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The Gundahl Complex of the New England Fold Belt, eastern Australia: a tectonic mélange formed in a Palaeozoic subduction complex

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Abstract—The New England Fold Belt of eastern Australia preserves a Palaeozoic fore-arc terrain with a magmatic arc, fore-arc basin and a subduction complex. The Gundahl Complex is a tectonic mélange of regional extent in the subduction complex. The matrix and slabs of the Gundahl Complex have six mappable lithofacies: argillite, greywacke–argillite, greywacke, argillite–tuff, bedded chert and greenstone. The argillite matrix is pervasively sheared with many slickensided shear fractures. Locally the matrix is formed by highly sheared greenstone. Greywacke and greenstone blocks are affected by internal shear zones and the blocks themselves pinch and swell. Folds, in places with axial-surface spaced cleavage, are common within those slabs comprised of well-bedded sequences. Bedding-plane shear and faulting at a high angle to bedding also occur in these slabs. On a map-scale much of the Gundahl Complex comprises slabs up to 10 km long in imbricate fault-bounded slices which repeat the disrupted pre-mélange stratigraphic sequence. Elsewhere there are lithologically distinctive blocks containing thick coherent sequences which are structurally incorporated into the Gundahl Complex. The unit is believed to have formed by accretion, imbrication and subsequent tectonic disruption of arc-derived sediments and less abundant pelagic sediment and greenstone in an ancient subduction complex.

INTRODUCTION

MÉLANGE was first described by Greenly (1919) in the Precambrian Gwna Group of Anglesey, Wales. He noted that the larger masses within the mélange typically formed ". . . trains of lenticles overlapping *en échelon* . . ." contained in a fine-grained matrix (Greenly 1919, p. 134). Greenly emphasized that this lenticular structure pervaded the entire mélange, occurring at all scales throughout the mélange matrix between the larger masses. He always used "mélange" with the adjective "autoclastic" to indicate a tectonic origin and implying that other origins for mélange may exist.

Controversy exists over the relative important of tectonic and sedimentary mixing processes in the formation of mélanges (e.g. Hsü 1968, Robertson 1977, Silver & Beutner 1980, Naylor 1982). Detailed analysis of the mesoscopic and macroscopic structures of mélanges is necessary to solve this problem for any one mélange terrain.

A significant, although by no means unique, tectonic setting has been recognized for mélanges in subduction complexes developed at consuming plate margins. It has been proposed that mélange may form by accretion and continued tectonic deformation of the upper portion of oceanic crust and overlying trench sediment wedges (e.g. Hsü 1971, G. F. Moore & Karig 1976, 1980, Connelly 1978, Jones *et al.* 1978, Nelson 1982). Others have suggested that olistostrome deposition in a trench or near trench environment may contribute to mélange formation in subduction complexes (Maxwell 1974; Gucwa 1975). Only limited exposures of modern subduction complexes occur and study of the structure of well-exposed ancient subduction complexes on land may help resolve these differences.

The New England Fold Belt of eastern Australia contains one of the more complete examples of an ancient subduction complex (Leitch 1975, Leitch & Cawood 1980, Crook 1980, Cawood 1982). This paper describes the internal structure, origin and setting of part of the Gundahl Complex, a tectonic mélange within the southeastern part of the New England Fold Belt. The Gundahl Complex is characterized by a lenticular structure, and this feature is best shown by the variation in size of lenticular chert slabs from small blocks less than 10 cm across up to slabs 10 km long.

GEOLOGIC SETTING

The southern part of the New England Fold Belt is subdivided into a western belt, called Zone A or the Tamworth Belt, and an eastern belt, called Zone B or the Tablelands Complex (Leitch 1974, Korsch 1977, Crook 1980, Korsch & Harrington 1981, Cawood 1982). Zone A contains a mildly deformed regressive sedimentary sequence, largely of Devonian to Carboniferous age, which is interpreted as the ancient fill of a fore-arc basin (Leitch 1975). Much of the sequence consists of marine mudstone interbedded with sandstone and conglomerate derived from a volcanic chain to the west (Leitch 1974). Near the top of the sequence Late Carboniferous terrestrial conglomerate and sandstone are interbedded with regionally extensive ignimbrite flows derived from the continental margin volcanic chain to the west (McPhie in press). Zone B has two main assemblages: (i) complexly deformed rocks consisting largely of poorly dated greywacke and argillite with less abundant chert and mafic volcanics, (ii) Permo-Triassic volcanic and intrusive rocks that postdate the older complexly deformed assemblage. Detailed mapping in

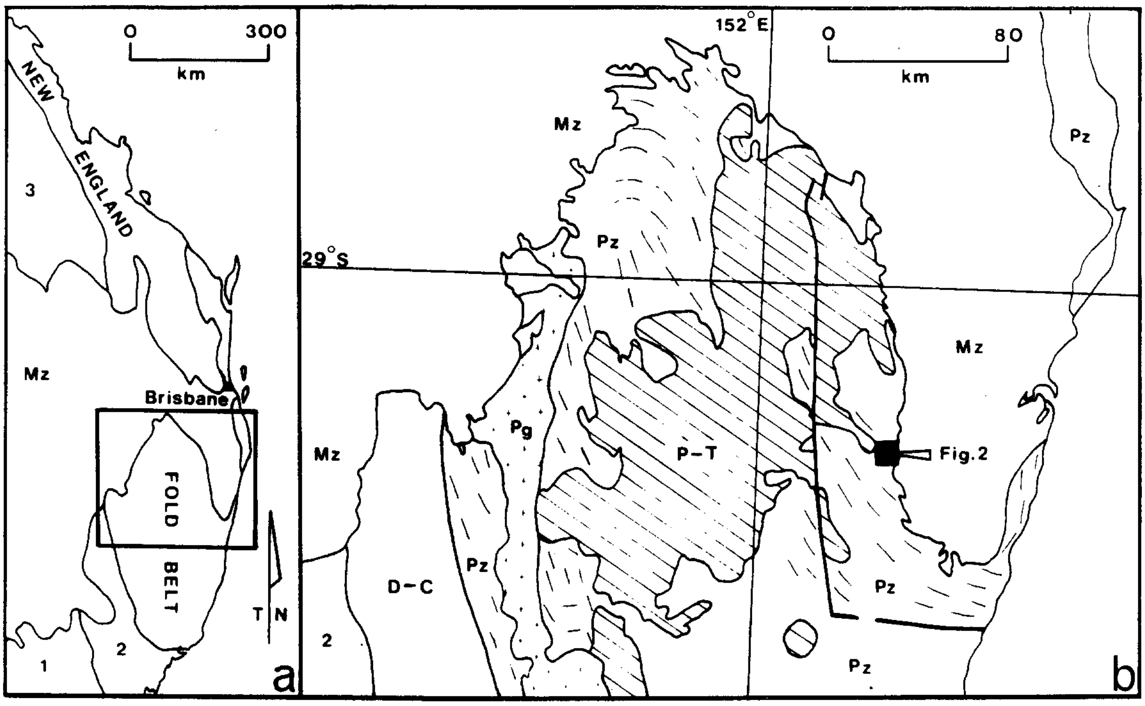

Fig. 1. (a) Regional setting for the New England Fold Belt. Key to tectonic units: 1, Lachlan Fold Belt; 2, Sydney Basin; 3, Bowen Basin; M_z, Mesozoic Great Artesian Basin. (b) Regional setting. Key: D–C, Devonian to Carboniferous of the Tamworth Belt; P_z, older complexly deformed assemblage of the Tablelands Complex; P_g, Early Permian granitoids; P–T, younger assemblage (Permo-Triassic volcanics and intrusives) of the Tablelands Complex.

the western part of the complexly deformed assemblage has demonstrated the existence of sedimentary mélange and imbricate fault slices, both of which are related to subduction (see Leitch & Cawood 1980, Cawood 1982). Tectonic mélange of regional extent (such as the Gundahl Complex) occurs throughout the older assemblage of Zone B and may also be related to subduction.

The area of study (160 km^2) in the Gundahl Complex occurs in inland northeastern New South Wales and is 250 km to the SSW of Brisbane (Fig. 1). The mélange has a strike length of 42 km and a width of 15 km. Equivalents of the Gundahl Complex extend along the exposed length of the fold belt (Fergusson 1982a). The unit is in fault contact to the SW with an extensive terrain dominated by deformed greywacke–argillite sequences (the Coffs Harbour sequence) and to the NE it is in fault-contact with a deformed unit of fine-grained tuffaceous rocks and volcanics (the Willowie Creek beds; Fergusson 1982a, b).

LITHOFACIES OF THE GUNDAHL COMPLEX

Structurally the Gundahl Complex consists of slabs and blocks of varying sizes embedded in a highly sheared matrix. The quantity of sheared matrix varies from almost nil to large tracts dominated by mélange matrix, although still rich in blocks up to tens of metres across. On the basis of detailed mapping at 1:10 000 scale within the Gundahl Complex, six main lithofacies have been identified, which are briefly described below for the least deformed exposures.

(1) *Argillite lithofacies.* Argillites are generally silty with varying quantities of silt-sized and less common sand-sized grains. Both massive and plane-laminated argillites are found. One massive pebbly argillite was found in this lithofacies at G.R. 5697 2020. It is at least 2 m thick and contains rounded clasts of feldspar porphyry, greywacke and rare limestone. The clasts are poorly sorted and range from sand-size grains up to 20 cm across.

(2) *Greywacke–argillite lithofacies.* Within slabs this lithofacies consists of alternating beds of argillite and greywacke commonly 1–10 cm thick. Sand-to-shale ratios vary from 1:1 down to 1:10. Undeformed beds are laterally persistant. Greywacke–argillite couplets are normally graded and contain sedimentary structures typical of CDE, BCDE and BDE Bouma-type units (see Bouma 1962). These features indicate turbidite deposition for this lithofacies.

(3) *Greywacke lithofacies.* Many slabs are dominated by massive greywacke. Some thick greywacke beds occur interbedded with the argillite and greywacke–argillite lithofacies. At a few localities conglomerate and/or breccia are interbedded with massive greywackes. All greywackes of the Gundahl Complex are lithic-rich with a predominance of intermediate to silicic volcanic rock fragments. The petrographic features of greywackes from the Gundahl Complex suggest correlation with similar rocks in the Early Carboniferous sequence of the Tamworth Belt (Day *et al.* 1978, Fergusson 1982a).

(4) *Argillite–tuff lithofacies.* Within slabs this lithofacies consists of alternating layers of argillite and grey–green tuff. Tuff layers are mainly 0.5–20 cm thick and have sharp bases and diffuse tops. Some tuff layers are graded while others are plane-laminated. Chemical analysis indicates that the tuff layers resemble silicic

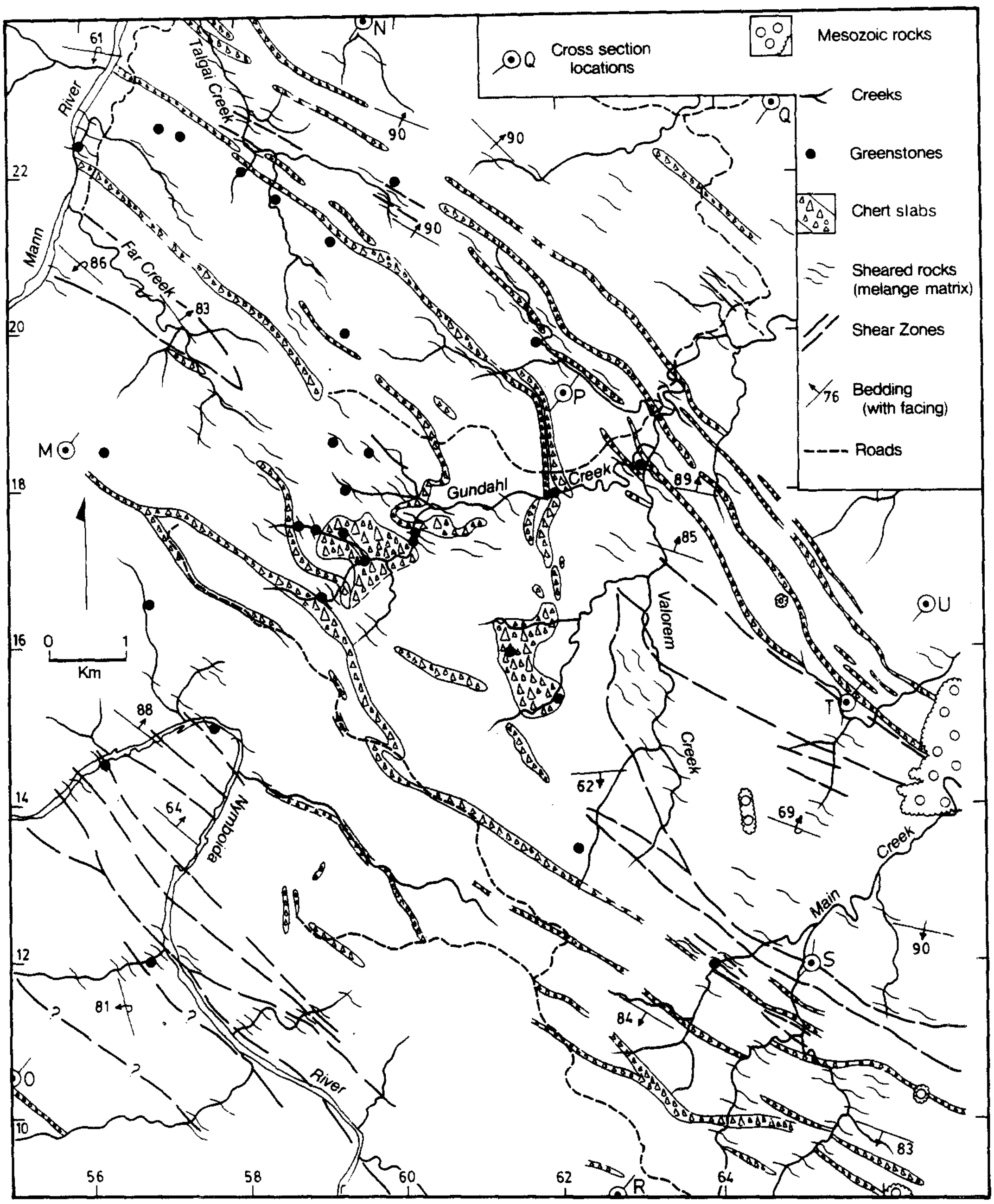

Fig. 2. Map of the Gundahl district showing chert slabs, greenstone localities, areas of exposed mélange matrix and shear zones within the Gundahl Complex. Locations for cross sections are also shown.

air-fall tuffs (e.g. Leitch 1981), although they may have been reworked or redeposited by turbidity currents.

(5) *Bedded chert lithofacies.* This consists of chert beds commonly 1–10 cm thick alternating with argillite laminae less than 1 mm thick. The chert is blue-grey in colour and occasionally contains poorly preserved outlines of radiolaria in thin section. Siliceous argillites with many well-preserved radiolaria also occur.

(6) *Greenstone lithofacies.* Within blocks the greenstones are either massive or amygdaloidal. Amygdaloidal greenstones are usually small fragments less than 1 m across, occasionally preserving concentric layering of amygdales which may have originated from larger pillow structures. The massive greenstones come from either massive flows or shallow dykes and sills.

Bedded chert and greenstone are volumetrically minor components in the Gundahl Complex (Fig. 2). Bedded cherts are the only slabs well enough exposed to be traced their full extent.

MÉLANGE MATRIX

For much of the Gundahl Complex slabs are selectively exposed and the extent of the soft matrix is difficult to determine. This is a common problem in mélange terrains (e.g. Duffield & Sharp 1976, Hamilton 1979). The mélange matrix consists of argillite-dominant lithologies of the argillite, greywacke–argillite, argillite–tuff lithofacies and in rare instances the greenstone lithofacies.

Argillite matrix is characterized by the presence of a foliation defined by closely spaced, crudely aligned fracture surfaces (Fig. 3). Where best developed this foliation consists of fractures spaced at the millimetre scale or less. Intersecting fractures divide the rock into lensoidal chips with the two longest axes of the chip lying in the plane of the foliation resulting in an anastomosing fabric. Surfaces of these chips are polished and in some larger fragments are striated (Fig. 3).

Where the foliation is poorly developed, the fractures are spaced up to 30 mm apart and separate domains of undeformed material. In thin sections of argillites, this spaced anastomosing foliation is defined by films of opaque material which truncate laminae of siltstone and fine sandstone. These films are either crushed material or pressure-solution residue (e.g. Moore & Allwardt 1980). There is no preferred orientation of platy or elongate grains associated with these films as would be expected for a slaty cleavage.

The greywacke–argillite lithofacies displays a complete spectrum from slabs of steeply dipping and mesoscopically folded strata to mélange matrix with complete disruption of greywacke beds. Examples of severely disrupted greywacke–argillite lithofacies are composed of irregularly shaped greywacke fragments of variable size enclosed by a matrix of argillite with a shear foliation (Fig. 3). Margins of the greywacke fragments are commonly hackly with many straight segments. Many fragments have equant or elongate fault-bounded rhombic outlines. Larger fragments are typically lenticular with adjacent smaller fragments aligned parallel to their outlines. Greywacke blocks of all sizes display either angular or extremely necked terminations.

In outcrops of less disrupted greywacke–argillite lithofacies, the thicker greywacke beds form diamond-shaped or lenticular boudins, while the more continuous, thinner greywacke beds show pinch and swell structures. Sparse rounded greywacke fragments occur in both highly disrupted and some less disrupted outcrops of this lithofacies. The greywacke of the rounded fragments may have had a lower ductility contrast during deformation than that forming the necked and rhombic fragments (Ramsay 1967, fig. 3–44).

The argillite–tuff lithofacies occurs mainly as slabs ranging up to 1 km across. In places, it forms mélange matrix characterized by total disruption of bedding resulting in wispy tuff fragments surrounded by sheared argillite. Instances of gradation between these end-members are uncommon for this lithofacies. Local features of argillite–tuff blocks include: sigmoidal boudinage (see Ramsay 1967, p. 108), pinched-out beds, abundant high-angle faults and common bedding-plane shears (Fig. 3).

Although the greenstones form blocks in the Gundahl Complex, some outcrops are so highly deformed they are best regarded as part of the sheared matrix (Fig. 3). In these instances, closely spaced shear zones form a pronounced foliation which wraps around small phacoids of carbonate and amygdaloidal basalt. Larger fragments of amygdaloidal basalt are coated with carbonate veins and slickensides. The foliation is generally planar but locally contorted and folded. The shear foliation is cut at a high-angle by several other sets of fracture surfaces.

Mixtures with blocks of greywacke, chert and greenstone embedded in argillite matrix are best developed on a macroscopic scale in the Gundahl Complex, though mesoscopic examples occur, particularly at the margins of large slabs. Within outcrops chert blocks are lenticular with planar faulted boundaries and they are aligned in the foliation of the argillite matrix (Fig. 3). In the sheared argillite matrix near chert slabs fragments of chert are accompanied by small pieces of greenstone. Greenstone blocks are usually equant or irregularly shaped. Some larger greenstone fragments have at least one edge parallel to an original cooling surface as defined by lines of vesicles.

INTERNAL MESOSCOPIC FEATURES OF SLABS

Evidence of shearing is not restricted to the mélange matrix. Slabs of both greywacke–argillite lithofacies and argillite–tuff lithofacies are commonly affected by abundant microfaulting. Faults at a high-angle to bedding typically have small displacements. Faults with movement in excess of 2–3 m juxtapose thin-bedded turbidites with massive greywackes. In addition, restricted areas of boudinage and pinch and swell structure occur. Bedding-plane shear zones occur within otherwise coherent sequences of well-bedded rocks (Fig. 3).

Many greywacke outcrops are cut by randomly oriented veins, either discrete or in networks (the web structure of Cowan 1982). In extreme cases, veins cover almost the entire exposure, resulting in a nondescript, apparently fine-grained, green rock. In thin section, the veins appear as distinct bands and less regular areas of small angular grains set in a dark brown to near opaque background (Fig. 3), and their boundaries with normal greywacke are mostly sharp. These veins have been noted in 45% of greywackes thin-sectioned from the Gundahl Complex, and in some areas are concentrated at the margins of massive greywacke blocks where sheared matrix is missing or minor (e.g. G.R. 5860 1110). These features are probably cataclastic veins similar to those described by Moore & Karig (1980) from sandstones of the Oyo Complex, a mélange on Nias Island (near Sumatra), and by Moore & Allwardt (1980) for sandstones in the Eocene Sitkalidak Formation of the Kodiak Islands (southern Alaska).

Internally, slabs of bedded chert vary from well-bedded sequences to areas of autoclastic mélange. (The adjective 'autoclastic' is used in the sense of Greenly 1919 to indicate *in situ* tectonic fragmentation.) Thickness variations in layers are common and may be original or the result of deformation. Areas of autoclastic mélange are comprised of rhomb-shaped fragments of chert in a sheared argillite matrix. Figure 3 shows contorted chert layers, with sigmoidal boudinage and pinch-and-swell structures within a chert slab. Many chert slabs are affected by faults and shear zones.

Blocks of greenstone are commonly cut by cataclastic veins of similar structure to those in greywacke, or by extremely irregular fractures. Radiolarian argillite, a

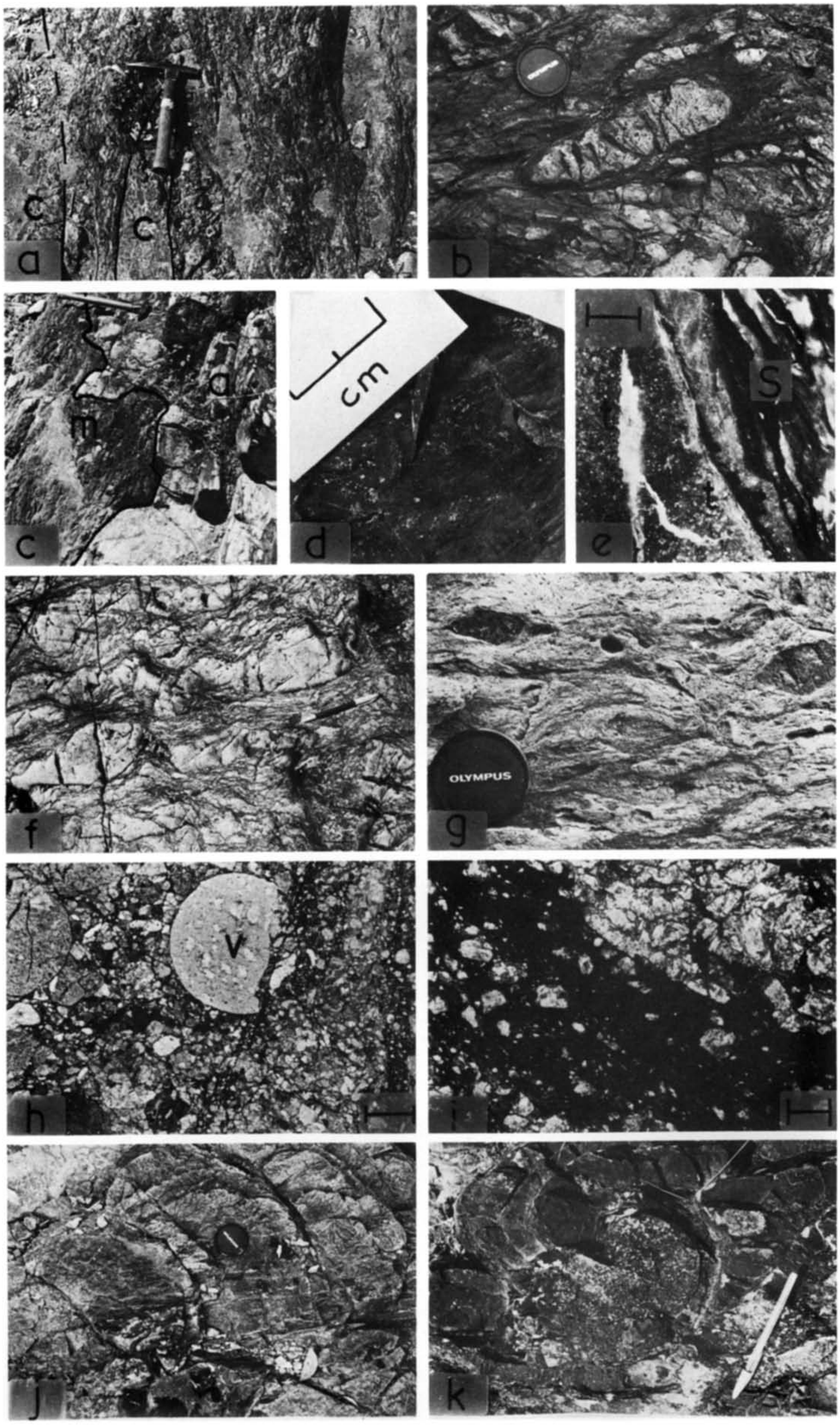

Fig. 3. (a) Sheared argillite matrix with chert fragments (c). (b) Sheared argillite matrix surrounding greywacke fragments. (c) Sheared argillite matrix (m) adjacent to an argillite–tuff block (a). (d) Striated surface in incipiently sheared argillite (scale 2 cm). (e) A bedding-plane shear zone (s) at the lower contact of a tuff bed (t. bar scale 3 mm). (f) Pinch-and-swell structure in autoclastic chert mélange. (g) Phacoidal greenstone fragments contained in autoclastic greenstone mélange. (h) Shear zone cutting a volcanic rock fragment (V). Bar scale 1 mm. (i) Shear zone in greywacke marked by grainsize reduction. Bar scale 0.25 mm. (j) An F_1 fold with axial-surface spaced cleavage in bedded chert. (k) An F_1 fold pair, with dramatic layer thickening by one chert bed above a décollement surface.

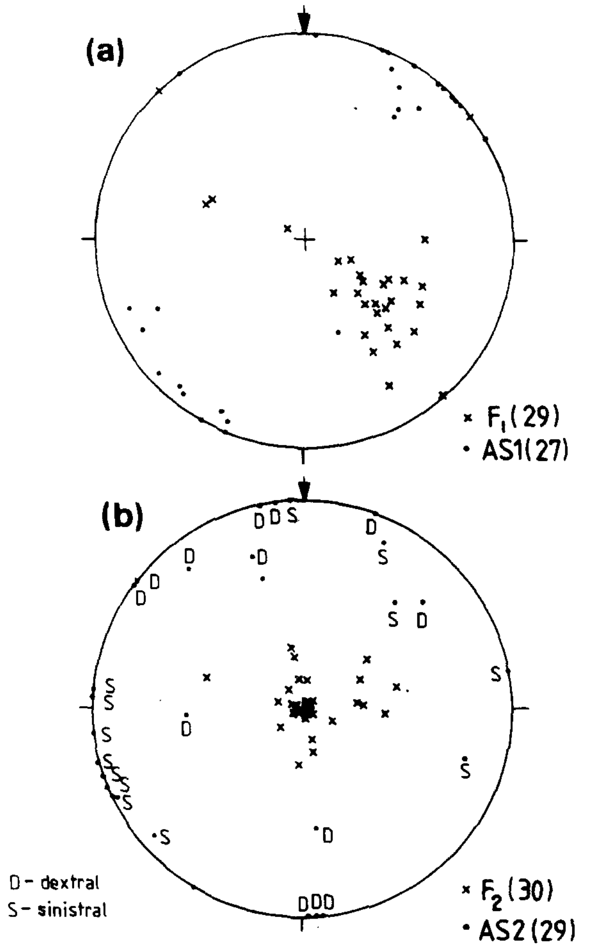

Fig. 4. (a) Equal-angle stereogram showing F_1 fold axes and poles to axial surfaces (AS1). (b) Equal-angle stereogram with F_2 mesoscopic folds and poles to axial surfaces (AS2). Where known, axial surfaces are designated as dextral (D) or sinistral (S) types.

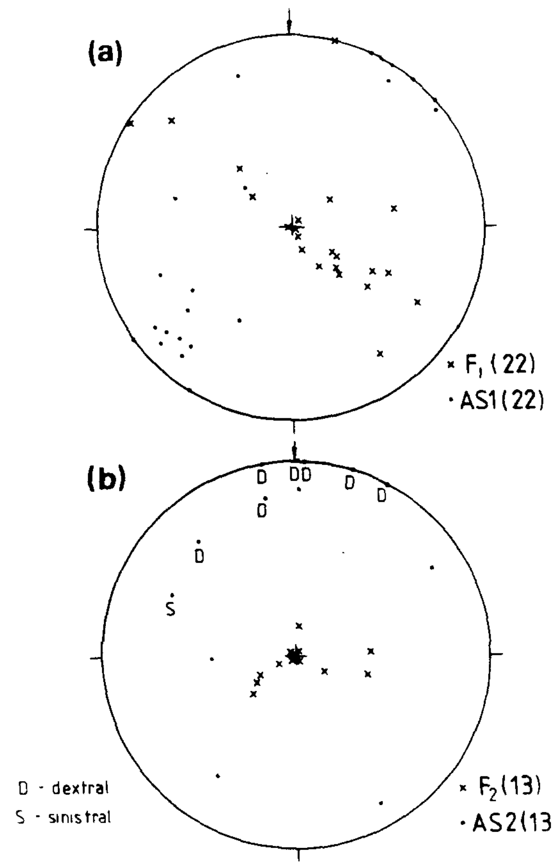

Fig. 5. (a) Equal-angle stereogram showing F_1 mesoscopic folds and poles to axial surfaces for cherts. (b) Equal-angle stereogram showing F_2 mesoscopic folds and poles to axial surfaces for cherts. Where known, axial surfaces are designated as dextral (D) or sinistral (S) types.

relatively minor lithofacies, forms fault-bounded angular blocks up to 10 m across set in sheared argillite matrix.

Mesoscopic folds

The Gundahl Complex contains two main groups of folds. Folds are relatively uncommon outside the bedded cherts.

F_1 mesoscopic folds trend to the SE with variable plunges and have steeply inclined or vertical axial surfaces (Figs. 4 and 5). F_1 fold pairs have both 's' and 'z' shapes, but no 'm' shapes have been recorded. A 1–5 cm spaced cleavage is developed parallel to the axial surfaces of some F_1 folds. Outside the bedded cherts F_1 folds typically have close interlimb angles and rounded to chevron profiles. Argillite layers interbedded with more competent greywacke or tuff display thickening in fold hinges.

F_1 mesoscopic folds are abundant within the bedded chert slabs. Most of these folds have tight to isoclinal interlimb angles. Variation within the one fold is considerable and some isoclinal folds die out to planar beds along their axial surfaces. At several localities F_1 folds are refolded by more open folds with a kink-like geometry typical of the F_1 folds (Fig. 6).

There is a variation in the style of F_1 folds in bedded cherts, which may be due to either soft sediment slumping or tectonic deformation of chert. The best evidence for soft sediment slumping is the truncation of folds by an overlying depositional contact (Helwig 1970). No examples of this feature have been found in the Gundahl Complex. Helwig (1970) lists 14 other criteria for identifying soft sediment slump folding but most apply to other fold forming processes. Several of the listed features are common in bedded cherts from the Gundahl Complex for example: décollement features, detached folds, disrupted bedding, isolated horizons of folds and curvilinear fold style.

A soft sediment slump origin for the F_1 folds of the bedded cherts is unlikely because their orientations and sense of vergence are consistent with F_1 folds in other lithofacies and some are associated with axial-surface cleavage (Fig. 3). Cleavage is widely accepted as a deformation fabric developed parallel to the plane of flattening and is unlikely to be found in soft sediment slumps (Wood 1974). A tectonic origin is thus likely for the F_1 folds in the bedded cherts of the Gundahl Complex.

In places tight to isoclinal F_1 folds in the bedded cherts are associated with faults. This probably reflects the lack of incompetent material, interbedded with competent chert beds, to fill fold cores during progressive tightening of folds. As a result faults have developed in fold hinges and locally these replace the axial surfaces. This con-

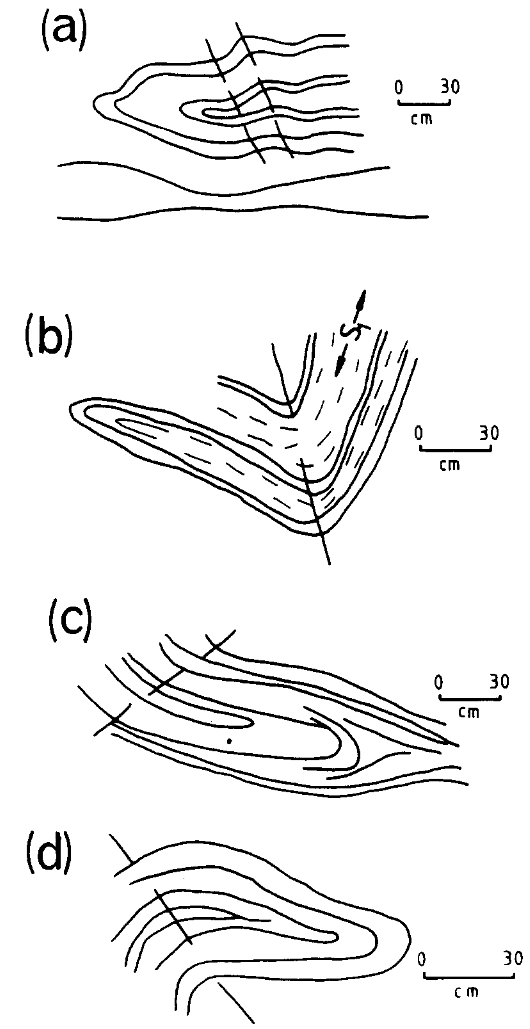

Fig. 6. Sketches from field notes and photographs of F_1 folds being refolded by F_2 structures. Note than in (b) an axial surface spaced cleavage (S_1) is also refolded.

trasts with fold development in interbedded mudstone–chert from the Franciscan Complex where faulting along axial surfaces has not occurred (Ramberg & Johnson 1976). Other F_1 folds in the bedded cherts of the Gundahl Complex are box-shaped and probably formed by kinking (cf. Orozco & Galvez 1979).

Most chert beds behaved competently during deformation, but some exhibit extreme changes in bed thickness indicative of incompetent behaviour (Fig. 3). The bedded cherts apparently varied in their degree of lithification at the time of deformation. Bedded cherts are known to require up to 25–50 Ma to lithify from siliceous oozes (Davies & Supko 1973, Kastner *et al.* 1977). Hence, it is entirely reasonable to expect some chert beds to have been only partly lithified at the time of deformation of the Gundahl Complex, provided this occurred not more than 50 Ma after deposition.

Axial planes of F_2 mesoscopic folds are typically upright or steeply inclined and oblique to bisecting surfaces. Plunges are steep to vertical. Most F_2 folds are open though close examples occur. Hinges are slightly rounded or angular in profile. Some well exposed F_2 folds change shape up and down their axial planes, dying out in both directions. Features such as angular hinges, asymmetry, and very short lengths of the short limb of folds with 's' and 'z' shapes, are consistent with these F_2 folds having originated as kinks that were tightened by later flattening (see Paterson & Weiss 1966). Although most F_2 folds occur in blocks, some refold the shear foliation of the matrix. Thus, the F_2 folding evidently postdates the formation of the mélange.

F_2 mesoscopic folds are generally either N- or W-trending. Most W-trending folds have a geometry implying a dextral sense of movement while the N-trending set usually indicates a sinistral sense of movement (Figs. 4 and 5). Both the kink-like geometry and the opposing senses of movement given by differently oriented sets of F_2 folds are consistent with a conjugate kink origin. If so, the maximum principal compressive stress was horizontal and directed NW–SE.

MACROSCOPIC STRUCTURE

The Gundahl area has been subdivided into eight structural domains numbered from 11 to 18, following on from the domains of the Coffs Harbour sequence, see Fergusson (1982b). Three structural associations based on groups of domains have been recognized in the Gundahl Complex:

(1) lenticular blocks of all lithofacies set in mélange matrix (domains 11, 12, 17 and 18);

(2) an apparently coherent sequence of greywacke and argillite surrounded by blocks of argillite–tuff (the Main Creek block, domains 13, 14 and 15) and

(3) extensive mélange matrix containing variably sized equant chert blocks (domain 16).

Lenticular block structural association

This structural association corresponds to the type II mélange of Cowan (1981), that is, an assemblage of lenticular blocks. At the macroscopic scale the most obvious feature of this association is the strong NW–SE grain, defined by trains of overlapping chert slabs and other slabs (Fig. 2). Major shear zones, bedding, shear foliation, axial planes of F_1 mesoscopic folds and disjunctive cleavage also have this trend and are all steeply dipping (Figs. 7 and 8). Locally this NW–SE grain has a slightly swirled appearance (Fig. 2).

Throughout most of domains 11, 17 and 18 younging directions and fold vergence indicate the slabs face to the NE. Exceptions occur throughout these domains and in domain 12 where most of the scarce younging indicators face to the SW. In spite of these changes in younging directions and the presence of many chert markers no major macroscopic fold hinges have been identified in the Gundahl Complex.

There is a complete spectrum in the sizes of slabs from less than 1 m across up to a slab 10 km long. The variation in size of the chert slabs in the Gundahl Complex is wide compared with the size ranges of chert slabs in other mélanges (e.g. Raymond 1974, Gucwa 1975,

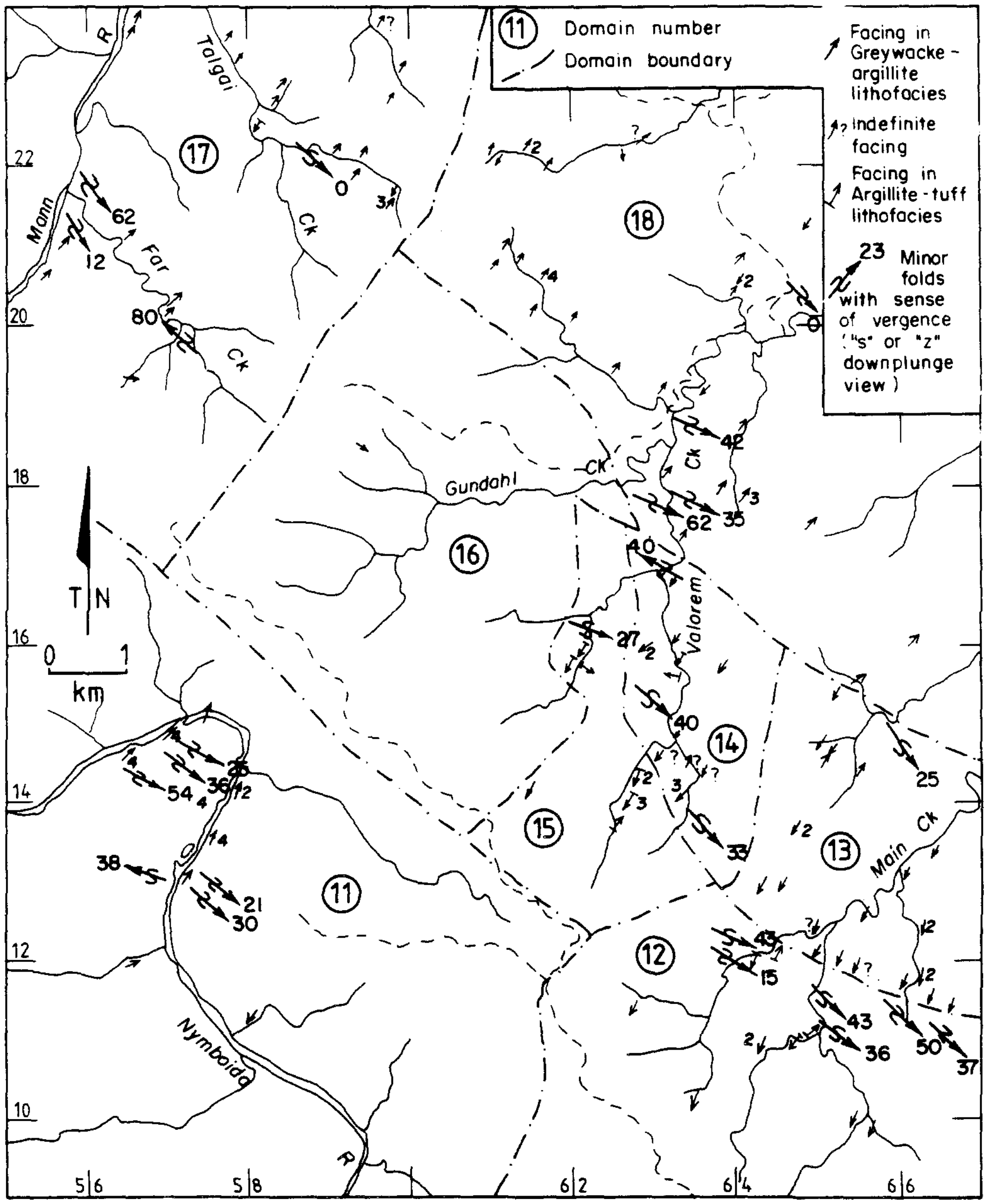

Fig. 7. Structural domain map for the Gundahl area showing younging directions (and the number of such determinations if more than one). Mesoscopic F_1 folds and their sense of vergence ('s' or 'z') are also shown.

Cowan 1978, Moore & Wheeler 1978). A similar variation in size of slabs of other lithofacies may also occur, but has not been detected due to poor exposure. Many of the 'chert slabs' could be parts of larger, lithologically diverse slabs rather than discrete slabs. Two undoubted examples of such slabs have been found on the Nymboida River bend at G.R. 5650 1450.

The map of the Gundahl district in Fig. 9 shows interpreted boundaries of the main blocks and slabs. Blank areas represent undifferentiated sheared argillite mélange matrix, but also include many overlapping slabs up to hundreds of metres in width and several kilometres long. Many slabs consist of a single lithofacies but at least 12 examples contain remnants of a pre-mélange stratigraphic sequence consisting of basal greenstone and bedded chert overlain by argillite–tuff which in turn is succeeded by a coarsening and thickening-upward sequence of turbidite-type lithofacies (Fergusson 1982a). It is apparent from Figs. 2, 8 and 9 that blocks containing similar lithofacies are repeated throughout the Gundahl Complex. The repetition of these slabs implies an imbricate-fault structure for the Gundahl Complex.

Main creek block and domain 15

Domains 13 and 14 cover the fault-bounded Main Creek block which is dominated by greywacke–argillite-type lithofacies. The northern part of the block consists of argillite–tuff lithofacies which may be in fault contact with and not part of the Main Creek block (Fig. 2). In domain 13 the structural trend is close to E–W, which changes to a NW–SE orientation in domain 14 (Fig. 7). Much of the Main Creek block appears coherent and has the structure of a steeply dipping homoclinal limb with younging directions consistently facing to the S and SW. Areas of bedding disruption and shearing are concentrated at the boundaries of the block where tectonic

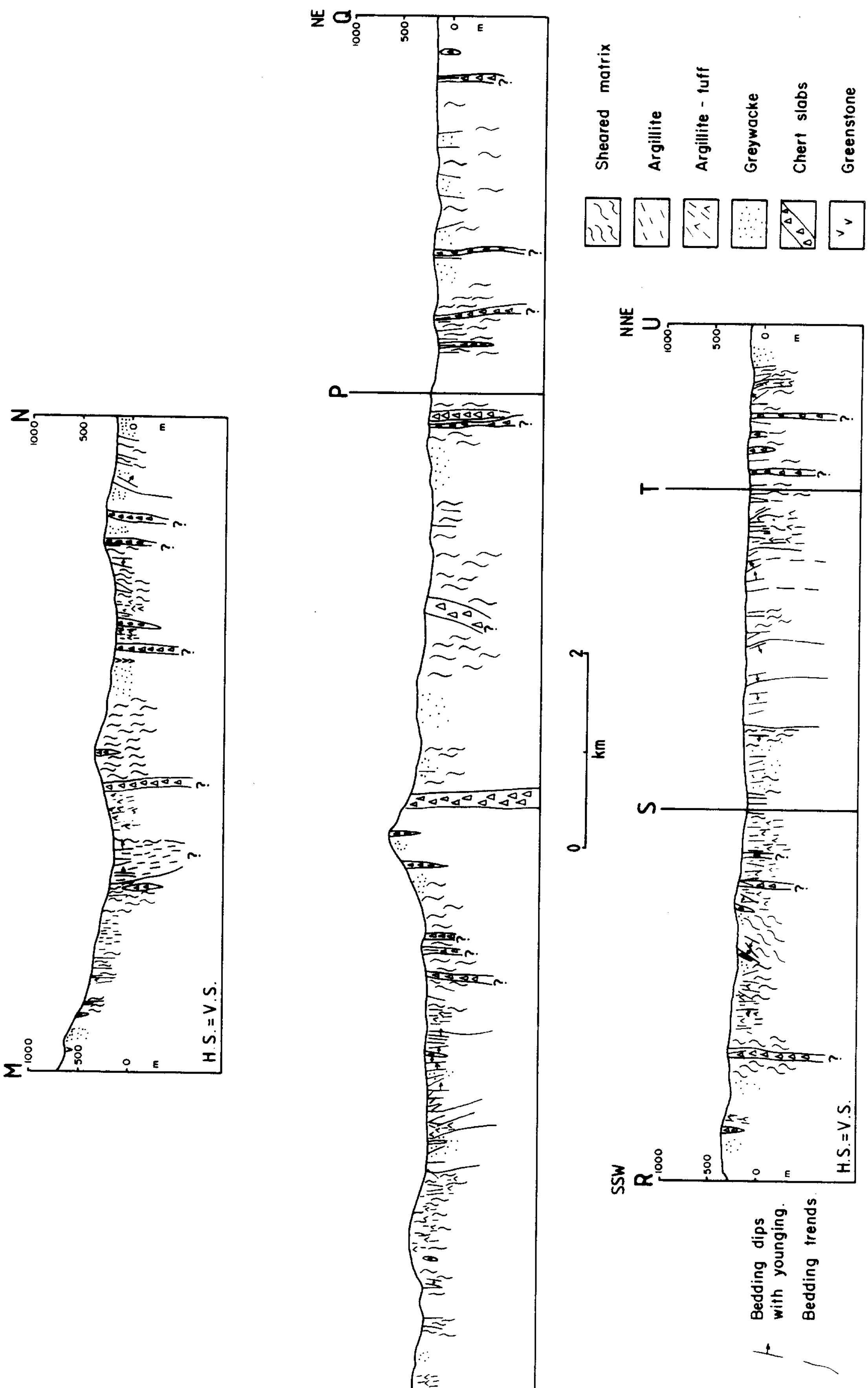

Fig. 8. Cross-sections for the Gundahl area. See Fig. 2 for locations and text for discussion.

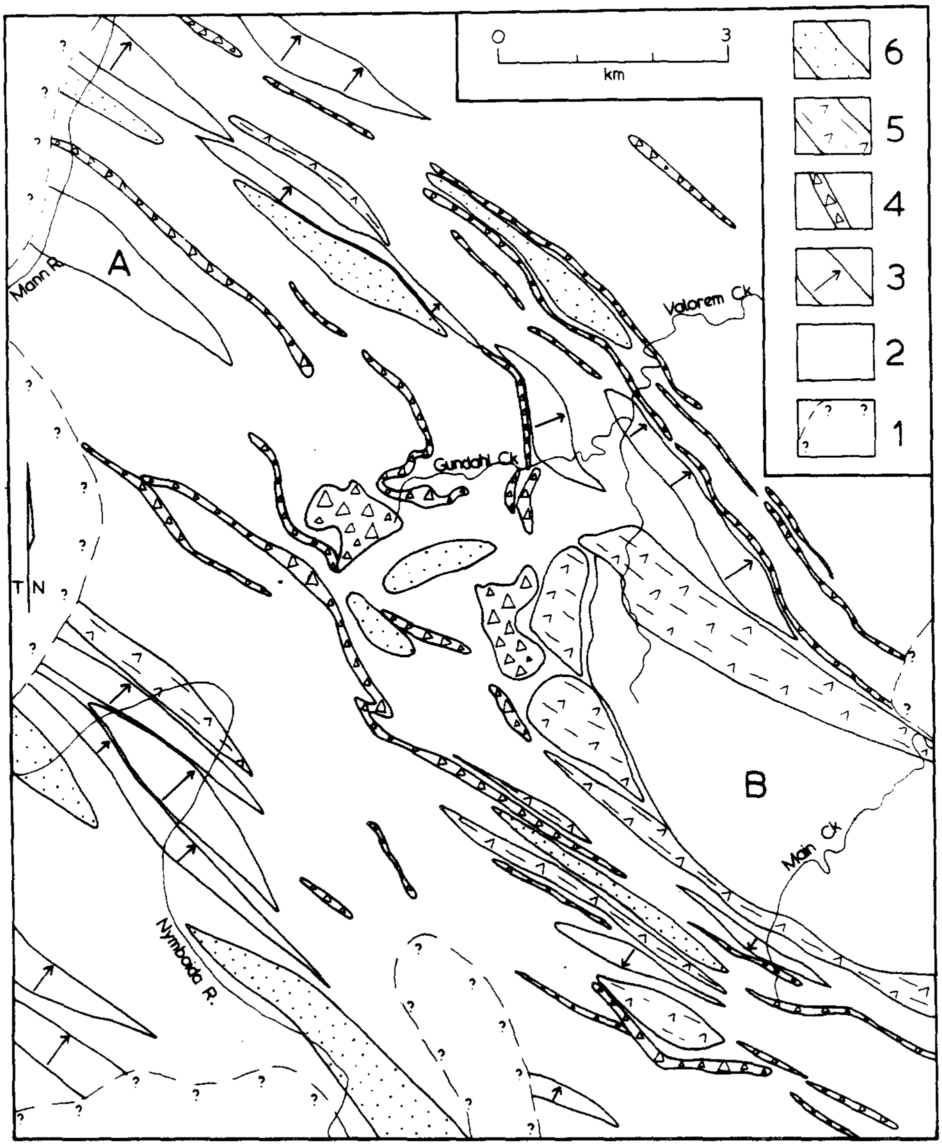

Fig. 9. Interpretation map of the Gundahl Complex in the Gundahl district showing the outlines of the major blocks. Key: A, Far Creek block; B, Main Creek block; 1, areas unmapped; 2, areas containing mélange matrix and smaller slabs; 3, blocks containing several lithofacies arranged in the pre-mélange stratigraphic sequence (with arrow in direction of younging); 4, chert slabs; 5, argillite–tuff slabs; 6, greywacke slabs.

thickening has occurred. The western margin is most severely affected and consists of a jumbled mass of greywacke and thoroughly sheared thin-bedded turbidites.

Domain 15 is to the west of the Main Creek block and it consists almost exclusively of large blocks of argillite-tuff lithofacies with rare greywacke–argillite lithofacies, bedded chert and greenstone. Bedding throughout the domain is ESE-trending. The relatively scarce younging directions in this domain indicate, with two exceptions, S-facing. Locally beds of argillite–tuff are folded and affected by bedding-plane shear (Fig. 3). The apparently very thick sequence of argillite–tuff lithofacies in domain 15 probably results from repetition in several concealed major fault slices or faulted folds.

Chaotic block structural association—Domain 16

On the macroscopic scale this domain is dominated by several large equant blocks of bedded cherts, with other slabs of chert, greywacke, and argillite–tuff, and less abundant, smaller (less than 100 m across) greenstone blocks (see Fig. 8, cross section OP). Structural trends tend to be irregular although shear foliation in the mélange matrix consistently trends NW–SE.

Chert slabs have been traced from other domains into the northeastern and southwestern corners of domain 16 (Fig. 2). Between these chert slabs is a large area of mélange matrix in which chert slabs up to several kilometres long either die out or terminate in blob-like masses. The complete disruption of greywacke–argillite layers of the mélange matrix is particularly well exposed.

Chert slabs in the central part of this domain commonly form bizarre outcrop patterns. In one instance a chert slab diverges from the general SE trend to form a loop around the nose of an open fold (G.R. 6065 1817). Another isolated equant mass at G.R. 1730 5950 has a core of thoroughly sheared greenstone and greywacke and is possibly a tectonically thickened chert slab folded back on itself during mélange formation.

DISCUSSION

Origin of the Gundahl Complex

The Gundahl Complex contains a chaotic assemblage of slabs in a sheared matrix. Several lines of evidence suggest that the principal processes responsible for its present features were tectonic.

(1) The mélange matrix is highly sheared. The occurrence of polished and slickensided fragments in addition to broken and boudinaged blocks support a tectonic origin for the block-in-matrix fabric.

(2) Slabs within the Gundahl Complex contain many features of tectonic origin: F_1 folds, axial surface spaced cleavage, bedding-plane shears, shear zones (within greywackes and greenstones) and areas of autoclastic mélange. Furthermore there is every gradation from steeply dipping coherent sequences within slabs to areas of mélange matrix in which any original bedding has been destroyed.

(3) The monotonous repetition of overlapping slabs separated by faults or regions of sheared matrix define an imbricate fault-slice structure. An excellent example of this structure occurs on the Nymboida River bend where several similar slabs are stacked parallel to each other, and at one position are separated by sheared greenstone matrix. Such an imbricate stacking of fault slices clearly results from tectonic processes.

(4) The contacts of the Gundahl Complex with the adjoining Coffs Harbour sequence and the Willowie Creek beds are not directly observable in the field. However, several features imply that these contacts are significant faults. The Willowie Creek beds–Gundahl Complex contact is marked by poor exposure and a topographic depression. Near the Willowie Creek beds contact the Gundahl Complex consists of many blocks with internal younging directions to the NE. Since the turbidite-type lithofacies of the Gundahl Complex are of probable Early Carboniferous age and the Willowie Creed beds are Siluro-Devonian a faulted contact is most likely. The contact between the Late Carboniferous (?) Coffs Harbour sequence and the Gundahl Complex is delineated by a distinct lithological change. Again, the proposed age differences between these units and the NE younging directions common to both supports the presence of a faulted contact. Major faulting at the margins of the Gundahl Complex is consistent with its tectonic origin.

These features clearly indicate the fundamental role of tectonic deformation in the formation of the Gundahl Complex. The evidence against its chaotic nature having formed by primary sedimentary mixing, prior to tectonic deformation, is considered below.

(i) The presence of argillite–matrix olistostromes is considered critical in recognizing a sedimentary mélange (Naylor 1982). In the Gundahl Complex, there is only one outcrop of an olistostrome with an undeformed mudstone matrix. However, the clasts in this olistostrome match the lithic detritus found in greywackes, and do not resemble any of the main lithofacies types found in mesoscopic-scale mélanges in the Gundahl Complex. In slabs of greywacke lithofacies, conglomerates and breccias with a greywacke matrix are more common. Again, the clasts are simply larger fragments of the normal range of greywacke detritus, with one exception in which dispersed chert cobbles occur. Sedimentary breccias or olistostromes with clasts derived from the six main lithofacies have not been identified in the Gundahl Complex.

(ii) Much of the turbidite-type lithofacies in the Gundahl Complex consist of silicic to intermediate volcanic detritus. The Gundahl Complex is unlikely to be a sequence of sedimentary megabreccias since slab-sized fragments with the same composition as the finer detritus of the turbidite-type facies are not present. Instead, the slabs of the Gundahl Complex are derived from the tectonic disruption of a distinctive pre-mélange stratigraphic sequence.

Deformational history of the Gundahl Complex

The Gundahl area has been affected by two deformations, similar to those proposed for the rest of the region (Korsch 1981). The mélange and related major structures were produced by the D_1 deformation. The D_1 trends are similar to those in the Coffs Harbour sequence further south. The D_2 deformation produced folds, faults and prominent lineaments transverse to the regional structural grain.

The block-in-matrix fabric and most deformational features within the slabs formed during the first deformation. Attempts to determine age relationships between specific D_1 structures in the Gundahl Complex have not been successful. Folding and axial-surface cleavage development within many slabs may have accompanied the shearing which produced the block-in-matrix fabric. Folds in bedded cherts were probably initiated prior to internal shearing of these slabs (see earlier discussion). Shear zones within greywacke and greenstone blocks probably formed synchronously with the mélange. Within several of these blocks some shear zones offset older shear zones indicating at least two episodes of shearing (e.g. samples R50268, R50269, R50258). In exposures containing both shear zones and mineral veins (with quartz, albite, carbonate and prehnite) the latter commonly cross-cut the former; only rarely are the mineral veins offset at the shear zones. Thus, it appears much of the shearing within greywacke and greenstone blocks predated hydraulic fracturing that probably formed the mineral veins (e.g. Norris & Henley 1976, Oliver & Leggett 1980).

On the larger scale, shearing and imbricate faulting of an originally coherent sequence of marine strata, with a chert-greenstone basement, produced the present outcrop patterns. The majority of shears and shear zones in the Gundahl Complex are aligned parallel to the elongation of the slabs. During mélange formation shearing must have largely proceeded along planes now oriented near vertical and trending NW–SE. Detailed study of a bedded chert exposure suggests dip–slip as opposed to

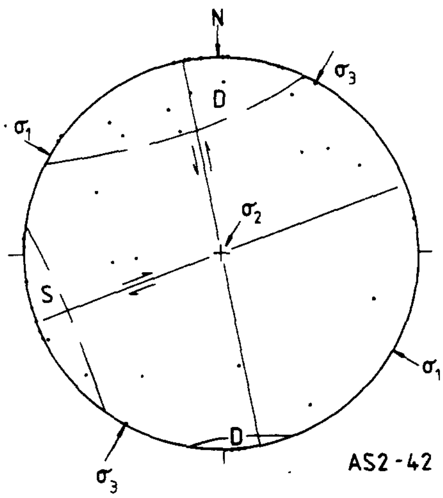

Fig. 10. Equal-angle stereogram showing poles to F_2 fold axial surfaces from the Gundahl area and their predominant senses of movement (D, dextral; S, sinistral). The principal stress direction (σ_1) has been calculated on the assumption that the two sets of fold orientations are part of a conjugate set.

strike-slip motion (Fergusson 1982a, Figs. 6–9). Folds in this exposure become tighter and more steeply plunging towards the northern end of the exposure where a shear zone crosses the chert slab. Such variation is consistent with a simple shear operating vertically parallel to the northeastern contact of the chert.

Disruption of slabs containing the coherent pre-mélange stratigraphic sequence proceeded by extensive bedding-plane shear resulting in the predominance of thin slabs. This was accompanied by internal deformation and fault repetition of the slabs plus the widening of areas of sheared matrix between the slabs. The causes of the unusual shapes of chert masses in domain 16 are more obscure. The extensive mélange matrix in this domain may have promoted flow (cf. Cloos 1982) which, coupled with exceptionally ductile behaviour of the chert masses, produced the distinctive outcrop pattern.

The second deformation was a discrete episode that postdated development of the mélange. For the Gundahl Complex, F_2 mesoscopic folds are related to one system of conjugate kinking with the principal compressive stress oriented NW–SE (Fig. 10). In addition to the F_2 folds there are other transverse features which evidently postdate mélange development. Small-scale faults trending northerly to northeasterly offset the shear foliation in the matrix and bedding within blocks. Korsch (1981) has found similar faults transverse to the principal structural trends. Prominent NE–SW lineaments transverse to the regional trends extend into nearby Permian volcanics. Since no offset has been detected along these lineaments they may belong to a major joint system.

Tectonic setting

The Gundahl Complex has lithofacies and internal structures characteristic of tectonic mélanges in circum-Pacific subduction complexes, such as the Franciscan Complex of California (Hsü 1971, Cowan 1974, 1978, Jones *et al.* 1978, Korsch 1982), the Uyak Complex of the Aleutians (Moore & Wheeler 1978, Connelly 1978), the Oyo Complex of Nias Island (Moore & Karig 1980) and the Chrystalls Beach Complex of New Zealand (Nelson 1982). These tectonic mélanges differ in the extent to which mesoscopic-scale mélange fabrics are developed, reflecting variation in the role of shearing during their formation. The Gundahl Complex is dominantly a map-scale mélange and possibly suffered much less shearing than some classical tectonic mélanges with extensive mesoscopic block-in-matrix fabric.

The pre-mélange stratigraphic sequence, remnants of which are found in the lenticular block structural association, is similar to modern trench sequences of the Pacific Ocean (e.g. Schweller & Kulm 1978). Bedded cherts overlie greenstones, and are probably derived from the diagenesis of pelagic radiolarian oozes deposited on the oceanic plate (e.g. Hsü 1971, Connelly 1978). The overlying argillite–tuff lithofacies probably formed from hemi-pelagic mud and interbedded volcanic ash layers. Similar deposits occur within oceanic settings up to 1000 km from active volcanic arcs (e.g. Ninkovich & Robertson 1975, Scheidegger & Kulm 1975). In a palaeo-trench these deposits were overlain by arc-derived terrigenous turbidites and fine-grained pelagic mud in trench-fill submarine fan deposits. Tectonic accretion and subsequent deformation at the toe of the subduction complex formed the lenticular block structural association of the Gundahl Complex.

Within the Gundahl Complex relatively large blocks dominated by turbidite-type lithofacies and/or argillite–tuff lithofacies are less deformed and sheared than surrounding areas. For example, the Far Creek block consists mainly of steeply dipping laminated argillite and is surrounded by strongly sheared argillite matrix with fractured greywacke blocks (Fig. 9). Similar features from the Franciscan Complex have been interpreted as the deformed fill of trench-slope basins (Smith *et al.* 1979). In the Franciscan Complex it has been possible to demonstrate local derivation of sediment from older portions of the subduction complex, which has been used as evidence to confirm a trench-slope setting (e.g. Cowan & Page 1975). Structural basins on modern trench-slopes are either filled with coarse sediment or starved of all but the finest grained sediment (e.g. Vittori *et al.* 1981). Interbedded mud and tuffaceous layers of a modern trench-slope setting have been described from Japan by Cadet & Fujioka (1980). Larger turbidite-type and argillite–tuff blocks of the Gundahl Complex may have formed from tectonic kneading of trench-slope basin fill on the ancient subduction complex (cf. Scholl *et al.* 1980).

The Main Creek block has internal younging directions to the SW which is the opposite to the regional pattern (Korsch 1981, Fergusson 1982a, b). It is conceivable this pattern may have resulted from differential movements along bounding faults during tectonic kneading of a trench-slope basin. Another possibility is that the Main Creek block is the deformed remnant of an abnormally thick submarine fan, deposited in the palaeo-trench, that was obducted during tectonic accretion in the manner proposed by Seely (1977) and Moore & Allwardt (1980). This explanation may also apply for the origin of the region of SW younging to the south of the Main Creek block (Fig. 7).

The structure of the Coffs Harbour sequence, the unit to the SW of the Gundahl Complex, is also consistent with a subduction complex setting (Fergusson 1982a, b). The Coffs Harbour sequence consists mainly of coherent turbidite sequences with rare chert and greenstone. Faulted folds in this unit have a regional vergence consistent with dominant NE younging directions (Fergusson 1982b).

The overall age progression of tectono-stratigraphic units bounding the Gundahl Complex is from the NE to the SW (Fergusson 1982a). This structure is in accord with a subduction complex with a trench retreating to the SW (Seely *et al.* 1974, Karig and Sharman 1975). However, an associated arc and fore-arc basin do not occur to the NE of the Gundahl Complex but are found over 200 km to the west (Leitch 1975, Day *et al.* 1978, Cawood 1982). This apparently anomalous configuration is explained when regional relationships are taken into account. The structural trends of the Gundahl Complex and the Coffs Harbour sequence when followed along strike define a major *z*-fold structure (Fig. 1) (Flood & Fergusson 1982, Fergusson 1982a). This *z*-fold structure formed during the Early Permian prior to extensive magmatic activity that formed the younger assemblage of the Tablelands Complex and after the cessation of subduction in the lastest Carboniferous. Formation of the *z*-fold structure has reoriented the Gundahl Complex and Coffs Harbour sequence from their initial positions parallel to the N–S Connors–Auburn Arches (magmatic arc) and Tamworth–Yarrol shelves (fore-arc basin). A full acount of the Early Permian tectonic events responsible for the *z*-fold is in preparation.

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