

# CORRELATION OF THE CAMPANIAN/MAASTRICHTIAN BOUNDARY IN N.W. EUROPE; CAN THE FORAMINIFERA FROM THE GOBAN SPUR PROVIDE SOME ANSWERS?

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Following designation of the Tercis-les-Bains section as the GSSP (Global Stage Stratotype and Point) for the base of the Maastrichtian it is necessary to establish firm stratigraphical correlation of this succession with other regions. One of the most important areas is that occupied by the chalk facies of N.W. Europe with its zonation based primarily on belemnites and, to a lesser extent, smaller benthonic foraminifera. The planktonic foraminifera used in international correlation are relatively rare in the N.W. European chalk succession but in the DSDP sites of the Goban Spur (N.E. Atlantic margin) there is a fauna that contains some elements of the international zonation based on planktonic foraminifera and many of the species used in benthonic zonations. In DSDP Site 548A the link between the “Boreal” definition of the base of the Maastrichtian stage and the “Tethyan” definition can be established.

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## INTRODUCTION

In a recent discussion of the base of the Maastrichtian Stage, Christensen *et al.* (2000) have provided a review of some of the issues. Their account develops from the deliberations over the definition of the GSSP (Global Stage Stratotype and Point) for the Maastrichtian presented by Odin (1996) as a result of the “Brussels Symposium on Cretaceous Stage Boundaries” in 1995.

The importance of the quarry at Tercis-les-Bains (5 km south-west of Dax, Landes, France) as the GSSP was presented to the Brussels meeting (Kennedy *et al.*, 1995) on the basis of its position linking the “Tethyan” nannofossil and planktonic foraminiferal zonations with the typical “Boreal” assemblages. Hancock *et al.* (1993) have attempted to demonstrate this linkage, correlating the Tercis succession with the standard N.W. European belemnite zonation of Schultz (1979).

The foraminiferal succession described from Tercis (Simmons *et al.*, 1996; Ward and Orr, 1997) is, however, poorly - or even badly - preserved and is lacking many important taxa. The planktonic foraminifera (mostly identified in thin-section) were not, at that time, diagnostic and the smaller benthonic foraminifera were extremely difficult to work with as a result of their poor state of preservation.

The problem for the definition of the base of the Maastrichtian has been the fact that the standard belemnite succession and zonation (Schultz, 1978, 1979; Christensen, 1995, 1996) is best preserved in the chalk facies of N.W. Germany and adjacent areas of the N.W. European shelf. In these chalks smaller benthonic foraminifera are abundant, well-preserved and stratigraphically significant. Localities in the Tethyan realm (e.g. Tunisia) may contain abundant planktonic foraminifera and calcareous nannofossils (and in many cases ammonites) but are difficult to equate with the N.W. European benthonic microfossil assemblages.

In this respect the DSDP/ODP boreholes of the Goban Spur provide a valuable link between the chalk facies in the north and the Tethyan realm in the south. The classic area of Maastricht, however, although in a “chalk” facies is represented by a relatively shallow-water succession with an assemblage of distinctive, symbiont bearing(?), larger foraminifera (*Siderolites*, *Orbitoides*, *Omphalocyclus*). The Maastricht succession is, therefore, of limited value as a GSSP; hence the search for a more suitable location.

## THE CAMPANIAN – MAASTRICHTIAN BOUNDARY

Subsequent to the Brussels meeting the Maastrichtian Stage Working Group have completed their work and agreed on a proposal. This was approved by the Voting Members of the IUGS Subcommittee on Cretaceous Stratigraphy (SCS), voted on by

	ZONATION NW GERMANY Schulz et al. (1984)	TRADITIONAL BELEMNITE ZONES	NORFOLK				
			Peake & Hancock (1961, 1970) Wood (1967)	Johansen & Surlyk (1990); Wood (1988)			
Upper Maastrichtian	Belemnella fastigata	Belemnella occidentalis	B. occidentalis	Grey Beds	Beacon Hill Grey Chalk Member (c.5m)		
	Belemnella cimbrica						
	Belemnella sumensis					with 'Ostrea lunata' White Chalk	Little Marl Point Chalk Member (5m)
						without 'Ostrea lunata'	
Lower Maastrichtian	Belemnella obtusa	Belemnella lanceolata	B. lanceolata	Sponge Beds	Trimingham Sponge Beds Member (c.3m)		
	Belemnella pseudobtusa			Porosphaera Beds	Sidestrand Chalk Member (10-12m)		
	Belemnella lanceolata			Sidestrand Chalk			
Uppermost Campanian	grimmensis/ granulosus	Belemnitella langei	Traditional B. mucronata zone	Paramoudra Chalk	Paramoudra Chalk		
	Belemnitella langei			Beeston Chalk (part)	Beeston Chalk (part)		

Figure 1. The standard succession of the Campanian/Maastrichtian boundary in N.W. Europe.

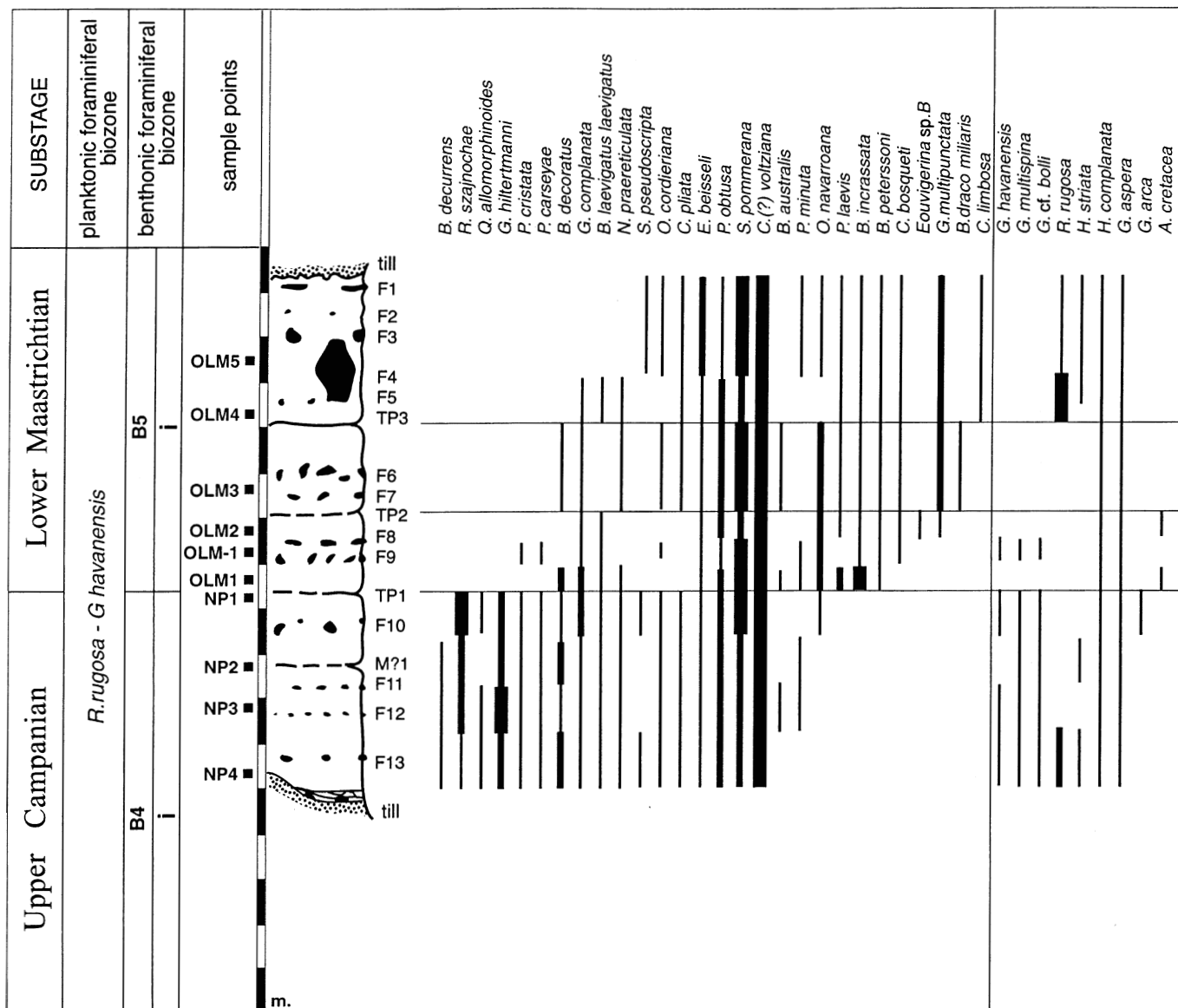


Figure 2. The foraminiferal distribution in the Overstrand Hotel Lower Mass. This succession can be compared with that recorded in Mortimore *et al.* (2001, fig. 4.32).

the Commission on Stratigraphy in 2000 and ratified by IUGS in February 2001; just days after the senior author presented this paper at the Ussher Society Annual Conference in Sidmouth (January 2001).

The GSSP for the base of the Maastrichtian Stage is placed at "level 115.2 metres on platform IV of the geological site at Tercis-les-Bains (Landes, France)". The Chair of the Working Group, Prof. Giles Odin, has now edited a volume of supporting data (Odin, 2001a). Within this volume there are numerous chapters on the planktonic and benthonic foraminifera, as well as a synthesis on how the faunas relate to other parts of Europe.

There are also reviews of other areas (e.g. Maastricht, northern Spain, central Italy) but, remarkably, little on the correlation of the new GSSP with the chalk facies of N.W. Europe. In that area the "Tethyan" planktonic foraminifera are barely represented and all inter-regional correlation using foraminifera involves the smaller, benthonic taxa (e.g. *Bolivinooides*, *Stensiöma*, *Reussella*, *Gavelinella* and *Neoflabellina*).

## THE BASE OF THE MAASTRICHTIAN IN N.W. EUROPE

The Maastrichtian succession of the "Boreal" area has been, historically, defined using the belemnite faunas that are extremely common (and well-preserved) in the area (Schultz, 1978, 1979;

Christensen, 1995, 1996). These authors (and others) traditionally use the base of the *B. lanceolata* Zone (Figure 1) for the base of the Maastrichtian. In the U.K. (Christensen, 1995, 1996) there is a suggestion that the very base of this zone may be missing and the best succession with which to provide a correlation from the belemnite zonation to the benthonic foraminiferal zonation is probably that at either Lägerdorf or Krons Moor in N.W. Germany. In this succession Schönfeld (1990) and Schönfeld and Burnett (1991) have described the foraminifera and established a zonation (Schönfeld and Burnett, 1991, fig. 2), the most distinctive feature of which is the overlap in the ranges of *Bolivinooides peterssoni* and *Globorotalites hiltertmanni*. The boundary between this concurrent range zone and the *Bolivina decurrens* interval zone is located almost exactly at the base of the *B. lanceolata* Zone.

In Norfolk the Campanian/Maastrichtian boundary (Figure 2) is taken as being within the Overstrand Hotel Lower Mass (Swiecicki, 1980; Hart *et al.*, 1989; Mortimore *et al.*, 2001; Hart and Swiecicki, *in press*). Unfortunately the marl seam at the boundary, when processed, yielded a residue with sand/gravel sized grains, indicating that there may be a thrust plane at this level. As the block of chalk at Overstrand is a rafted block of Cretaceous chalk within glacial sediments the presence of a number of thrust planes was not unexpected. More recent work on this block (Mortimore, *pers. comm.*, 2001) has suggested that

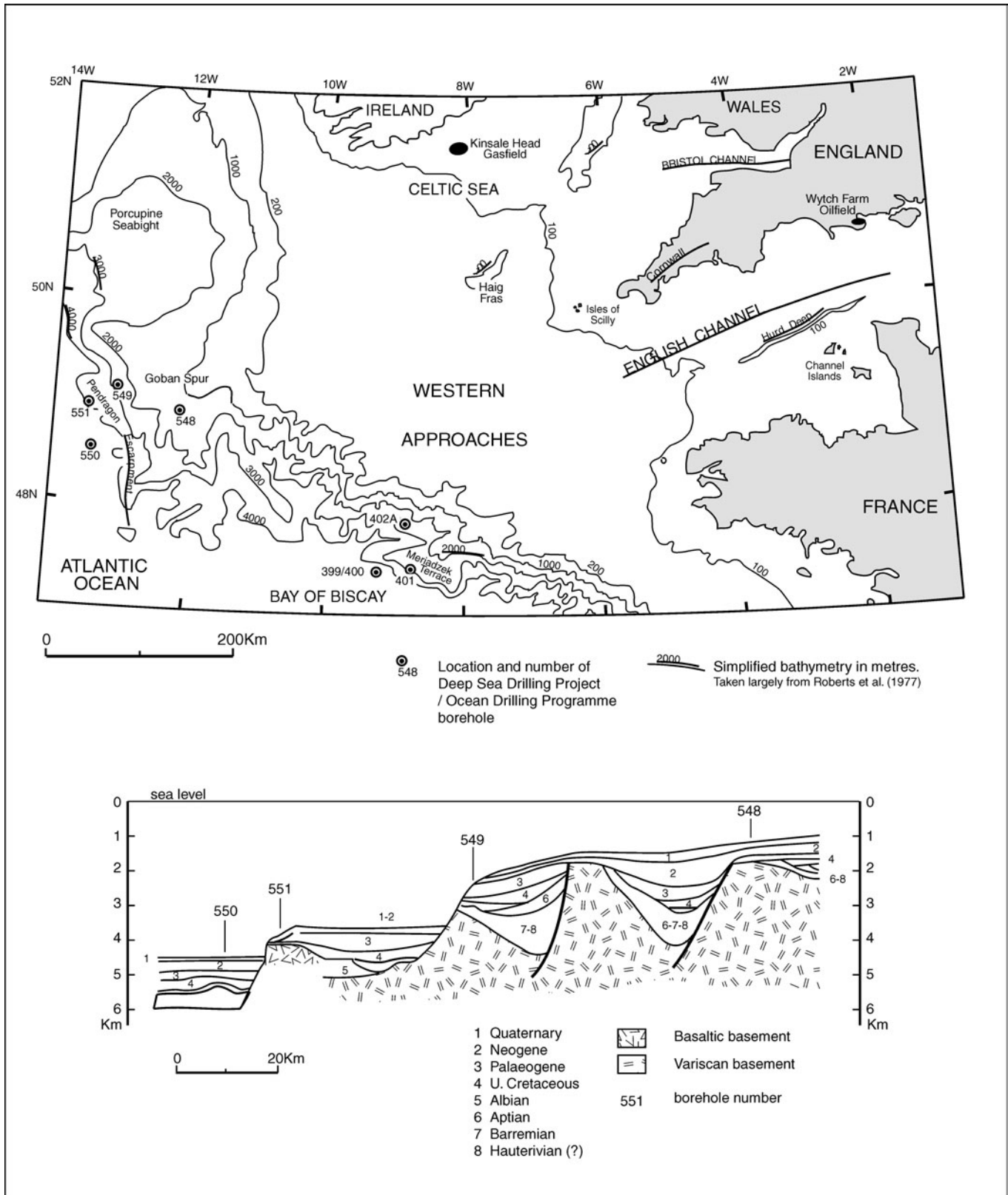
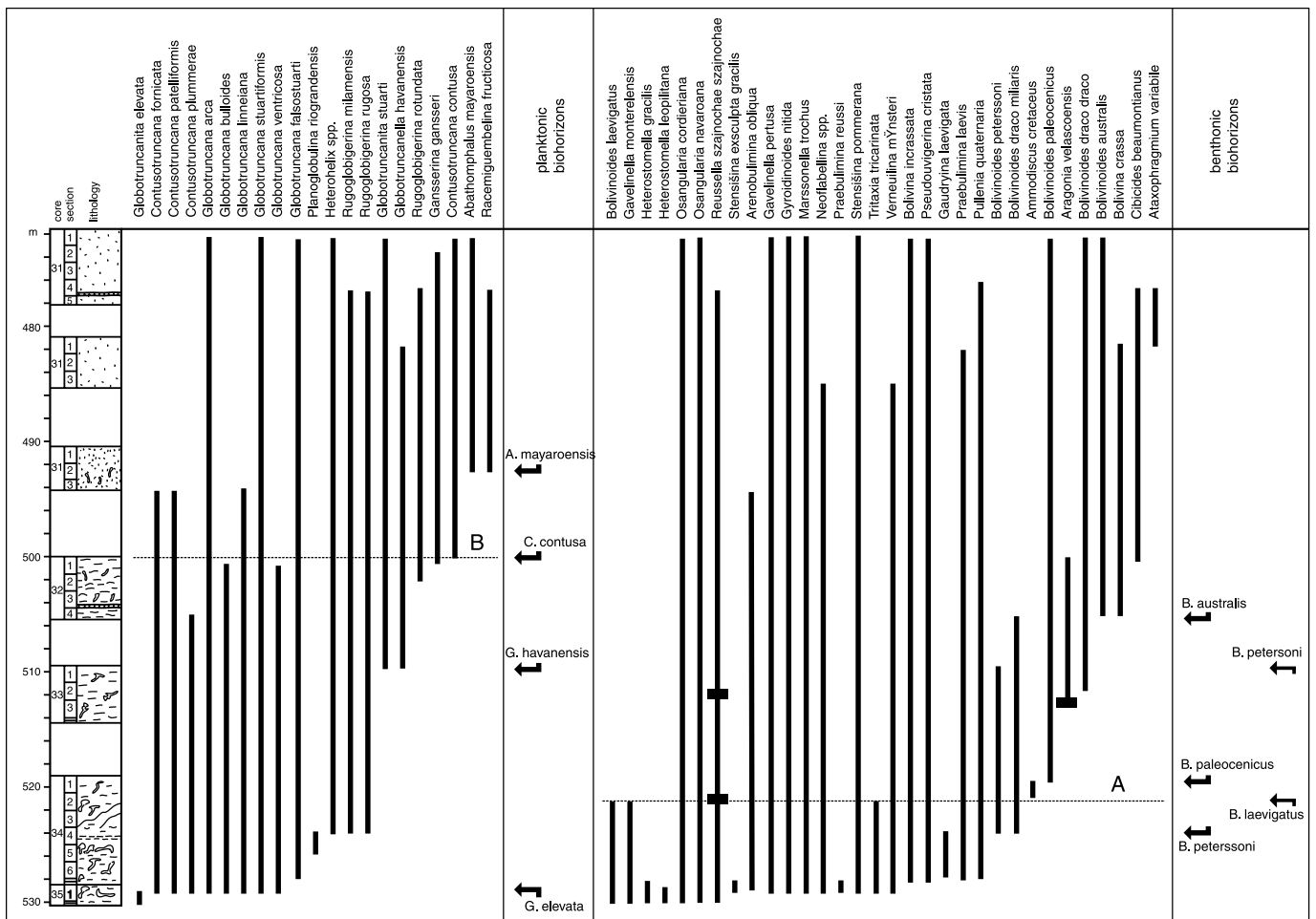


Figure 3. Locality map of the Goban Spur (modified after Hart, 1998) and a cross-section of the sites (after Hart and Duane, 1989).

the marl is a “real” marl seam and does not appear to be a thrust or any other type of dislocation. In Figure 2 it will be noted that the ranges of *G. biltermanni* and *B. peterssoni* do not overlap (within the resolution of our sampling) and, as a result, the *G. biltermanni*/*B. peterssoni* concurrent range zone of the Lagerdorf succession is missing (approximately 8 m of strata). The flood of *R. szajnochae szajnochae* immediately below the boundary is a distinctive marker horizon for regional correlation within the Southern North Sea Basin.

The planktonic foraminifera of the Overstrand succession are distinctive, though lacking in internationally recognised “marker” species. *Globotruncanella havanensis* straddles the boundary but other keeled globotruncanids and globotruncanitids are absent. A flood of *Rugoglobigerina* in the upper part of the succession is quite distinctive and either indicates a migration event of some sort or, perhaps, a slight deepening of the basin. At about this level in the New Jersey succession, Miller *et al.* (1999) record a marked sea level highstand, following their



**Figure 4.** Distribution of foraminifera in DSDP Site 548A, Goban Spur. This is an amalgamation of data from Schönfeld and Burnett (1991), Ball (1985) and our more recent work. The benthonic and planktonic biohorizons indicated are those that the authors regard as being the most significant. The blocks on the ranges of two taxa (*A. velascoensis* and *Reussella szajnochae szajnochae*) indicate flood abundance. The generalised lithology is based on the core photographs and a log in Schönfeld and Burnett (1991). The *B. peterssoni* and *C. contusa* biohorizons are emphasised in the range chart.

temperature-induced (polar ice?) lowstand in the vicinity of their Campanian/Maastrichtian boundary. Their 'maximum flooding surface' is within the *G. gansseri* Zone and before the appearance of *A. mayaroensis* (a correlation based on an extrapolation with ODP Sites 305, 463 and 690).

This "flood" event of *Rugoglobigerina* is also marked over much of the North Sea Basin by the immigration of "southern" planktonic taxa and by an overall increase in size of the planktonic species (Bailey *pers. comm.*, 2001).

## THE GOBAN SPUR

The northern edge of the Bay of Biscay, which rifted from the northern margin of the Iberian Peninsula in the earliest Cretaceous (Masson *et al.*, 1985) was drilled by Leg 80 of the Deep Sea Drilling Project. Sites 548-551 are located on the seaward edge of the Goban Spur (Figure 3). Detailed foraminiferal analyses (Ball, 1985; Hart, 1985, 1987; Hart and Ball, 1986; Leary and Hart, 1988; Schönfeld and Burnett, 1991) have already been published. The most interesting feature of the fauna is that there is an admixture of smaller benthonic taxa that are comparable to those of the N.W. European chalk facies and planktonic foraminifera with a more "Tethyan" aspect (see Figure 4).

The planktonic foraminifera used to identify the Campanian/Maastrichtian boundary are, however, a long-standing problem. Following the monograph by Robaszynski *et al.* (1984) it became generally accepted that the top of the *G. calcarata* Zone marked the base of the Maastrichtian. This interpretation was the result of an input into the debate of petroleum industry

micropalaeontologists who, in looking for a suitable marker for the base of the Maastrichtian stage, elected to use the most characteristic extinction event in that part of the succession; the last appearance of *G. calcarata*. It was soon recognised (e.g. Burnett *et al.*, 1992) that the correlation of the base of the Maastrichtian stage (as defined by the appearance of *B. lanceolata* in the chalk facies of N.W. Europe) with the extinction of *G. calcarata* was incorrect and that a better definition of the Campanian/Maastrichtian boundary was needed (Schönfeld and Burnett, 1991; Burnett *et al.*, 1992). There are those, however, who would argue (e.g. Puckett and Mancini, 1998) that the extinction of *Globotruncanella calcarata* (= *Radotruncana calcarata* of some authors) still provides the most acceptable datum for the Campanian/Maastrichtian boundary. In the early 1990's it was recognised that the *B. lanceolata* definition for the base of the Maastrichtian stage fell within the range of *Globotruncana falsostuarti*. In their later compilation Robaszynski & Caron (1995) indicate that the base of the Maastrichtian stage (at  $71.3 \pm 0.5$  Ma) lies within the *G. gansseri* Zone.

In the Goban Spur succession (Figure 4) *Gansserina gansseri* and *Globotruncanella stuarti* are present and their appearance is some way above the *B. decurrens* interval zone which Schönfeld and Burnett (1991) place at the base of the "Boreal" Maastrichtian stage (as defined by the base of the *B. lanceolata* Zone). This agrees, in general, with Christensen *et al.* (2000, fig. 2) although the details are a little unclear in their reasoning. In the Site 548A succession (Figure 4) the key biohorizons are identified, although there is some concern that some of the ranges of the "Tethyan" planktonic foraminifera



appears within the *B. paleocenicus* Interval Zone (UKB21 of Hart *et al.*, 1989). *B. paleocenicus* is present (Hart *et al.*, 1989, fig. 7.16) in the Trimmingham succession of Norfolk but *C. contusa* has not yet been recorded from any of the on-shore localities in the area. While this might be due to the water depth in the area it is clear that further work on the placing of the new Campanian/Maastrichtian boundary in the chalk succession must be undertaken as a matter of some urgency.

## SUMMARY

In answer to the question posed at the outset it is quite clear that further work on the Goban Spur succession and other DSDP/ODP sites in the Bay of Biscay will be required. It is a pity that a micropalaeontologist familiar with the benthonic faunas of N.W. Europe did not have the opportunity to study the Tercis material (see comment in Odin, 2001b, p. 812, paragraph 2) prior to the publication of the Odin (2001a) volume. As a result of this omission the newly defined GSSP for the base of the Maastrichtian Stage is not accurately correlated with the "Boreal" succession of the chalk facies. This requires quite urgent attention if there is to be a considerable degree of confusion.

## ACKNOWLEDGEMENTS

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## APPENDIX

There follows a taxonomic listing of all the species mentioned in the text or used in the figures. The authorship of the species is for information only and none of these references appear in the reference list.

### Planktonic foraminifera

- Abathombphalus mayaroensis* (Bolli); *Globotruncana mayaroensis* Bolli, 1951
- Archaeoglobigerina cretacea* (d'Orbigny); *Globigerina cretacea* d'Orbigny, 1840
- Contusotruncana contusa* (Cushman); *Pulvinulina arca* Cushman var. *contusa* Cushman, 1926
- Contusotruncana fornicata* (Plummer); *Globotruncana fornicata* Plummer, 1931
- Contusotruncana patelliformis* (Gandolfi); *Globotruncana contusa patelliformis* Gandolfi, 1955
- Contusotruncana plummerae* (Gandolfi); *Globotruncana fornicata plummerae* Gandolfi, 1955
- Gansserina gansseri* (Bolli); *Globotruncana gansseri* Bolli, 1951
- Globigerinelloides aspera* (Ehrenberg); *Phanerostomum asperum* Ehrenberg, 1854
- Globigerinelloides* cf. *bolli* Pessagno, 1967
- Globigerinelloides multispina* (Lalicker); *Biglobigerinella multispina* Lalicker, 1948
- Globotruncana arca* (Cushman); *Pulvinulina arca* Cushman, 1926
- Globotruncana bulloides* (Vogler); *Globotruncana linnei* (d'Orbigny) subsp. *bulloides* Vogler, 1941
- Globotruncana linneiana* (d'Orbigny); *Rosalina linneiana* d'Orbigny, 1839
- Globotruncana falsostuarti* Sigal, 1952
- Globotruncanella havanensis* (Voorwijk); *Globotruncana havanensis* Voorwijk, 1937
- Globotruncanita calcarata* (Cushman); *Globotruncana calcarata* Cushman, 1927
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- Globotruncanita stuarti* (de Lapparent); *Rosalina stuarti* de Lapparent, 1918
- Globotruncanita stuartiformis* (Dalbiez); *Globotruncana (Globotruncana) elevata* Brotzen subsp. *stuartiformis* Dalbiez, 1955
- Heterobelix complanata* (Marie); *Gümbelina complanata* Marie, 1941
- Heterobelix glabrans* (Cushman); *Guembelina glabrans* Cushman, 1938

- Heterobelix striata* (Ehrenberg); *Textularia striata* Ehrenberg, 1840
- Heterobelix* spp.
- Marginotruncana marginata* (Reuss); *Rosalina marginata* Reuss, 1845
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- Rugoglobigerina hexacamerata* Bronnimann, 1952
- Rugoglobigerina milamensis* Smith & Pessagno, 1973
- Rugoglobigerina rugosa* (Plummer); *Globigerina rugosa* Plummer, 1927
- Rugoglobigerina rotundata* Brönnimann, 1952
- Rugoglobigerina scotti* (Bronnimann); *Trinitella scotti* Bronnimann, 1952

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- Aragonia velascoensis* (Cushman); *Textularia velascoensis* Cushman, 1925
- Arenobulimina obliqua* (d'Orbigny); *Bulimina obliqua* d'Orbigny, 1840
- Ataxophragmium variabile* (d'Orbigny); *Bulimina variabilis* d'Orbigny, 1840
- Bolivina crassa* Vasilenko & Myatliuk *sensu* Koch, 1977
- Bolivina decurrens* (Ehrenberg); *Grammostomum decurrens* Ehrenberg, 1854
- Bolivina incrassata* Reuss, 1851
- Bolivinooides australis* Edgell, 1954
- Bolivinooides decoratus* (Jones); *Bolivina decorata* Jones (in Wright), 1875
- Bolivinooides draco draco* (Marsson); *Bolivina draco* Marsson, 1878
- Bolivinooides draco miliaris* Hiltermann & Koch, 1950
- Bolivinooides laevigatus* Marie, 1941
- Bolivinooides paleocenicus* (Brotzen); *Bolivina paleocenicus* Brotzen, 1948
- Bolivinooides peterssoni* Brotzen, 1945
- Cibicides beaumontianus* (d'Orbigny); *Truncatulina beaumontiana* d'Orbigny, 1840
- Cibicides bosqueti* (Reuss); *Rosalina bosqueti* Reuss, 1862
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- Coryphostoma pliata* (Carsey); *Bolivina pliata* Carsey, 1926
- Eponides beisseli* Schijfsma, 1946
- Gaudryina laevigatus* Franke, 1914
- Gavelinella complanata* (Reuss); *Anomalina complanata* Reuss, 1851
- Gavelinella monterelensis* (Marie); *Anomalina monterelensis* Marie, 1941
- Gavelinella multipunctata* (Bandy); *Planulina multipunctata* Bandy, 1951
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*Osangularia navaroana* (Cushman); *Pulvinulinella navaroana* Cushman, 1938  
*Praebulimina carseyae* (Plummer); *Buliminella carseyae* Plummer, 1931  
*Praebulimina laevis* (Beissel); *Bulimina laevis* Beissel, 1891  
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*Praebulimina reussi* (Morrow); *Bulimina reussi* Morrow, 1934  
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*Pullenia quaternaria* (Reuss); *Nonionina quaternaria* Reuss, 1851  
*Pyramidina minuta* (Marsson); *Tritaxia minuta* Marsson, 1878  
*Quadriformina allomorphinoides* (Reuss); *Valvulina allomorphinoides* Reuss, 1860  
*Reussella szajnochae szajnochae* (Grzybowski); *Verneuilina szajnochae* Grzybowski, 1896  
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*Stilostomella pseudoscripta* (Cushman); *Ellipsonodosaria pseudoscripta* Cushman, 1937  
*Tritaxia tricarinata* (Reuss); *Textularia tricarinata* Reuss, 1844  
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# TOURMALINE-QUARTZ-CASSITERITE MINERALIZATION OF THE LAND'S END GRANITE AT NANJIZAL, WEST CORNWALL



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Nanjizal is one of the few locations in the southern segment of the Land's End Granite (Early Permian) where magmatic-hydrothermal tin mineralization has been worked. Three principal mineralization episodes are recognized. The first episode comprises steeply dipping ENE-WSW striking tourmaline ± quartz veins precipitated from magmatic-hydrothermal fluids during regional NNW-SSE extension; they are not associated with metalliferous mineralization. The second episode is represented by two sets of vertical/sub-vertical tourmaline veins striking, respectively, 280° and 340°. The NNW striking set hosts tourmaline-quartz-cassiterite (± alkali feldspar, apatite, zircon) mineralization and was worked for tin during the 19<sup>th</sup> Century. The first generation of tourmaline in these veins is dominated by the Mg-rich end-member, dravite. The subsequent two generations of tourmaline are dominated by the Fe-rich end-member, schorl, together with zoned cassiterite with Fe-rich cores and Fe-poor rims. The NNW striking tourmaline-quartz-cassiterite veins at Nanjizal have a similar orientation to cassiterite-bearing veins within the St. Just Mining District further north. It is possible that the mineralization at Nanjizal was contemporaneous with mineralization in the St. Just Mining District and hence related to a later magmatic episode and the renewed release of magmatic-hydrothermal fluids during ENE-WSW extension. The third mineralization episode is dominated by steeply dipping WNW-NNW striking quartz-limonite-chalcedony veins that are associated with wall rock hematization and kaolinisation. Schorl-quartz-cassiterite mineralisation is relatively uncommon in S.W. England but there are remarkable similarities between the vein parageneses at Nanjizal and the Birch Tor-Vitifer area of Dartmoor; both are likely to have been sourced from predominantly magmatic-hydrothermal fluids.

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## INTRODUCTION

The Land's End Granite to the south of the St. Just Mining District (Dines, 1956) is not normally associated with metalliferous mineralization. Localised tin and copper workings are present, but they are generally ancient and poorly documented (e.g. Hamilton Jenkin, 1962). Nanjizal (SW 356 237), or Mill Bay, located approximately 2 km SE of Land's End (Figure 1), is an exception as near surface tin workings that were described in a contemporary 19<sup>th</sup> Century account can still be examined. The bay is developed in coarse-grained megacrystic granite and is bounded by the rocky headlands of Carn Boel to the north and Carn Lês Boel to the south (Figure 2). Quaternary head deposits locally overlie the granite and alluvial deposits cover the narrow valley floor of the Nanjizal Stream. Remains of a wheel pit and leat occur close to the mouth of the stream (Figure 2); these were associated with water powered mineral stamps and a corn mill, at different times during the 19<sup>th</sup> Century (Hamilton Jenkin, 1962). Nanjizal is an important site as it confirms that tin mineralization occurs within the southern segment of the Land's End Granite that is often regarded as barren. This paper describes the geology and mineralization at Nanjizal, examines evidence for a link with mineralization in the St. Just Mining District and makes a comparison with similar styles of tin mineralization elsewhere in SW England.

## PREVIOUS WORK

The only known primary reference relating to mineralization and mining at Nanjizal is a short article in the Mining Journal of November 8th 1845 that reported a paper read to the Royal Geological Society of Cornwall by Joseph Carne who had visited the site whilst mining was active (Anon., 1845). He described two

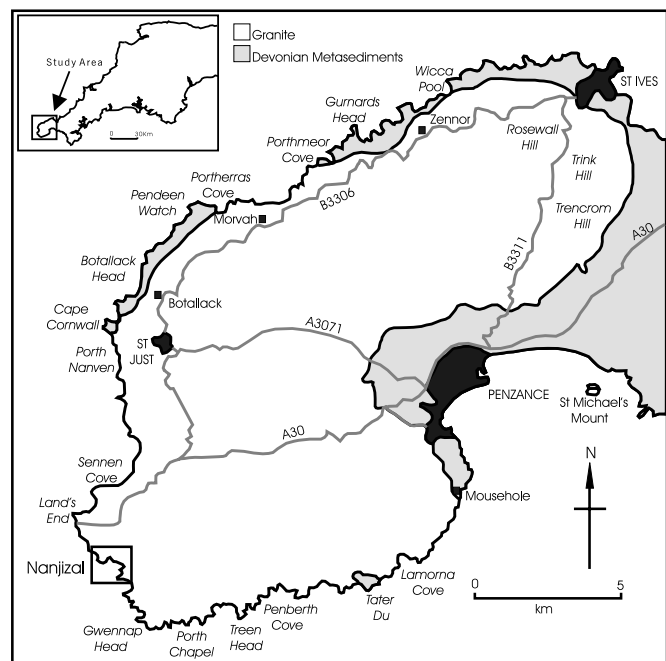


Figure 1. Map of the Penwith Peninsula showing the location of Nanjizal.

openworks on the north side of Nanjizal; they were driven on steeply dipping, N-S trending, discontinuous, 'schorl rock' masses, comprised of schorl, quartz and cassiterite, that were termed 'floors' by the miners (Anon., 1845). One of the floors had a

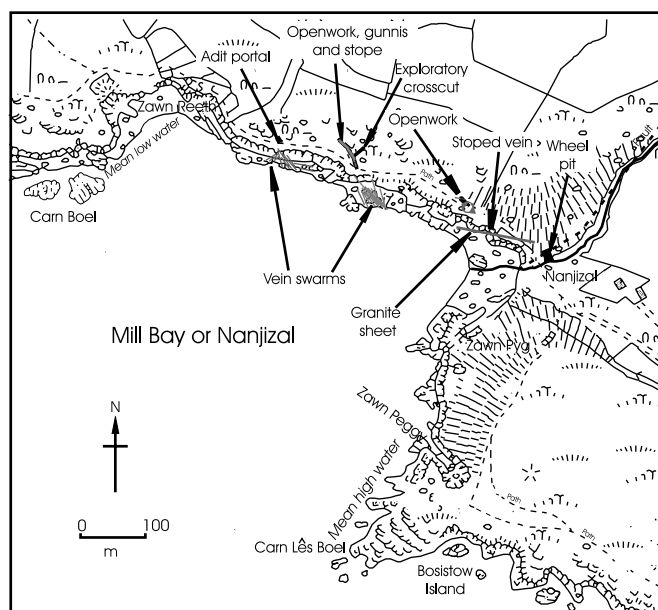


Figure 2. Sketch plan of Nanjizal showing the main features referred to in the text.

maximum dip length of approximately 20 feet and varied from seven to 16 feet in thickness, the other floor varied from one to eight feet in thickness and had been followed 100 feet into the hillside; neither floor cropped out in the adjacent cliff. Mineralised veins of similar orientation to the floors were not recognised, but cassiterite enrichment occurred where the floors were intersected by a later set of narrow veins (Anon., 1845). Carne considered the schorl floors to be contemporaneous with the host granite and the later vein set to have acted as the feeder pathway for the tin mineralization (Anon., 1845). The tin ore was extracted by blasting and underwent crushing at the water-powered stamps close to the Nanjizal stream. It is probable that there had been a long history of occasional tin extraction at this site as 'evident marks', observed when the 1840s workings commenced, were interpreted as having been 'wrought by others long before' (Anon., 1845).

## GEOLOGY

Nanjizal is underlain by the coarse-grained megacrystic granite of the St. Buryan lobe of the Land's End Granite (Salmon and Powell, 1998) that is Early Permian in age (Chen *et al.*, 1993, Chesley *et al.*, 1993). It is typically leucocratic with a quartz-plagioclase-alkali feldspar-biotite-muscovite groundmass > 5 mm in grain size, and carries scarce large (up to 10 mm), subhedral to anhedral, accessory cordierite crystals. The alkali feldspar megacrysts are euhedral to subhedral and can reach up to 100 mm in length. Pegmatitic pods are present in the granite, comprising pink feldspars and quartz. A microgranite sheet, approximately 1 m thick dipping 10° ENE occurs at the base of the cliff on the north side of the beach (SW 3568 2368). Its boundaries are diffuse, suggesting the host granite was not fully crystallised at the time of intrusion, and schorl is concentrated towards the upper contact. The granite forms steep castellated cliffs approaching 60 m in height that are controlled by prominent, sub-vertical, joint sets trending approximately 000°, 060°, 090° and 120° with a further set dipping at 05-08° towards the northeast.

A steeply dipping fault zone, striking 050° to 090°, and marked by the line of the Nanjizal Stream, crosses the beach and passes out to sea. The onshore exposure, just below the lowest point of the cliffs, shows the fault zone to be 4 m in width, comprising a series of discrete fractures, and associated with kaolinisation and intense veining of the granite. These veins range from anastomosing mm-scale to composite (quartz-dominated) structures up to 0.75 m in width. Several episodes of fracturing

and fluid flow are indicated by crosscutting relationships and variations in vein mineralogy from early tourmaline/quartz (striking 050° to 070°) to later hematite ± quartz (striking 300°). Vein sets are also well exposed throughout the Nanjizal cliffs and shore platforms away from this fault zone (Figure 2). Three principal mineralization episodes have been distinguished on the basis of crosscutting relations, morphology and paragenetic associations.

### Episode 1

The earliest vein set is vertical/sub-vertical, striking predominantly 050°-070°, with the largest proportion trending 060° (Figure 3a). The veins are up to 10 mm in width, usually show indications of tensile opening, and have schorl margins plus a central infill of quartz. The schorl shows bridging textures (e.g. Halls *et al.*, 2000) that are cut by the later quartz infill. Veins of similar orientation and paragenesis are commonly observed throughout the coastal section from Nanjizal eastwards to Treen Head (SW 397 219).

### Episode 2

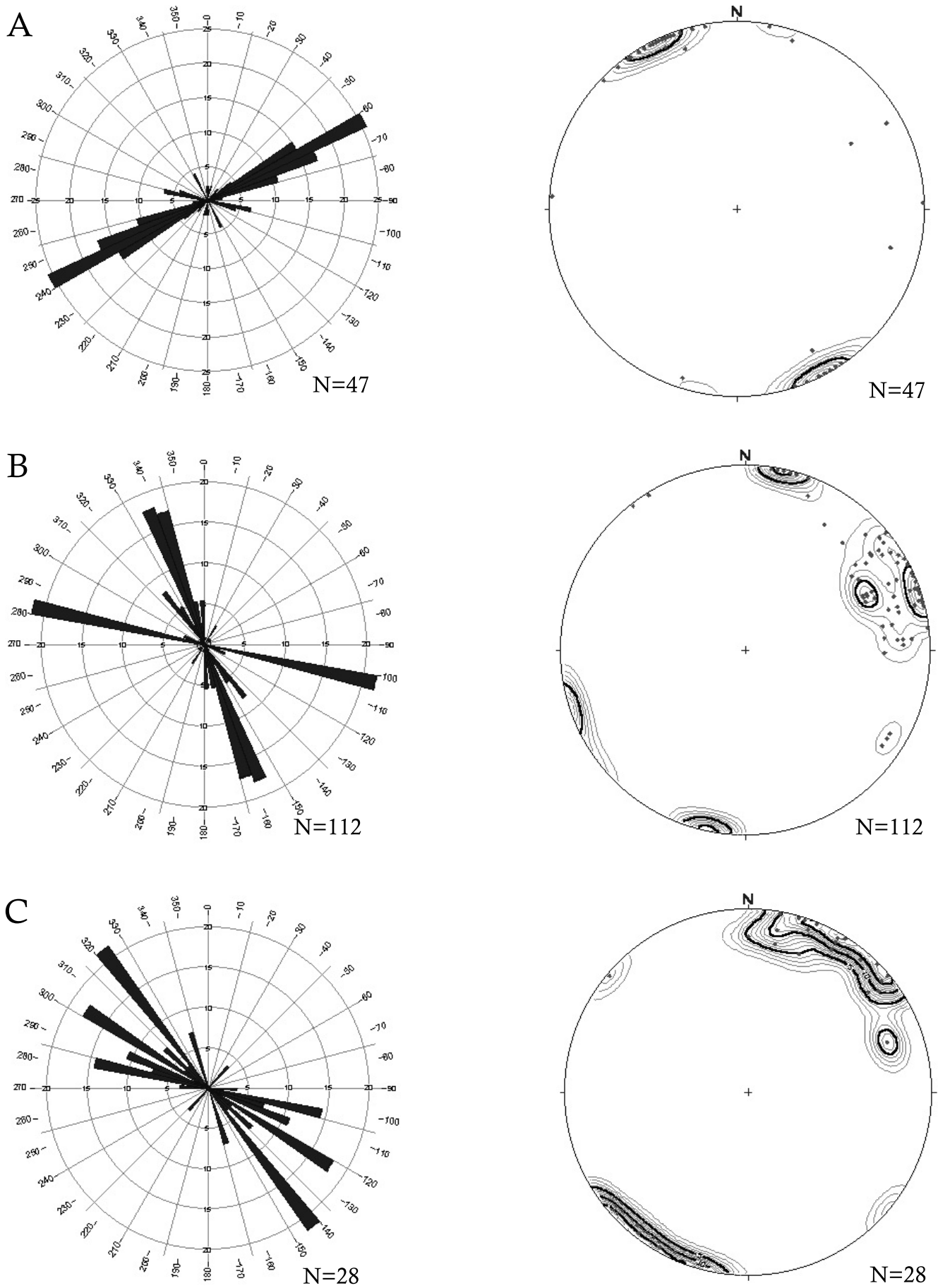
The second episode is represented by two sets of vertical/sub-vertical schorl veins (1-3 mm width) striking, respectively, 340° and 280° (Figure 3b). These veins, often closely spaced, also appear to be largely tensile and have remarkably uniform widths and orientations over dip lengths of several metres. Some veins anastomose and the slightly thicker veins sometimes indicate more than one stage of infilling, although the majority appear to be single stage. A subset of the 340° striking veins occurs on the foreshore and cliffs on the north side of the bay and is associated with cassiterite mineralization. The veins are marked by variable widths along strike (though most vary between 1-10 mm) and dips that range from vertical to 70°. Although essentially composed of schorl, the thicker veins can also carry minor quartz and feldspar. The veins are associated with up to 50 mm of wallrock alteration, primarily silicification, that is particularly evident on weathered surfaces. Some 340° striking veins cut mm-scale 280° trending veins and thus the cassiterite-bearing veins may represent a late 'pulse' at the end of this particular episode.

### Episode 3

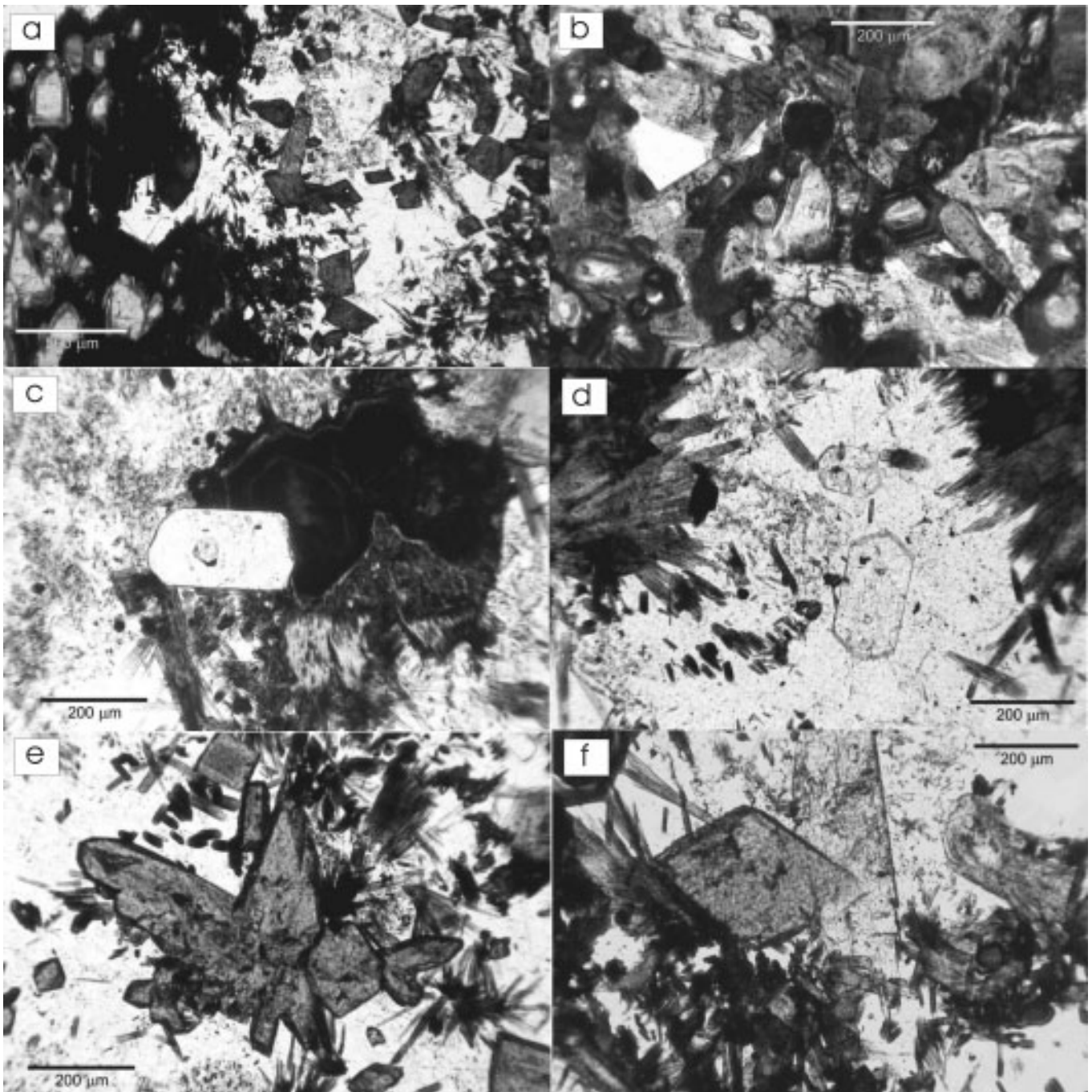
The third major vein set is dominated by quartz and trends predominantly between 280° and 325°, but with some veins trending 345° and 045° (Figure 3c). The majority of veins appear to be hosted by joints, but some (up to 0.7 m in width) are hosted by faults that in some cases display slickenlines compatible with oblique-slip movement, as do parallel fractures containing minor hematite. The surrounding granite is partially hematized and, locally, kaolinised. The quartz veins are typically steeply dipping or vertical and the larger veins show a banded texture. The quartz infill is accompanied by limonite-rich bands and chalcedony. The largest vein of this set crops out on the beach, dips south at 75° and is heavily brecciated and recemented, with multiple banding. The same vein also crops out in the roof of a large sea cave, and it may have been stoped in the past, but the evidence is inconclusive. This vein set cuts all the other tourmaline veins on the beach and surrounding cliffs; the relationship between these veins and the 'cassiterite-bearing veins' was not demonstrated in outcrop, but it is likely that the quartz veins post-date all the tourmaline-dominated assemblages.

## METALLIFEROUS MINERALIZATION

The metalliferous mineralization that was formerly worked at Nanjizal is related to two vein swarms (trending 320°-346°) that are exposed in foreshore and cliff outcrops on the north side of the bay (Figure 2). The veins do not appear to have been worked below the cliff tops, but adjacent to the coast path (SW 35381 23813) a drive has been mined on a ~0.1 m wide vein that appears to be the result of the merging of narrower structures.



**Figure 3.** Rose diagrams and contoured equal area lower hemisphere pole plot stereograms for (a) tourmaline (schorl)-quartz veins, (b) tourmaline (schorl) veins and (c) quartz-limonite-chalcedony veins at Nanjizal.

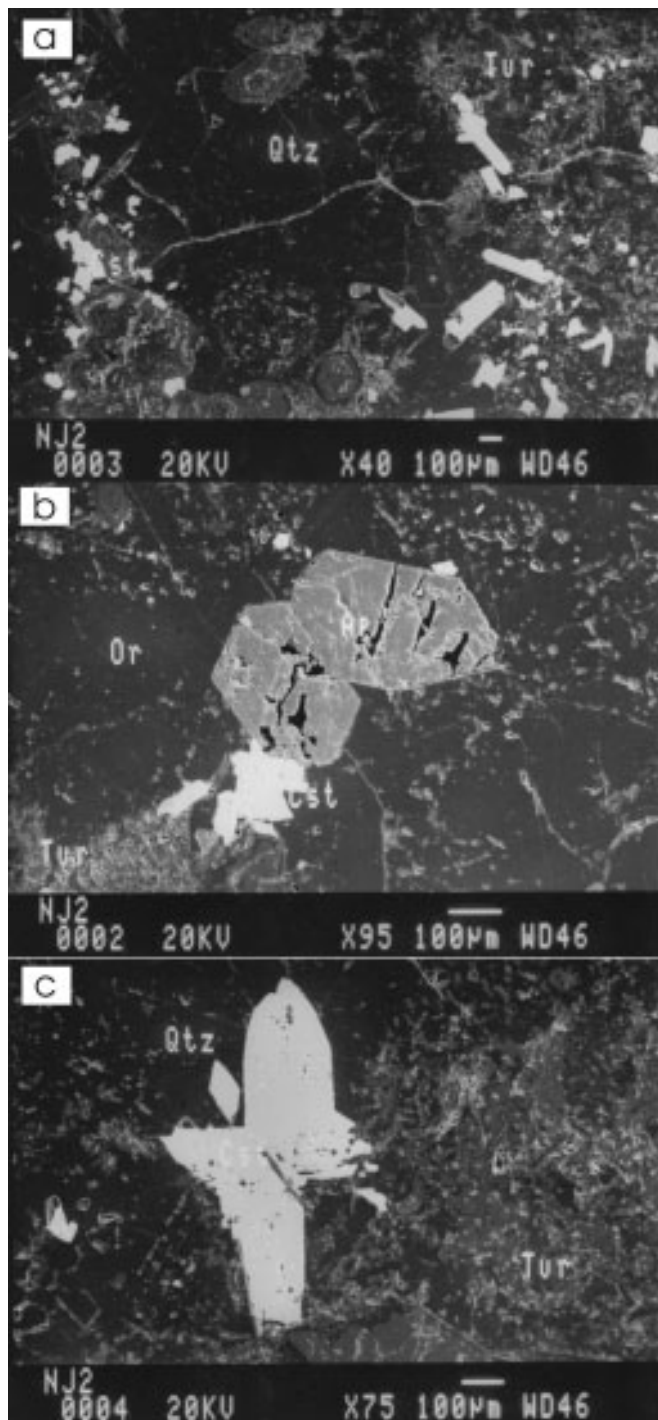


**Figure 4.** Thin section photomicrographs (plane polarised light) showing (a) zoned dravite crystals overgrown by later schorl (left side of photograph); also present are zoned euhedral cassiterite crystals in a matrix of fine acicular schorl, quartz and feldspar, (b) large, zoned, second-generation schorl crystals with minor apatite and late hematite, (c) a subbedral apatite crystal (transparent, centre) intergrown with zoned schorl and overgrown by later fine acicular schorl in a feldspar/quartz matrix, (d) euhedral apatite crystals and fine acicular and radiating schorl crystals in a quartz/feldspar matrix, (e) zoned euhedral cassiterite crystals overgrown by fine schorl in a quartz/feldspar matrix, and (f) zoned euhedral cassiterite crystals overgrown by fine schorl in a quartz/feldspar matrix (optical slide PPL x 10).

This drive falls away rapidly from the portal and at least one further level has been driven off it northwards into the hillside.

A much larger excavation extends NW from the coast path 150 m further east (SW 35527 23797). It initially takes the form of an openwork extending 15 m from the path (as in the previous location the corresponding vein swarm appears unworked), before passing into the hillside as a drive, some 3 m high by 2 m wide. Just prior to this point what appears to be an exploration crosscut has been driven approximately 20 m towards 050°, partially within head. The surface has been breached at what appears to be the end of the crosscut. The main drive extends a further 23 m into the hillside; there is an extensive (8 m) breach of the surface to leave an open gunnis only 3 m from the portal and a second small breach 2 m beyond that. The final 9 m of the

workings are within a stope measuring some 7 m long by 6 m (maximum) high, with a 2 m stub at the NW end. The stope varies from 2-3 m in width as the miners took some of the adjacent veins during extraction. The walls of the stope and gunnis show that several veins run into the workings and merge to form larger structures; several of these larger veins combine to form the main 'lode' or 'floor' that has been worked. This structure has a lensoid form with an approximate orientation of 302°/70° SW and a maximum width of ~1 m; there are multiple splays along strike and several subparallel veins within the heavily reddened granite. Some vein surfaces show slightly oblique slip (pitch 80°) slickenlines, whilst a prominent fault surface within the stope indicates reverse dip-slip movement.



**Figure 5.** Scanning electron microscope images showing (a) zoned tourmaline crystals, euhedral cassiterite (Cst) with schorl (Tur) overgrowths in a quartz (Qtz) matrix, (b) euhedral apatite (Ap) crystals with cassiterite (Cst) in a tourmaline (Tur) and orthoclase (Or) matrix, and (c) a euhedral twinned cassiterite (Cst) crystal in a tourmaline (Tur) and quartz (Qtz) matrix.

### Mineralogy

In hand specimen the vein material largely comprises coarse-grained black schorl, in radiating acicular masses, 10–30 mm in length, with minor quartz and feldspar. Cassiterite cannot be identified with the naked eye. Subsequent examination using a binocular microscope revealed euhedral to subhedral light brown cassiterite crystals interlocked with schorl and quartz, and as freestanding ‘sparable’ crystals varying in length from 0.15–0.50 mm within small vugs. Further analysis of vein specimens was undertaken using transmitted light microscopy, X-Ray diffraction (XRD), scanning electron microscopy (SEM) plus energy

dispersive spectrum (EDS) analysis for confirmation of principal minerals, and X-Ray fluorescence spectrometry (XRFS). The EDS analysis utilised a semi-quantitative comparison of key major element spectrum peak heights; five or more analysis points were used per grain in the case of larger tourmalines, usually in a traverse from rim to core to rim.

Optical examination under plane-polarised light (PPL) indicated three generations of tourmaline. The earliest tourmaline (light-medium brown in PPL) occurs as aggregates of subhedral zoned crystals (Figure 4a) that individually reach up to 100  $\mu\text{m}$  in diameter. Semi-quantitative EDS analysis revealed high Mg/Mg+Fe ratios and indicated a composition close to the Mg-rich end-member dravite; the presence of which was also detected by XRD analysis. The most abundant tourmaline varies from pale lilac to blue in PPL (Figure 4b) and occurs as: (i) large euhedral zoned crystals, up to 200  $\mu\text{m}$  in diameter, that occur singly or in agglomerated masses, and as fine overgrowths on the larger zoned crystals (Figure 4c), and (ii) radiating groups or single euhedral acicular crystals (usually <50  $\mu\text{m}$  in length) scattered as inclusions in other phases. Semi-quantitative EDS analysis of both occurrences revealed generally high Fe/Fe+Mg ratios and indicated a composition close to the Fe-rich end-member schorl, although a few grains had lower ratios indicating a higher Mg content. The EDS analysis confirmed that zoned dravite was overgrown by schorl and that this corresponded to the transition from light-medium brown to pale lilac or blue tourmaline in PPL.

Other phases present include apatite, in euhedral to subhedral colourless transparent crystals up to 400  $\mu\text{m}$  (Figures 4c, d), sometimes intergrown with, or nucleating on, the large zoned schorl; rare subhedral zircon up to 40  $\mu\text{m}$ ; alkali feldspar in anhedral to subhedral crystals reaching several mm (turbid in PPL, Figure 4c); quartz in irregular anhedral crystals reaching up to 10 mm; and cassiterite in zoned euhedral crystals, up to 600  $\mu\text{m}$ , occurring as radiating groups (Figure 4e) or as single euhedral crystals (Figure 4f). The zoning in some of the cassiterite crystals is pronounced, with brown cores (Fe-rich on basis of EDS analysis) passing outwards, via yellow-brown, to almost colourless rims (Fe-poor on basis of EDS analysis). Several cassiterite crystals have nucleated on the large zoned schorl crystals, while being overgrown or acting as nucleation sites for the finer schorl overgrowths. Similar relationships were demonstrated during SEM examination (Figures 5a–c). A whole rock XRF analysis of a vein specimen from the largest stope indicated 1.94% Sn.

## DISCUSSION

### Origin of the veins and mineralising fluids

The first episode of mineralization is hosted by tensile, ENE–WSW striking, steeply-dipping tourmaline  $\pm$  quartz veins that are consistent with having developed in the regional NNW–SSE extensional regime that was established following Variscan convergence (Alexander and Shail, 1995, 1996). There is little or no metalliferous mineralization associated with these veins and they were probably precipitated from magmatic-hydrothermal fluids derived from the immediately surrounding host granite of the St. Buryan lobe, dated at  $274.5 \pm 1.4$  Ma (U–Pb, monazite) by Chen *et al.* (1993).

The second episode of mineralization is hosted by two sets of subvertical fractures with mean strikes of 280° and 340°. These geometrical relations are consistent with the sets having formed as conjugate shear fractures ( $\sigma_1$ , NW–SE;  $\sigma_3$ , NE–SW). However, the available kinematic evidence suggests that both the fractures and their infills developed in a tensile regime; bridging textures are consistent with high fluid pressures and hydraulic fracturing (e.g. Halls *et al.*, 2000). Mutual crosscutting relationships occur between the two vein sets but cassiterite mineralization and accompanying wall rock silicification is associated with the latest generation of infilling and hosted primarily by the 340° striking fracture set. Localised ENE–WSW extension must therefore have persisted during the cassiterite mineralization.

The earliest fluids passing through the 340° striking fractures precipitated zoned dravite. Such zonation is typical of tourmalines

precipitated from magmatic-hydrothermal fluids (e.g. London and Manning, 1995) and a similar origin is invoked for the fluids at Nanjizal. Zircon may also have precipitated at this time, but it is also possible that it may have been inherited from the host granite. Large zoned schorl and cassiterite crystals were subsequently precipitated; the Fe zoning in the schorl is accompanied by a progressive decrease in the Fe content of cassiterite. Apatite and alkali feldspar were also precipitated and the apatite occasionally provided a nucleation site for schorl. A second episode of schorl precipitation formed radiating overgrowths and isolated crystals and was accompanied by the precipitation of small euhedral cassiterite crystals. It was followed by precipitation of alkali feldspar and, finally, quartz. The transition from dravite to schorl plus cassiterite precipitation may reflect changes in fluid chemistry brought about by mixing between magmatic-hydrothermal and oxidising Fe-rich fluids (e.g. Williamson *et al.*, 2000; London and Manning, 1995).

The final episode of mineralization at Nanjizal is represented by NW-SE to WNW-ESE striking subvertical quartz-chalcedony-limonite veins. These are associated with much fine-scale shearing and fracturing and localised hematization and kaolinisation. The fractures and veins are largely tensile, although some possess a small component of sinistral shear. Protracted movement is indicated by recemented breccias in some of the veins. It is likely that faulting of the tourmaline vein system in the stope (dip-slip reverse/extensional and oblique sinistral) occurred at this time and also, possibly, the early phases of movement on the Nanjizal fault which cuts the tourmaline mineralization and runs parallel (at the beach) to the fracture-hosted quartz veins.

### *Comparison with other mineralised areas in S.W. England*

Tourmaline-cassiterite veins in Cornwall are usually characterised by hydrothermal schorl-buergerite (similar in composition to schorl, but with Fe<sup>3+</sup> replacing Fe<sup>2+</sup>) 'blue peach' that post-date barren schorl veins (e.g. Farmer, 1991; Farmer and Halls, 1993). Cassiterite-bearing schorl veins are unusual and have seldom been worked; only two examples are known elsewhere in the Land's End Granite and these were small-scale workings similar to those at Nanjizal. A schorl-cassiterite vein, worked under the name of Boscowan Rose Mine, crops out in the cliffs and foreshore at Boscowan Cliff (SW 433 229) near St. Loy's Cove (Hamilton Jenkin, 1962). Similar material has also been identified (Bruce Grant *pers. comm.*, 2001) as loose blocks in soil near Carn Galver (SW 430 360). The Grylls Bunny schorl-cassiterite deposit at Botallack (Jackson, 1974) has a replacive rather than a vein origin.

Elsewhere in S.W. England, the best-documented occurrence of schorl-cassiterite veins is the Birch Tor and Vitifer complex within the central part of the Dartmoor Granite. The veins are near-vertical fractures with up to four paragenetic stages: (i) massive Fe-rich tourmaline with relatively little quartz, (ii) quartz-tourmaline-cassiterite, (iii) quartz-specular hematite, and (iv) jasper or chalcedonic quartz (Shepherd *et al.*, 1985). There are clearly close similarities with the Nanjizal mineralization and detailed fluid inclusion studies indicate that the first three parageneses were formed by high salinity magmatic-hydrothermal fluids derived from a common source that were variably mixed with cooler, lower salinity, groundwaters (Shepherd *et al.*, 1985; Wayne *et al.*, 1996).

### *Possible relationship to the St. Just Mining District*

The first episode of steeply dipping ENE-WSW striking tourmaline veins at Nanjizal was not associated with metalliferous mineralization but has a similar orientation to veins associated with cassiterite mineralization in the Land's End Granite around St. Ives and further east in the Camborne-Redruth Mining District (e.g. Dines, 1956). All of these veins are likely to have formed during regional NNW-SSE extension during the Early Permian

(e.g. Moore, 1975; Shail and Wilkinson, 1994). At this stage, magmatic-hydrothermal fluids capable of precipitating cassiterite were not available in the Nanjizal area.

Subvertical NNW-SSE striking schorl-cassiterite veins form a subset of the second mineralization episode at Nanjizal and have a similar orientation to cassiterite-bearing veins within the St. Just Mining District further north (e.g. Garnett, 1962, Jackson *et al.*, 1982). Mineralization within the St. Just area post-dates the emplacement of the "St. Just wedge" granite that is undated but, on the basis of field relationships, is younger than the granite of the St. Buryan lobe (Powell *et al.*, 1999). It is possible that the cassiterite mineralization at Nanjizal was contemporaneous with mineralization in the St. Just Mining District and hence related to a later magmatic episode and the renewed release of magmatic-hydrothermal fluids during ENE-WSW extension. Quartz-tourmaline veins with a similar NNW-SSE orientation have been identified across southern and western Penwith from Nanjizal to Mousehole (SW 469 265) and though largely uneconomic they may demonstrate that the St. Just mineralising 'event' was far more widespread than its economically defined centre would suggest.

## CONCLUSIONS

The three principal vein mineralization episodes at Nanjizal record the formation, reactivation and infill of fractures, under conditions of varying stress regime and evolving fluid composition, before, during and after the emplacement of the latest components of the composite Land's End Granite. The first mineralization episode is represented by steeply dipping ENE-WSW striking tourmaline ± quartz veins that are broadly coeval with veins of similar orientation elsewhere in the Land's End Granite. Steeply dipping NNW-SSE striking schorl-cassiterite veins, that were worked for tin in the 19<sup>th</sup> Century, are associated with the latter stages of the second mineralization episode and are unusual by reason of their paragenesis and location, well outside the main mining districts associated with the Land's End Granite. The fluids were primarily of magmatic-hydrothermal origin but, on the basis of comparisons with other recent work, may mark the transition from purely magmatic-hydrothermal (high-Mg) fluids to those with a groundwater component (high-Fe, oxidising). The orientation of the schorl-cassiterite veins at Nanjizal is similar to the majority of the cassiterite-bearing veins worked in the St. Just Mining District. It is likely that these, and tourmaline-quartz ± rare cassiterite veins of similar orientation across southern Penwith, were formed in response to the same mineralization event. The Nanjizal schorl-cassiterite mineralization is similar to the quartz-tourmaline-cassiterite veins hosted by the Dartmoor Granite. The Nanjizal veins might represent either the 'roots' of a more extensive system that evolved upwards into the more usual 'blue peach' dominated tourmaline assemblage or the trapped remains, unable to interact with larger volumes of meteoric fluids, of a lode system that never was. The third mineralization episode is dominated by steeply dipping WNW-NW striking quartz-limonite-chalcedony veins that are associated with wall rock hematization and kaolinisation.

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