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Indosinian deformation of the Songpan Garzê Fold Belt, northeast Tibetan Plateau

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Abstract

Deformation of the Songpan Garzê Fold Belt, southwest China, occurred progressively during the Indosinian orogeny (ca. 230–200 Ma). Two phases of south-directed deformation are identified: D_1, associated with pervasive thickening of the Songpan Garzi sedimentary pile and detachment of that portion of the fold belt onlapping the Yangtze passive margin; and D_2, a localized phase of deformation associated with transpressive shortening of the fold belt's southeast margin. An arcuate form-surface in the southeast fold belt reflects the distribution of D_1 and D_2 structural phases and the diachronous migration of these phases into the fold belt. This migration accommodated lateral growth and cumulative sinistral transpression within the fold belt's eastern margin. An enigmatic metamorphic complex, the so-called Danba antiform, is constrained to have formed during the early stages of the D_2 deformation. This was associated with diapiric upwelling of buoyant migmatised basement and domal distortion of the overlying metasedimentary pile.

Keywords: Indosinian orogeny; Progressive deformation; Basement-cored antiform; Décollement; Songpan Garzê Fold Belt; Tibet

1. Introduction

The Songpan Garzê Fold Belt is one member of a network of Permo-Triassic mobile belts that make up the northeast Tibetan Plateau and southwest China (Fig. 1). Previous work in this region has focussed on the protracted evolution of the plateau's margin, marked by the Longmen Mountains Thrust Nappe Belt (Fig. 1), and its relationship to Cenozoic (Himalayan) orogenesis in Asia (Dirks et al., 1994; Burchfiel et al., 1995; Kirby et al., 2000). Relatively little research has examined the early Mesozoic (Indosinian) tectonic evolution of the plateau interior, formed by the Songpan Garzê Fold Belt. Throughout most of the fold belt, Indosinian deformation is associated with lower greenschist facies metamorphism. Locally, however, areas of amphibolite facies metamorphism broadly coincide with the intrusion of syn- and post-tectonic plutons that constrain the Indosinian and Cenozoic deformation events (Roger et al., 1995, 2004; Wallis et al., 2003). These plutons are generally believed (Roger et al., 2004) to be sourced from an underlying Proterozoic basement that is part of the Yangtze block.

This paper focuses on Indosinian deformation of a region surrounding the township of Danba in the southeast Songpan Garzê Fold Belt (Fig. 1). Fabrics preserved in this region display an arcuate trend that encompasses a sequence of high-grade metamorphosed Paleozoic rocks (Huang et al., 2003a; Wallis et al., 2003) that make up the Danba antiform (Fig. 2; Xu, 1991; Burchfiel et al., 1995). These Paleozoic sedimentary sequences overlie the Proterozoic basement of the Yangtze block and the interface between the two is believed to be a décollement developed during a homogeneous Indosinian thickening event (D_1) (Calassou, 1994; Roger et al., 2004).

Calassou (1994) and Burchfiel et al. (1995) identified a post-D_1 ductile deformation within the fold belt, although neither described the geographic distribution of those structures nor their kinematic relationship to D_1 Indosinian thickening. Roger et al. (2004) described a second generation of south-directed Indosinian deformation within the Danba antiform but details of the relationship of that

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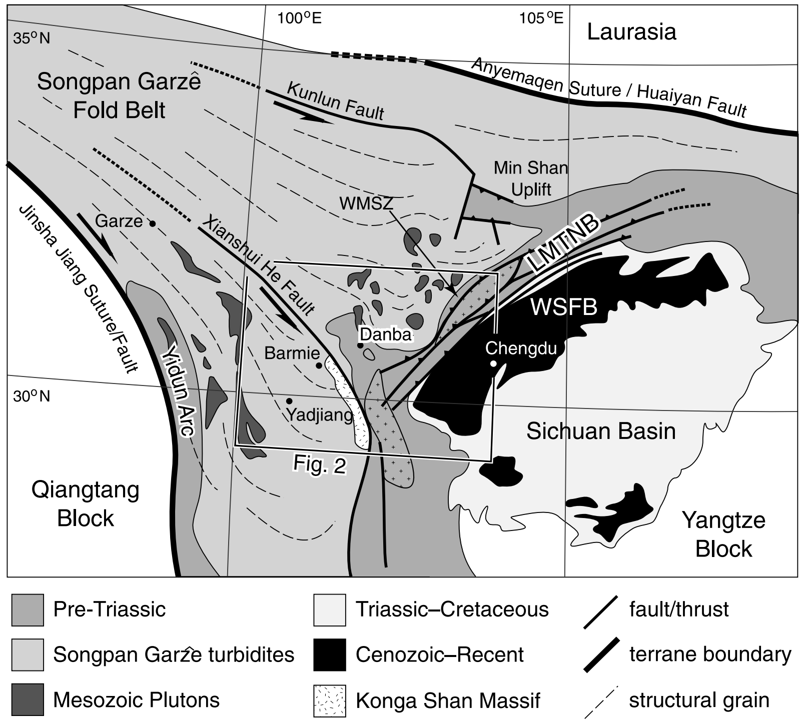


Fig. 1. Map of the major tectonic elements of southwest China, including the Songpan Garzê Fold Belt, Sichuan Foreland Basin, Western Sichuan Foreland Basin (WSFB) and surrounding continental blocks. Also illustrated are the major brittle fault zones that dissected the fold belt and reactivated its margins during the Cenozoic. Differential strain between the Songpan Garzê Fold Belt and Yangtze Block was accommodated by a listric array of southeast-directed thrusts known as the Longmen Mountains Thrust Nappe Belt (LMTNB).

deformation to development of the décollement surface are lacking. Burchfiel et al. (1995) also described 'late folding' that they inferred to be responsible for significant overturning of earlier D_1 structures and suggested that at least some of this late folding was Cenozoic in age and contributed to the arcuate rotation of structural fabric. Further, Burchfiel et al. (1995) suggested that late folding was locally oblique to the D_1 Indosinian phase and partially explained the structure of several metamorphic domes in terms of oblique fold interference.

In this paper we attempt to show that much of this deformation is related to two progressive phases of Indosinian shortening and that the Cenozoic overprint has an insignificant impact on the Indosinian architecture. We identify two main phases of progressive Indosinian deformation within the Songpan Garzê Fold Belt (D_1, D_2). Both phases are associated with the development of upright folds (F_1, F_2) and pervasive cleavages defined by an alignment of layered silicates. S_1 is a slaty cleavage, S_2 is either a crenulation cleavage or differentiated layering, and both are constrained by overprinting relationships to have developed prior to the emplacement of ca. 190 Ma post-orogenic granites (Calassou, 1994; Roger et al., 2004). We relate formation of the arcuate structural trend recognised in this fold belt to the domal evolution of the Danba antiform and the structures recognised along the Tibetan Plateau's eastern margin and in the Longmen Mountains (Fig. 1).

2. Structure of the southeast Songpan Garzê Fold Belt

The triangular shaped Songpan Garzê Fold Belt (Fig. 1) is confined by major terrane boundaries, marked by ophiolite-defined sutures and magmatic arcs (Chang, 1997; Reid et al., 2004). The northern boundary of the fold belt, marked by the A'nyêmaqên suture (Fig. 1), accommodated northward subduction of Paleo-Tethys during the Indosinian Orogeny (Sengör, 1984; Yin and Nie, 1993; Chang, 1997). To the east, the Songpan Garzê Fold Belt is juxtaposed against the passive margin of the Yangtze Block. Early work in the region interpreted this juxtaposition to reflect either intraplate subduction of the Songpan Garzê basin (Sengör, 1984; Lou, 1991) or emplacement of an allochthonous fold belt (Burchfiel et al., 1995). Most recent studies, however, have interpreted this juxtaposition to primarily reflect onlapping deposition of Songpan Garzi turbidites onto a passive margin (Calassou, 1994; Chen et al., 1995; Worley and Wilson, 1996). Prior to the Indosinian Orogeny, the eastern Songpan Garzê basin's 6–8 km succession is inferred to have disconformably overlain a 5–7-km-thick succession of Paleozoic platform sediments that formed the cover of the Yangtze passive margin and the Proterozoic basement on which it was constructed (Chen et al., 1995; Li et al., 2003).

Following the onset of the Indosinian Orogeny, sometime after 230 Ma (Bruguier et al., 1997), the Yangtze passive margin and its stratigraphic relationships were

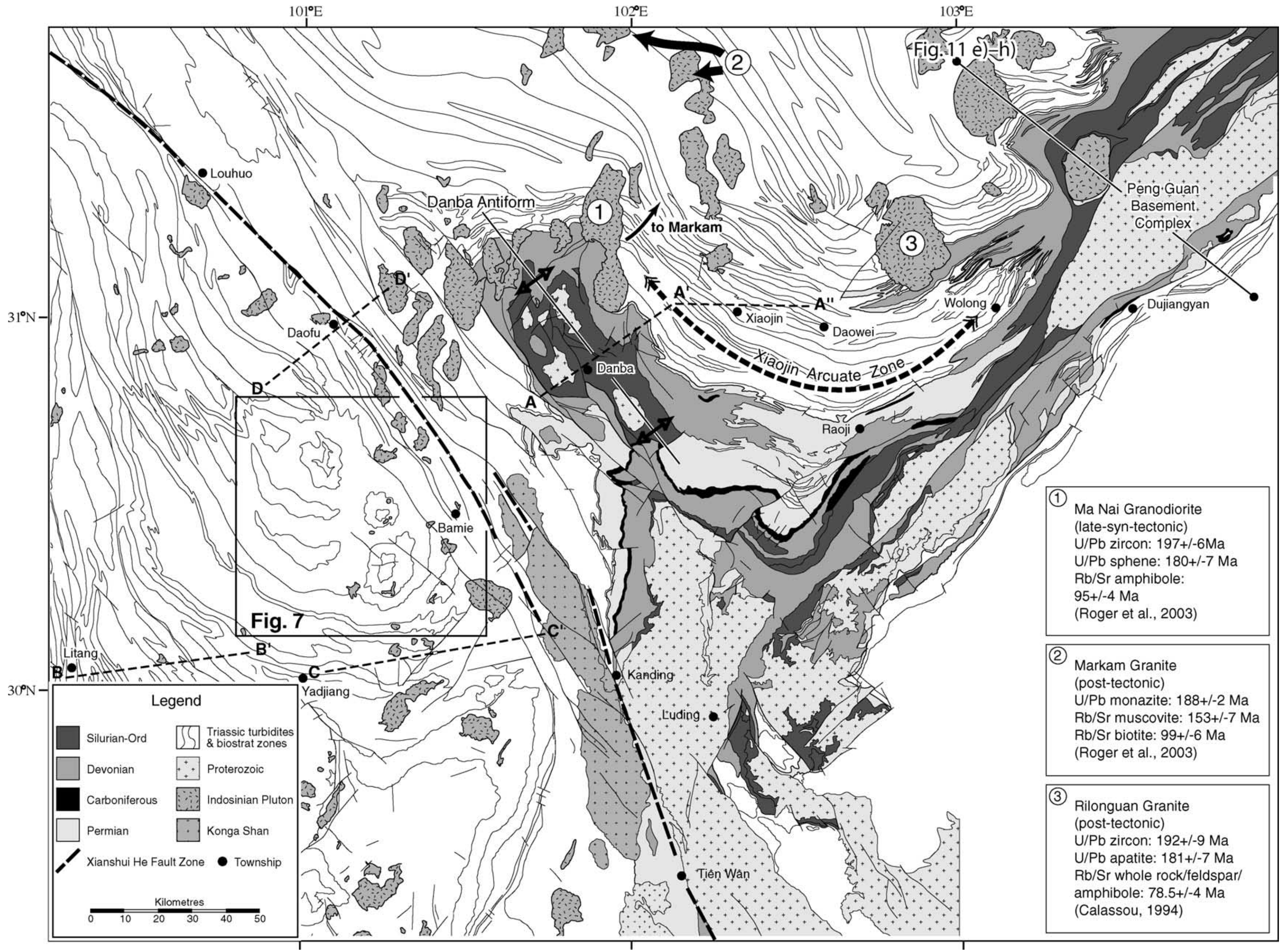
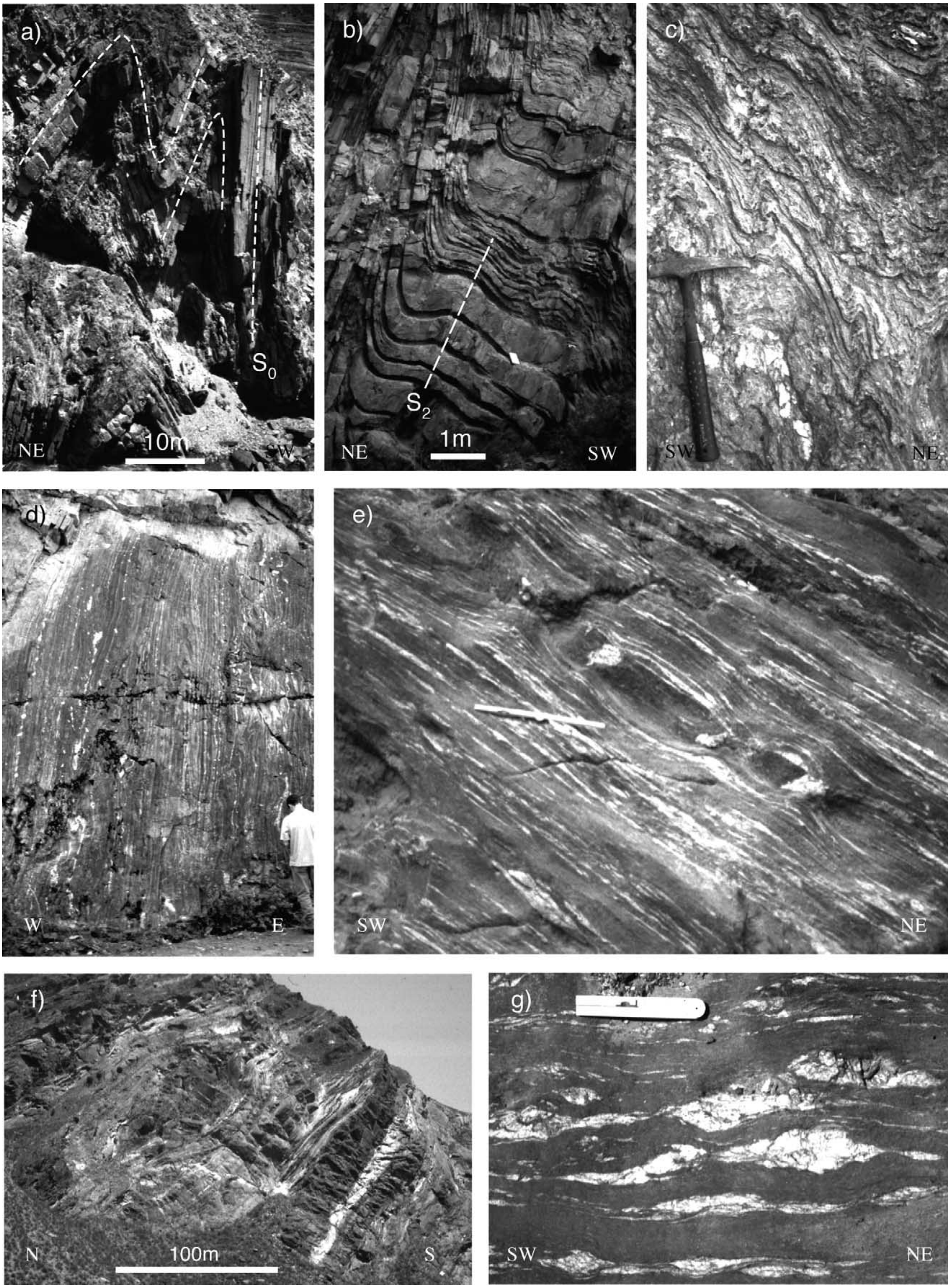


Fig. 2. Geological map of the Danba region, southeast Songpan Garzê Fold Belt, adapted from SBGMR (1981). This region contains the Xiaojin arcuate zone, as reflected by the distribution of Triassic biostratigraphy, and the Cenozoic Xianshui He fault zone. The township of Danba is central to a major complex of high-grade Paleozoic metasediments known as the 'Danba antiform'. Also indicated are several late-syn-tectonic and post-tectonic plutons in the region, for which Calassou (1994) and Roger et al. (2004) described U/Pb and Rb/Sr ages, and the locations of cross-sections illustrated in Figs. 4 and 6 (dashed lines).


a)
S_0
NE
10m
SW
b)
S_2
NE
1m
SW
c)
SW
NE
d)
W
E
e)
SW
NE
f)
N
100m
S
g)
SW
NE

modified considerably. Differential strain between the thickening Songpan Garzê Fold Belt and the Yangtze block resulted in structural inversion of the passive margin (Burchfiel et al., 1995; Chen and Wilson, 1996) and southeast-directed emplacement of the Longmen Mountains Thrust Nappe Belt (Lou, 1991; Dirks et al., 1994). Progressive shortening of this thrust nappe belt and thin-skinned deformation of the passive margin's Paleozoic–Triassic sedimentary pile was accommodated by a south-east-ward propagating array of listric thrusts (Burchfiel et al., 1995; Chen et al., 1995). During the latter stages of the Indosinian Orogeny, hinterland thickening and emplacement of the Longmen Mountains Thrust Nappe Belt flexurally loaded the Yangtze passive margin, resulting in subsidence of the Western Sichuan Foreland Basin (Chen et al., 1995; Li et al., 2003). The key features of Indosinian structural development are described below using strike-normal profiles across four significant portions of the Songpan Garzê Fold Belt (Fig. 2).

2.1. Transect A: Xiaojin–Danba–Bamie

The road from Xiaojin to Danba exposes an excellent section through shortened Triassic and Paleozoic lithologies on the eastern flank of the Danba antiform (Fig. 2). This section also transects a rotation of structural fabric that occurs on map-scale (Fig. 2), termed the 'Xiaojin arcuate structure' (Xu, 1991). Typical F_1 folds have wavelengths of many tens of metres and amplitudes of 50 m or more (Fig. 3a) with a slaty cleavage parallel to the axial surface. Localized thrusting sub-parallel to the S_1 axial surface is evident throughout the sequence, commonly attenuating F_1 fold limbs and reorienting S_1 fabrics (Fig. 4). Whilst thrusting post-dates all pervasive F_1 folding, the orientation and offset of these thrusts mimics the local variability of S_0–S_1 dips and the scale of F_1 structures (Fig. 4). No earlier structural elements are observed and this style of folding, thrusting and pervasive fabric development is found to be characteristic of the earliest structures preserved throughout the region (Fig. 4).

Around Xiaojin, progressive reorientation of D_1 structure is evidenced by fine crenulation of S_0–S_1 surfaces. Moving westward from Xiaojin towards the Danba antiform, post-D_1 reorientation becomes increasingly prominent (Fig. 4, section A′–A″). West of Xiaojin, this is characterised by northeast dipping thrusts with consistent top-to-the-south sense of transport. This thrusting reorients and reactivates bedding-parallel D_1 thrusts to coaxially deform F_1 hinges. Within reoriented hinges, localized development of a second fabric (S_2) is observed that dips systematically to the northeast, is coaxial to S_1 and is recognized throughout the transect and the Danba region. Some 30 km west of Xiaojin (Fig. 2), an excellent cross-section through heavily dissected D_1 folds is exposed (Fig. 4 at A′). The remnant cores of adjacent D_1 anticlines and synclines are juxtaposed by D_2 thrusts and coaxially refolded into box-shaped folds (Fig. 3b). Unlike similar D_1 structures, D_2 thrusts are associated with a distinct top-to-the-southwest sense of transport (Fig. 4).

Further west, within the mid-lower Paleozoic on the eastern flank of the Danba antiform (Fig. 4, section A–A′), few relicts of macroscopic D_1 structure can be identified. For the most part, the approximately 25-km-long section through the Devonian and upper Silurian is characterised by monotonous northeast-dipping S_2-parallel bedding with rare sections of open F_2 folding (Fig. 3c). Open parasitic F_2 folds have wavelengths of up to 15 m, amplitudes of around 10 m and verge southwest-ward, with northeast-dipping axial surfaces (Fig. 5). Coaxially refolded F_1 parasitic hinges are observed, although the difference in scale between F_1 and F_2 makes such structures rare.

Immediately east of Danba, deformation of the lower Silurian is marked by a distinct change in deformation intensity and metamorphic grade. The earliest fabrics (S_1) are defined by a biotite–muscovite cleavage that is coaxial to pervasive isoclinal folding (F_1) and structures indicative of intense layer-parallel strain (Fig. 3d). Boudinage of mafic dykes and quartz veins that are common to the Silurian strata occurs on length scales from tens of centimetres (Fig. 3e) to many tens of metres (Fig. 3f). Foliation boudinage is also common and accompanied by in-situ partial melting (Fig. 3g). D_1 structure within the lower Silurian preserves a consistent top-to-the-southwest sense of transport, evidenced by southwest-verging syn-D_1 thrusts and asymmetric isoclinal F_1 folds. F_1 fold axes continue to trend northwest–southeast, and L_1 stretching lineations and major boudin axes are found to parallel fold axes. This parallelism and an obliquity between the regional tectonic transport direction (Calassou, 1994) and stretching lineation orientation are inferred to reflect 'rolling' lineation development as described by Passchier (1997).

This style of deformation is characteristic of a D_1 layer-parallel high-strain zone that can be traced throughout the lowest Silurian around Danba and is particularly well exposed south of Danba. This high-strain zone is well preserved within the core of the Danba antiform due to an apparent decline in the intensity of post-D_1 deformation (Fig. 4, section A–A′). Second generation (S_2) fabrics are

Fig. 3. Indosinian structures within transect A–A′–A″ (section line is marked on Fig. 2). (a) Typical large-scale F_1 fold in the Triassic east of Xiaojin. Note syn-D_1 top-to-the-southwest attenuation of the southwest limb of this package; (b) box-shaped distortion of F_1 hinges in Triassic rocks on the road to Danba; (c) small, open F_2 folds, pervasive D_2 deformation and macroscopic crenulation of S_1 fabrics within Palaeozoic rocks on the eastern flank of the Danba antiform; (d) high layer-parallel strain S_1 fabrics in the Silurian east of Danba. Note the irregular boudinage of quartz veins; (e) boudinage of a small mafic dyke in the lower Silurian south of Danba; (f) large mafic boudin in escarpment of lower Silurian, just south of Danba; (g) boudinaged pegmatites, which probably formed as a result of intra-folial boudinage within the basal décollement.

variable in morphology; they either crenulate S_1 or are manifested as a second biotite-defined foliation that may envelope biotite and garnet porphyroblasts. The intense D_2 overprint observed on the antiform's eastern flank is not observed within the core. Rather, layer-parallel D_1 structure is reoriented about a second generation of large, upright folds (F_2) with similar wavelengths to those described further east. West of the Danba anticline, toward Bamie (Fig. 2), the intensity of this D_2 deformation continues to decline until D_2 is evidenced only by crenulation lineations on S_1 surfaces and subtle warping of D_1 structure.

Moving westward towards Danba from Xiaojin, S_1 axial surface cleavages are modified by increasingly pervasive S_2 development. D_2 deformation initially crenulates, then largely obliterates the S_1 fabric entirely. Throughout transect A (Fig. 4), relict S_1 fabrics preserve the peak metamorphic zonation of the antiform (SBGMR, 1981; Huang et al., 2003a). This zonation is largely stratigraphically concordant, but also locally disrupted by a Cenozoic metamorphic overprint (Wallis et al., 2003). In contrast, S_2 fabrics defined by biotite and garnet-bearing assemblages within the eastern flank of the Danba Antiform occur throughout Paleozoic stratigraphy.

Localized ductile D_3 deformation was identified in the vicinity of Danba and within the frontal portions of the Xiaojin arcuate zone by the development of S_3 crenulation cleavages (areas 9–11 in Fig. 5). D_3 is extremely localized and, in outcrop, structurally insignificant; nowhere is D_3 observed to reorient earlier macroscopic structures. There are two orientations of D_3 form-surface: (1) a general north–south orientation in the Danba area that Wallis et al. (2003) interpreted to reflect a $\sim$10% shortening that may coincide with later Cenozoic deformation; and (2) east–west and north–south orientations that are only slightly oblique to D_2. This latter deformation appears to be equivalent to the more pervasive D_{3p} Indosinian deformation described within the Wenchuan Maowen Shear Zone to the northeast (Worley and Wilson, 1996).

Other post-D_2 modification near Danba is restricted to isolated strike-slip faulting that is correlated with the development of the Cenozoic Xianshui He fault zone (Allen et al., 1991; Roger et al., 1995). Typical larger faults are several metres in width, with gouge planes preserving coarse sub-horizontal slickenfibres indicative of sinistral transport. At map scale (SBGMR, 1981), this dissection produced negligible distortion of the Danba antiform's structural geometry or peak metamorphic zonation.

2.2. Transect B: Litang–Yadjiang and Transect C: Yadjiang–Konga Shan

This portion of the Songpan Garzê Fold Belt, between the Xianshui He Fault Zone and Yidun Arc (Fig. 1; Reid et al., 2004), is often described as the Yadjiang terrane (Chang, 1997). Again the initial D_1 structural phase is characterised by tight, upright (F_1) folding and weak axial-planar and bedding-parallel thrusting (Fig. 6). Pervasive S_1 fabric development is defined by muscovite and chlorite-bearing assemblages; characteristic of most of the lower–mid-Triassic throughout the fold belt. Similar to the Danba area, D_1 structures are reoriented by a progressive D_2 phase of structural development; identified by localized S_2 foliation development and open folding on a scale smaller than F_1. D_2 reorientation within the Yadjiang terrane is considerably less intense than that described east of Danba (Fig. 6, B–B′ and C–C′). The 'Yadjiang' metamorphic complex, some 70 km southwest of Danba, is characterised by concentric biotite, staurolite and andalusite (chiastolite) isograds that mimic doming of Triassic strata and are discordant with F_1 and F_2 folding (Fig. 7). This complex is thought to reflect the metamorphic halo of a late-orogenic pluton at depth (Xu et al., 1992).

In contrast to the Xiaojin arcuate zone, S_1 and S_2 within the Yadjiang terrane are not coaxial along this transect (Fig. 6, C–C′). Consequently oblique fold interference, perhaps emphasised by a decrease in F_1 scale, is common between Yadjiang and the Konga Shan Massif (Fig. 6, C–C′). Such interference appears to result from a variable S_1 orientation, rather than the arcuate S_2 geometries observed within the Xiaojin arcuate zone (Fig. 5).

2.3. Transect D: Daofu Area (across the Xianshui He fault zone)

In the vicinity of Lohuo and Daofu (Fig. 2), outcrop is dominated almost exclusively by macroscopic D_1 structure akin to that described around Xiaojin. Characteristically tight F_1 folds (Fig. 6, D–D′) are associated with pervasive, slaty northwest-trending S_1 cleavages (Fig. 5). Weak D_1 thrusting is observed, parallel to the refracted S_1-parallel axial surface, but does not interrupt adjacent anticline–syncline geometries. In general, progressive D_2 deformation is evidenced only by steep L_2 lineations on the S_1 axial surface. Where rare localised F_2 crenulations are observed, the S_2 axial surface strikes northwest-ward and is effectively co-planar to S_1 (Figs. 5 and 6, section D–D′).

Northeast of Daofu (Fig. 6, D–D′), this architecture is crosscut by the intrusion of post-orogenic hornblende granites and minor mafic dykes, which appear typical of Mesozoic intrusions described elsewhere in the region (Roger et al., 2004). The Xianshui He fault zone (Allen et al., 1991) also locally disrupts D_1 structure (Fig. 2).

3. Structural evolution of the Songpan Garzê Fold Belt

3.1. Pervasive D_1 shortening and detachment

D_1 deformation is interpreted to reflect a primary homogeneous shortening of the fold belt, equivalent to the penetrative D_1 deformation described previously by Calassou (1994), Dirks et al. (1994) and Worley and Wilson

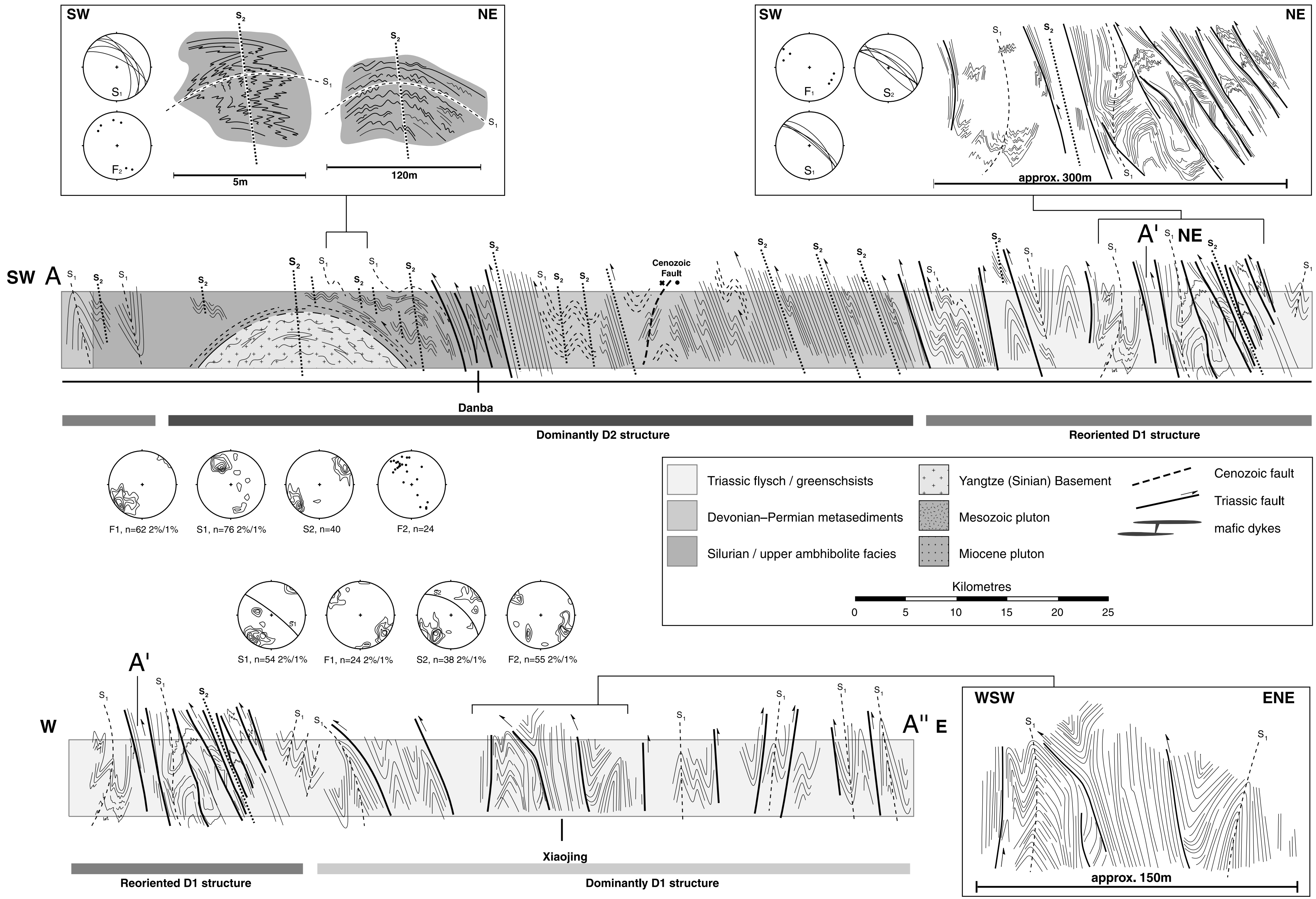
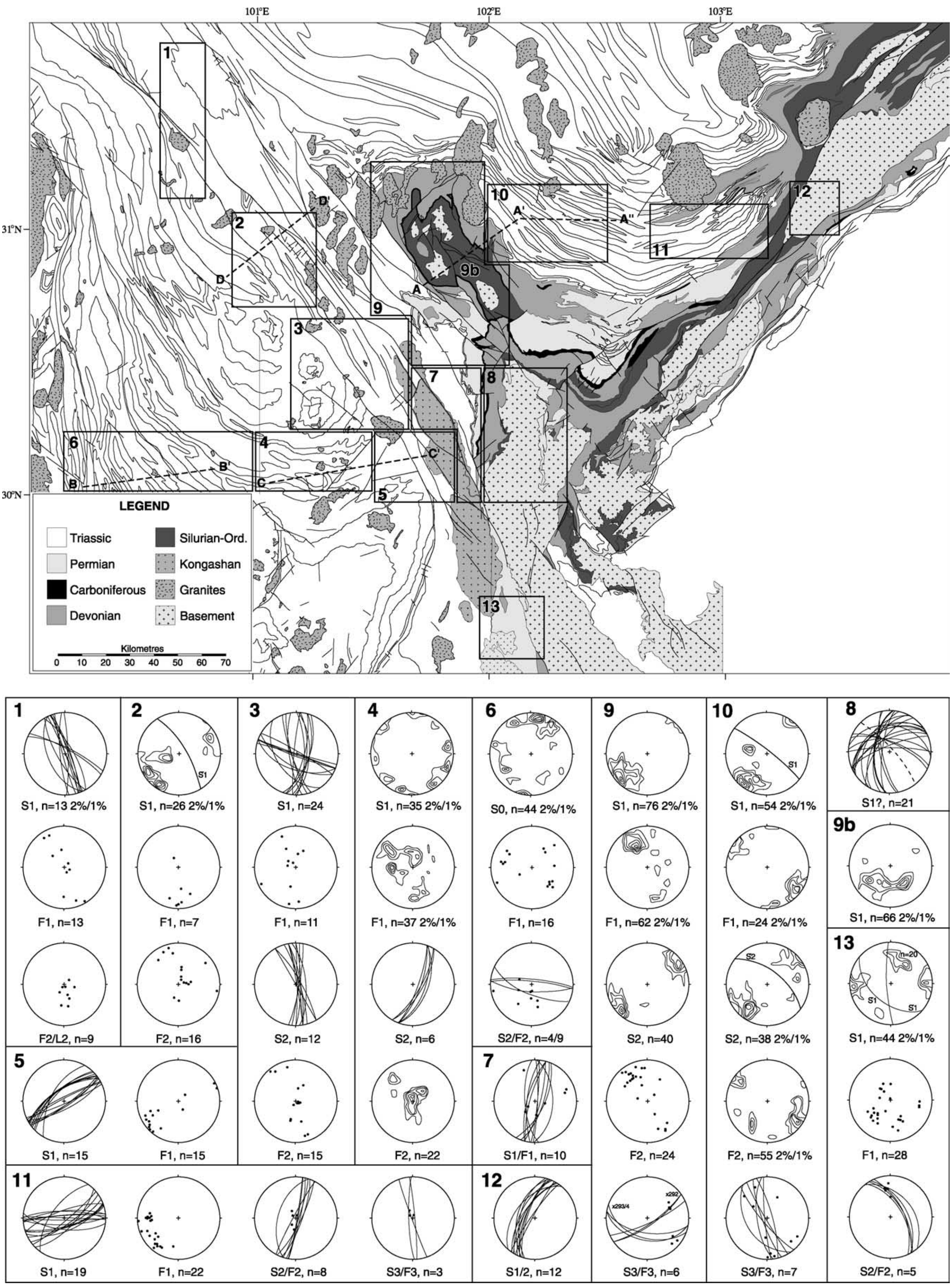


Fig. 4. Schematic cross-section (A–A′–A″) through the Danba antiform and Songpan Garzê Fold Belt, southwest of Xiaojin. Section line is marked on Fig. 2. This cross-section reflects a westward increase in the intensity of D_2 modification within the eastern flank of the Danba antiform. All stereonets are lower hemisphere equal area projections, contoured at 2%/1% (data/area).


101°E
102°E
103°E
31°N
30°N
1
2
3
4
5
6
7
8
9
9b
10
11
12
13
A
A'
A''
B
B'
C
C'
D
D'
LEGEND
Triassic
Permian
Carboniferous
Devonian
Silurian-Ord.
Kongashan
Granites
Basement
Kilometres
0 10 20 30 40 50 60 70
S1, n=13 2%/1%
F1, n=13
F2/L2, n=9
S1, n=26 2%/1%
S1
F1, n=7
F2, n=16
S1, n=24
F1, n=11
S2, n=12
F2, n=15
S1, n=35 2%/1%
F1, n=37 2%/1%
S2, n=6
F2, n=22
S0, n=44 2%/1%
F1, n=16
S2/F2, n=4/9
S1, n=76 2%/1%
F1, n=62 2%/1%
S2, n=40
F2, n=24
S3/F3, n=6
S1, n=54 2%/1%
F1, n=24 2%/1%
S2, n=38 2%/1%
F2, n=55 2%/1%
S3/F3, n=7
S1?, n=21
S1, n=66 2%/1%
n=20
S1, n=44 2%/1%
F1, n=28
S2/F2, n=5
S1, n=15
F1, n=15
S1/F1, n=10
S1, n=19
F1, n=22
S2/F2, n=8
S3/F3, n=3
S1/2, n=12
x292
x293/4
S2

(1996) and with the 'syn-metamorphic' deformation identified by Burchfiel et al. (1995). Significantly, the S_1-parallel form surface may be traced about the arcuate rotation of structural grain that characterises the southeast margin of the fold belt (Fig. 8). It is only within the basal layer-parallel high-strain zone that a heterogeneous D_1 strain gradient and consistent kinematic asymmetry are observed. A shallowing and intensification of S_1 foliations towards the base of the Silurian and a transition from tight, upright F_1 folds and syn-D_1 thrusts to structures indicative of high layer-parallel strains reflect this (Fig. 9).

The basal décollement (Calassou, 1994; Roger et al., 2004) is characterised by intense, isoclinal F_1 folding of Silurian strata, quartz veins and basement fabrics (Fig. 3d and e). F_1 folds are coaxial between the sedimentary pile and basal décollement, although, L_1 stretching lineations are observed to rotate, from upright and sub-orthogonal to the F_1 fold axis within the pile to flat-lying and sub-parallel to F_1 axes within the basal décollement (Fig. 9). This rotation of L_1 stretching lineations is interpreted to reflect a transition from homogeneous, pure-shear-dominated shortening within the Songpan Garzi sedimentary pile to 'rolling' lineation morphologies indicative of increasingly simple-shear-dominated deformation within the basal décollement (Fig. 9).

The basal décollement is identified throughout the lowest Paleozoic strata of the Danba antiform, where it is significantly reoriented about both D_2 structure and the antiform's basement topology (Fig. 4, section A–A′). Despite progressive reorientation, the basal décollement preserves a consistent south-verging kinematic asymmetry, also recognised by Calassou (1994), which reflects none of the geographic heterogeneity characteristic of D_2 deformation within the Danba antiform.

3.2. Progressive post-D_1 Indosinian deformation

Intense D_2 deformation is confined to the eastern flank of the Danba antiform and Xiaojin arcuate zone, where it is interpreted to reflect an increasing D_2 strain gradient towards the margin of the fold belt (Fig. 8). Worley and Wilson (1996) identify a similar strain gradient at the opposite end of the Xiaojin arcuate zone. In both instances, a foreland-ward increasing D_2 strain gradient is observed to reorient both upright D_1 structures within the Songpan Garzi sedimentary pile and a D_1 high-strain zone at the base of the Paleozoic.

The S_2-parallel form surface also traces the arcuate structural grain of the Xiaojin arcuate zone, enveloping the eastern flank of the Danba antiform and encompassing the syn-tectonic form surfaces of portions of the Ma Nai Granite (Figs. 2 and 8). Nowhere does this result from post-D_2 reorientation; rather this change in D_2 structural orientation is inferred to have developed during the D_2 deformation. The arcuate geometry of the D_1 form surface east of Danba must, to a large degree, reflect reorientation about the later D_2 form surface and is consistent with south-directed Indosinian shortening (Fig. 8). Given the uniformity of regional D_1 deformation, there is good reason to believe that the Yadjiang terrane reflects the pre-D_2 form surface geometry of the Xiaojin arcuate zone.

Throughout the Yadjiang terrane, F_1 and F_2 are not parallel to the S_2-axial surface (Fig. 8). Consequently, where the arcuate S_1-axial surface swings to the east near Yadjiang, oblique F_1–F_2 interference geometries are common (Fig. 8). The D_1 form-surface is preserved intact in the Yadjiang terrane due to significantly less-intense D_2 reorientation than that described east of the Danba antiform. This decrease in D_2 intensity is probably linked to the development of the Danba antiform and localization of post-D_1 strain against its northeast margin.

Northwest of these arcuate structural features (Fig. 8), evidence of D_2 deformation is all but absent within the fold belt. In the Lohuo–Daofu area (Fig. 6, D–D′), D_2 deformation is evidenced only by steep crenulation lineations on S_1 surfaces. Rare S_2 fabrics are sub-parallel to the S_1 axial surface and not associated with the development of the macroscopic D_2 structure (Fig. 6). The orientation of D_1 and D_2 structures (Fig. 5) and the marked difference in scale between F_1 and F_2 folds are inconsistent with the extensive structural overturning described by Burchfiel et al. (1995).

3.3. D_1–D_2 interference and the progressive evolution of Xiaojin arcuate structure

The distribution and juxtaposition of structural phases (Fig. 8) should reflect a spatial variation in the total amount of strain accumulated during the Indosinian Orogeny. This requires that the development of progressive structural phases was diachronous, as in the model of Gray and Mitra (1993). Gray and Mitra (1993) concluded that progressive structural phases developed diachronously within a terrane as deformation 'fronts' migrated and that the eventual static distribution of progressive structural phases was not temporally correlatable. Instead, the distribution of progressive structure reflects spatial variations and geographic heterogeneities in the total strain accumulation during a given tectonic episode.

Worley and Wilson (1996) and this study (Fig. 8) describe the distribution of two major and one minor structural phases that are inferred to have developed prior to the emplacement of the Rilonguan Granodiorite at ca. 192 Ma (Fig. 2; Roger et al., 2004). We recognise two strain accumulation gradients within the fold belt: (1) a broad south-southwest-ward decrease in strain accumulation in the Yadjiang terrane (Fig. 8); and (2) a foreland-ward

Fig. 5. Structural data from the Danba region, subdivided geographically. All stereonets are lower hemisphere equal area projections, contoured at 2%/1% (data/area).

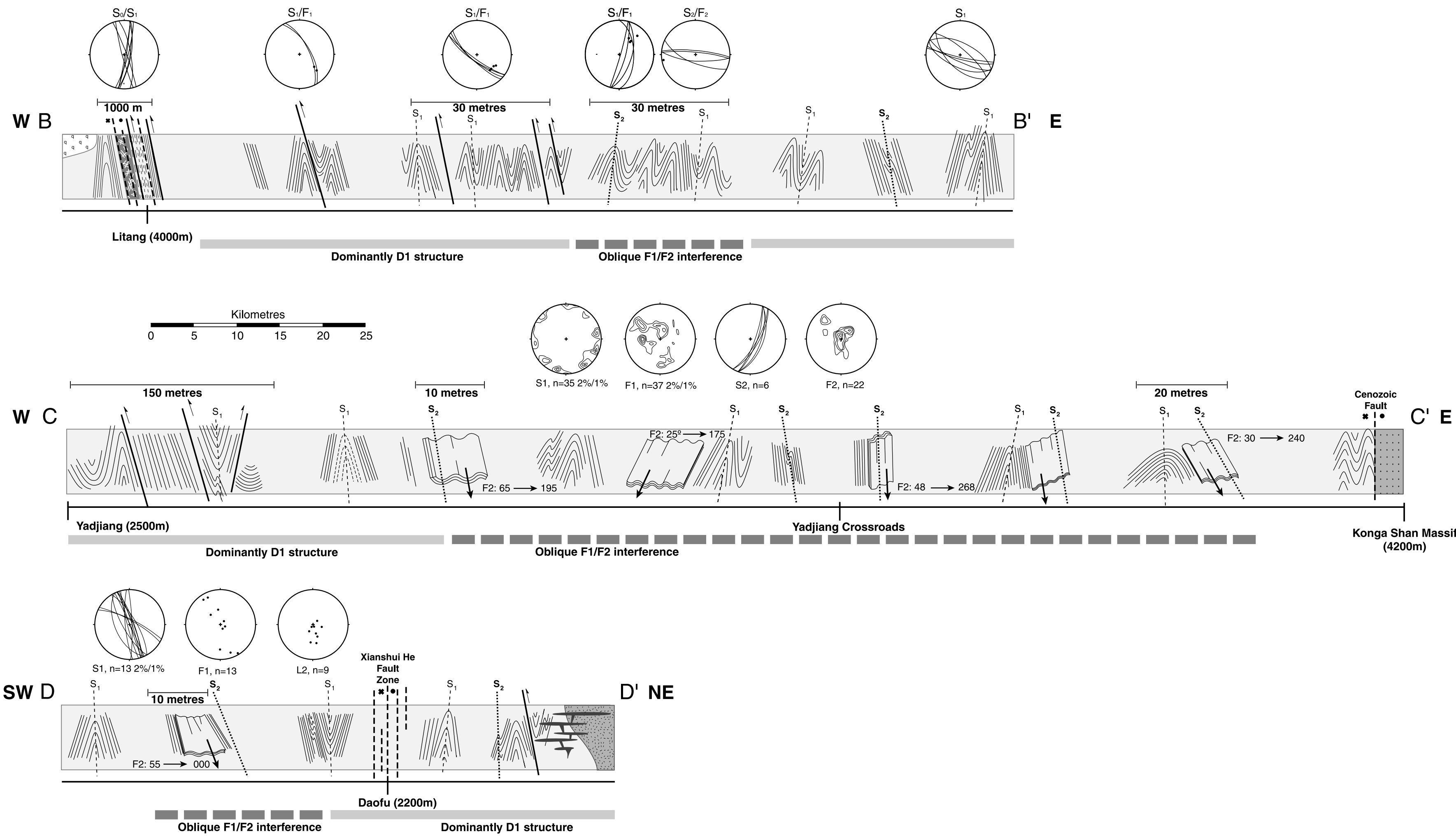


Fig. 6. Schematic cross-sections through the Yadjiang terrane, between Yadjiang and Litang (B–B′) and Yadjiang and the Konga Shan Massif (C–C′), and schematic cross-section across the Xianshui He Fault Zone at Daofu (D–D′). Section lines are marked on Fig. 2. All three transects identify less-intense, yet more oblique, D_2 reorientation than that described east of Danba. Equal area stereonets are contoured at 2%/1% (data/area).

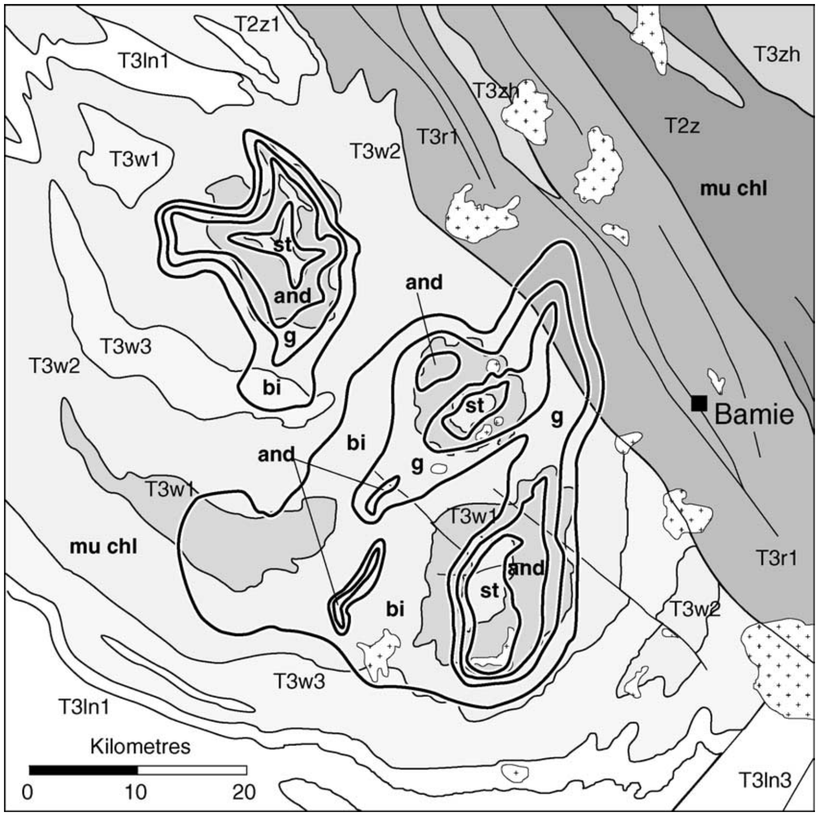


Fig. 7. Metamorphic zonation of the Yadjiang metamorphic complex, after SBGMR (1981) (refer to Fig. 2 for location). The greyscale of Triassic stratigraphy increases with age (T2z being the oldest and darkest). Metamorphic zonation of the Yadjiang metamorphic complex is interpreted by Xu et al. (1992) to reflect upwelling of a Jurassic pluton at depth.

localization of D_1 thickening and an increase in progressive strain accumulation toward the eastern margin of the fold belt.

As suggested by Dirks et al. (1994), Burchfiel et al. (1995) and Worley and Wilson (1996), the southeast margin of the fold belt was a sinistral transpressive shear zone that accommodated differential strain between the thickening fold belt and the adjacent Yangtze Block. Like other shear zones, this transpressive margin would have grown with time as it accumulated an increasing finite offset (Ramsay and Huber, 1983). However, unlike model shear zone growth, the crystalline basement of the Yangtze Block must have provided a significant impediment to southeast-ward growth of the shear zone. Thus the transpressive margin, and hence that portion of the fold belt within which the arcuate rotation of structural grain occurred, would have preferentially grown northwest-ward into the fold belt.

The distribution of progressive structural phases in the southeast fold belt (Fig. 8) is interpreted to reflect diachronous interference between south-directed shortening and the lateral growth of a maturing, constrained shear zone adjacent to the margin of the Yangtze Block (Fig. 10). Indosinian deformation is inferred to have been characterised by west-northwest-ward migration of D_2 and locally a D_3 deformation in response to an increasing sinistral offset on the interface between the fold belt and the Yangtze Block (Fig. 10). This migration was mimicked by westward propagation of the margin's arcuate structural fabric. Southeast-ward propagation of the Longmen Mountains Thrust Nappe Belt is viewed as the mechanism by which limited symmetric growth of the fold belt–Yangtze Block interface was accommodated (Fig. 11).

3.4. Indosinian evolution of the Danba antiform

Exhumation of the Danba antiform's basement core is constrained to have occurred: (1) after homogeneous D_1 thickening and metamorphism of the overlying sedimentary pile and formation of the sub-horizontal basal décollement (Figs. 9 and 11a); (2) before formation of the D_2 high-strain zone on the antiform's eastern flank and reorientation of the basal décollement (Fig. 11b); and (3) before the post-tectonic Ma Nai and Rilonguan granites (Fig. 2). The Danba antiform is therefore interpreted to have been exhumed during the early D_2 phase of progressive deformation and must have been complete prior to emplacement of the post-tectonic portions of the Ma Nai Granite at ca. 197 Ma (Roger et al., 2004) that crosscuts the antiform's eastern margin (Figs. 2 and 11c and d).

It is difficult to explain the structure of the Danba antiform entirely in terms of progressive contractional deformation. Within the antiform, migmatised Proterozoic

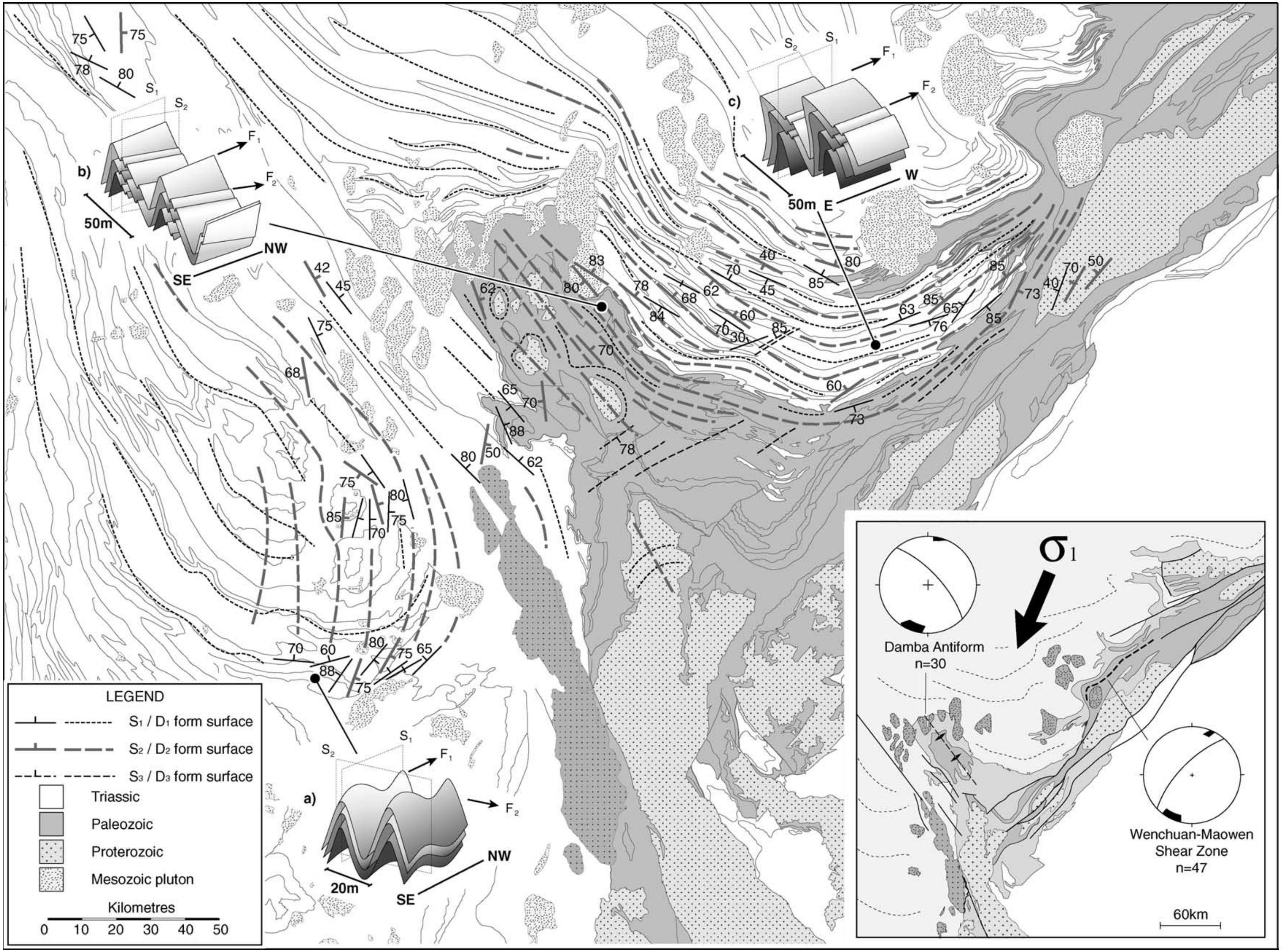


Fig. 8. The geographic distribution of progressive Indosinian structures in the southeast Songpan Garzê Fold Belt. D_2 deformation is confined to the regions of arcuate structural grain that characterise the eastern margin of the fold belt. Also illustrated are typical fold interference geometries from different portions of the fold belt. The insert shows that paleostress reconstructions (after the methods of Oncken, 1988) from the D_2 form-surface orientation are consistent with the same north-northeast to south-southwest oriented compressive stress field that is inferred to have driven the dominant D_1 Indosinian deformation.

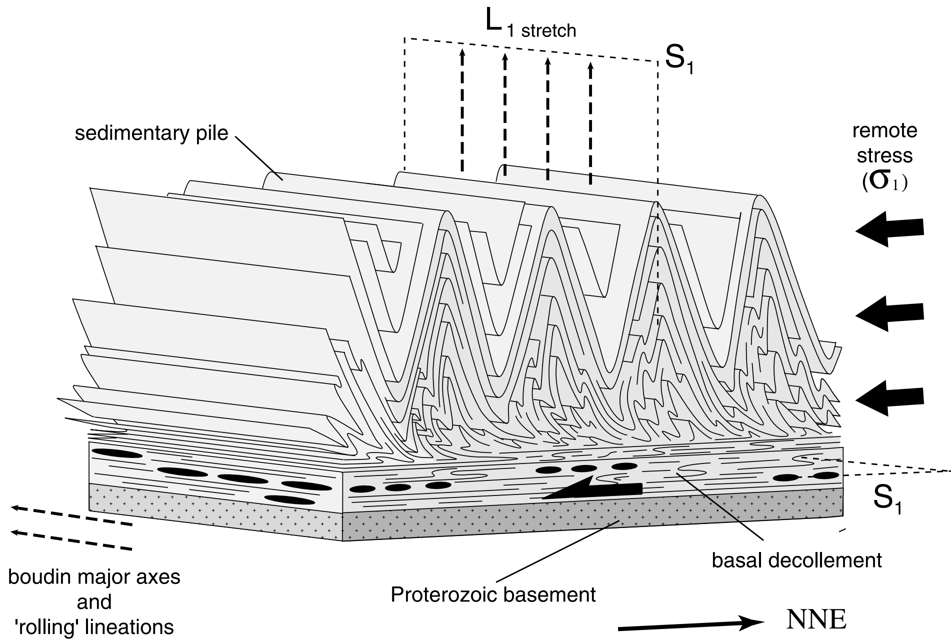


Fig. 9. Conceptual block diagram of D_1 Indosinian deformation of the Yangtze passive margin. South-directed shortening of the eastern fold belt was accommodated by décollement of the Palaeozoic–Triassic sedimentary pile from the Proterozoic basement of the Yangtze passive margin. Structurally, such décollement is reflected in the transition from pervasive upright folding within the upper pile to intense layer-parallel fabric development within the lower-Paleozoic. This transition is mimicked by a continuum of L_1 lineation orientation, from upright 'stretching' lineations within the pile, to fold-axis-parallel 'rolling' lineations within the basal décollement.

basement outcrops as domal exposures enveloped by concentrically zoned upper-Sinian and Silurian strata (Calassou, 1994). These 'domes' are discontinuous along the axis of the antiform and coincide with peaks in local topography (SBGMR, 1981). Both Calassou (1994) and Burchfiel et al. (1995) interpreted these domes to reflect oblique dome-and-basin-style interference. However, such interpretations are inconsistent with the two generations of progressive sub-coaxial folding (Fig. 5) and the aforementioned differences in scale between F_1 and F_2 would preclude the geometry and extent of symmetric Type-1 interference that Calassou (1994) and Burchfiel et al. (1995) proposed.

The structural and metamorphic character of the Danba antiform closely resembles those of similar-grade metamorphic domes in the Alaskan Peninsular and Canadian Cordillera. Calvert et al. (1999) described a basement-cored sillimanite–gneiss dome in the Kigluaik Mountains, Alaska, that they inferred to have been developed in a thickened sedimentary pile. Like the Danba antiform, the contact between the core of this dome and the enveloping low-grade cover is not an extensional detachment. Calvert et al. (1999) proposed that the Kigluaik Dome was exhumed by diapiric upwelling of buoyant migmatitic rocks, some time after the terrane achieved peak metamorphic conditions; a buoyancy-driven mechanism that they inferred would act independently of the tectonic stress regime. Vanderhaeghe et al. (1999) described a similar evolution from the Thor–Odin Metamorphic Dome, Canadian Cordillera, where exhumation was driven by partial melting and diapiric upwelling of basement rocks. Vanderhaeghe et al. (1999) suggested that many ambiguous field structural relationships within the enveloping pile could be attributed to doming of a flat-lying mid-crustal décollement above upwelling migmatised basement.

A buoyancy-driven exhumation mechanism seems to best explain domal distortion of the sedimentary pile above the basement core of the Danba antiform (Fig. 11). Such a model potentially accounts for the timing of antiform exhumation, just prior to or synchronous with emplacement of early basement-derived syn-tectonic plutons such as the Ma Nai Granite (ca. 197 Ma, Roger et al., 2004) and perhaps as little as 3 Ma before the onset of post-orogenic magmatism (Fig. 11d).

Syntectonic exhumation of the Danba antiform is therefore attributed to the diapiric rise of its migmatised basement core, during the early stages of progressive D_2 deformation (Fig. 11). It is inferred that the apparent antiformal character and structurally concordant northwest plunge of the Danba antiform (Fig. 7) reflect subsequent D_2 shortening of the enveloping basal décollement and Paleozoic pile (Fig. 11). In fact, the Danba antiform is not the only metamorphic complex in the region that has been interpreted to reflect the diapiric exhumation of Indosinian metamorphic rocks; the Yadjiang metamorphic complex (Fig. 7) and the Jurassic plutons described by Roger et al. (2004) are also inferred to be diapiric structures.

The timing of exhumation and kinematics implicit in our interpretation are incompatible with Burchfiel et al.'s (1995) core-complex-style models of basement exhumation.

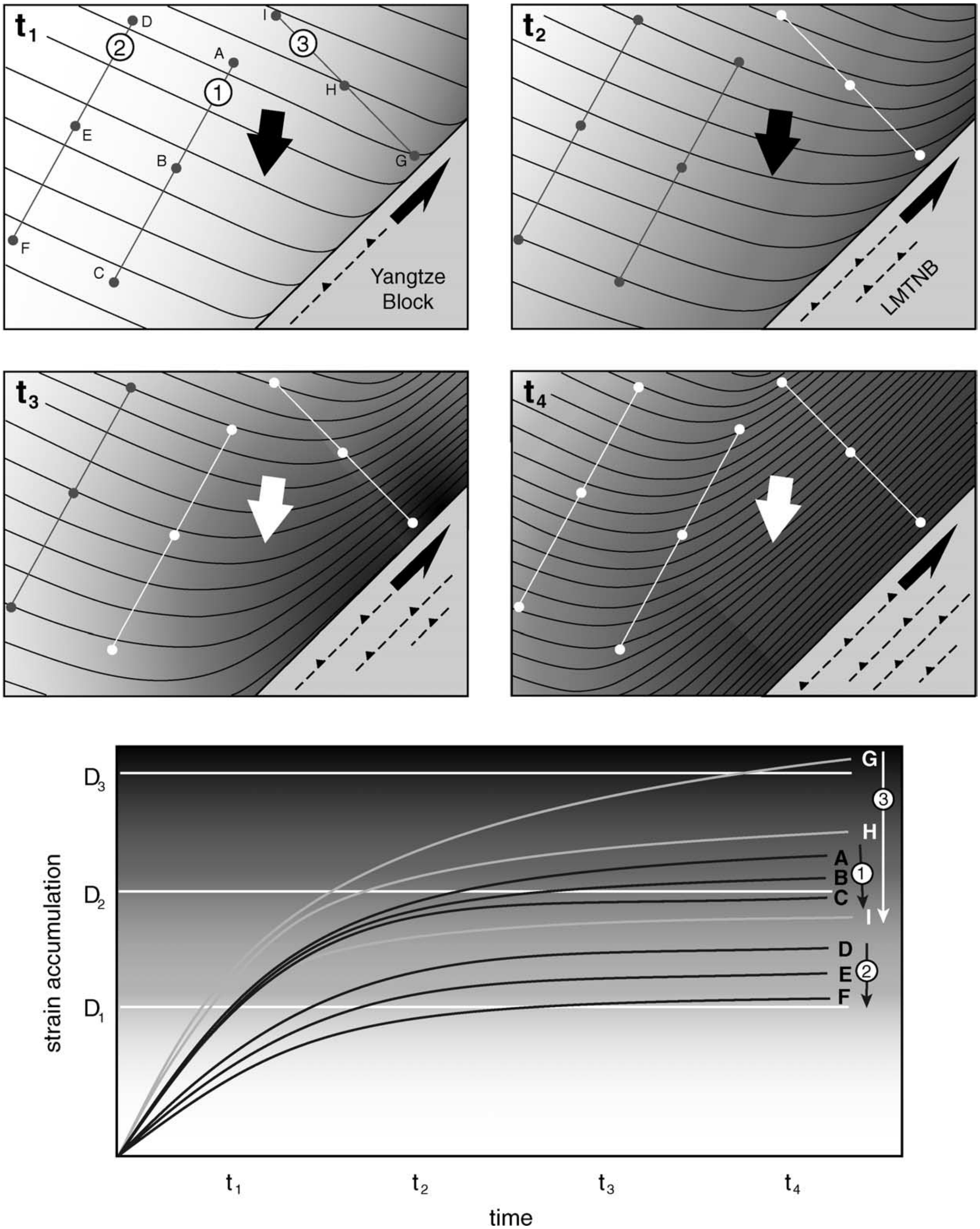


Fig. 10. Progressive deformation within the southeast fold belt, adjacent to the Yangtze Block is thought to have been characterised by the migration of deformation 'fronts' and the propagation of an arcuate structural fabric. Using the superposition of progressive structure as a proxy for strain accumulation, conceptual strain accumulation versus time profiles are illustrated for nine localities within three transects. Whilst transects (1) and (2) describe south-southwest decreasing instantaneous strain gradients, they themselves are part of a northwest-decreasing continuum (3) reflecting lateral growth of the fold belt's transpressive eastern margin. Limited symmetric growth of the Songpan Garzê Fold Belt–Yangtze interface was accommodated by southeast-ward propagation of the Longmen Mountains Thrust Nappe Belt (LMTNB).

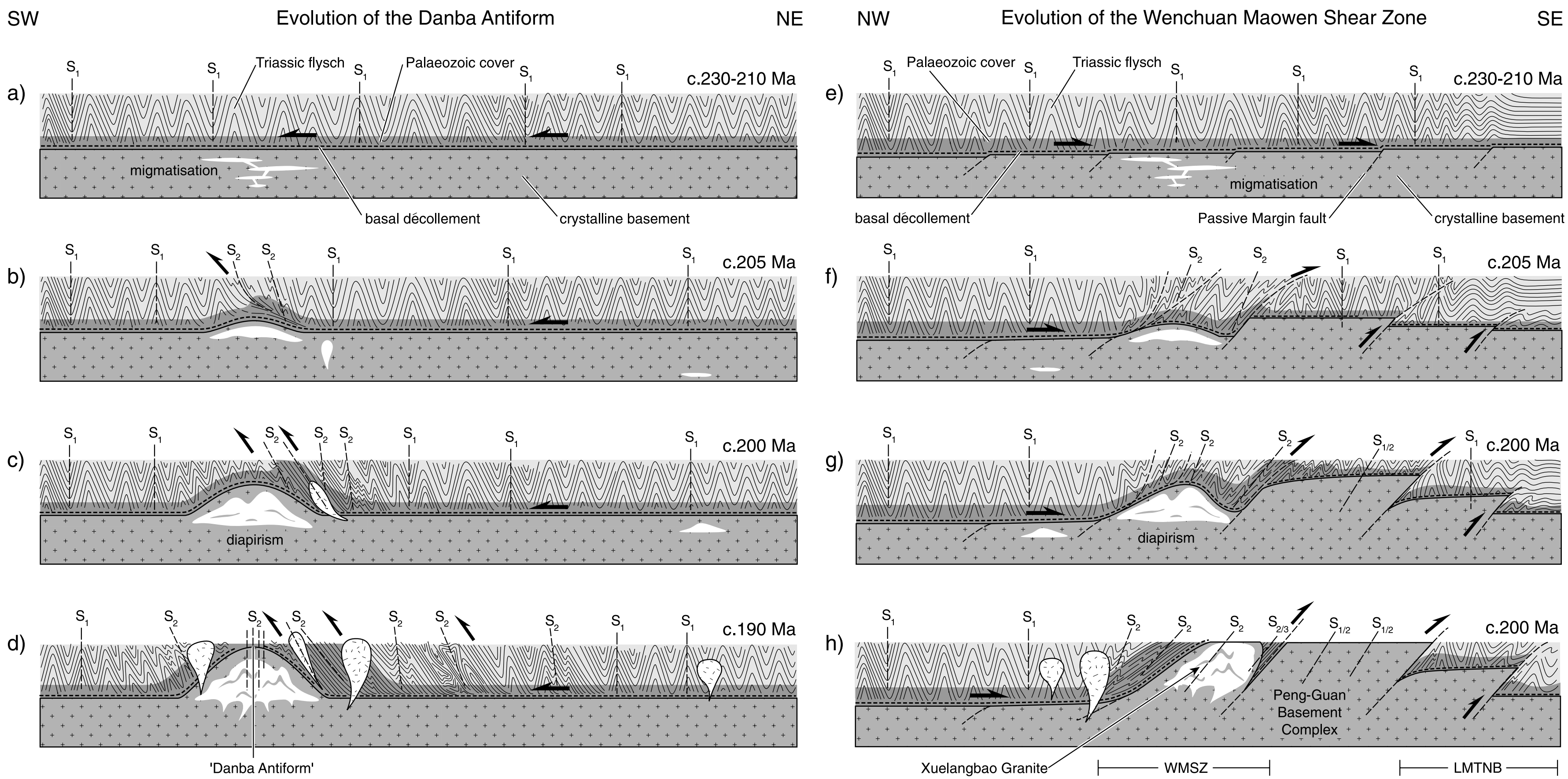


Fig. 11. Conceptual cross-sections showing Indosinian exhumation of metamorphic sequences in the eastern Songpan Garzê Fold Belt; (a)–(d) evolution of the Danba antiform along the cross-section in Fig. 4; (e)–(h) evolution of the Wenchuan Maowen Shear Zone, in the strike-normal section indicated in Fig. 2. (a) Regional décollement and south-directed D_1 thickening of the sedimentary pile preceded ((a) and (b)) late orogenic migmatisation of the Yangtze basement. (c) and (d) Pooling of partial melt and diapiric upwelling of the antiform's core resulted in doming of both Palaeozoic strata. (d) Progressive south-directed D_2 deformation was localised against the eastern flank of the Danba antiform. The antiform continued to provide a focus for late-syn- to post-tectonic magmatism. A parallel evolution is inferred for the Wenchuan Maowen Shear Zone, in which both diapiric upwelling and structural inversion of the Yangtze passive margin effected exhumation of basement complexes.

Nowhere in the fold belt are significant extensional structures observed that might have accommodated differential exhumation or exposure of the Danba antiform during the Triassic. In fact, all available evidence suggests that the Danba antiform's core provided a focus for the accumulation of south-directed D_2 contractional strain (Fig. 4, section A–A′). Furthermore, Indosinian aged metamorphic textures (Huang et al., 2003b) within the Danba antiform are ~140 million years older than both the Cenozoic extensional exhumation proposed by Burchfiel et al. (1995) and the Cenozoic metamorphic event inferred by Wallis et al. (2003).

3.5. Relationship between the Danba antiform and the Wenchuan Maowen Shear Zone

Several parallels may be drawn between the evolution of the Danba antiform and that of the Wenchuan Maowen Shear Zone (Fig. 2), which point to wider late-orogenic thermal activity within the southeast fold belt. Like the Danba antiform, the Wenchuan Maowen Shear Zone is host to a complex of concentrically zoned Paleozoic metasediments that envelope an enigmatic basement-derived core, the Xuelangbao Granite. This syntectonic body is one of several basement/granite complexes in the Wenchuan Maowen Shear Zone that are structurally equivalent, yet discontinuous along strike, and sheathed by Cambro-Ordovician stratigraphy (Fig. 2). Unlike the Danba antiform, the relationship between emplacement of the Xuelangbao Granite and syntectonic basement anatexis is relatively well established (Worley and Wilson, 1996). In fact, the geometric association between this pluton and the metamorphic isograds of the enveloping Paleozoic pile (Worley and Wilson, 1996) is very similar to the inferred distortion of syn-D_1 metamorphic zonation within the Danba antiform (Fig. 11).

In both metamorphic complexes, syntectonic emplacement and exhumation of anatectic basement is inferred to have been spatially and temporally related to progressive D_2 deformation. Like the eastern margin of the Danba antiform, the tectonically exposed western margin of the Xuelangbao Granite provided a focus for localization of intense progressive D_2 strain. Furthermore, the transition to D_2 deformation in the Wenchuan Maowen Shear Zone has been correlated with transpressive exhumation of the Peng–Guan basement complex (Worley and Wilson, 1996) and structural inversion of the Yangtze passive margin's basement architecture (Chen and Wilson, 1996).

4. Conclusions

The rocks of the Songpan Garzê Fold Belt record a history of Late Triassic (Indosinian Orogeny) crustal thickening (D_1–D_2) and progressive exhumation, that culminated in the emplacement of post-orogenic granites at ca. 190 Ma. These events are associated with a south-directed shortening that produced regionally extensive tight to isoclinal D_1 folds, thrusts and a ductile décollement at the base of the Songpan Garzi sedimentary pile. D_2 structure was characterized by localized, open re-folding, on smaller scales, and the formation of a high-strain zone within the eastern flank of the Danba antiform. It is concluded that progressive structural development 'migrated' with time, synthetic to strain accumulation within the fold belt's transpressive southeast margin, adjacent to the Yangtze block.

The latter stages (D_2–D_3) of the Indosinian Orogeny were characterized by exhumation of the Danba antiform and possibly a change in the local stress field that may have triggered the ascent of early Jurassic plutons (~190 Ma). Regional parallels may be drawn between the structural and thermal evolution of the Danba region and that of the Wenchuan Maowen Shear Zone. In both instances, the progression to localized D_2 structural development is correlated with the onset of basement-involved deformation and anatexis. Post-Indosinian deformation was associated with a change in regional stress, to an east–west orientation, which is marked by brittle and, locally, ductile Cenozoic deformation.

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