50th Kaikoura05

The Organising Committee extends a warm welcome to all delegates and visitors to Kaikoura, where it all began 50 years ago.

Please note that all information in this publication was correct at the time of going to print. However, due to factors beyond our immediate control, such as weather, road conditions and permission for land access, some unexpected late changes in field trip routes and itineraries may be required.

Bibliographic References:

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Kaikoura

Field Trip Guides

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Field Trip Guides – Contents

Field Trip 5A

STRUCTURE AND TECTONICS OF THE KAIKOURA PENINSULA

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STRUCTURE AND TECTONICS OF THE KAIKOURA PENINSULA

FIELD TRIP ROUTE

1. Lookout and drive to Seal Point:

a. Leave Town Hall Conference Centre at 8:30 a.m. for the lookout point at the water tank on the crest of the peninsula. This site serves as a good vantage point to discuss the general tectonic setting of the Kaikoura area.

b. Back on the coast road east to the Seal Point car park a section through the southeastern limb of the Race Course Anticline gradually steepens to dip at over 60° SE, exposing the dominantly limestone succession until it passes into the Waima Formation siltstone-filled core of the asymmetric Fyffe Syncline. By the car park, dips have reversed to 30^{o} W and then flatten across the shore platform onto the crest of the Atia Anticline. Seal Reef re-exposes the underlying Spy Glass limestone in the crest of the anticline, uplifted by a cross-cutting fault.

2. The shore platform

a. Five minutes walk southwest along the shore platform on Waima Fm. siltstone to the first small embayment, the flaggy, slightly-glauconitic Spy Glass limestone reappears on the plunging anticline crest. The next wide section of shore platform provides excellent examples of folding on all scales and generations with the associated structures on the southeast limb

b. After crossing a significant fault, the upper interbedded marl member of the Amuri limestone occupies the centre of the eroded dome forming Spaniards Bay where the field relationships of the cryptic early cleavage are well displayed.

c. The bored and phosphatised contact (the controversial Marshall Unconformity) between the two limestones, overlain by approximately two metres of greensand interbedded with the lower Spy Glass limestone, is well exposed up the length of the southeastern peninsula of Spaniards Bay. Details of folds can be mapped with great accuracy, but in broader terms the enveloping surface closes around the flank of the dome in response to the reversal of plunge of the northeast trending fold train. Recent expansion of the seal colony now complicates access.

d. The last shoreline section crosses another significant northwest-striking fault. Exposed in a high cliff face, a complex pattern of folds is related to disseminated shear deformation associated with northeast striking reverse faulting. This end of the shore platform coincides with the structural col separating the two major dome culminations in the Seal Point Anticline produced by the Spaniards Bay and Whalers Bay cross-cutting anticlines.

3. The cliff top

The Walkway track accesses the cliff top onto a prominent marine terrace surface. Time permitting, a ten minute walk further southeast provides a view over the Whalers Bay structure, before following the cliff top back above Spaniards Bay to the car park. The marine terrace flight can be seen in profile and evidence of ongoing deformation in relation to the folding pointed out. This will be an opportunity to raise wider issues for discussion relating to the timing and origin of the succession of structures identified, and how these relate to local tectonic history and to wider regional questions.

Figure 1

Oblique aerial view of Kaikoura Peninsula with Spaniards Bay in the foreground.

T1 to T5 are the marine terraces recognised by Ota et al. (1996)

Axial traces of the major folds are in dashed lines:

GCA = Golf Course Anticline;

RCA = Race Course Syncline;

FS = Fyffe Syncline; AA = Atia Anticline.

Significant faults are shown in solid lines.

Photo by L. Homer, courtesy GNS Science.

1. THE TECTONIC SETTING OF KAIKOURA PENINSULA

Topics for the Lookout

a. Tectonic Setting

Kaikoura Peninsula lies in a highly dynamic setting at the junction of the northeast trending convergence of the southern Hikurangi Margin and the dominantly strike-slip transpressive Hope Fault. The latter is currently the most active element of the Marlborough Fault Zone and is now the effective continuation of the Alpine Fault along which the majority of the plate boundary motion is being transferred.

On the largest scale each of the transpressive Marlborough Faults is separated by a major Torlesse Group basement-cored anticlinorium, with the Cretaceous-Tertiary cover preserved in each footwall fault-angle and wrapped around the plunging hinge zones along the coast. To the north of Kaikoura, rapid uplift of the Seaward Kaikoura Ranges reflects subduction underplating. Crustal shortening on multiple, southeast-facing thrust faults such as the Jordan Thrust, further folds the basement and cover rocks on kilometre scale wave lengths to create structures like the Puhipuhi Syncline, seen in profile up the coast. Kaikoura Peninsula is underlain by such a train of folds. Haumuri Bluff, in view to the south, again represents the cover sequence dipping off the flanks of another large anticline. Thrust faulting on this scale continues offshore (Barnes et. al., 1998).

The Hope Fault is strongly segmented attaining slip-rates quoted from several sources by Langridge et.al (2003) at between 18 to 32 mm/yr west of the Charwell River, with slip being transferred into the thrust system towards the coast (van Dissen and Yeats, 1991). It retains a strong geomorphic expression of recent displacements as it splits before going offshore (Simpson, 1995) and can be traced across the continental shelf eventually to swing north (Barnes et. al., 1998).

The deep Kaikoura Canyon lies 7 km south of the peninsula, and is likely to be structurally controlled, but is clearly modified by submarine erosion and large volumes of sediment. However, the subduction dominated system extends further south to the vicinity of the Conway Trough, at which point the thrust system reverses face. Offshore, east-west striking normal faults of the North Mernoo Fault Zone on the north slope of the Chatham Rise approaches to within a few kilometres of this complex and onshore, similar structural trends suggest overprinting of these faults by the thrust system (Barnes, 1994; 1996).

b. Major structural elements

Two pairs of kilometre scale, northeast trending folds control the structure, influencing the morphology of the Kaikoura Peninsula and have here been allocated names. From west to east the first pair are the Golf Course Syncline and Race Course Anticline reflecting the coincidence of the respective axial traces with these prominent amenities. Torlesse Group basement crops out in the core of the anticline on the south shore. The anticline occupies the narrow waist of the peninsula with the Cretaceous-Tertiary cover beds appearing in the cliff faces and shore platform on both limbs. The contact with cover beds is not exposed and readers are referred to Field Trip 7 (this volume) for details of the stratigraphy exposed along both coastal sections. Eastward, the peninsula widens where the coast morphology is controlled by the erosion resistance of the limestone forming points and reefs, relative to the softer clastic units that coincide with the bays.

The eastern pair of folds is not as deeply exposed. Fyffe Syncline is strongly asymmetric with the uppermost unit the Waima Formation siltstone exposed on both sides of the peninsula right to the eastern coastline around the doubly plunging terminations of the Atia Anticline.

Beneath the siltstone, the uppermost limestone, the Spyglass Formation (equivalent to the Weka Pass Formation further south) is separated by the phosphatised Marshall Unconformity from the uppermost members of the Amuri Limestone. These three units are exposed down most the southeastern shoreline where the axial trace of the anticline is crossed in several places by embayments in the cliff. The cliff and wide shore platform exposures provide good sections through the crest and eastern limb of this open fold and the train of flanking intermediate and small scale folds.

The anticline reverses plunge twice creating two major domed culminations coinciding respectively with the centres of Spaniards and Whalers Bay. As will be demonstrated, a case can be made for superposition of a set of northwest trending cross folds creating a dome and basin pattern on a similar range of wave lengths and scales. Minor structures are associated with each phase, and some structures appear to predate both phases of folding.

Some subtle reverse faulting is associated with the northeast trending folds, but much greater disruption occurs in association with a set of later, northwest-striking, rotational tear-faults with progressive change in throw along their lengths.

Clearly ongoing uplift and deformation has continued into the late Quaternary and the relationship of this deformation to the underlying structures will be a matter for discussion.

c. Marine terrace sequence

The evidence for Quaternary deformation is expressed in the flight of uplifted and tilted marine terraces which extend to the highest surface on the Peninsula. Allocating ages to these erosion surfaces and consequential uplift rates has been a matter of debate (Bull, 1984; Ota et. al. 1996). More detailed work on the loess cover sequence is currently in progress and will be introduced at this meeting and summarised below (Tonkin et. al., 2005).

***Soil stratigraphy of aeolian cover beds on Kaikoura Peninsula*.**

Loess is reported on the upper four of five terraces (T1 highest to T5 lowest) on Kaikoura Peninsula. In their reconnaissance Ota et al. (1996) recognised three loess members on T1 and T2 and two loess members on T3 and T4. They did not record loess on T5. With the exception of a diagram (their figure 10, p58) interpreting the stratigraphy of loess columns, there is no information on textural properties or the criteria used to distinguish the soil stratigraphy of the loess. The latter is the basis for recognising the number of loess members.

A re-examination of the loess during a Lincoln University field trip in 2000, indicated that the soil stratigraphy was far from obvious. Furthermore the ‘loess’ was unusual in that clay was the dominant texture. A more systematic auger examination of the loess stratigraphy of T1, T2, and T3 on the western side of the peninsula was begun in 2005. The purpose was to reassess the loess stratigraphy on the peninsula in order to facilitate a comparison with soil stratigraphic studies of the loess on terraces at Kekerengu and Charwell (see poster paper Tonkin et al. – this conference).

The data summarized in Table 1 is a selection of the auger observations made to date. An example of the soil morphological features recorded in an auger log is presented in Table 2. The boundaries between horizons cannot be defined with any precision, and sometimes are little more than a guess. Exposure of a section, by trenching the loess is the only way of improving the soil stratigraphic interpretation.

Kawakawa tephra (22.6ka) has been recorded in a section of loess 1 exposed on the shoulder of T1 (P. Almond pers comm. 2003). An amino acid age of 110±20 ka for *Tawera* shells in the estuarine sediments at the base of the loess on T1 (Ota et al., 1996) is at present the only date constraining the age of this marine terrace and the loess that overlies it.

Terrace		1			2			3		
Elevation (m)		c. 95 m			c. 75 – 64 m			c. 54 – 52 m		
Loess thickness **(m)**		4.2	4.1	4.5	1.9	2.9	2.6	2.7	2.1	2.1
No. loess **members**		3	3	3	1 (2?)	2	2	1 (2?)	1	1
Thickness of loess members	**1**	1.3	1.8	1.75	1.8	2.1	1.0	1.9	2.1	2.1
	2	1.35	0.9	2.25*	0.15	0.8	1.6	0.3	na	na
	3	1.55	1.42	0.5*	na	na	na	na	na	na
Marine or **Beach sediments**		clay + flints, gwke.gravel and sand		not seen	clay + flints, gwke.gravel and sand			clay + flints, gwke.gravel and sand		
Underlying lithology		muddy limest.	not seen		not seen	muddy limestone		limest.	not seen	
Depth of auger hole (m)		5.1	5.4	5.3	2.2	3.7	3.8	2.7	2.7	2.7

Table 1: Summary of data from auger logs from terraces 1,2 and 3 on the western side of the Kaikoura Peninsula

Kaikoura Peninsula 20.04.05
Terrace 1, Auger hole 1 (E173 41.589 S42 25.201)

Loess 1			Loess 2			Loess 3			estuarine or beach muds		
horizon depth-cm boundary	matrix colour mottles	texture consist-ence	horizon depth-cm boundary	matrix colour mottles	texture consist-ence	horizon depth-cm boundary	matrix colour mottles	texture consist-ence	horizon depth-cm boundary	matrix colour mottles	texture consist-ence
A 25 clear	10YR2/2	clay loam	2bBtg1 220 gradual	10YR5/4 10YR5/6 2.5Y7/1 veins 8mm	clay firm sticky v.plastic	3b2Btr 320 gradual	2.5Y7/3 5YR5/8 m.m-c.p.	clay firm sticky v.plastic	4b3Bt1 450 gradual	10YR5/6 10YR5/3 f.m.f.	sandy clay v.firm sticky v.plastic
Btg1 50 gradual	2.5Y7/3 10YR5/6 m.m.d.	silty clay firm sticky plastic	2bBtg2 265 gradual	5Y7/1 10YR5/4 10YR5/6 m.m.d.	clay firm sticky v.plastic	3b2Btg 360 gradual	10YR4/6 2.5Y7/1 veins	silty clay firm sticky plastic	4b3Bt2 476 gradual	10YR5/4 2.5Y8/1 (flints)	heavy clay v.firm v.sticky v.plastic
Btg2 90 gradual	10YR4/6 10YR6/2 m.m.d.	clay v. firm sticky plastic				3b2Bt(g) 420 diffuse	10YR5/4 10YR6/3 f.m-f.f.	silty clay v. firm sticky plastic	5b3Bt 495 clear	10YR5/4 2.5Y8/2 (flints)	gravel in clay firm sticky plastic
Bt 130 diffuse	2.5Y6/4 10YR6/2 veins 4-2mm	clay sli.brittle sticky plastic							6C 506 abrupt	2.5Y7/4 2.5Y8/1 (shell + flints)	gravely clay loam sli.firm sli.sticky plastic

Soil descriptors (Milne etal 1995), colours Munsell notation
mottles:f-few/c-common/m-many // f-fine/m-medium/c-coarse // f-faint/d-distinct/p-prominent

overlies muddy limestone

Table 2: Auger log from Terrace 1

Topics for the shore platform

2. MAJOR AND MINOR NORTHEAST-TRENDING FOLDS

a. Large, Kilometre-Scale folds

The Atia Anticline and associated Fyffe Syncline are the more extensively exposed of the peninsula fold pairs and allow for more detailed observations on the fold character. Although there is a contrast between the well-bedded, indurated limestones that appear much more deformed and the more massive overlying siltstone, there is no doubt that the bedding in the siltstone parallels the folded surface of the limestone and folding postdates deposition of the sequence. The mechanical contrast has lead to shortening strain being accommodated in the limestone by intense folding on several scales whereas the siltstone has thickened by variable amounts of pure shear manifest in a weak axial planar cleavage becoming quite slaty in the hinge zones. Consequently the siltstone bedding serves as a simplifying, enveloping surface that traces out the form of the macroscopic and intermediate scale folding, showing a characteristic conical style at the plunging closures.

The multilayer character of the limestones forces a conjugate box-style fold form with broad crests and a cascade of asymmetric outward facing kink folds on the limbs, reversing vergence across the hinge zones of both the large and intermediate scale folds.

b. Intermediate-scale folds

On a shorter wave length in the order of tens of metres, secondary folding is accurately picked out by the outcrop pattern of the contacts between the siltstone and limestone and the phosphatised contact between the two limestones (Fig. 2). Again the fold style is typically conjugate with tight chevron cores opening to flat polyclinal box forms. The marker beds are frequently either interrupted, or duplicated, by otherwise subtle bedding-parallel, reverse faults to which the folding is clearly related. The connection between thrust faulting and intensity of folding is well demonstrated in one of the cliff sections.

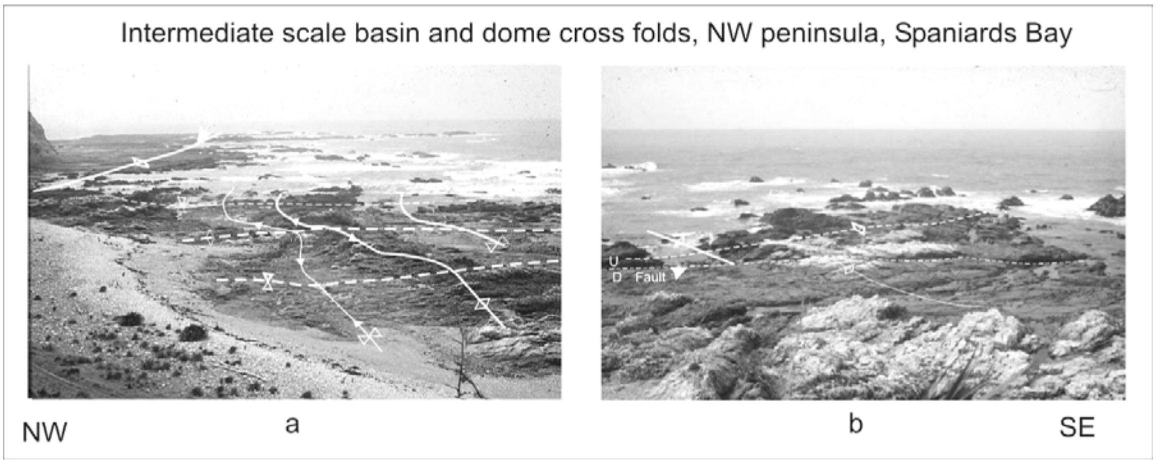


Figure 2: Intermediate scale folds on the peninsula northeast of Spaniards Bay picked out by the contact between Waima Fm. siltstone (smooth depressed areas) and Spyglass Fm. limestone (rough dark or white elevated areas).

a. Siltstone filled northeast trending syncline opening to two elliptical basins separated by narrowing at the plunge reversal caused by a northwest trending cross anticline. Note the sinuous axial traces of this and adjacent folds related to folding by the cross folds providing evidence of relative age.

b. Dome of limestone at the intersection of the same cross fold anticline further out on the platform

c. Minor, metre-scale folds

The spectacular development of small, metre scale mesoscopic folds in the limestones immediately catch attention (Fig. 3). Historically these were interpreted as syn-depositional, soft-sediment structures predating deposition of the siltstone and induced by gravitational slumping on the sea floor (Bradley and Waterhouse, 1957). Several observations make this unlikely.

- There is a clear geometric relationship between the orientation of the axes of these folds and the larger scale folding, as well as vergence changes across the intermediate folds.
- The folds are associated with a stylolitic cleavage forming an intersection lineation parallel to the fold hinges, inferring both a degree of induration and prolonged compression at the time of fold formation (see below for a discussion of cleavages).
- There appears to be a pre-folding cleavage which is folded around the hinges.

In detail, fold morphology is affected by mechanical differences in the two limestone lithologies, the degree of shortening strain and the localised effect of anomalously thick beds.

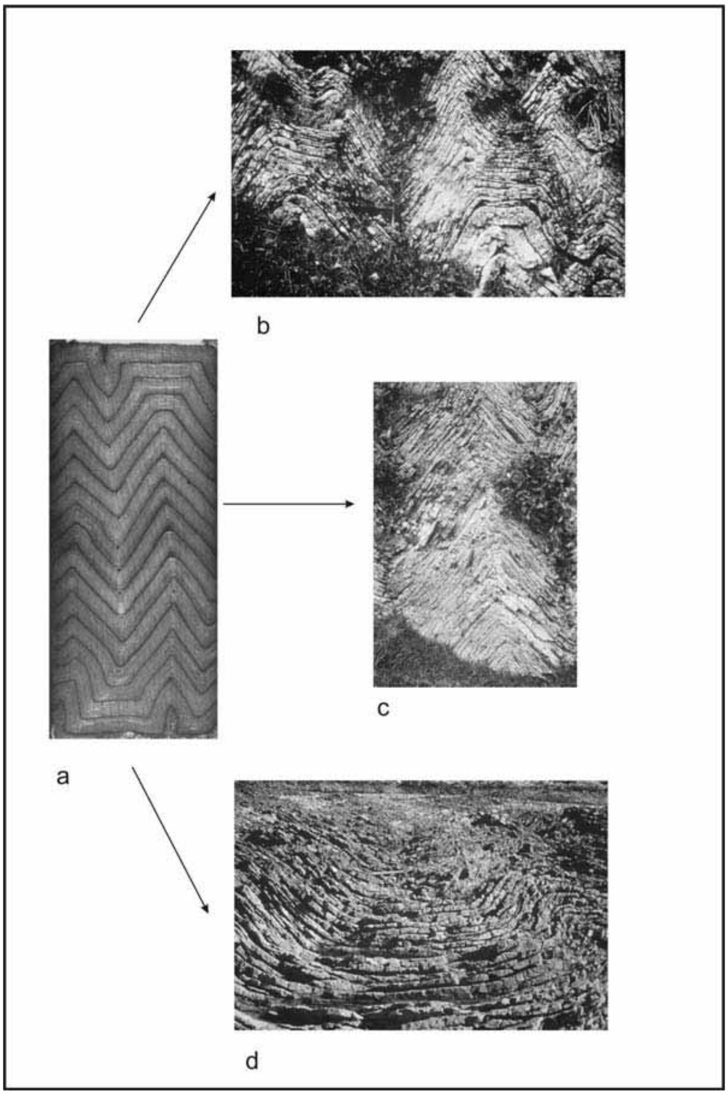


Figure 3: Relationships in mesoscopic fold styles.

a. Experimental folding in multilayered media showing the transition from box to chevron folding during incremental shortening of the stack. (Price and Cosgrove, 1990)

b. “Millepede” box folds resulting from resistance to shortening by the presence of a thick bed.

c. Regular chevron folds in uniformly bedded limestone

d. Box syncline with chevron anticlines, typical of the basal part of a folded stack.

3. MAJOR AND MINOR NORTHWEST-TRENDING FOLDS

a. Dome and Basin Interference pattern

The Atia Anticline forms an elongate pericline, plunging out to sea at both ends, but also reversing plunge to form two domed culminations, the Spaniards Bay and Whalers Bay Domes. The formation of undulations on a fold crest can be the product of a single fold forming event and does not necessarily require discrete overprinting by a cross fold system. In this case, the evidence for a second suite of folds, trending generally northwest to north-northwest, is strong. The generation of a regular wave-length "egg-carton" interference pattern can be seen not only

on the macroscopic scale, but also expressed on analagous intermediate and metre scale folding (Fig.2), presumably reflecting the same mechanical controls in the lithology. Zones of plunge reversal delineate the cross-cutting axial traces, the lower order folds producing local undulations on the regional plunge reversals associated with at the intersection of the two sets of major folds.

b. Related tear and rotational faulting

The regularity of the interference pattern is disrupted by late stage faulting. This appears to reflect the complex strains induced by the cross folding and has generated a system of predominantly northwest-striking faults. Several examples show evidence of significant rotation and dividing the structure into a series of fault bound domains. Intense brecciation is a feature of these faults, particularly in the hinge zones.

c. Geometric evidence for relative age of fold systems

Strictly, an end member Type 1 (Ramsay,1967) dome and basin pattern cannot separate the relative ages of the superposed fold sets on purely geometric criteria, because neither axial plane is folded by the other and both sets of fold hinges reverse plunge. In practice any departure from $\beta = 90°$(growth direction of second fold lies within the axial plane of the first fold) will result in warping of the axial surface of the older fold set reflected by variations in strike of the axial trace. There is also the "corrugated iron effect" insofar as it is much easier to generate a simple cylindrical first generation fold system in planar bedding than force the complex strains produced by cross-folding, particularly where the folding is by a flexure mechanism. The later folds will usually have a relatively longer and less regular wave-length and be associated with secondary faulting. It is possible to demonstrate both of these criteria where the interference pattern is most extensively displayed on the area of shore platform forming the northeastern peninsula of Spaniards Bay.

The outcrop pattern of axial traces can be used in conjunction with stereographic analysis of the reversal of plunge of the first phase minor folds. If the cross folding is predominantly by buckling, predictably the plot of minor folds should form one, or both, of a pair of wedge shaped concentrations centred on corresponding small circles. The centre of the small circle defines the trend and plunge of the second phase fold axis (strictly the *b*-kinematic axis). The size of the small circle defines α the angle between the first and second phase fold axes. This axis must also lie in the *ab* plane (=axial plane) of the second phase folds which is constrained by mapping out the strike of the cross fold axial traces and by the orientation of any potential axial planar cleavage.

The plots reproduced in Fig 4 are consistent with these predictions and imply an original angle of 78° between the two folds. Further, comparison of plots from the two fault separated domains of Spaniards Bay show small, but significant differences, where the internal angular relationships are maintained, but the plots are externally rotated by block faulting. This supports the view that the faulting is late stage.

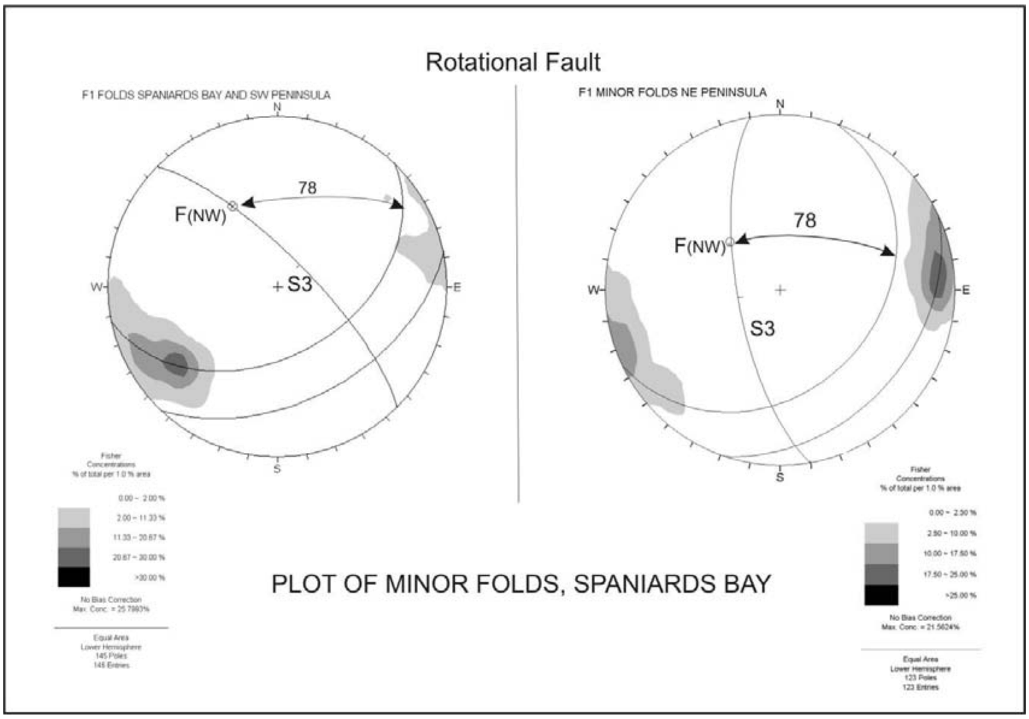


Figure 4: Plot of minor folds associated with the northeast-trending folds and compatibility of the plot with a predictive model for flexure slip on a northwest trending second fold phase. The axial S_3 is constrained by the strike of zones of plunge reversal (axial trace of cross-folding) and by the orientation of a set of fracture cleavages discussed below. The implication is that the earlier folds are refolded about a moderately plunging fold axis, with an initial angle of 78° between the two folds and rotated from an orientation of 312/58° to 330°/45° from the northeast to southwest domains. Dip directions of the steep S_3 are observed to reverse in the two domains.

4. POLYPHASE CLEAVAGE DEVELOPMENT AND RELATED ISSUES

a. The problematic pre-folding cleavage

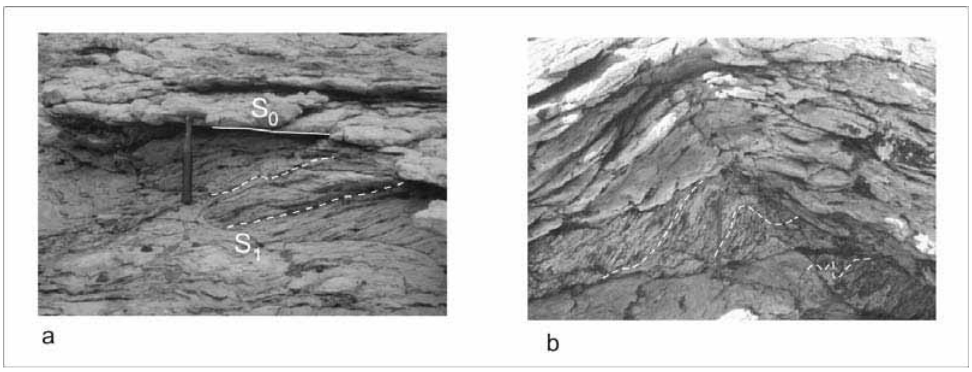
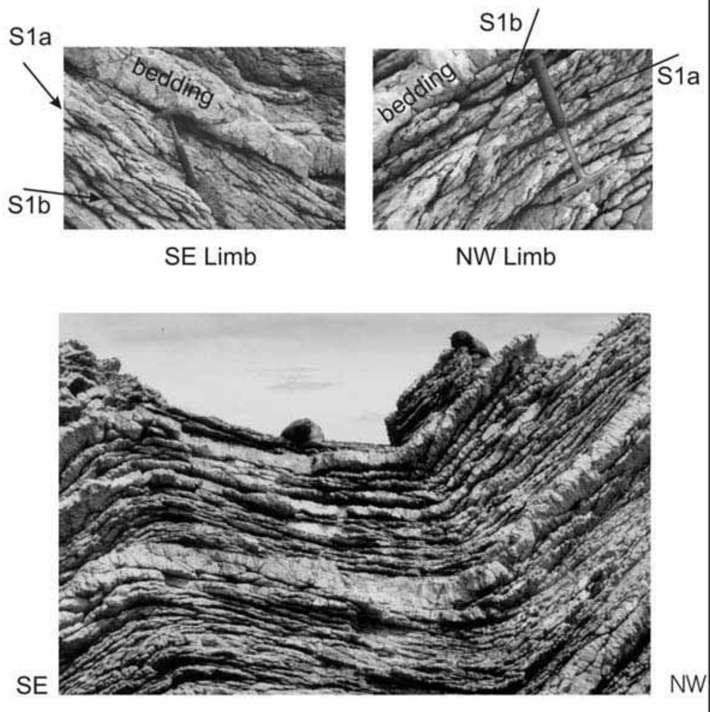


Figure 5: a. Slaty cleavage (S_1) in marl beds oblique to bedding (S_0).
b. Folding and crenulation of the slaty cleavage by the northeast trending folds. View to northeast.

The nature and history of cleavage development is complex and presents several problems. Most easily identified in the marly beds of the upper Amuri Limestone, there is a well developed slaty cleavage that forms an acute angle with bedding (Fig 5a). This is clearly crenulated on the centimetre scale parallel to the northeast trending minor folds and also maintains a constant vergence relationship to bedding around the hinge zones, clearly being refolded by these minor folds (Fig 5b). It is also crenulated parallel to the northwest trending set and on geometric grounds evidently pre-dates both fold phases.

In the adjacent micritic limestone beds the slaty cleavage converts to a spaced, fracture cleavage S_1 maintaining the same acute angular intersection and sense of vergence. The intersection lineation L_1 (S_1/S_0) is wrapped obliquely around the fold hinges implying a general discordance between this structure and the earliest obvious folding.

More problematic still, is the expression of related pre-folding planar structures in the Spy Glass Formation, where a similarly oriented spaced cleavage has a "conjugate" companion S_{1b} verging into bedding at an acute angle in the opposite direction and also clearly folded around the hinges of minor folds. The result is a lozenge fabric to the limestone giving the bedding its characteristic ropey appearance. These cleavage surfaces are clearly activated along with bedding during flexure-slip folding.



Folding of early S1a and S1b cleavage in Spy Glass Fm.

Figure 6:

Development of two spaced planar structures oblique to bedding (picked out by anomalously thick beds). S_{1a} has the same vergence relationship to bedding as the slaty cleavage S_1 in Fig.5 and can be clearly seen in the lower photo rotated around the fold hinges. S_{1b} is less evident but produces the lozenge fabric also folded with S_{1a}

No other fold or deformation structures have been found on the peninsula associated with this early cleavage, but a similar structure is widely developed in the Amuri Limestone throughout North Canterbury (Nicol,1992). The age of formation is debatable, but there is some evidence that this is much older than the folding. Lewis (1992) describes a similarly oriented structure controlling borings at the unconformity between underlying Amuri Limestone and the Weka Pass Limestone (Spy Glass equivalent) in North Canterbury, although it is clearly present in both limestones (older part of transgressive Spy Glass - Weka Pass facies) at Kaikoura, suggesting an early Oligocene age for the cleavage event. No analagous structure has been identified in the Waima Formation.

b. Stylolitic fracture cleavage in limestone and the northeast fold set.

A younger cleavage system S_2 , characterised by stylolitic solution (Fig 8a), is geometrically related to the northeast fold system in that it develops an intersection lineation L_2 (S_2/S_0) parallel to the fold hinges. In the axial zone of simple chevron structures the cleavage is axial planar, but on the limbs tends to fan, maintaining an orientation perpendicular to bedding, raising the question of whether the structure is established before, or during the early stages of shortening. Paradoxically in box folds there are cases where the cleavage overprints and transects the Y-shaped hinge zones indicating that the cleavage forming compression and ongoing pressure solution continues well after the cessation of folding.

c. Cleavage in the Waima siltstone

In the Waima siltstone, the axial planar structure takes the form of a reticulate, anastomosing system of elongate lozenges which parallel an incipient slaty structure in the most intensely shortened domains (Fig. 7). This structure evolves from the curious rounded blocky fabric developed over much of this unit. However, in detail these rounded blocks can be seen to be formed from sets of widely- spaced, subparallel planar fractures. Increased flattening deforms the blocks into progressively more elongate lenses which are still clearly delineated by subparallel planar sets rotated toward the flattening plane, until a strongly axial-planar fabric is formed. Splitting the rock on this fabric will often yield a calcite coating with a subperpendicular fibre lineation indicative of the kinematic *a* direction.

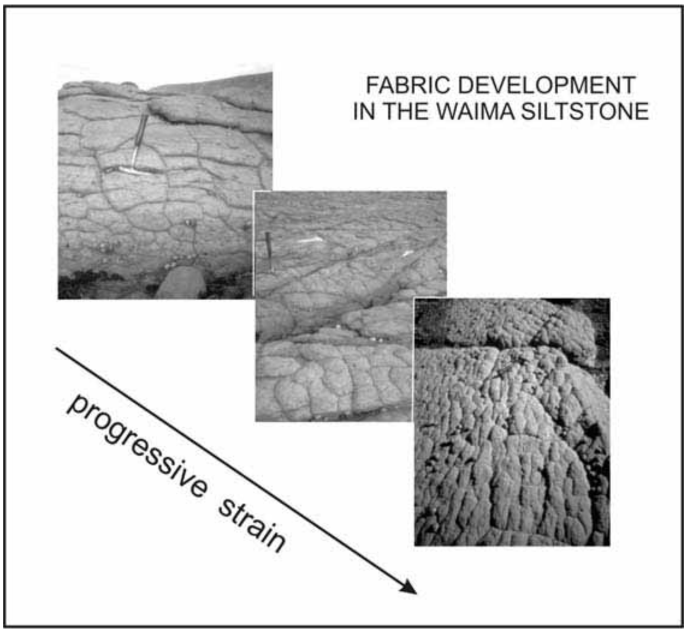
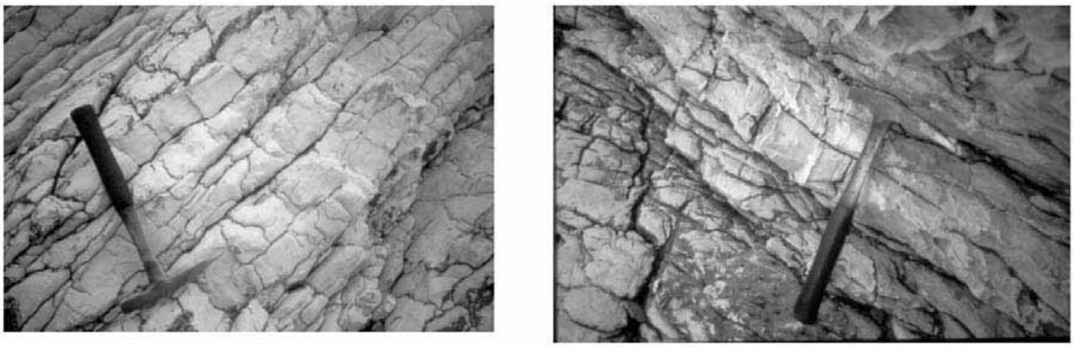


Figure 7: Flattening strain in the hinge zones of the northeast folds rotates the quasi-orthogonal blocks (top left) to elongate lozenges defined by two acutely intersecting spaced fracture cleavages It is not clear whether the original blocky structure pre-dates and is unrelated to folding.

d. The extensional fracture cleavage associated with the northwest folds

There is also a candidate for an axial planar structure associated with the cross-folding S_3. This is a spaced cleavage on the cm to decimetre scale frequently characterised by calcite vein filling suggestive of some post formation extension. This cleavage also controls some secondary fracturing and it is likely that some of the stretching and differential motion needed to accommodate the strains is taken up on these structures. The orientation of this structure within each domain further constrains the stereographic model in defining the orientation of the second generation folding.



a b

Figure 8: a. Stylolitic fracture.cleavage ($S_{2)}$ developed perpendicular to bedding (view to northeast); note intersection lineation with bedding surface above hammer handle. This is parallel to fold hinges.

b. Calcite filled $S_{3.}$fracture cleavage (view to southeast)

Topics for the cliff top

5. THE UPLIFT OF MARINE TERRACES

Deformation of terrace surfaces

The T3 surface of Ota et al. (1996) occupying the neck of the peninsula is visibly tilted in a northwesterly direction dropping approximately 10 m over the length and not an orientation that would be expected for a primary shoreline gradient. They suggest this is indicative of a general tilting up towards the southeast elevating the seaward end of the peninsula, and compatible with the progressively more extensive exposure of eroded shore platform towards that side. This observation implies that tilting continues into the Holocene and relict sea stack tops above the present platform may be related to Holocene episodic uplift.

The same authors present some estimates of uplift rates based on correlation of the marine surfaces with Pleistocene high sea level stands, but as noted only one direct (amino acid racemisation) date is available to support the interpretation. Individual uplift rates for each terrace produce a reasonably internally consistent range from 0.9 to 1.2 m/ka and variance would be expected because uplift is accompanied by tilting.

At the eastern end of the peninsula a suite of terraces T3 to T5 grade down to the north east and southwest from the centre, compatible with both a primary marine erosion surface gradient and with the general plunge of structures. The T4 surface is not sharply defined or planar, and recently the surface has been the subject of a class exercise GPS survey from which a terrane model has been derived. The surface appears broadly domed up to a point which coincides with the inferred trace of the Spaniards Bay cross-fold anticline suggestive of ongoing fold growth.

Because of the beach and slope deposits accumulated at the wave cut notch marking the former cliff base behind each erosion surface, an accurate reconstruction of deformation would require a more intensive combination of accurate surveying and shallow geophysical methods to pick the erosion surface and place the elevations accurately and resolve the true number of terrace degradation events.

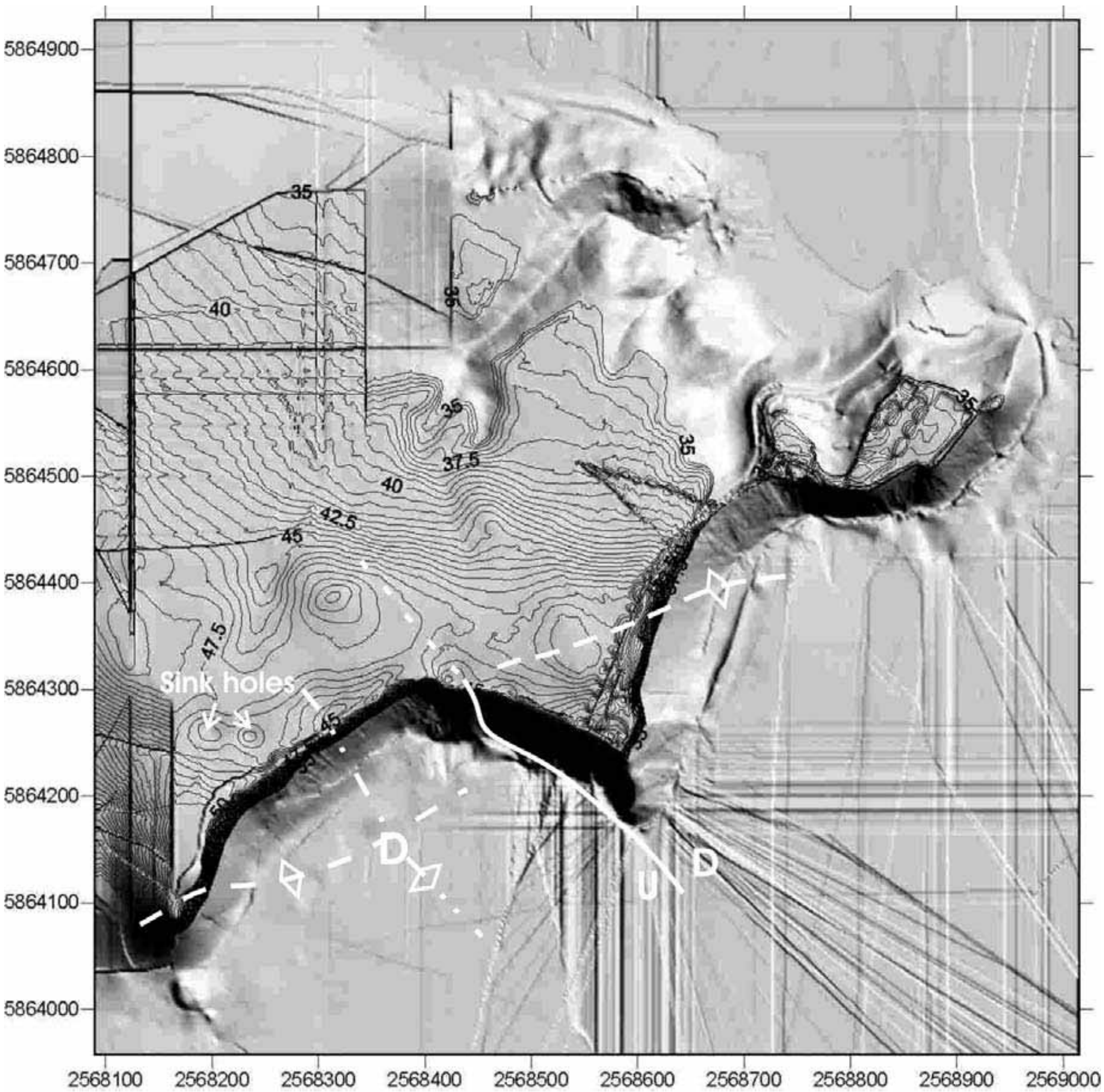


Figure 9: DEM of uplifted marine terraces showing contouring the terrace surface at 0.5m intervals. elevated areas on the T4 surface coincide with the crest of the Atia Anticline the northwest side of the Spaniards Bay Dome truncated by the cliff and along strike on the upthrown side of the fault on the north side of the bay separating the two domains.

6. WIDER TECTONIC SETTING AND ISSUES

There are questions which arise from the observations presented here that raise local and regional issues.

- *Implications for local seismic sources and related hazard.*

Given the setting, the folding at Kaikoura seems almost certainly to be driven by underlying east facing thrust faults as Ota et al. have suggested. This is totally compatible with the fold style, where the asymmetric form of the Race Course Anticline may reflect a blind thrust breaking off a basal thrust decollement, for which there is some support in anomalies in the stratigraphy on the eastern limb. The box style and irregularly distributed strain on the long southeastern limb of the Atia Anticline are suggestive of fault-bend folding over an underlying ramp and minor thrusts clearly occur in association with the folding. The evidence of late Quaternary tilting and episodic uplift in the Holocene would suggest a potential seismic source with implications for Kaikoura Town as well as the more evident proximity of the Hope Fault. Secondarily the implication of uplift of the seabed together with the instability of the nearby Kaikoura Canyon sediment accumulation compounds the tsunami potential.

- *The nature of local and regional interference folding*

The evidence that the northeast trending folds are associated with ongoing deformation presents a paradox in that the general evidence supports later overprinting by the northwest cross folding with some indication of activity on this system as well. Evidence of essentially coeval basin and dome cross folding is widespread throughout the northern South Island. In Canterbury the two trends are north to northeast (similar to Kaikoura) and east-west. It is thought that the latter is controlled by reactivation and inversion of the normal faults of the onland extension of the North Mernoo Fault Zone by regional northwest to southeast principal horizontal compression. Cross folding within the currently active northeast striking thrust fold systems is also documented further north in Picton (Nicol and Campbell,1990). While all these settings relate to ways of accommodating oblique transpression, the data from Kaikoura suggests that here, the kinematics of cross-folding are generated about plunging north to northwest trending rotation axes. The structures suggests that folding is also accompanied by stretching and extension of the northeast fold set by macroscopic faulting and by opening of the S3 cleavage. A possible mechanism may be by superimposing secondary shear folding on the thrust system where the axis of shear rotation is consistent with the shear couple generated by oblique motion on the north-northwest regional dips of the Hope and other Marlborough Faults.

- *The origin and relationship of the widespread early S_1 cleavage*

There is a widespread consensus that some form of regional diastrophism affected the South Island in the Oligocene, reflected in the stratigraphy, unconformities and cryptic structures. Broadly this has been interpreted as heralding the early indications of the new plate boundary configuration. How such a widespread penetrative fabric develops in the carbonates at the oblique angle to bedding without apparently being related to other macroscopic structures and precisely when it was formed remains an unanswered question.

- *Specifics of cleavage forming processes.*

Despite the wide literature relating to the origin of cleavage related structures, the mechanism of “fracture” cleavage – cm scale regularly spaced joint-like discontinuities – that are clearly associated with folds and shortening strain remain the least satisfactorily explained. The variety of morphologies, the timing of formation relative to folding and the secondary processes exhibited by the cleavage families seen on the foreshore, present questions which do not yet seem to be adequately explained.

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