. The panels suggest the position in time in billions of years (Ga) before present of the geologic examples discussed in the thesis.

Vanuit de lucht gezien, vertoont de 3500 miljoen jaar-oude North Pole Chert (=kiezelafzetting) in de Pilbara, West-Australië, een goed bewaard groeibreuken-patroon. De panelen suggereren de positie op een tijdas in miljarden jaren (Ga) vanaf heden van de geologische voorbeelden, beschreven in het proefschrift.

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GROWTH STRUCTURES

EXAMPLES OF INTEGRATED SEDIMENTOLOGICAL AND STRUCTURAL-GEOLOGICAL BASIN ANALYSIS

GROEISTRUCTUREN

VOORBEELDEN VAN GEINTEGREERD SEDIMENTOLOGISCHE EN STRUCTUREEL GEOLOGISCHE BEKKENANALYSE.

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit Utrecht
op gezag van de Rector Magnificus, Prof. Dr. H. O. Voorma,
ingevolge het besluit van het College voor Promoties
in het openbaar te verdedigen
op maandag 17 mei 1999 's middags om 4.15 uur.

door

Wouter Nijman

geboren op 14 september 1939
te Rotterdam

1999

Promotoren: **Prof. Dr. P. L. de Boer**
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Contents

Voorwoord en samenvatting

Het onderzoek, waarop mijn proefschrift is gebaseerd, beweegt zich op het grensvlak van twee geologische disciplines, de sedimentologie, de leer van afzettings-gesteenten (zandsteen, klei, kalk, etc.) en de structurele geologie met als onderwerp de vervorming of deformatie van gesteenten. Sedimentaire processen worden beïnvloed door kosmische en klimatologische processen, zeespiegel-bewegingen en deformatie van de aardkorst. Voor de vorming van sedimenten zijn nodig opheffing en verwering in een brongebied, en daling en afzetting in een bekken, dus verticale bewegingen. Deformatie-processen werken daarentegen vaak parallel aan het aardoppervlak (rek, compressie, zijschuiving), dus horizontaal. Om de invloed van de deformatie op de sedimentatie te kunnen begrijpen, moeten de deformatieprocessen worden vertaald naar verticaal gerichte bewegingen van de aardkorst.

"Groeistructuren" ("growth structures") zijn deformaties, die tijdens sedimentatie in afzettingsgebieden actief zijn. Zij verraden hun activiteit door de vorming van onregelmatigheden, zoals plooien en diktewisselingen, in de gelaagde bekkenvulling. Het zijn daarom de éérste vervormingen van sedimenten, meestal gevolgd door verscheidene latere deformaties. Die moeten de één na de ander worden gereconstrueerd en glad gestreken om de groeistructuren zichtbaar te maken en te begrijpen.

Sedimenten bevatten vaak een nagenoeg continu verslag van de invloed van het deformatieproces. Ze kunnen ook worden gedateerd ten opzichte van elkaar (relatief, met behulp van fossielen), en in jaren (absoluut, m.b.v. van het radioactief verval van elementen in mineralen). Dat maakt het mogelijk de variatie in snelheid, richting en intensiteit van de deformatie in de tijd te bestuderen, iets dat lang niet altijd mogelijk is door directe structureel geologische analyse.

De studie van groeistructuren houdt dus in het ontrafelen van zowel het mechanisme van afzetting als van de vervorming van sedimenten. Dit soort onderzoek wordt meestal verricht in delen, door afzonderlijke onderzoekers met diverse doelstellingen, op uiteenlopende tijdstippen en op verschillende schaal. Het achteraf bijeenbrengen van dergelijke gegevens draagt alle risico's in zich van extra interpretatiefouten.

Het proefschrift benadrukt het voordeel van een geïntegreerde benadering vanaf het begin van het onderzoek. Het gedrukte deel vergelijkt een aantal relaties tussen sedimentatie en deformatie aan de hand van voorbeelden, grotendeels ontleend aan eigen onderzoek, uitgevoerd samen met collega's en vele doctoraal-studenten. De voorbeelden hebben betrekking op een aantal gebieden van geheel verschillende ouderdom: het Vroeg-Archaïcum (± 3450 miljoen jaar geleden) van NW-Australië (Pilbara) en van Zuid-Afrika (Barberton Mountains), het Proterozoïcum (± 1750 milj. jr.) van het Mount Isa-gebied in Queensland (NO-Australië), het Carboon (± 300 milj. jr.) van het Cantabrisch gebergte in NW-Spanje, en het Eoceen (± 50 milj. jr.) van de zuidelijke Pyreneeën in NO-Spanje. In de periode 1989-1998 is dit onderzoek gepubliceerd en een vijftal artikelen daarvan maken, op CD, deel uit van het proefschrift.

Aangetoond wordt, dat gelijktijdig sedimentologisch en structureel geologisch onderzoek aan hetzelfde geologische systeem in alle genoemde voorbeelden heeft geleid tot nieuwe inzichten. Die betreffen dan de beginfase van de deformatie in sedimentaire bekkens, gelegen in mobiele zones van de aardkorst en in de tijd gespreid over nagenoeg de gehele geschiedenis van de aarde. Zij dragen zo bij tot een beter begrip van de geodynamische ontwikkeling van onze planeet.

Preface and Summary

This thesis is based on research in the interface of two geological disciplines, sedimentology (the study of sediments, like sandstone and limestone) and structural geology (the study of rock deformation). Sedimentation is influenced by cosmic and climatological processes, sea-level change, and deformation of the earth's crust. Prerequisites for the generation of sediments are uplift and erosion in source areas, and subsidence and deposition in basins. Contrary to these vertical motions, deformation is often acting (sub)parallel to the earth's surface, i.e., horizontally (tension, compression, wrenching). To understand the influence of the deformation on sedimentation, the horizontal effects of deformation have to be translated into vertical ones.

Growth structures are deformations active during sedimentation. They cause irregularities in the pattern of basin infilling. They represent the first deformation of sediments, and are generally overprinted by several later phases of deformation. It, therefore, requires stepwise restoration and elimination of these later structures to detect the growth structures.

Since sediments can be dated, in a relative sense with fossils and absolutely (with the decay of radioactive elements in minerals), growth structures can be calibrated chronologically. This allows to determine variations in the rate of displacement, direction, and intensity of the deformation process, which is often difficult to detect directly by structural analysis.

The study of growth structures, therefore, comprises both the analysis of the mechanism of sedimentation and that of deformation. This kind of research is generally done separately by different scientists with diverse aims, and at different scales. Combination in retrospect of such data easily leads to misinterpretations.

The thesis emphasizes the advantage of integrated analysis from the very beginning of a research project in the combined fields of sedimentology and structural geology. The printed part considers that interrelationship with examples from research in mobile belts of a wide range of ages, carried out with colleagues and many MSc students: the early Archaean (± 3450 million years ago) of NW Australia (Pilbara) and South Africa (Barberton Mountains), the Proterozoic (± 1750 Ma) of the Mount Isa area in Queensland (NE Australia), the Carboniferous (± 300 Ma) of the Cantabrian Mountains in NW Spain, and the Eocene of the southern Pyrenees (± 50 Ma). The results of these studies have been published in the period 1989-1998. A choice of five articles forms, on CD, part of this thesis.

In all instances, integrated analysis of one and the same geological system, carried out at the same time, produced new insights on synsedimentary deformation in mobile belts covering a large part of the earth's history. They so contribute to a better understanding of the geodynamic evolution of our planet.

Growth structures: examples of integrated sedimentological and structural-geological basin analysis

Introduction

Growth structures: relationships between sedimentation and deformation
Faults and folds, active during sedimentation, progressively induce thickness differences, unconformities, and onlapping and offlapping contacts in the stratigraphic record (Fig. 1). Growth structures, therefore, contain a special record of the relationship between deformation at shallow crustal levels and sedimentation at the earth surface. The analysis of such relationships in several mobile belts, ranging from Early Archaean greenstone belts to the Alpine orogenic setting of the Pyrenees, is the subject of this thesis. In particular, the added value of simultaneous investigation of deformational and sedimentary structures in one and the same geological system is emphasized. At the scale of field observation this prevents much of the imminent misunderstanding involved in combining in retrospect datasets and interpretations obtained from each discipline separately.

What is meant by added value? The incremental evolution of style and rate of a deformation process cannot be unravelled merely from structural analysis of geometry and kinematic indicators. It is, however, recorded in the architecture of those deposystems that are highly sensitive to structural control, in particular coarse-clastic deposystems such as alluvial and subaquatic fans. One of the earliest papers highlighting this relationship is Riba's 1976 paper on progressive rotational unconformities in the South Pyrenees. Acceleration and deceleration of the controlling thrust process was deduced from the geometry of stacked unconformities in foreland basin alluvial fans. The concept was expanded by Miall in 1978 and recently revisited in the literature (Williams et al. 1998). Another fundamental paper is Heward's 1978 publication on Carboniferous alluvial fans in the Cantabrian Mountains, which relates vertical grainsize trends and facies shifts to the style of deformation and to changes in the balance of erosion/uplift vs subsidence/aggradation. These papers triggered to a large extent my interest in the field of deformation and sedimentation, and two of the studies included below are directly related to them.

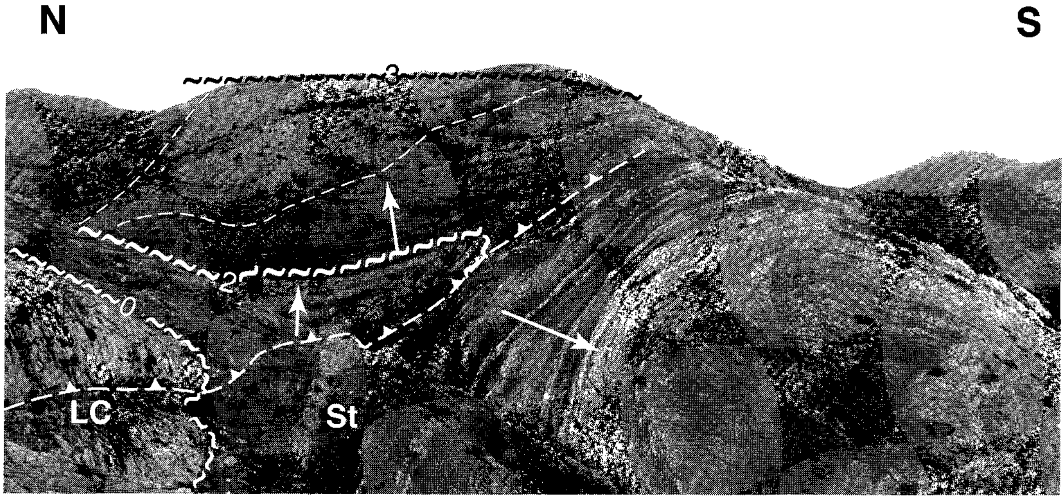


Fig. 1. Stephanian alluvial fan conglomerate (St) deposited on the Esla thrust sheet of the South Cantabrian Zone, NW Spain, during surficial collapse and backthrusting. The conglomerate fans show internal asymmetrical growth folds and stacked rotational unconformities. Main thrust direction of Esla thrust sheet is to the left (NE-wards), backthrust direction to the right (S-wards).
LC: Lower Carboniferous limestone in top of Esla thrust sheet; '0', '2' and '3' stacked rotational unconformities (unconformity '1' outside picture); arrows indicate fan-progradational coarsening-up sequences

Often the relationship between deformation and sedimentation is considered at the scale of plates and basins, i.e., of large-scale tectonic control. Many studies on foreland basin development discuss relationships between crustal flexure and the large-scale distribution of sedimentary and tectonic loads (e.g. Sinclair et al. 1991; Jervey 1992; Peper 1993; Millán et al. 1995; Vergés et al. 1995). The smaller-scale responses of basin architecture to individual structures such as fault-bend folds and antiformal stacks are now receiving more and more attention (e.g. Zoetemeijer et al. 1993; DeCelles 1994; DeCelles et al. 1995; Peper & De Boer 1995; Hardy et al. 1996; Den Bezemer 1998; Mascle & Puigdefàbregas 1998). Numerical structural modelling is still mainly concerned with sedimentation in response to basin-wide crustal-scale controls instead of operating at the resolution now encountered in studies of sedimentary architecture. Detailed chronological control is absolutely necessary for such studies, but this is not always available.

Wherever the relationship between sedimentation and deformation is subject of investigation, later deformation has to be stripped off in order to determine the possibly synsedimentary character of the early deformation. Both the backstripping and the assessment of synsedimentation demand thorough structural-geological investigation at a scale appropriate to sedimentary basin architecture. The examples discussed therefore all resulted from long-duration projects with the involvement of many investigators, amongst which tens of MSc students.

Geodynamically, it makes a substantial difference whether, for instance, D1 isoclinal folds in passive slope deposits are related to a regional, plate-motion-induced, post-sedimentary, compressive stress field, or to collapse due to a sedimentation-induced stress system generated by slope progradation. Collapse is often more readily associated with extensional processes due to crustal collapse at the scale of an orogen than with gravity collapse due to inherent instability of a deposystem itself. Nevertheless, collapse due to slope instability may obtain the size of an orogen (Agulhas shelf, South Africa: 750x106 km^2; Dingle 1977). Since the theory of thin-skin tectonics was developed, thrusting due to gravity sliding is a bit out of vogue. However, this mechanism appears to contribute substantially to the first deformation phase in many orogenic basins (e.g. De Wit 1982, Ricci Luchi 1986). The transition from mass waste as a sedimentary process to thrust folding as a deformation process is often gradational as we know from the transition of well-organized flysch, via chaotic flysch, into hinterland-dipping thrust units of the Swiss Alps (Milnes & Pfiffner 1977; Caron et al. 1989).

The question of synchronicity of sedimentary and deformational processes can only be resolved through detailed stratigraphical-sedimentological analysis. For example, concurrence of tensile and compressive deformation, inheritance and replay of old structures, and structural inversion all are much better tackled by combined sedimentological and structural-geological investigation than by either one individually. To illustrate this, I have collated a series of such investigations that I completed during the last decade.

The method of investigation

The examples referred to in this thesis originate from structural-geological and sedimentological analysis in key areas of about 25 km^2 within deformed belts. They were selected because they comprise deformed coarse-clastic deposystems, often located at intersections of deformational structures. In the southern Pyrenees, our training area for young university students for decades, the dataset now covers the sedimentary architecture and structure of an entire basin. This allows for basin-wide correlation with a resolution of about 5 metres stratigraphic thickness, corresponding to a scale of channel fills and crevasse splays, the architectural elements of Miall (1985a).

Sedimentological analysis consisted of 1:100 vertical grainsize and facies logging, and of detailed mapping of, in particular, coarse-clastic deposystems. Emphasis is on the 3D distribution and geometry of architectural elements, the geometry of recognizable increments of basin infilling, and stacking patterns of architectural elements and unconformities.

Chronological data have been derived from existing sources, such as absolute datings for the Archaean, detailed biostratigraphy on Carboniferous flora in the Cantabrian Mountains, and combined biostratigraphical and magneto-stratigraphical data for the South Pyrenees. Not all examples required the same detail in geochronologic correlation. For the South Pyrenees, the cyclicity in the basin and the question of structural *vs* orbitally-forced climatic and eustatic controls required much more accurate dating than that to establish the depocentre shift in the Cantabrian Mountains. In the latter case, a resolution up to the level of biostratigraphical substages sufficed. Studies of the Precambrian always need more geochronological control than available or affordable, and so depend to a greater degree on assumption than studies of the Phanerozoic. This may be partly compensated by mapping in detail lithostratigraphical and structural relationships and marker beds.

Apart from detailed mapping (1:12,500) using aerial photographs and satellite imagery, structural-geological analysis involved the study of brittle deformation such as fracture, subsidiary fault and fold patterns within and outside major shear zones, and analysis of slickensides.

In the context of integrated structural-geological and sedimentological analysis, the 3D distribution of tectonic and stratigraphical contacts is important. Growth faults may change laterally into unconformities. Stacked unconformities contain a record of step by step deformation during their formation. Deformation due to sedimentary slope instability may have a relationship with truely tectonical deformation. Depocentre shift may be directly related to the shift of structural axes of individual folds or of entire basins.

Several of the concepts involved will be reviewed below and illustrated with examples. Most of these have been applied and developed during my own research and many examples refer to the papers that compose this thesis (Table I) *). First, the topics and areas involved in this study will be briefly summarized.

TABLE I

Concepts	**examples from**
hierarchy of grainsize trends in vertical sequences	[3], [4], Nijman et al. 1992b
fan skewing	[3], Nijman et al. 1992b, Hooke 1972, Steel 1988
stacked unconformities	[2], [3[, [4]
growth folds	[2], [4], [5]
growth faults	[1], [2], [3], Barberton greenstone belt, South Africa; Mandl & Crans 1981; ECORS: Roure et a1. 1989 inversion [2], [3], ECORS: Roure et a1. 1989
gravity collapse	[1], [3], Barberton greenstone belt, South Africa;
depocentre shift	[2], [3], [4]
translation of tangential motion into vertical displacement	[4], Nijman et al. 1992a
drainage bends in multi-component basin fills	[3], [4], [5]
basin misfit, rotation	[5]
mixed-mode control	[3], [5]
replay of inherited structures; role of lineaments	[2], [3], [5]
shallow vs deep crustal control	[1], [3]

Archaean greenstone belts of the Pilbara, NW Australia: inversion of growth faults.

Within the Pilbara project of Utrecht University (White et al. 1998, Nijman 1998) basin analysis focussed on the geometry and stacking of unconformities and on the structural control of sedimentation at two stratigraphical intervals: Early Archaean sedimentary cherts of the Warrawoona Group and Mid-Archaean sandstones and conglomerates of the Gorge Creek Group [1], [2] (Figs. 2 and 3).

*) Throughout the text of this chapter these papers are referred to as: [1] to [5]; figures in these papers as: (Fig. 1 in [1]). The titles of the five papers are listed at the top of the list of references at the end of the chapter.

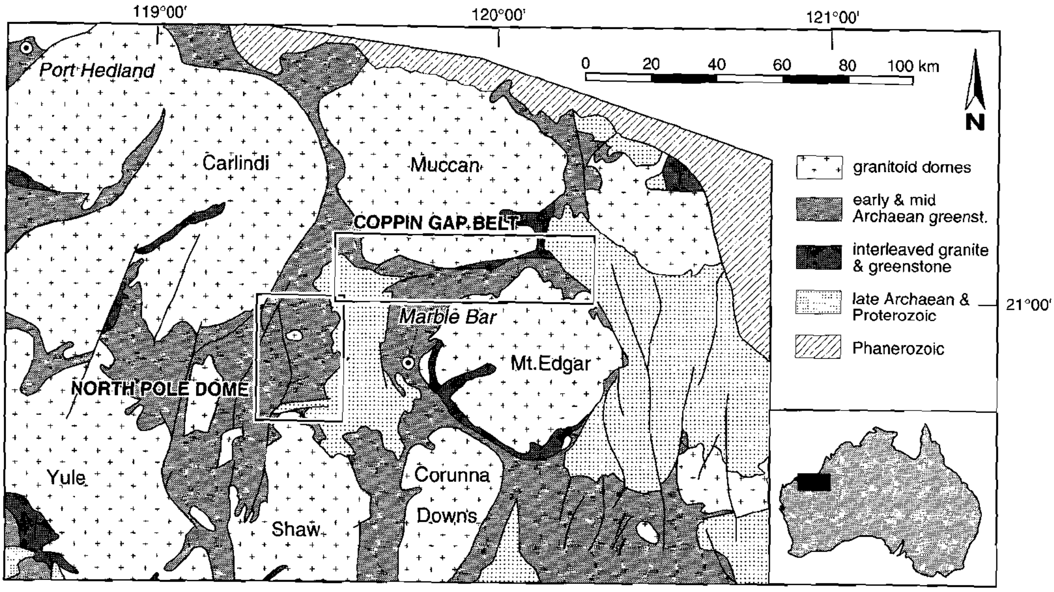


Fig. 2. Geological map of the Archaean Pilbara Block, showing the position of the North Pole Dome and Coppin Gap greenstone belt.

Sedimentary facies and deformation patterns of the 3.5 Ga-old North Pole Chert (Fig. 3) [1], show that synsedimentary tensional faults controlled not only thickness and facies distribution but also the occurrence of primary chert, of decametre-sized synsedimentary barite mounds, and of chert-barite veins.

Subsequently, the faults and the sediments they controlled were affected by low-angle thrusting and doming of the lower Archaean rock suite above the North Pole batholith, one of the granitoid complexes that characterize the geology of the Pilbara.

The second example concerns the 3.3 Ga transition of the volcanic assemblage of the lower Archaean Warrawoona Group to the mid-Archaean clastic sediments of the Gorge Creek Group in the east-striking Coppin Gap greenstone belt (Figs. 2 and 3) [2]. Arrays of tensile growth faults ("1" in Fig. 3) in the 3.46 Ga old suite of felsic volcanics, arenites, and cherts belonging to the Warrawoona Group are similar to that of the North Pole Dome, though oriented differently and associated with huge accumulations of megabreccia comprising felsic volcanic agglomerates. Basal detachments to the normal faults and other similar shear zones ("2" in Fig. 3) climb eastwards through the lower Archaean rock suite in a ramp/flat fashion. Tectono-stratigraphical relationships in footwall and hangingwall, and deformation patterns in shear zones generally reflect crustal shortening with eastward vergence along most of the earlier low-angle tensile fault zones, a clear indication of inverted tectonics (*cf* Zegers 1996). Although definite geochronological prove is still lacking, large-scale tectonic repetition of the early Archaean stratigraphical column appears to have taken place (Fig. 3).

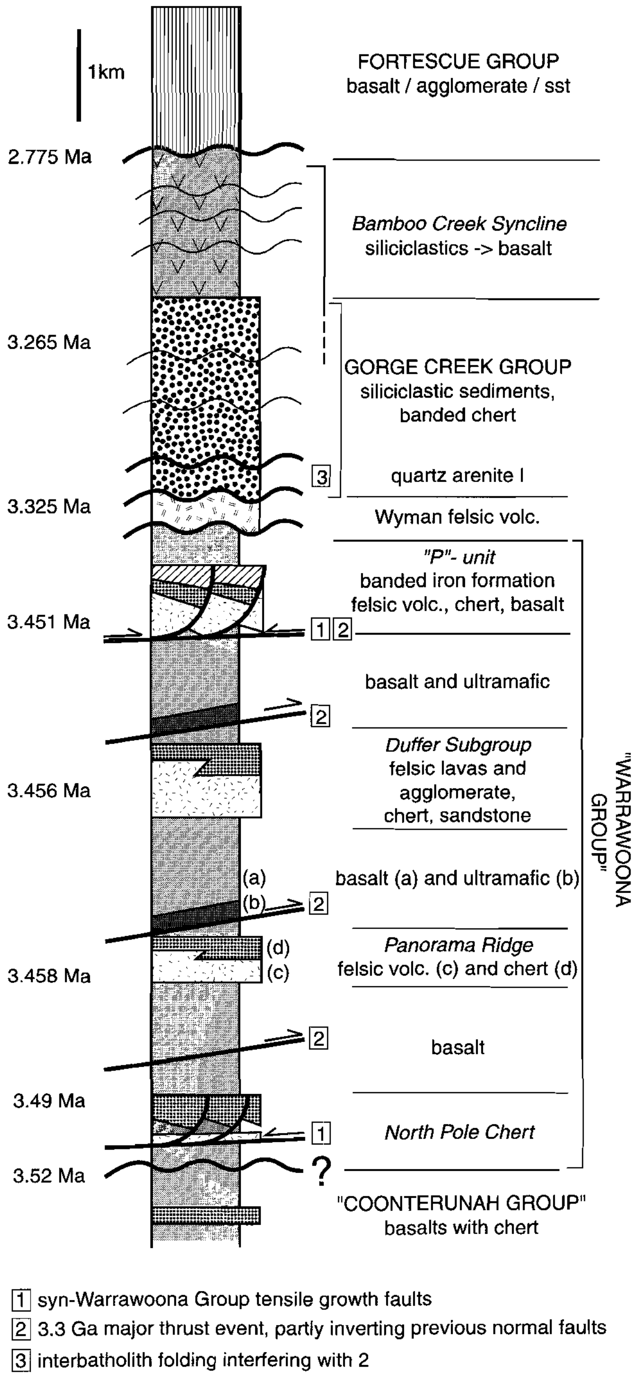


Fig. 3. Tectono-stratigraphical column of events along the North Pole-Coppin Gap traverse of the Archaean East Pilbara Craton. This figure shows tectonic repetition of D1-extension-controlled rock assemblages of felsic volcanics and cherts (3.45 - 3.49 Ga) in the overall mafic basaltic environment of the Warrawoona Group. Tectonic repetition is due to D2-thrusting accompanied by influx of significant amounts of siliciclastic sediments from 3.3 Ga onwards (Gorge Creek Group). (After Nijman 1998).

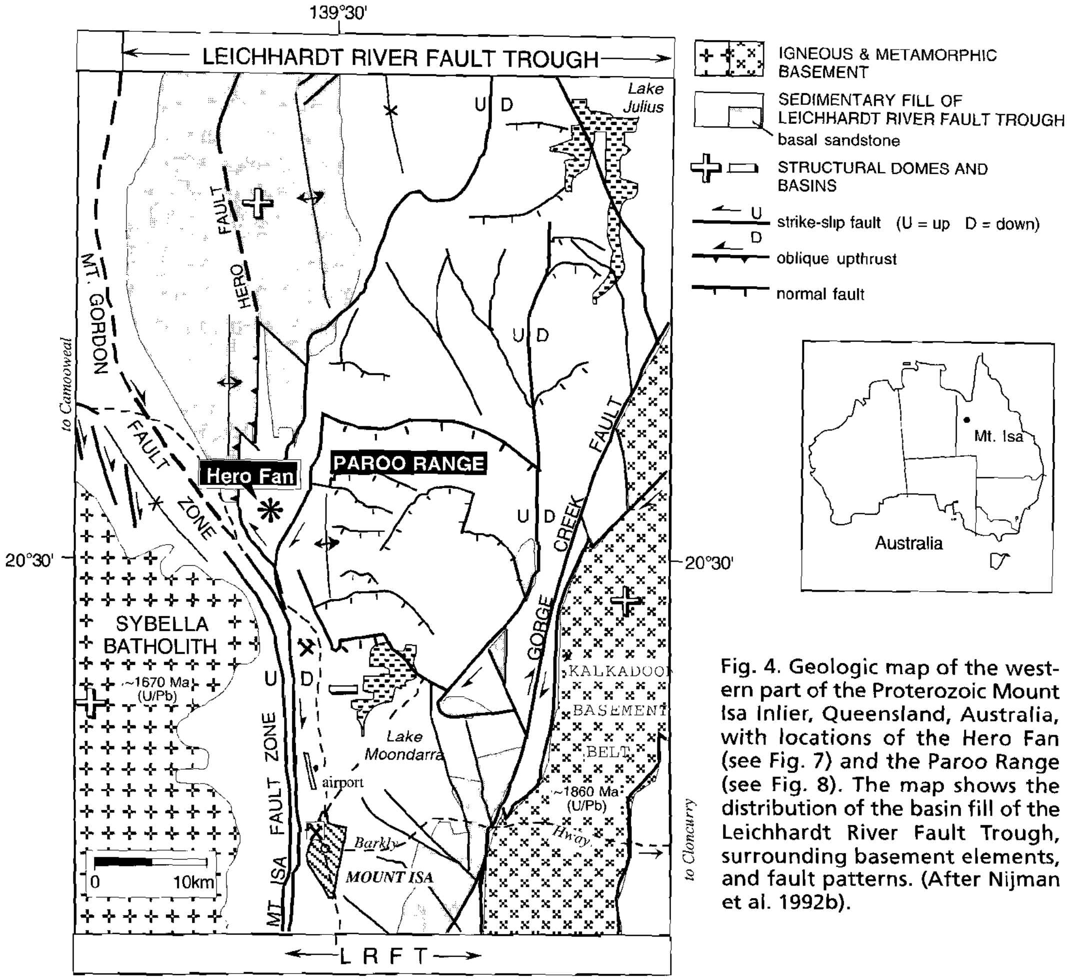


Fig. 4. Geologic map of the western part of the Proterozoic Mount Isa Inlier, Queensland, Australia, with locations of the Hero Fan (see Fig. 7) and the Paroo Range (see Fig. 8). The map shows the distribution of the basin fill of the Leichhardt River Fault Trough, surrounding basement elements, and fault patterns. (After Nijman et al. 1992b).

The Proterozoic of the Mount Isa Inlier, NE Australia: an oblique-slip belt

Some illustrations in this chapter have been derived from studies carried out in the Proterozoic (circa 1.75 Ga) of the Mount Isa Inlier, Queensland, Australia (Nijman et al. 1992 a,b) (Fig. 4). The Mount Isa Inlier represents a mobile belt composed of two fold belts, the Western and Eastern fold belts, separated by a basement high. The main compressive deformation, the Isan Orogeny, took place around 1.6 Ga ago (Blake & Stewart 1992). The Western fold belt comprises the Leichhardt River Fault Trough (Fig. 4). The sedimentary fill is composed of three cover sequences, deposited prior to the Isan orogeny, each composed of a rift and a sag phase. Sedimentological and structural-geological analysis in the Leichhardt Fault Trough revealed that strike-slip growth structures formed during the second cover sequence and locally continued to be active into the third. Their recognition allowed to add the strike-slip component to the tectonic concept of the belt. Normal growth faults of the third cover sequence had already been described previously (for further detail and references: see Nijman et al. 1992a,b).

The Carboniferous Variscan Cantabrian orogen: fanglomerates, thrusting and escape tectonics
In this classical area (Fig. 5) of circa 0.30 Ga thin-skinned tectonics, current models of the complex fold and thrust belt seem to have approached a successfull synthesis without the necessity for extreme regional bending to account for the characteristic horse-shoe form of this segment of the Variscan Orogen (Pérez-Estaún et al. 1988). In these models fundamental wrench faults (e.g the León, Cardaño and Southern Boundary Lineaments), whose influence is recorded throughout the Paleozoic stratigraphical history, have been considered subordinate to compressional tectonics revealed by the Westphalian thrusts. The latter structures have been reported to be unconformably overlain by Stephanian alluvial fans spreading across small intramontane coal basins, controlled by wrench-fault tectonics. This suggests transtensive orogenic collapse after the main compressional stage.

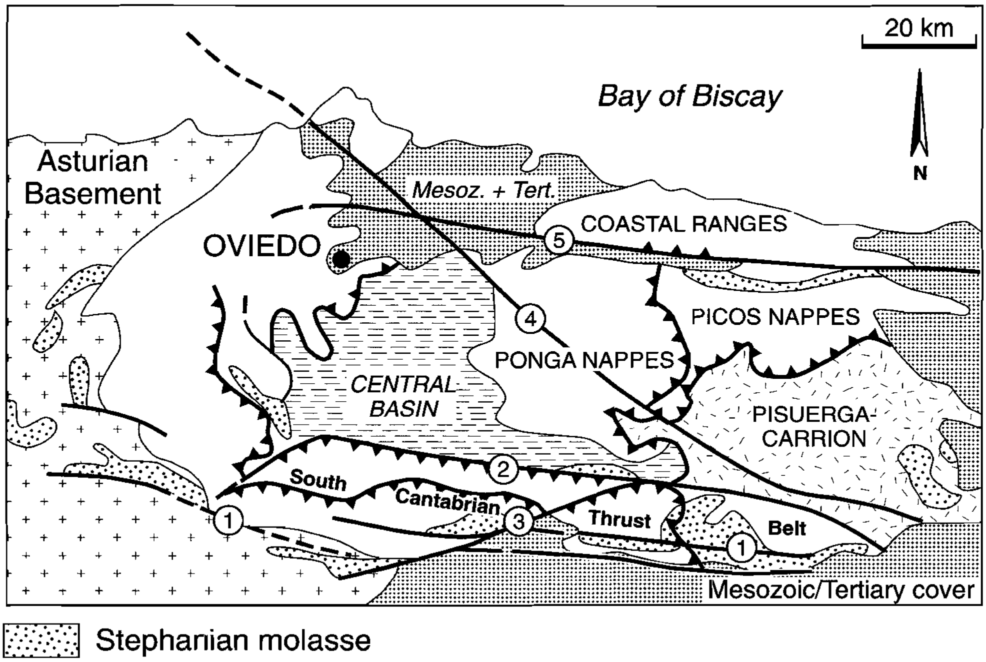
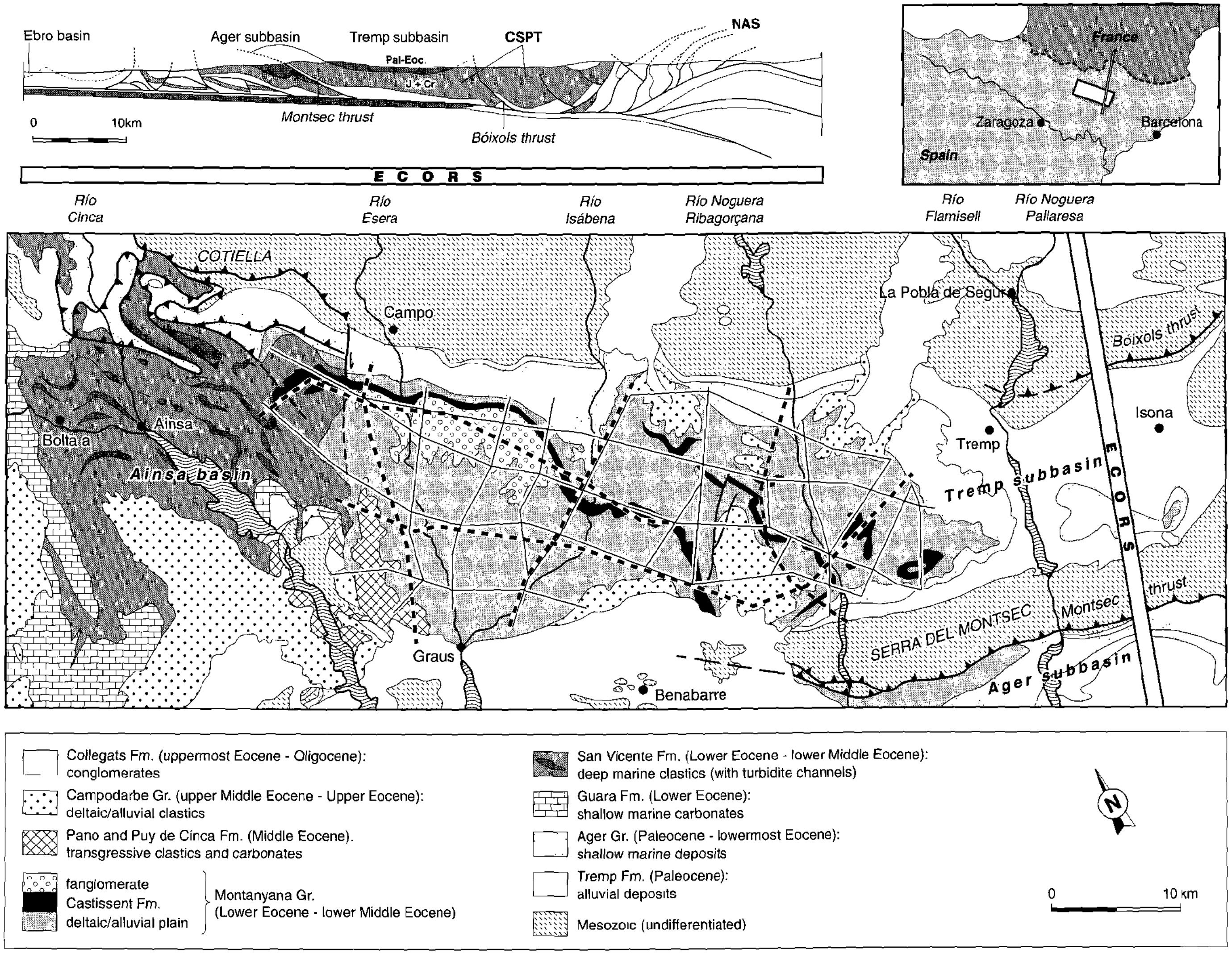


Fig. 5. Map of structural units of the Variscan Cantabrian Orogen, NW Spain: 1: Southern Boundary Fault; 2: Léon Lineament; 3: Porma Fault; 4: Cardaño Fault; 5: North Cantabrian Lineament. Note that the major lineaments evidently traverse the arc structure. However, their activity *during* thrusting can be inferred from detailed analysis of coarse-clastic syndeformational molasse fans. These relationships between molasse sedimentation and deformation have been studied in the South Cantabrian or Leonide Zone (see also Fig. 9). (After [3]).

Fig. 6. Geological map and section of the Lower Tertiary Tremp-Ager basin (inset) in the Spanish Pyrenees; with database grid of stratigraphic traverses (full lines), structural profiles (dashed lines), and trace of the ECORS deep seismic section. The top figure represents the southern part of the ECORS profile through the Central South Pyrenean thrust sheet (CSPT with the Nogueras antiformal stack (NAS) at the rear, the Ebro foreland basin at the front. (After [4]).



Ebro basin
Ager subbasin
Tremp subbasin
CSPT
NAS
Pal-Eoc.
J + Cr
0
10km
Montsec thrust
Bóixols thrust
E C O R S
France
Zaragoza
Barcelona
Spain
Río Cinca
Río Esera
Río Isábena
Río Noguera Ribagorçana
Río Flamisell
Río Noguera Pallaresa
COTIELLA
Campo
La Pobla de Segur
Bóixols thrust
Isona
Tremp
Boltaña
Ainsa
Ainsa basin
Tremp subbasin
E C O R S
Graus
Benabarre
SERRA DEL MONTSEC
Montsec thrust
Ager subbasin
Collegats Fm. (uppermost Eocene - Oligocene): conglomerates
Campodarbe Gr. (upper Middle Eocene - Upper Eocene): deltaic/alluvial clastics
Pano and Puy de Cinca Fm. (Middle Eocene). transgressive clastics and carbonates
fanglomerate
Castissent Fm.
deltaic/alluvial plain
Montanyana Gr. (Lower Eocene - lower Middle Eocene)
San Vicente Fm. (Lower Eocene - lower Middle Eocene): deep marine clastics (with turbidite channels)
Guara Fm. (Lower Eocene): shallow marine carbonates
Ager Gr. (Paleocene - lowermost Eocene): shallow marine deposits
Tremp Fm. (Paleocene): alluvial deposits
Mesozoic (undifferentiated)
N
0
10 km

Integrated analysis of the relationship between fan deposits, thrust and wrench tectonics [3] demonstrates that the Stephanian fanglomerates are synorogenic molasse since they have been largely affected by Variscan thrust tectonics during their sedimentation. It also shows that the the molasse fans spread over and between the advancing thrust fronts from sources in the foreland basin of the thrust belt, the Westphalian Central Coal Basin (Fig. 5). This is a drainage opposite to the normal molasse fan orientation away from the thrust front and outward with respect to the orogenic axis. A more complex control than that of the thrust system alone has been found to be responsible for this deviating facies pattern.

The Tertiary Tremp-Ager piggyback basin in the South Pyrenees

The Tertiary (0.05 Ga) Tremp-Ager basin [4] (Fig. 6) was carried piggyback on the Central South Pyrenean (CSP) thrust sheet. The basin architecture has been recorded in a numerical database. Detailed facies maps and a large number of digitized sedimentary logs form the basis for the stratigraphical correlation of the distribution of architectural elements along a grid of traverses. Chronostratigraphical correlation is based on biozones and palaeomagnetic data. The database provides a detailed picture of the geometry, internal architecture and stacking patterns of the increments of basin infilling.

Eight megasequences are distinguished, each between 148 and 404 m thick. They are aperiodic, and span time intervals between 400 and 1400 ka. Although most of the megasequence boundaries can easily be related to third-order sea-level fluctuations, preponderant structural control is indicated by their correlation with sharp reversals in the pattern of basin-axis shift in transverse cross-sections of the basin, and with flank unconformities. Sea-level fluctuations influenced the megasequential architecture accounting, for instance, for extreme progradation as observed in the Castissent Sandstone (Marzo et al. 1988).

The megasequences consist of a large number of basin-wide cycles, at the average 44 m thick, with an average periodicity of 124 ka, very crudely approximating the 100 ka of orbital forcing. Aggradational, amalgamated sheet, fan-progradational and fluvial-expansion cycles correlate with episodes of specific structural or sea-level control. The pattern of stacking of the cycles conforms to the structurally controlled megasequential basin-axis shift on which it is superposed. Climate fluctuations appear to have played a prominent role only in generating minor subcycles observed in some parts of the basin fill.

In an earlier article [5], the position of the Tremp-Ager basin is discussed in relation to the surrounding structures and basins. It was pointed out that the then available information led to a misfit of Tertiary basin axes. The solution to these problems of palinspastic basin misfit have much to do with the way the emplacement of thrust sheets is interpreted. The pattern of growth structures, unconformities and synsedimentary deformation along the oblique ramps of the CSP thrust sheet plays an important role in that discussion.

Internal and external fan geometry in response to deformation

Hierarchy of grainsize trends in vertical sequences

Grainsize distributions, as recorded in sedimentary logs, yield information on a diversity of geological processes, such as the mode of deposition (progradation, retrogradation, lateral accretion); the relative rates of uplift, subsidence, erosion, and aggradation; the slope gradient; and the hydrodynamic system (*cf* Paola et al. 1992). Simple rules relating fining-upward trends with scour-and-fill processes like channel filling, and coarsening-up sequences with fan-lobe progradational units are well known in sedimentological practice. Grainsize distributions can be analyzed at the hierarchical levels of superimposed basin fills, basin fills, deposystems (tracts), architectural elements (e.g. channel fills, mouthbars), and beds (e.g., a pebbly sandstone bed representing a single mass flow or a cross-laminated (co)set representing a stream flow condition) (Fig. 7).

In sedimentology, the concept of an observation hierarchy has been established by Miall, for instance in his ranking system of paleocurrent data (Miall, 1985b). It is important to realize that grainsize trends at a high hierarchical level, e.g. in fan sequences, strongly reflect structural and/or base-level control. The lower ranks, on the other hand, are highly influenced by the mode of deposition: FU (fining-up = normally graded) beds, for instance, by ripple migration or dilute mass flows, and reverse grading by dense mass flows (Fig. 7).

Heward (1978) drew attention to the fact that in a simple, normal-fault-controlled source-basin relationship, acceleration of uplift at a constant rate of erosion would lead to retrogradation of the fan and steepening of its slope (fan segmentation), with a scree-covered fault scarp as an end member. On the other hand, if erosion keeps pace with a more moderate uplift, fanhead entrenchment and cannibalism would cause strong progradation into the basin and flattening of the gradient. Climate factors were not considered. This approach was revived ten years ago during the early stages of sedimentary numerical modelling. It led to a discussion whether maximum progradation in fault-controlled basins coincides with increasing tectonic activity or with tectonic quiescence (the "two-phase stratigraphical model " of Heller et al. 1988; see also Flemings & Jordan 1990).

One step higher in the hierarchy of fan geometry, superimposed fans constituting basin-fill sequences record this sort of change in processes, and also the mode of deformation of the basin margin. By using the enveloping surface of fan fringe deposits in 2D and 3D, one can distinguish between control by back-stepping normal faults, propagating thrust faults, or by strike-slip systems (Miall 1978, Steel 1988).

In the study of the Tremp-Ager basin [4] the use of fan-enveloping surfaces has been applied both to differentiate between aggradational, progradational, and expansion cycles, and to identify the stacking pattern of cycles within megasequences. This led to distinction between thrust-sheet control and base-level control on the filling of the piggyback basin.

Fan skewing

As early as 1972, Hooke in his description of Tertiary alluvial fans of Death Valley, California, introduced the concept of fan skewing: an asymmetric or skewed fan-lobe distribution resulting from strike slip along the controlling fault, causing shift between drainage area and site of fan deposition (Fig. 8a).

Later, Steel and Gloppen (1980) and Steel (1988) elaborated the concept (*cf* Dabrio 1990). Though not explicitly, Steel (1988) provided a twofold definition of fan skewing (Fig. 8b). First, a *morphological* skewing is caused by fan progradation combined with strike-slip motion. Steel emphasized that the dominance of CU-FU and CU-over-FU sequences can be explained completely by fan skewing during strike slip. In his example fining-up is not the result of abandonment by diminishing fan activity, but of moving the active fan sidewards through the observa-

HERO FORMATION TYPE SECTION

COORDINATES BASE: 6757-355411 TOP: 6757-357412 (sheet Kennedy Gap, Mt. Isa Inlier)

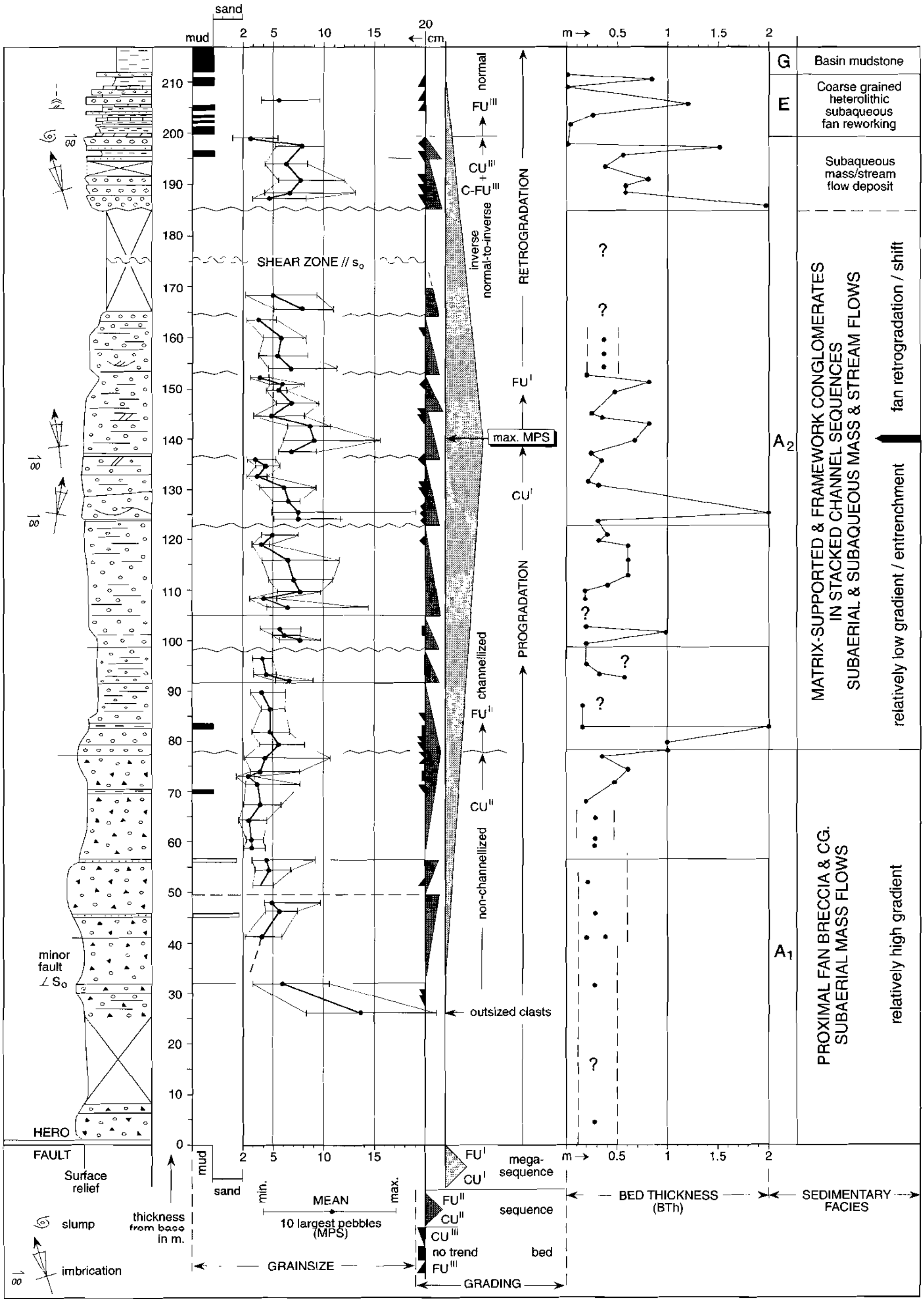


Fig. 7. Sedimentological log through the type section of the Proterozoic Hero alluvial fan, Mount Isa Inlier, Australia. The fan is located close to a block-bounding fault (*cf* Fig.8c). The section illustrates the importance of grainsize distributions to analyse fan behaviour and mode of structural control. For location, see Fig. 4. (After Nijman et al. 1992b).
Three levels of vertical grainsize distribution are distinguished:
(1) A grainsize trend at *megasequence* scale (n x 100 m thick) is defined by the enveloping surface of MPS (mean maximum particle size) values. After steady coarsening-up (CU) to a maximum MPS at 140 m, the trend reverts into fining-up (FU).
(2) At *sequence* scale (n x 5 m), CU changes to FU at 77 m concurrently with a facies change from fan breccia to conglomerate.
(3) At *bed* scale (n x 1m), the first 200 metres show dominance of inverse (CU) and inverse-to-normal (CU/FU) over normal (FU) grading. Normal grading is the rule only in the uppermost 10 m of the log.
Interpretation: The CU-FU megasequence provides information on fan behaviour: a change from fan progradation to retrogradation, or a lateral shift of the fan body with respect to its point source. The sequence trend is explained as a change from active fan lobe deposition (CU) to channel infilling (FU), and, therefore, as a change towards channelized flow at a lower slope gradient than in the initial stage of fan sedimentation. Note that this change occurs during continuing coarsening-up at megasequence scale (i.e., during progradation).
Bed-scale trends are particularly indicative of the depositional mechanism. Dominance of inverse over normal grading means that mass-flow mechanisms prevail over stream flow during deposition of the bulk of the fan. Only the uppermost 10 metres are consistently stream-flow deposited. Assuming that the amount of mass flow is related to slope gradient and fan activity, persistence of mass-flow deposition, while the megasequence becomes FU, does not indicate the waning of the fan mechanism itself. Rather, it indicates the lateral shift of the active fan away from the observation point (see also Fig. 8).

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tion point by strike slip. Secondly, a *compositional* skewing, which is an asymmetry in facies distribution in which conglomerate interfingers with mudstone at the high-gradient leading lateral edge of the relatively moving fan body, while a sandstone tail occurs at the lower-gradient trailing edge (Fig. 8b). This compositional skewing depends on the facies distribution within the receiving basin and on the local slope gradients.
The example from the Mid-Proterozoic of the Mount Isa Inlier, Australia, illustrates both the morphologic and the compositional skewing (Nijman et al. 1992b) (Figs. 7 and 8c).

Fan skewing also played an important role in deciphering the complicated control on the deposition of Upper Carboniferous molasse fans in the Cantabrian Mountains (Fig. 9a) [3]. Clockwise skewing of these fans has got little to do with the surficial thin-skin thrust regime of the Cantabrian Orogen, but reflects predominantly the strike-slip motion along the Léon Lineament, a deep-seated basement fault, now at the surface, inherited from the pre-orogenic passive margin. The latter belongs to a system of fundamental basement faults related to escape tectonics along the edges of the Iberian promontory pushing northwestwards into the Variscan Orogen (Matte 1986) (Fig. 9b; see also the final section of this chapter). Of course, such an important conclusion cannot be drawn from the observed skewing pattern alone, and one should look for other convergent evidence as well. But given such information, the skewing pattern reveals controls which cannot be proved solely on structural-geological grounds.

Stacked unconformities

No better proof of growth structures exists than in the stacking of angular unconformities over active positive structures (Fig. 1). It is evident that for their identification, the unconformities have to be traced into conformable contacts away from the positive structures. Very diagnostic

N.B. text continues on page 26.

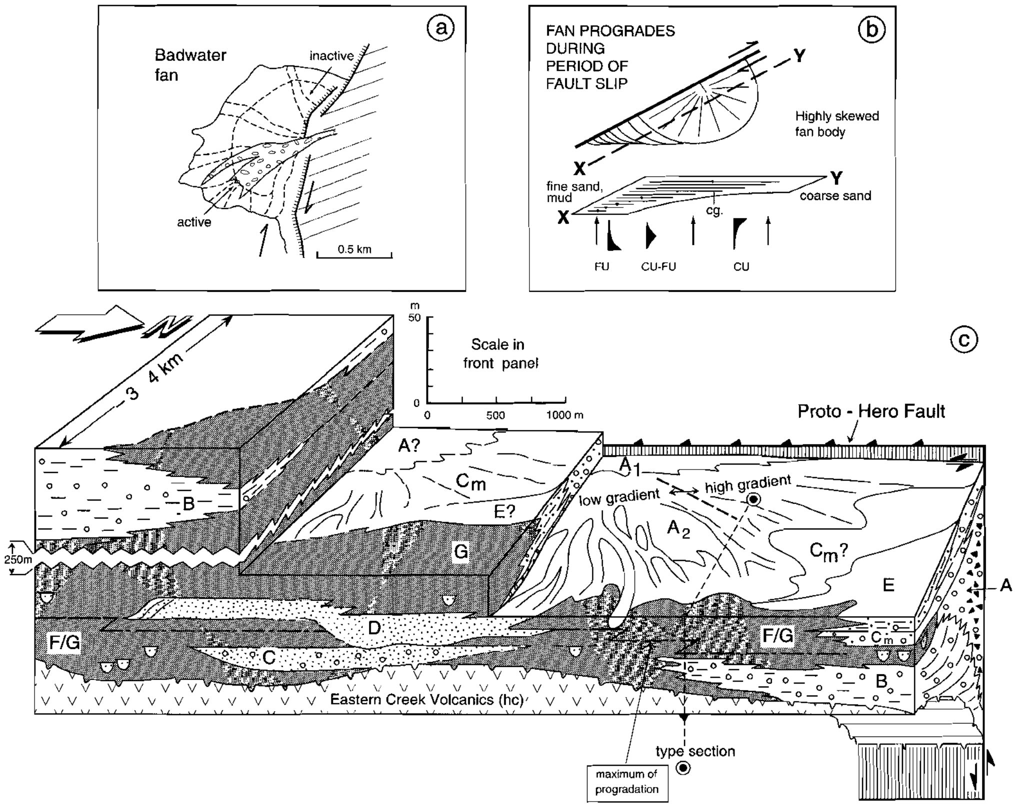


Fig. 8. Fan skewing and strike-slip control.

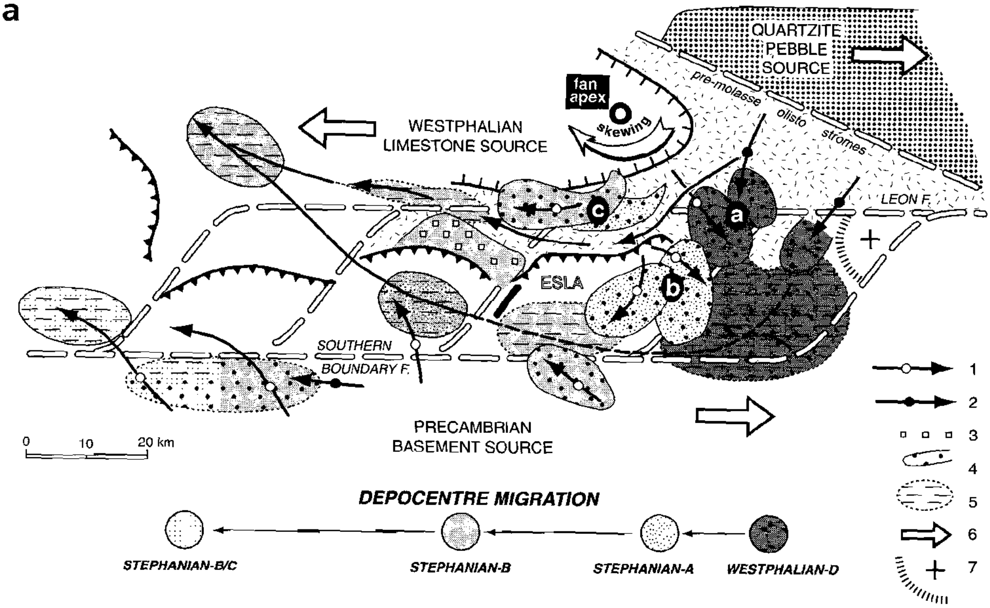
(a) The original concept of fan skewing stems from dextral strike slip-controlled fans in Death Valley, USA, and refers to an asymmetric distribution of coarse-grained fan conglomerate due to lateral shift between source and depocentre (after Hooke 1972).

(b) Fan progradation during strike slip results in obliquely-skewed stacking with unequal slope gradients and facies distributions on both sides of the fan, and in dominance of CU and CU/FU over FU (after Steel 1988).

(c) Block diagram of the Proterozoic Hero Fan in the of the Mount Isa Inlier, Australia (after Nijman et al. 1992b; for location see Fig. 4). The figure shows facies relationships between A: mass-flow-dominated fan conglomerate/breccia (A_1: CU, A_2 FU); B: fine-grained pebbly wacke; C: pebbly sandstone (C_m: massive); D: FU-sandstone; E: coarse-grained heterolithic facies; F fine-grained heterolithic facies; and siltstone (G). Fan skewing is evident from the distribution of high-gradient conglomerate facies on northern fan slopes, lower-gradient chanellized sandy facies on the southern slope, and from southward depocentre shift within the Hero Fan and into the stratigraphically next higher fan (facies B). The fault control in this example is interpreted as sinistral strike slip. "Type section" refers to the sedimentary log of Fig. 7.

Fig. 9a Sinistral pull-apart basin model for the South Cantabrian Zone during the Upper Carboniferous Variscan Orogeny. Basement wrenching accounts for surficial distribution of tectonofacies (flysch-type olistostromes and molasse) and thrust units, fan skewing and structural compartmentalization. Unidirectional opening of the pull-apart structure is indicated by one-sided, westward depocentre shift. (After [3]).
1 = polymict fan dispersal; 2 = dispersal of reworked quartzite conglomerate, 3 = thrust-front debris fans; 4 = alluvial fans; 5 = distal fan and coal basin facies; 6 = inferred direction of basement block movements; 7 = low-grade metamorphic dome; a – c = skewed stacking of Westphalian-D to Stephanian-B alluvial fans along the Léon Lineament.

a



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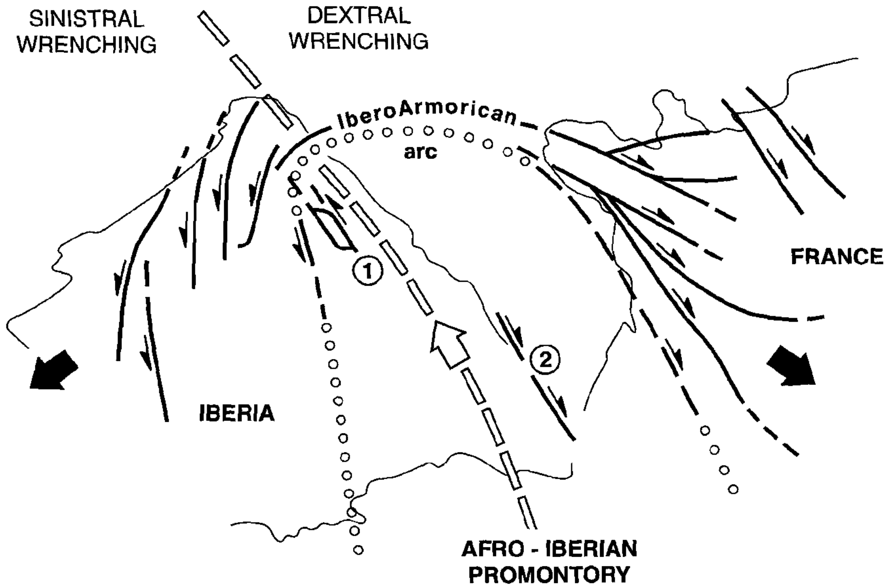
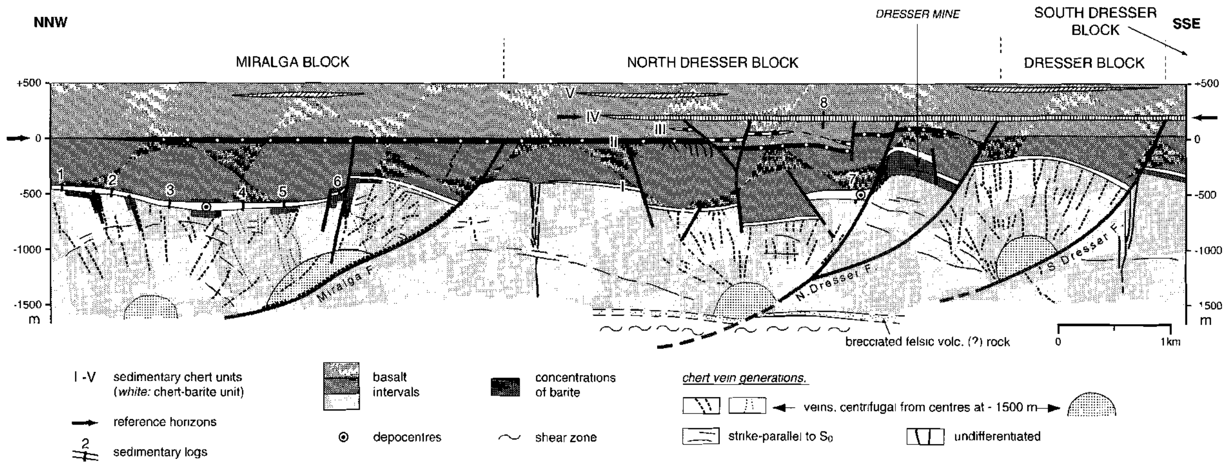


Fig. 9b. Generalized map (after Matte 1986; and [3]) showing basement promontory structure of the Ibero-Armorican arc of the Variscan Orogen with fault patterns due to escape tectonics. Note that sinistral pull-apart occurs at "1" (Stephanian basins, South Cantabrian Zone); dextral strike slip at "2" (Stephano-Permian basins of the Pyrenees). Pull-apart basin generation as controlling mechanism both for thin-skinned thrust faulting and molasse fan patterns in the South Cantabrian Zone tallies to the proposed promontory structure.

Fig. 10. The relationship between chert sediments and tensile growth faulting in lower Archaean greenstone belts. Both figures at the same scale.

(a) North Pole Chert (NPC), Warrawoona Group, Pilbara craton, NW Australia; after [1]. Restored cross-section along the NPC shows an array of synsedimentary, listric, tensional growth faults with thickness differential in the infilling sequence of cherts (I-V) and interlayered pillow basalts. Chert units II and IV are used as horizontal reference. Sites 1-8 are locations of sedimentary logs. Swarms of synsedimentary hydrothermal chert-barite veins fan upwards from silica-poor centres that project at or near the growth-fault planes in the underlying basalt at 1500 m below reference. Other chert-vein generations are strike-parallel, or at right angles to bedding without obvious fanning. The faults merge from a basal shear zone with intense hydrothermal chemical alteration of the sheared basalt. The NPC represents a shallow tidal basin, probably related to a major caldera-collapse structure in the early crust of the earth.

(b) Buck Ridge Chert (BRC), Onverwacht Group, Barberton greenstone belt, Kaapvaal craton, South Africa. Fieldwork, in the second half of 1998, resulted in this preliminary geological map which also represents a near cross-section through the upper Hooggenoeg Formation. The section shows a striking correspondence in geometry and size of the normal fault array with that of the NPC in the Pilbara [Fig.(a)]. West-block-down normal faults converge downwards in bedding-parallel sinistral shear zones with west-facing thrusts. This concurrence of compressional and tensional structures is highly diagnostic for surficial gravitational collapse. Roll-over anticlines are more pronounced than in the NPC. The eastern part of the fault-block array has been distorted by continued collapse and sliding. Another difference is the large volume of felsic intrusion to just below the infilling sedimentary chert. A direct connection between the felsic intrusive rock and surficial felsic lava flows within the BRC along feeder channels (at ❈) could be assessed. Geochemically, these two felsic rock types are identical (De Wit et al. 1987). The BRC probably represents a caldera-lake deposit. (Based on field data of De Vries, Houtzager, De Wit, Dann, King, and Nijman, 1998 and previous years).



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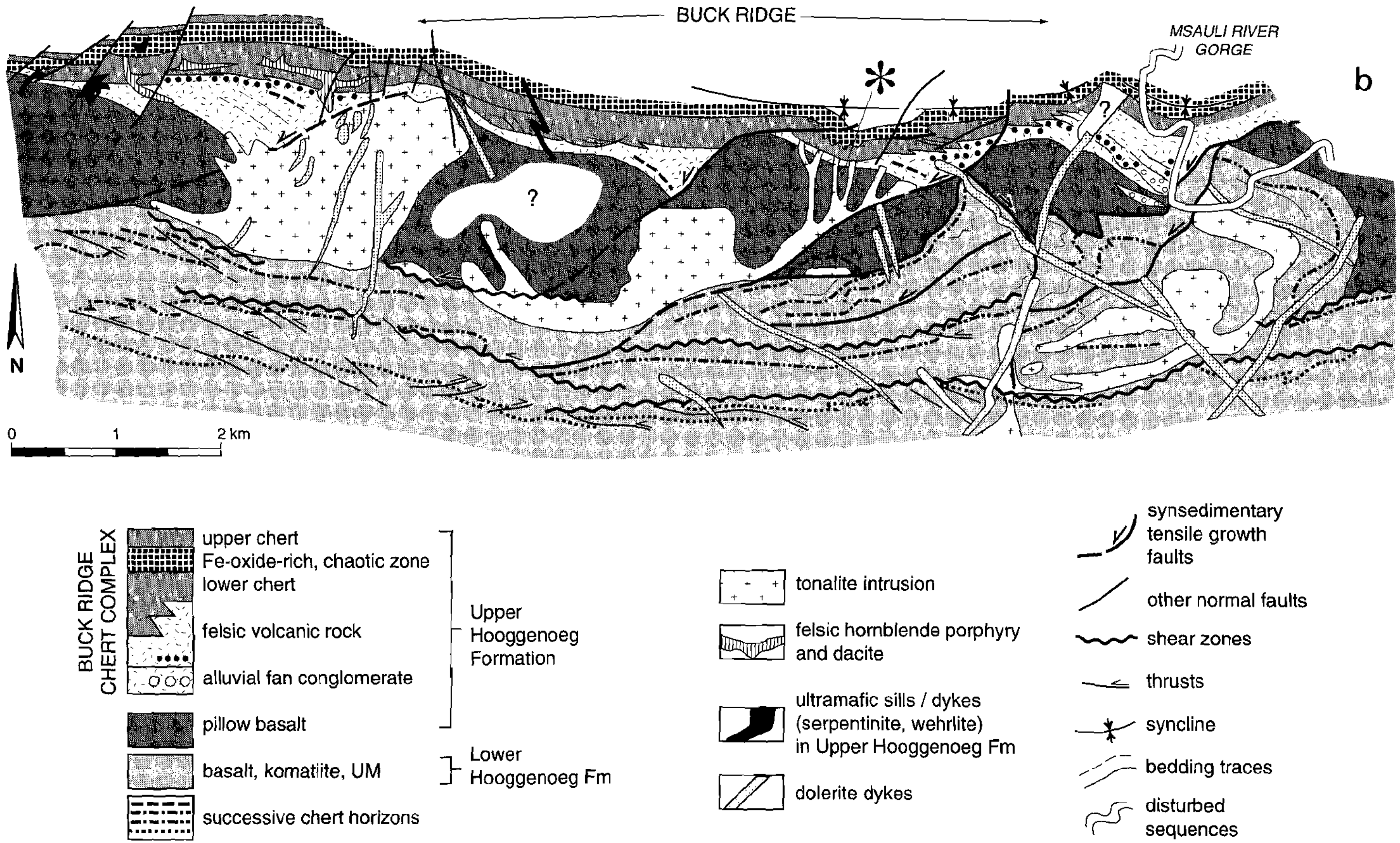
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b
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BUCK RIDGE CHERT COMPLEX
upper chert
Fe-oxide-rich, chaotic zone
lower chert
felsic volcanic rock
alluvial fan conglomerate
pillow basalt
Upper Hooggenoeg Formation
basalt, komatiite, UM
Lower Hooggenoeg Fm
successive chert horizons
tonalite intrusion
felsic hornblende porphyry and dacite
ultramafic sills / dykes (serpentinite, wehrlite) in Upper Hooggenoeg Fm
dolerite dykes
synsedimentary tensile growth faults
other normal faults
shear zones
thrusts
syncline
bedding traces
disturbed sequences

are stacked unconformities in asymmetric compressional structures where, in the steepening flanks, rotation may tilt and even overturn every previously formed unconformity in succession, thereby stepwise increasing its angle (*cf* Miall 1978). The mode of stacking furthermore appears to be indicative of the rate of thrust motion. In that respect, Riba (1976) and Williams et al. (1998) have already been mentioned.
Pronounced examples of stacked unconformities are illustrated in the cross-section through the fluvial-dominated eastern compartment of the South Pyrenean Tremp-Ager basin [4], in the corresponding deeper water Ainsa basin along the oblique ramp of the Central South Pyrenean thrust sheet (Peña Montañesa) [5], in the Esla thrust sheet of the Cantabrian Mountains [3], and in the Bamboo Creek syncline of the Coppin Gap greenstone belt in the Pilbara [2]. They all yield new information about the mode and intensity of synsedimentary deformation, in particular in combination with other diagnostic features, such as rotational slickensides (Peña Montañesa), depocentre shift (Bamboo Creek syncline), and surficial gravity-collapse faults (Esla thrust sheet).

Growth faults and folds, collapse structures and gravity sliding

Growth structures, whether faults or folds or combinations play a role throughout the studies on deformation and sedimentation that compose this thesis. The study of growth faults was initiated largely by petroleum geologists. Listric normal faults in the Niger Delta oil field, a classical example of growth faulting, show considerable offset downdip along the fault plane, but (near-) absence of offset at the surface, since the forming of fault relief is continuously compensated by sedimentation (Bruce 1973).
Crans et al. (1980) and Mandl and Crans (1981) placed this type of faults in the physical context of gravitational collapse of a labile overpressured delta slope. Characteristically, such slump structures show extensional faults in the head and compressional thrusts in the toe. They tend to propagate stepwise, keeping pace with the progradation of the slope-forming deposystem (Galloway 1986). The stepwise growth and decay is caused by an alternation of fault-enhancing sedimentary loading at the head of the collapse structure and subsequent relaxation of overpressure by water escape through the relatively coarse and permeable, freshly deposited sediment.

In general, growth faults, whatever their shape and offset may be, are characterized by a stratigraphical thickness differential between hangingwall and footwall. It is this feature which, in the Early Archaean (3.5 Ga) chert-filled basins of both the Pilbara (W.Australia, [1]; Zegers et al. 1996) and Barberton (South Africa), reveals a major synsedimentary control by listric tensional faults on the formation of these earliest known sedimentary basins (Fig. 10).
Here too, the observation cannot be uniquely interpreted, unless supported by a chain of interrelationships between diverse geological phenomena [1]. Both stratigraphically and with respect to the provenance of its sandstone component, the North Pole Chert of the Pilbara was related to felsic volcanism in an otherwise basalt-dominated subaqueous volcanic environment. The listric normal growth faults were induced by moderate uplift, coincident with felsic volcanism. Swarms of chert-barite veins arose from the growth-fault planes, and created hydrothermal vents in the shallow sedimentary basin formed by collapse due to the faulting. Barium, silica and sulphur emanated from these vents into a stratified tide-influenced water body, only about 50 m deep.

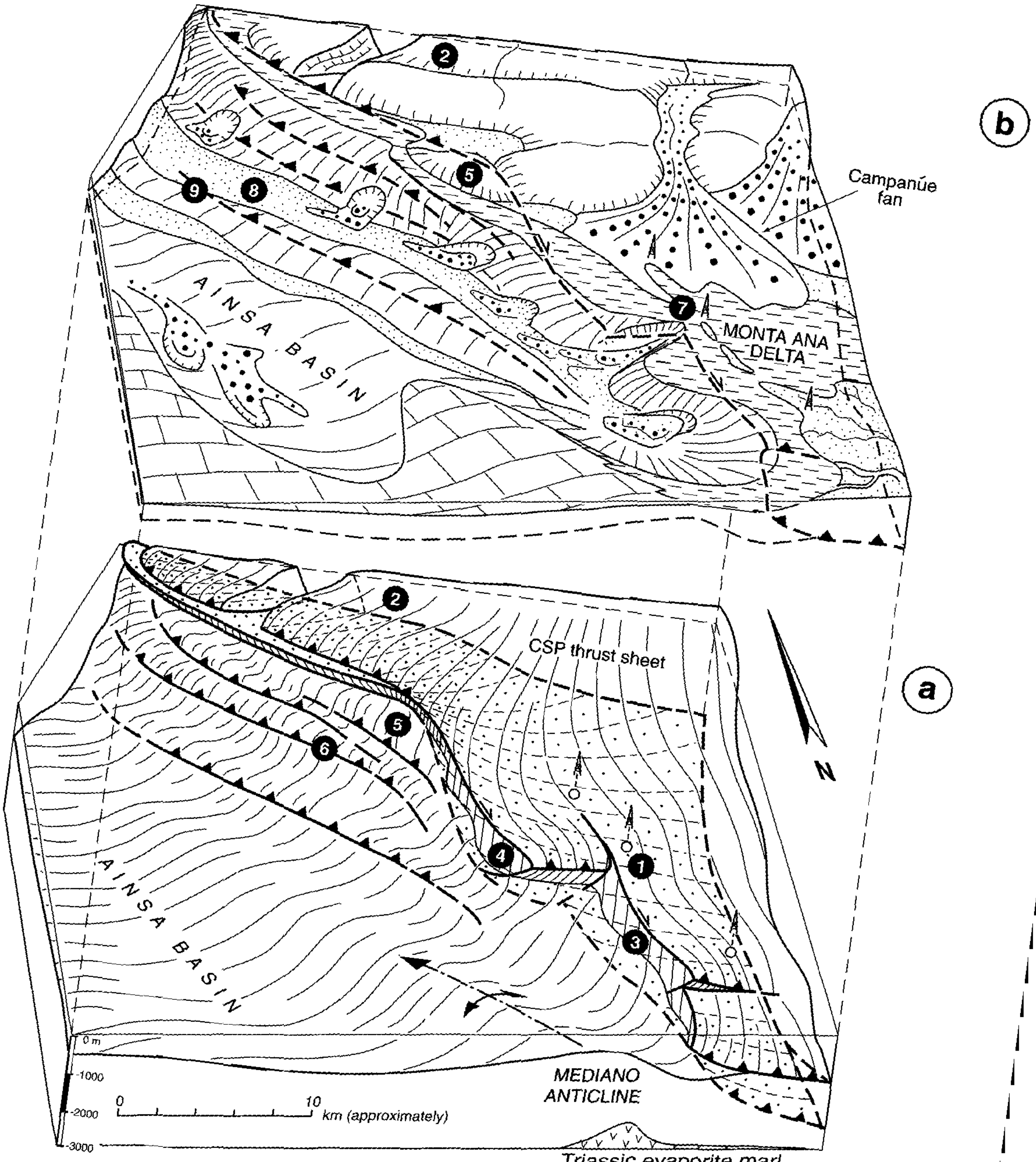
In the Pilbara, both the Early Archaean extension and the subsequent, Mid-Archaean (3.3 Ga), low-angle thrusting are accompanied by growth structures. In the Coppin Gap Belt of the Pilbara Craton [2], huge Mid-Archaean influxes of quartzose sandstones testify to a significant change in crustal behaviour at the end of the Early Archaean. These sandstones are hosted in a primary tectonic relief formed by transposition of unidirectional thrust imbricates orthogonal to folds of the synclinorial greenstone belt developing between granitoid plutons rising to high crustal levels. The recognition of the complex pattern of stacked unconformities and infilling of growth synclines by successive clastic suites, amongst which much conglomerate and coarse sandstone, is a necessary prerequisite for the understanding of the style and relative timing of the deformation during that crucial episode of crustal development (*cf* Lamb 1986).

In the previous discussion on stacked unconformities, the role of growth structures in the analysis of the South Pyrenean Tremp-Ager basin has already been mentioned. Growth structures abound along the western oblique ramp of the Central South Pyrenean (CSP) thrust sheet [5]. As early as 1977, Arthaud and coworkers described growth anticlines in that area. The combination of subsurface data with outcrop observations represented in the structural cross-section through the Esera valley (Fig. 4a in [4]; *cf* De Boer et al. 1991) offers a good example of the gradual levelling-out of en-echelon thrust folds during the late stage of Eocene basin infilling. At that time, the delicate balance between sedimentation and deformation of the piggyback basin gradually changed in favour of sedimentation, with the resultant overfill of the growth structures.

An integrated structural-geological and sedimentological approach along the oblique ramp adds substantially to the understanding of the deformation process of the entire thrust sheet. Along the oblique ramp, *en-echelon* parasitic thrust folds are connected by tear faults (Fig. 11).

The ramp rapidly descends eastwards to smooth out in a Triassic evaporite-hosted sole thrust underlying the bulk of the CSP thrust sheet. Further north, one of the vertical tear faults of the oblique ramp, the Foradada fault, flattens westwards to a low-angle thrust, the Cotiella thrust, emplacing Upper Cretaceous platform carbonates on Eocene slope sediments. The rapid westward ramping of the sole thrust to this high level of overthrusting was accompanied by considerable shear and frontal shortening in and below the Peña Montañesa unit in the footwall of the Cotiella thrust. Stratigraphical/sedimentological evidence reveals a higher platform carbonate content in the latter unit than in its surrounding slope deposits (Fig. 4 in [5]). This facies difference predestined the Peña Montañesa unit to act as a separate structural unit along the oblique ramp. Shortening was accompanied by the formation of a stack of slip sheets which, from their rear within the basin margin towards their front at the basin floor, show spectacular transitions from eutectonic thrust deformation with pervasive foliation to gravitational downslope slide structures and olistostromes accompanied by unconformities, respectively (Fig. 5 in [5]). Multiple slickensides along slip planes between the sheets display consistent rotation (Fig. 7 in [5]), as does the foliation (Fig. 6 in [5]), recording rotational emplacement of the slip sheets.

This intricate combination between deformation and contemporaneous slope sedimentation along the oblique ramp of a major thrust sheet, can be compared with that along the eastern oblique ramp of the CSP thrust sheet. A definite difference in timing of deformation and rotation, and in style of deformation between the western and eastern oblique ramps is revealed (Burbank et al. 1992a,b; Martinez-Peña et al. 1995; Bentham & Burbank 1996; Vergés &


b
Campanúe fan
MONTA ANA DELTA
AINSA BASIN
a
CSP thrust sheet
N
AINSA BASIN
0 m
-1000
-2000
-3000
0
10
km (approximately)
MEDIANO ANTICLINE
Triassic evaporite marl

Burbank, 1996). The latter is considerably younger than the former, and develops thrust folds parallel to the ramp rather than stepped tear faults. The difference of style of deformation along the opposite lateral ramps also forms an argument in the way emplacement of the thrust sheet is interpreted (see below).

Another result worth consideration is the transition from hinterland-dipping thrusts to foreland-dipping frontal gravity-controlled slides or slip sheets with the development of synsedimentary major recumbent folds [5] (*cf* Muñoz et al. 1994). It compares with the Infra-helvetic complex of the Swiss Alps where slip sheets announce the arrival of the Helvetic units (Milnes & Pfiffner 1977), and also with the occurrence of the Ponga gravity nappes (Fig. 5) in front of the the thin-skin thrust belt of the Cantabrian Mountains (Julivert and Arboleya 1986). Moreover, with the development of antiformal stacks below the rear of the upper South Pyrenean thrust sheets, the latter probably tend to become rootless with the development of extensional structures (Seguret 1972). These have been largely omitted in later structural analyses of the area. The result of disruption and uplift at the rear of a thrust sheet may have induced a change to a gravitational mode of emplacement during the upper Eocene aftermath of thrust translation [4, 5].

Translation of tangential displacement into vertical motion: deposystem geometry and mixed-mode basins

Much information on the style of synsedimentary deformation has been recorded in the 3D shape of deposystems, defined by their outline and depocentres. Important is the relationship between sedimentary and structural axes of a basin: the closer they coincide, the greater the structural control on basin infilling. The interpretation of the shape of deposystems in terms of negative tectonic relief (e.g. tectonically generated accommodation space) demands a detailed knowledge of the surface expression of different styles of deformation. Being used in geology to work with end-member models, one easily forgets that most of the observed deformation pat-

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Fig. 11. 3D-model of (a) the western oblique ramp of the Eocene CSP thrust sheet of the South Pyrenees (Spain), and (b) the transition between Montañana delta in the Tremp-Ager piggyback basin and the corresponding slope deposits of the Ainsa basin, controlled by the oblique ramp of the thrust sheet. The upper block diagram fits directly on top of the lower one. The time interval shown is the Lower Lutetian. Figure approximately to scale. (After Nijman & Nio 1975, [5], Mascle and Puigdefàbregas 1998; see also [5] for further reference).

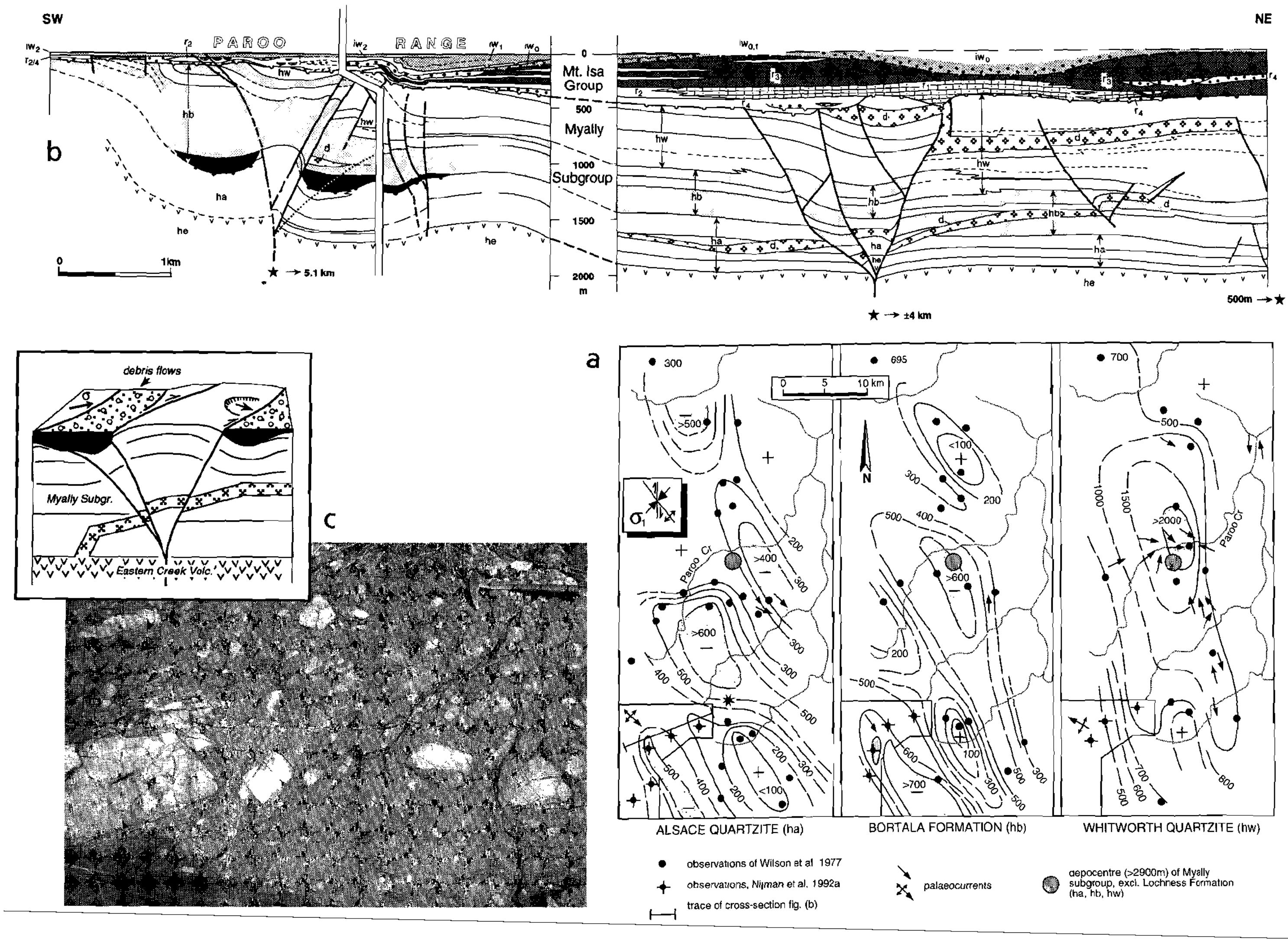
(a) *(below)* The CSP basal thrust plane rapidly climbs westwards from below -4000 m at the Centenera-1 borehole (1) to near-surface below the Cotiella massif (2). *En-echelon* dextral tear faults (3, 4) cause stepwise offset of the thrust structure of the oblique ramp. The dogleg structure formed by the Cotiella thrust and the Foradada tear fault (4) is the site of strong compressive deformation of the Peña Montañesa block (5). The latter is thrust upon frontal slip sheets developed in the footwall of the structure (6). Shortening in the footwall, the floor of the Ainsa basin, proceeds by southwestward fault propagation.

(b) *(above)* The thrust substrate largely determines the basin shape and facies distribution. During the Lower Lutetian, overfill along the Montañana delta front (right hand side) caused burial of the lateral ramp of the thrust sheet and increased slope instability. The Besians delta-front gully (7) developed from collapse of the delta slope at the site of an underlying footwall syncline. The Ainsa basin is underfilled, probably due to bypassing of sediment to the deeper basin floor further to the NW. Major submarine channel fills, like the Arro channel (8), occupy growth synclines. The channels tend to overstep southwestwards with the propagation of the thrusts in the footwall block. The thrust planes show frequent lateral transitions into unconformities (9), also an indication of a variable balance between deformation and sedimentation.

terns are of mixed mode (Gibbs 1987). These patterns are therefore more complicated than those derived from, for instance, pure normal faulting or thrusting. The geometry of deposystems may reflect not only the behaviour of a basin-marginal fault, such as alluvial fans along the leading thrust fault of a foreland basin, but also of intrabasinal structures like *en-echelon* folds in a wide zone of simple shear between two moving plates (*cf* Fig. 12a).
A situation of underfill (Fig. 11) creates the better opportunity to reconstruct the geometry of deformational structures, since not only the distribution of thickness but also of facies will be influenced by growth structures that regularly affect the sediment-water/air interface. Overfill of growth structures in a basin may still create differential thickness, but may not influence the facies distribution.
At basin margins, the controlling deformation structure defines the fall line of the basin and therefore intensely influences both facies and depocentre, even in situations of overfill (thrust margin with rapidly basinward moving facies zonation combined with outward moving depocentre) (Fig. 11).
In all situations, a thorough knowledge of geomorphic expression of styles of upper crustal deformation is necessary to trace the way back from deposystem shape to controlling style of deformation. For pure normal faults this is not difficult to visualize. Leeder and Gawthorpe (1987) give instructive examples of the influence of normal listric fault block rotation on facies distribution in single and multicomponent systems, particularly of alluvial fan facies (see also next section). Combined with Heward's 1978 concepts, it is easy to recognize that an increase in rate of listric normal faulting produces fan-head entrenchment and strong fan progradation above the pivot line of the halfgraben, but fan retreat and steepening along the hangingwall of the normal fault.

Strike-slip transport, tangential to the earth's surface, is much more complicated to translate into patterns of uplift and subsidence.
The style and sequence of deformations above a strike-slip master fault at depth have received much attention in literature (e.g., Tchalenko 1970, Wilcox et al. 1983, Naylor et al. 1986). However, very few papers deal with the surface expression of such complicated structures as Riedel-faulted *en-echelon* folds or with basin formation during the principal displacement stages of strike-slip faults (*cf* Biddle & Christie-Blick 1985). In recent sandbox experiments, Nieuwland (1998) considers the translation of strike-slip motion into basin formation for the first time sys-

Fig. 12. Strike-slip-controlled sedimentation patterns of the Mid-Proterozoic Myally Subgroup, Paroo Range (framed in fig.[a]; see for regional setting Fig. 4) and surroundings, Mount Isa Inlier, Australia. (After Nijman et al. 1992a).
(a) Large-scale *en-echelon* folds inferred from isopach patterns in three successive formations of the Myally Subgroup are interpreted to result from north-oriented dextral shear in the basement [s1: SW-NE on the left]. Juxtaposition of folds (at *) is probably due to late strike slip along an east-striking transverse fault (*cf* Fig. 4).
(b) D_1-flower structures in a SW-NE cross-section along the Paroo Range. The section has been restored for later D_2 to D_5 deformations. The flower structures occur at regular distances of about 4.5 km (*) in the Myally Subgroup (ha,hb,hw). They diverge upwards from the top of the Eastern Creek Volcanics (he) (*cf* Fig. 12a), and are unconformably overlain by the Mount Isa Group (r_{1-4}, w_{0-2}).
(c) Block diagram of the transpressive flower structure at the left hand side of Fig. 12b; rim synclines are filled with matrix-supported bouldery mass-flow deposits (photograph: 30 cm hammer for scale). They are derived from the adjacent central part of the flower structure: clear evidence for the synsedimentary character of the deformation.


SW
NE
PAROO RANGE
Mt. Isa Group
Myally Subgroup
b
0 1km
★ → 5.1 km
★ → ±4 km
500m → ★
debris flows
Myally Subgr.
Eastern Creek Volc.
c
a
ALSACE QUARTZITE (ha)
BORTALA FORMATION (hb)
WHITWORTH QUARTZITE (hw)
Paroo Cr
observations of Wilson et al 1977
observations, Nijman et al. 1992a
trace of cross-section fig. (b)
palaeocurrents
depocentre (>2900m) of Myally subgroup, excl. Lochness Formation (ha, hb, hw)

tematically and quantitatively (*cf* Gölke 1996). In the Penninic and/or Valais troughs of the Swiss Alps, an important feature as compartmentalization of flysch basins may have been caused by such *en-echelon* strike-slip structures (Kelts 1981, Homewood & Caron 1982). The influence of early strike slip on the formation of later thrust sheets may so have been considerable. Generally, later deformation has rendered such early deformation structures inaccessable to conventional structural-geological analysis. Deposystem shape then is the only record left to consider.
The influence of intrabasinal strike-slip deformation is well demonstrated by the example from the Mount Isa Inlier, where synsedimentary strike slip was shown to be the first-phase deformation in this mobile belt by integrated structural-geological and sedimentological analysis (Nijman et al. 1992 a,b) (Fig. 12).

In the study of the Central South Pyrenean thrust sheet [4], controls of thrust-sheet displacement on vertical movements have been extensively discussed. In a complicated thin-skinned thrust belt like that of the South Pyrenees, the amount of uplift or subsidence depends on how and along what sort of structural elements shortening was accommodated at a particular stage of basin evolution (Fig. 13, and for more detail Fig. 15 in [4]; see also Artoni & Meckel's 1998 study of the Barrême thrust sheet-top basin in the French Alps). Some of the vertical effects of this deformation resemble base-level changes: uplift of a piggy-back basin by up-dip displacement of the thrust wedge along the sole thrust has the same effect as base-level lowering. Other effects are exclusive to structural control, such as one-sided lowering in the rear of the thrust sheet coeval with uplift in the toe during transport of the thrust sheet through its own bending point. This leads to the next topic related to large-scale growth structures within structurally-controlled basin settings.

Basin-axis shift, depocentre migration and basin architecture: one- and multi-component basin fills and drainage bends

The interplay of marginal alluvial fans, longitudinal transport systems, and intrabasinal growth structures is very well illustrated in most narrow trough-shaped orogenic basins, characterized by active lateral slopes and a gently plunging basin axis. The drainage patterns are characterized by sharp bends (e.g., Fig. 8 in [4]), which render any simplification of source-basin relationship based on 2D cross-section, such as done in the present state of the art of numerical modelling, of limited value. Moreover, given important changes in the total crustal mass balance of an orogen, longitudinal drainage may reverse over 180°, even more than once, during a basin's history (e.g. Eisbacher 1985: molasse in Canadian Rocky Mts. and Swiss Alps; *cf* S. Pyrenees: Tertiary vs Recent drainage).
In such complicated time-integrated settings, tracing of the shift of basin axis or depocentre over successive short increments of basin infilling may yield important information on the behaviour of the controlling deformation. For such analysis, the basin architecture has to be known in substantial detail (*cf* Bentham et al. 1992).
Outward depocentre migration of basins, away from the orogenic axis, is the rule during the compressive phase of an orogen. This is well illustrated by the Upper Cretaceous to Upper Tertiary basin sequence of the Pyrenees (Puigdefàbregas & Souquet, 1986; see also Fig. 6 in [4]) and the Oligocene to Pliocene history of the Molasse basin (e.g. Burckhard & Sommaruga 1998).

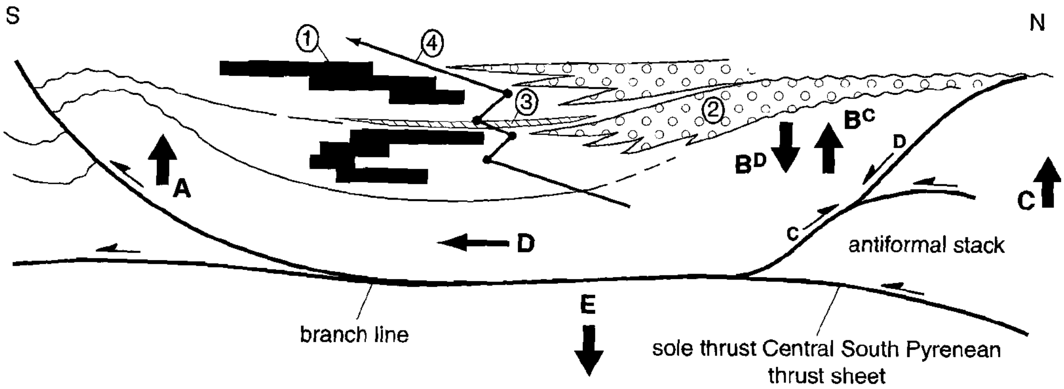


Fig. 13. Graphical representation of the translation of thrust motion into patterns of uplift and subsidence. 1: axial fluvial system; 2: alluvial fan systems; 3: marine or brackish water onlap; 4: trace of basin axis; A: thrust sheet toe uplift; B: effects at rear of the thrust sheet: uplift (B^C) related to antiformal stacking and backthrusting (C), subsidence (B^D) related to forward gravitational thrust sheet motion (D); E: foreland basin subsidence. (Modified after Marzo et al. 1988 and [4])
Depending on the rate of thrust sheet motion through its synclinal bending point, the balance between frontal or rear uplift, and the rate of sediment supply, the position of the basin axis is subject to lateral shift. (For further considerations, see Fig. 15 in [4]).

If such a pattern of depocentre shift is absent or has been interrupted, integrated analysis of deposystem and structure may help analyse the cause. This is the topic of the next two examples.

In the Cantabrian Mountains [3], molasse fans drain anomalously away from the foreland basin, backwards into piggyback basins of the arched thin-skinned fold belt. There, the drainage bends into a generally strike-parallel direction. Although these clastic deposits have been generally considered post-orogenic (Ziegler 1989; Alonso et al. 1991), a syn-thrust timing of their deposition has now been documented (p. 286 in [3]; Nijman & Savage 1991). The observation of Upper Carboniferous stepwise, fold belt-parallel depocentre shift between major sinistral lineaments with skewed fans (Fig. 9a), led to the interpretation of a two-tier structural control. Strike-slip between deep-seated basement blocks accounts for a pull-apart basin structure (Fig. 9b). The resultant space was accommodated by upper crustal thin-skin thrusting and sedimentation. Tectonic control, therefore, is of mixed-mode type which is important for the general structural solution of this part of the Variscan Orogen.

Another example is provided by the Tremp-Ager piggyback basin of the South Pyrenees [4]. On the general Upper Cretaceous to Tertiary outward (=southward) *inter*-basinal depocentre migration of the orogenic successor basins, an *intra*-basinal zig-zag trace of the basin axis is superimposed coinciding with stratigraphical megasequence boundaries (Fig. 13). Antithetic, northward basin-axis shift might correlate with activation of the southward motion of the thrust sheet as long as the controlling frontal branch line of the propagating piggyback system remains stationary. If on the other hand, the branch line propagates in the direction of interbasinal depocentre shift, a next successor basin hosts the newly shifted basin axis, and thus depocentre. Such intrabasinal basin-axis shifts have been numerically modelled by Zoetemeijer (1993) and by Den Bezemer (1998). Zoetemeijer produced synthetic depocentre shift in a piggyback basin during forward propagation of the thrust front, antithetic during out-of sequence back-stepping. Den Bezemer et al. (1998) added grainsize distributions to a much more elaborate (but still 2D) numerical model of fault-bend fold basins. Den Bezemer (1998) could reproduce the zig-zag trace of the Tremp-Ager basin axis, in particular for the gravity emplacement variant mentioned in my work (Fig. 15c in [4]; *cf* Tucker and Slingerland 1996: *their* fig. 15) This illustrates the power of numerical modelling, when constrained by field observations.

Basin misfit and rotational emplacement of thrust sheets: replay of inherited structures

Over the past ten years, a wealth of data has been published on the sedimentary architecture of the Pyrenean Cretaceous and Tertiary basins. Over the same period, the understanding of shallow and deeper structures of the Alpine Pyrenean belt has increased considerably, in particular because of the ECORS deep seismic data (Roure et al. 1989; Muñoz 1992) and the restoration of several other cross-sections (Vergés et al. 1995).

The sedimentological and structural-geological approaches to Pyrenean geology, successfull as they were, have nevertheless led to inconsistencies in the models of the Alpine evolution of the Pyrenees.

In the South Pyrenees, the ensemble of Tertiary orogenic basins does not really reconstruct to a comprehensive paleogeographical fit. This is extensively discussed in my 1989 article on thrust-sheet rotation and Tertiary basin configuration [5]. The paper was meant to be a discussion paper, reviewing the state of the art shortly after the publication of the first results of the ECORS deep seismic profile. Clearly, the ECORS data failed to encompass the 3D South Pyrenean basin configuration. However, a palinspastic solution was proposed to best fit the restorations in cross-section available in 1989. The model implied rotations of the thrust sheets carrying the basins. The rotations had been partly revealed by paleomagnetic observations, partly by direct structural observation of thrust-sheet asymmetry and measurememnt of rotational slickensides. It led to a paleogeographical basin configuration in which the basin compartments are oriented *en-echelon* with respect to the Iberian plate boundary and to the Pyrenean suture, the North Pyrenean Fault Zone (Fig. 17 in [5]). The South Pyrenean basins so resemble in configuration and scale the intrabasinal growth folds of the Mount Isa Inlier (Fig. 8a).

Subsequently, new data have been published on the amount of shortening in the eastern Pyrenees and along the eastern ramp of the CSP thrust sheet (Muñoz 1992; Vergés et al. 1995; Vergés & Burbank 1996). These publications provide stratigraphical correlations based on detailed paleomagnetic analysis studies and magneto-stratigraphy, and prove beyond doubt the existence of rotations (see also Dinarès et al. 1992, Keller 1992).

On the basis of that new evidence, Vergés and coworkers advocate a paleogeographical solution in which the clastic sediments of the Tremp basin are derived exclusively from the Pyrenees. This implies that the source-depocentre relation between the Tremp-Ager basin and the eastern Pyrenean source area was not dramatically disrupted during thrust evolution. Fundamental in that solution is a due southward transport of the CSP thrust sheet in conjunction with the higher thrust sheets of the eastern Pyrenees. The two lateral oblique ramps show pronounced rotations of the footwall sediments, clockwise along the western oblique ramp anticlockwise along the eastern ramp (*cf* Martinez-Peña et al. 1995).

In fact, the Vergés and Burbank (1996) study focusses mainly on the paleogeography from the Upper Eocene onwards, i.e., when the true Ebro foreland basin configuration came into existence. This leaves much of the argumentation of my 1989 paper intact. The sediments in which rotation now has been measured are of a different age along the west side of the CSP thrust sheet than these along the east side. This also supports the proposed emplacement, first by motion to the southwest, then by sliding to the southeast [5: p.37 ff.].
The configuration of thickness distribution during the Jurassic-Cretaceous (Peybernes 1976), the replay of old lineaments, the structural asymmetry of the Montsec thrust sheet, and the palaeocurrent directions bending northwestwards from the Tremp-Ager piggyback basin in the direction of the Axial Zone of the western Pyrenees still have to be accounted for. On the other hand, the proposed *en-echelon* structure of pre-Upper Eocene basins implies assumptions about the continuation of the Catalan basin which are speculative and not easy to prove.

Summary and conclusions

The Archaean basins
The Archaean basins probably offer the most illustrative example of the impact recognition of growth structures and associated unconformities may have on a structural concept of crustal development ([1,2], *cf* Lamb 1986). The observation that the normal faults of the North Pole Dome, the Coppin Gap Belt, and the Barberton Belt are synsedimentary and synvolcanic is important for the interpretation of these basins, since growth faults may be expected to have had a direct relationship with the volcanic and sedimentary basin shape.
In the Pilbara, the Early Archaean arrays of tensile growth structures are not unidirectional, and are apparently unrelated to the geometry of batholith doming. Felsic volcanic events coincide with extensional growth faulting. Combined with the extensive hydrothermal veining and venting, this might support a model of subaqueous caldera collapse for these early basins. At present, the association of barite and silica with bimodal volcanism is known from white smokers in submarine calderas situated in relatively deep (back)arc settings of the west Pacific (Ishibashi & Urabe, 1995). The North Pole Chert, however, was deposited in a shallow-water environment [1]. The barite mounds, similar in appearance to the Miocene gypsum mounds of the Mediterranean (Schreiber et al. 1976), are interpreted as primary deposits, that provided clasts to diamictite layers in the surrounding onlapping basin fill sequence. Hydrothermal vents and lava flows must have raised the water temperature, locally to above boiling point [1].
In the Barberton greenstone belt, chert precursor sediments and felsic lava have been related to phreato-plinian explosive volcanism (Heinrichs 1984). In the Buck Ridge Chert, now under investigation (Fig. 10b), felsic intrusion to a level only a few hundreds of metres below the water-sediment interface must also have accounted for a high thermal gradient (*cf* De Wit et al. 1987).

Little is known about the thickness of the Early Archaean crust, its rigidity or how much of it underwent brittle deformation. In the Pilbara, tensile collapse structures and related deposystems at the Early Archaean earth surface may have been superposed on linear extensional structures at depth (Zegers et al. 1996). The data do not support an explanation of extension in terms of orogenic collapse after crustal thickening. If intense tectonic slicing and stratigraphical repetition did occur after deposition of the lower Archaean Warrawoona Group (Zegers 1996, White 1998, [2]), the rigid basaltic upper (?) crust at the onset of Mid-Archaean thrust tectonics would have been only an estimated 3 to 4 km thick, corresponding with the thickness of the slices involved in upper crustal deformation ([2], Nijman 1998). In the Barberton greenstone belt, on the contrary, extension at the uppermost crustal level may have coincided with important Early Archaean thrusting and crustal thickening (De Ronde and De Wit 1994, De Wit et al. 1987). Linearity of facies patterns and of crustal deformational trends (e.g., backarc and arc settings, *cf* Eriksson et al. 1994, 1997), however, is far from being proved and mainly based on analogy with Phanerozoic and Recent plate configurations.

The Early Archaean chert basins formed episodically within an overall mafic/ultramafic volcanic environment. They were situated around sea level. The near-absence of normal clastic sedimentary sequences from the greenstone sequences in both Pilbara and Kaapvaal cratons indicates that relief was low, and hinterland restricted.
Vlaar (1986) and Vlaar et al. (1994) advocate a geophysical model of a thick, cooling Archaean lithosphere composed of a thin greenstone belt-bearing protocontinental crust (17.5 km) floating on 40 km basalt overlying 250 km of harzburgite. The model of a stratified lithosphere is mainly based on the assumption of a hot mantle rising diapirically to shallower depths where pressure-release melting generated a thick basaltic upper manle (for reviews of other models, see e.g., Zegers [1996] and De Wit & Ashwal [1997]). It is interesting that this matches the observations and inferences on the volcano-sedimentary basin formation in several aspects. According to the model, surficial cooling of the basalt layer generates the foundering of microplates of hydrated basalt which, with pressure increase at depth, pass into eclogite. Upon sinking into the underlying harzburgite, eclogite will start to remelt generating tonalite and basalt. Additional basaltic magma is formed by pressure-release melting of the upwelling harzburgite replacing the sinking eclogite. Cooling, sinking and remelting of basalt through its eclogite phase and the subsequent rise of tonalitic and basaltic magmas may account for the episodic bimodality of the volcanism during formation of the chert basins.
Moreover, the growth-fault controlled basins of the Lower Archaean of the Pilbara and Barberton areas seem to have resulted from uplift of the crust, since the basin fills are regressive with respect to the underlying pillow basalts. Such uplift was accompanied by felsic igneous activity and evidently by stretching. In the North Pole Chert [1] of the Pilbara (and probably also in the Buck Ridge Chert of the Barberton greenstone belt), the basin sequence terminates with a transgressive onlap showing a return through subsidence to the subaquatic conditions for ubiquitous and widespread formation of pillow basalt.

In Vlaar et al.'s (1986,1994) model, the Early Archaean protocrust still remained too thin and too weak to allow large horizontal stresses necessary for normal plate tectonics and to support major relief to form source areas. In such a crust, large collapse structures can be expected to have formed. In both cratons, substantial uplift and primary relief must have been generated for the first time during the 3.3 Ga-old inversion from tensile deformation to thrusting and inter-batholith compression (Eriksson et al. 1997, [2]). It produced the first major influx of siliciclastic sediments from nearby sources (alluvial fans), reworked in coastal deposystems (quartz arenites) [2] and in deeper water turbidites.

Finally, the interference of doming over rising batholiths with regional low-angle thrust deformation (two modes of crustal behaviour that form another matter of hot debate in Archaean geology [De Wit & Ashwal 1997, Hamilton 1998, De Wit 1998]) would not have been detected without knowledge of the onlap relations and stacking patterns of unconformities. They tell us how to back-rotate pre-unconformity deformational structures. This, in turn, bears on their geometric and kinematic interpretation: many shear zones appear to have been low-angle detachments, either tensional, compressional or both in succession.

The Mount Isa mobile belt
Growth structures in the Mount Isa Inlier revealed a synsedimentary history of strike-slip deformation of the belt starting as early as the deposition of the Myally Subgroup in the second cover sequence. Transpressive and transtensive processes operated synchronously with sedimentation of shallow marine sandstone and marginal fan deposits; an origin of the Mount Isa belt hitherto unknown. It turned out that many structures considered to be coeval with or later than the main-phase compression have been inherited from that early phase. The origin of the Mount Isa Inlier, therefore, cannot be entirely explained as a rift basin (Blake & Stewart 1992), but the longitudinal fault-block structure of the belt may have been formed along a transform contact, like the geologic setting of the Californian shelf.

The Cantabrian Orogen
The Variscan Cantabrian Orogen [3] surprisingly shows that late-stage coarse-clastic alluvial fans better reflect control by deep-seated crustal wrench faults than by surficial thrust structures. At least partly, the thin-skin thrust pattern depends on the same deep-seated mechanism. Transtensional basement control is responsible for block tilting, modifying the backfolding of the thrust sheets and generating the concurrent collapse of its fanglomerate cover. Such a conclusion can only be reached by thorough 3D integrated analysis. Drainage and skewing patterns can be recognized that way and they showed to be necessary elements to detect the synsedimentary two-tier structural control, which forms a strong argument in favour of the overall role of escape tectonics in that part of the Variscan orogen.
Stephanian sinistral pull-apart tectonics in the basement of the Cantabrian Mountains mirrors that in the Pyrenees (Fig. 9b), where a dextral transtensional setting has been interpreted from clastic sedimentation patterns by Speksnijder (1985), and where the importance of Variscan extension along the axis of the present-day mountain range was stressed by Vissers (1992). Such a basement configuration for the Cantabrian Mountains and the Pyrenees fits the concept of escape tectonics (Matte 1986) related to the motion of the Palaeo-Africo-Iberian promontory. The latter was responsible for the initiation of the Ibero-Armorican Arc of the Variscan Orogen.

The Tertiary basins of the Pyrenees
The piggyback basins of the Tertiary Pyrenean orogen [4] offer a good example of interplay between two growth structures: the antiformal stack at the rear, and the frontal thrust fold. Although subsidence also depends on the mass balance at deeper crustal levels, the mutual structural relationships of the front and rear sides of the thrust sheet largely control the architecture of sequences and cycles in the piggyback basin and the "wobbling" trace of the basin axis.
Many growth structures, by their nature, are related to slope instabilities in the sedimentary basin in which they occur. Basinward updip thrusting and downdip gravitional sliding are often

not well analysed or distinguished from each other; and, gravitional emplacement of thrust sheets may have been largely underestimated. At least during its later development, this may be the case with the CSP thrust sheet in the South Pyrenees.

At a larger scale [5], in particular the analysis of growth structures along the oblique ramps of the CSP thrust sheet suggests that inheritance of structures, asymmetry of deformation patterns, and rotation tally with a mixed-mode structural regime, rather than with a simple compressive thin-skin thrusting regime. Both strike slip and rotations, if not recognized or accounted for, hamper the 2D restoration of cross-sections, because unknown rock volumes have moved into and away from the trace of the section.

Evidently, this also bears on the 3D structural concept. For the Alpine cycle of the Pyrenees, synorogenic sinistral strike slip along the North Pyrenean Fault system is well defined structurally, stratigraphically, and from paleomagnetism and plate rotation. *en-echelon* structures, partly along older lines of passive margin extension and structures inherited from the previous Variscan Orogeny, play a role in defining the Alpine basin shape. This renders a solution for the orogenic basin configuration attractive in which not the inversion from extension to thrusting at right angles to the orogenic axis is the fundamental control of basin formation, but a transition from sinistral transtension to transpression [Fig. 17 in [5]). Here again, at an orogenic scale, a strong correlation between sedimentological investigation and structural analysis appears to be an effective means of finding solutions to problems of basin misfit and space.

Conclusion

In summary, recognition and detailed integrated analysis of growth structures add substantially to the understanding not only of the evolution of sedimentary basins, but also of the kinematics of the deformation which controls these basins.

This holds in particular for the Phanerozoic examples discussed, because the process of growth can be calibrated chronologically. Also in the Proterozoic, the analogy with the Phanerozoic examples and the comparable crustal composition and plate behaviour helps to interpret growth structures in terms of geodynamic models. Sedimentologically, there is a major difference: the largely unknown influence of the absence of vegetation on rates of erosion and sedimentation, in particular in non-arid environments.

To interpret Archaean growth structures geodynamically, much more chronostratigraphical control remains a first need. Because of their relationship with sedimentation patterns on the one hand, and with tonalite intrusions, volcanic feeders, and hydrothermal vents on the other, the Archaean growth structures provide a special clue to the interpretation of the build-up of the early crust and its topographic expression, and of the interface between lithosphere and hydrosphere. Detection of emersion surfaces may even help to directly interpret the early atmospheric conditions. Analysis of the tidal character of some of the Archaean sediments, and of the interaction between growth structures and fluid circulations are promising ways to go. And although the possibilities for comparison with Phanerozoic and Recent examples are very restricted, it will be worth the effort.

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Curriculum vitae

Born (1939) and educated (till 1957) in Rotterdam, the author finished his studies in biology and geology at Free University in Amsterdam, specializing on the Mesozoic carbonate platform of the Central Apennines, and became a lecturer at that university in 1966. In the national, university education program on sedimentology (I.O.S), he lectured carbonate sedimentology. After having moved to the Geological Institute of Leiden University in 1972, the sedimentology of clastic deposystems, in particular in the Pyrenees, Cantabrian Mountains, and South Portugal, became a major issue of his research. In 1979, as a senior sedimentologist he joined, for a decade, the Department of Structural Geology with which he moved to the new Institute of Earth Sciences at Utrecht University, linking up sedimentology with structural geology in teaching and research. In 1984/85, he spent a year at the University of Adelaide, South Australia, while also working with Broken Hill Propriety Ltd. on the application of concepts of structurally controlled sedimentation in the geology of base metals in the Flinders Ranges. This brought the Precambrian within sight and, from 1985, emphasis was on the sedimentation and structural control, first of Proterozoic (Mount Isa), then of Archaean sedimentary basins (Pilbara) in Australia. Recently, in 1998, a 3-months stay at Cape Town University widened the scope of that research to imply the Archaean of South Africa. In the meantime, in the Sedimentology Group at Utrecht University, continued interest in the South Pyrenees has now led to a numerical modelling study of the Tremp basin.