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May 9, 2000
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U.S. Nuclear Regulatory Commission
ATTN: Deborah DeMarco
Office of Nuclear Material Safety and Safeguards
Two White Flint North
Mail Stop 7 C6
Washington, DC 20555

Subject: Transmittal of paper: Structural Geology of the Tompire Bay Outcrops, Eastern Northern Range, Trinidad

Dear Ms. DeMarco:

The enclosed manuscript entitled Structural Geology of the Tompire Bay Outcrops, Eastern Northern Range, Trinidad is based on the work done as part of Professional Development activity by Dr. David Ferrill. This manuscript is being submitted to the 14th Caribbean Geological Conference. The enclosed is the final version and has been through Center and Journal review. Some of the techniques used to develop the uplift history of the Northern Range of Trinidad are similar to those used in determining the uplift history of Bare Mountain. This professional development activity provides Dr. Ferrill with additional experience in the interpretation of the geologic history of a mountain range and increases his professional reputation. This paper is being submitted for your information only; no review is requested.

If you have any questions please contact Dr. David Ferrill at (210) 522-6082 or me at (210) 522-5252.

Sincerely,

Budhi Sagar
Technical Director

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for: Proceedings, 15th Caribbean Geological Conference

Structural geology of the Tompire Bay outcrops, eastern Northern Range, Trinidad

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ABSTRACT

We present a study of the structures exposed in 340 m of nearly continuous, superbly well-exposed, coastal outcrops along Tompire Bay in the eastern Northern Range of Trinidad. We describe the characteristics, sequence, and geometry of the structures, present several representative sketch cross-sections of parts of the outcrops, and interpret deformation conditions and tectonics. The rocks at Tompire Bay experienced two major phases of deformation and fabric development. Bedding is well preserved in low strain zones, which are generally developed in thick metasandstone layers. We interpret that the upright NE-SW striking spaced to slaty cleavage, upright buckle folds, and contraction faults formed in the upper crust, probably during E-W dextral transpression. The second deformation phase produced ramp-flat fault systems, fault-bounded forced folds, and spaced cleavage, and probably occurred when these rocks were at shallower depths. We interpret that the NW-SE striking vertical π-girdle of S_2

poles resulted from movement on D_2 faults and that the D_2 structures may be due to later regional extension.

INTRODUCTION

The Northern Range of Trinidad (Fig. 1) is an uplifted mountain block in the Caribbean-South American plate boundary zone. The range contains predominantly metasedimentary rocks of greenschist and subgreenschist grade (Frey et al. 1988; Weber et al. in review). $^{40}Ar/^{39}Ar$ and fission track studies indicate that these rocks were metamorphosed in the mid-Tertiary, then exhumed and uplifted during the Neogene (Foland et al. 1992; Foland and Speed 1992; Algar 1993; Algar et al. 1998; Weber et al. in review). Deformation in the Caribbean-South American plate boundary zone was driven by Tertiary dextral-convergent relative plate motion (Speed 1985, 1986; Robertson and Burke 1989; Russo and Speed 1992; Algar and Pindell 1993; Russo et al. 1997; Flinch et al. in press), which may be ongoing today (e.g., DeMets et al. 1990). Alternatively, dextral Caribbean-South American plate motion may now be slightly divergent (e.g., Deng and Sykes 1995).

In this paper, we describe and interpret the superbly well-exposed structures along 340 m of nearly continuous coastal outcrops along Tompire Bay in the eastern Northern Range (Figs. 1, 2). These outcrops provide a nearly continuous exposure of a long train of major folds, expose many small-scale structures, and permit bedding-cleavage and other structural relations to be studied in detail. Barr (1963) first mapped the geology of the eastern Northern Range; his results were included on Kugler's (1961) geological map of Trinidad. Although bedding and cleavage were not distinguished on his map, Barr's (1963) work showed that planar structural elements dip steeply, and thus form an upright fabric, across much of this region. Algar (1993) restudied the geology of the eastern Northern Range, and Weber et al. (in review) analyzed these rocks in their broader geothermometry study of the metasedimentary rocks of the Northern Range. Weber et al. (in review, and 1999) speculated that the Northern Range, like the Pyrenees (e.g., Carreras and Capela 1994, 1995; Aerden 1995; Garcia-Sansegundo 1996; and references therein), is tectonically two-tiered: a low-grade, upright-fabric domain structurally overlies a high-grade, subhorizontal-fabric domain. Upper domain rocks are exposed primarily in the eastern Northern Range, but are also preserved in down-dropped fault blocks along the southern margin of the Northern Range (Weber et al. in review). The Tompire Bay rocks and structures described in this study are characteristic of those in the upper domain and because of their exceptional quality and extent may serve as a type section.

The fieldwork presented here was done in the summer of 1997. The property on which this work was done was then part of the Green Acres estate owned by Mr. Hugh Lee Pow of Cumana (Redhead) village. We mapped the Tompire Bay outcrops by pace-and-compass methods and constructed a continuous sketch cross-section at a scale of 1:400 in the field. Three segments of the continuous cross-section are presented here, including two sections showing representative structures in metasandstone and metamudstone from the first deformation phase (Figs. 3 and 4), and one section illustrating structures typical of the second deformation phase (Fig. 5). We interpret the sequence, deformation conditions, and tectonics of these structures based on their observed characteristics and geometry. For a description of the structural coding system used here (D_i, S_i, F_i, etc.) see the caption on Table 1 or any standard structural geology textbook (e.g., Davis and Reynolds 1996, p. 472).

Bedding (S_0) is well preserved in low-strain zones, which are generally developed in thick metasandstone layers, but is commonly transposed by an early (S_1) spaced to penetrative (slaty) cleavage in metamudstone-rich rocks. The D_1 structures at Tompire Bay include F_1 major and minor folds, S_1 slaty cleavage, and f_1 faults. The D_2 structures at Tompire Bay include f_2 ramp and flat fault systems, fault-bounded forced F_2 folds, and S_2 spaced cleavage. We interpret that the upright D_1 structures are consistent with having accommodated E-W dextral transpression. D_2 structures deform D_1 structures and include folds with subhorizontal axial surfaces and down dip vergence, consistent with vertical shortening and horizontal extension.

TOMPIRE BAY STRUCTURES

The Tompire Bay outcrops described below begin about a hundred meters south of the Tompire River, continue south to Point Playas, and trend approximately north-south (Fig. 2). We arbitrarily labeled the first outcrop south of the Tompire River 0 m as a reference point. Point Playas, a natural sea wall held up by thick, resistant metasandstone layers, is 340 m south of this point, beyond which outcrops are present but not described here. Figures 3, 4, and 5, show representative sections of outcrop to illustrate many of the features described in the text and summarized in Table 1. Other locations of occurrence for structural features are noted in parentheses in the following text for the benefit of future investigators.

We interpret that the rocks at Tompire Bay have experienced two principal phases of folding and fabric development (Table 1). Bedding (S_0) is still well preserved in low strain zones, which are generally developed where thick metasandstone layers are concentrated, especially between 230 m and 339 m (e.g., Fig. 3). These metasandstone layers are sedimentary beds that were resistant to internal deformation and contain well-preserved graded- and cross-bedding. Such graded- and cross-bedding was used to determine younging (way up) directions (e.g., Fig. 3).

The earliest (F_1) folds in the Tompire Bay outcrops are folds of bedding (S_0). F_1 folds are generally upright and have NE-SW striking subvertical axial surfaces and shallowly plunging hingelines (Fig. 6). F_1 folds are also commonly accompanied by a spaced to slaty S_1 cleavage that strikes NE-SW and is subvertical (i.e., is upright), and have interlimb angles that vary from 0-100° (Figs. 3, 4, 5, 6).

The largest-scale F_1 folds in the Tompire Bay outcrops are major folds in a long fold train of thick metasandstone beds (208-320 m). This exposed fold train, part of which is shown in Fig. 3, is remarkable; this is one of the few places in the Northern Range where F_1 major folds can be seen and examined in their entirety. Large F_1 anticlines and synclines in the train have amplitudes of about 10 m and apparent wavelengths that range from 10-100 m. The fold wavelengths are reported here as apparent because the fold train is cut by many faults and segments of it have moved horizontally relative to one another. The major F_1 folds are generally symmetric and thus give no indication of a dominant sense of tectonic transport. On the other hand, F_1 minor folds on the limbs of the large F_1 anticlines and synclines are generally asymmetric and parasitic, verging toward the crests of the major anticlines. Rotated domino fault blocks at 264 m (Fig. 3; also Algar 1993, Fig. 4-19) also give a parasitic sense of shear relative to the F_1 major folds, and are thus interpreted here as D_1 structures.

East-west striking faults, similar to those mentioned above that cut the major F_1 fold train at 208-320 m, are common throughout the Tompire Bay outcrops (Fig. 6). Trains of asymmetric minor F_1 folds verging up the dip of the f_1 faults are common in the fault. The f_1 faults also have other drag features or offsets generally indicating reverse dip-slip in cross-section (c.f., 253 m in Fig. 3; reverse-slip indicators also present at 34 m, 83 m, 101 m, 300 m, 315 m, and 325 m). The f_1 faults thus appear in cross-section to be f_1 contractile faults. However, when viewed on horizontal surfaces, f_1 faults commonly show drag features indicative of dextral offset. The few f_1 faults that were exposed well enough that we could study them in detail have oblique slip indicators (e.g., slickenfibers and frictional striae with 20-30° plunge angles). f_1 extensional faults and en echelon vein arrays that accommodated F_1 hinge-parallel stretching were also observed (335 m, not shown here).

In the folded metasandstone beds in the F_1 major fold train described above (208-320 m), S_1 cleavage is heterogeneously, and only weakly, developed. Where present, S_1 is a spaced cleavage that is approximately axial planar to the major folds (c.f., 260 m in Fig. 3). S_1 is a continuous, slaty cleavage in the metamudstone-rich parts of this fold train (300-320 m). S_1 generally cuts bedding (S_0) discordantly (note that S_1 cleavage is oblique to bedding at 260m and 265m in Fig. 3). S_1 cleavage is subparallel to S_0 where the F_1 major folds in the train are tight to isoclinal (210 m and 317 m, not shown).

S_1 is a pervasive, continuous, slaty cleavage from 0-127 m where metamudstone-rich rocks predominate (e.g., Fig. 4), and it is approximately axial planar to abundant F_1

minor folds. Bedding (S_0) in these mud-rich rocks has been highly strained and modified, and modestly to fully transposed by the S_1 tectonic foliation. Thus S_1, not S_0, is the dominant layering (e.g., Fig. 4). Thick metasandstone beds (S_0) are rare from 0-127 m (c.f., Fig. 4). Where present in this section, thick metasandstone beds have been heterogeneously and only modestly strained (neck zones in boudin trains are present at 245 m, 218 m, 205 m). Thin beds (S_0) of metasandstone, metaconglomerate, and metacarbonate are common from 0-127 m, and have been highly stretched and tectonically thinned on the limbs of F_1 minor folds (c.f., 90-100 m, Fig. 4). High-strain stretching and thinning of F_1 fold limbs is generally so great that many F_1 minor folds are intrafolial, with only isolated fold noses "swimming" in otherwise uniform looking slate (e.g., Figs. 4, 5). From 116-127 m, S_1 has anomalously shallow dips, which may be due to later F_2 folding (see discussion of the D_2 structures below).

The distinguishing characteristic of the F_2 folds at Tompire Bay is that they clearly fold, and thus post-date S_1 and F_1 axial surfaces (c.f., Fig. 5; F_2 folds are also present at 12-20 m, 40-44 m, 70-90 m, 102-112 m, 175 m, 183 m, 190-200 m, 216 m, 220 m, 283 m). In general, F_2 folding accommodates only relatively modest strain in these outcrops, but the D_2 event is probably important to understand because it records a distinct change in structural style and kinematics from the D_1 event. F_2 folds have subhorizontal, NE-SW trending hingelines (Fig. 6) and occur as either individual folds or short fold trains only several folds long. F_2 folds are most abundant where metamudstone rocks predominate, and are virtually absent where many thick metasandstone layers are concentrated. The stiff metasandstone layers probably resisted D_2 deformation. F_2 folds occur in fault-bounded panels that are detached from adjacent homoclinal panels of S_1

(Fig. 5). Generally, the bounding detachment faults follow layer-parallel flats along S_1 foliation planes. We interpret these detachments as f_2 faults because of their consistent association with the F_2 folds. F_2 folds are both symmetric and asymmetric. Those that are asymmetric have predominantly a top-down-the-dip of the f_2 detachment sense of vergence.

An axial-planar, spaced S_2 foliation is generally developed in association with the F_2 folds. The wide, cm-scale spacing of S_2 suggests that it formed by pressure solution. S_2 strikes are consistently NE-SW, but S_2, while predominantly shallowly dipping, takes on a complete spectrum of dip angles (vertical to horizontal) and dip directions (NW to SE; Fig. 6). Poles to S_2 thus form a NW-SE striking vertical great circle (π-girdle) on a stereoplot (Fig. 6). We have observed no outcrop-scale evidence for later folding of S_2 (i.e., for F_3 folding) that could have produced this girdle pattern. The heterogeneous distribution of S_2 dip directions within the outcrops also rule out that F_3 folding (e.g., broad arching) could have produced this girdle pattern. We interpret that the observed S_2 girdle pattern resulted from movement on f_2 ramp and flat fault systems that were predisposed to have NE-SW strikes by the preexisting NE-SW strike of S_1 in the homoclinal panels in which they developed.

INTERPRETATION

We interpret that the F_1 major folds formed by buckling of stiff, thick, competent metasandstone beds in a less competent metamudstone matrix. The vergence of F_1 minor folds and D_1 domino blocks indicate that the stiff metasandstone beds moved systematically, with a parasitic sense, relative to one other during F_1 folding. The spaced and slaty nature of the S_1 cleavage indicates that pressure solution was the dominant grain-scale deformation mechanism. In nearby rocks, Weber et al. (in press) observed only minor quartz crystal plasticity and estimated relatively low temperatures of D_1 deformation (200-330°C) based on temperature-sensitive calcite and quartz microstructures and fission track data. In summary, we interpret that D_1 folding and faulting at Tompire Bay occurred in the upper crust and that the D_1 structures are kinematically consistent with having accommodated E-W regional dextral transpression.

Because the ensuing D_2 event produced mostly fault-related structures, which are dominantly brittle at the outcrop scale, and S_2 pressure solution cleavage, we interpret that D_2 probably took place at shallower levels in the crust than D_1. We interpret that the F_2 folds are forced folds, not free buckle folds related to contraction, that formed by the bending of S_1 at irregularities on f_2 fault surfaces (i.e., at fault ramps) or by fault propagation (e.g., see Davis and Reynolds 1996, p. 413). Top-down-dip vergence is dominant for the F_2 folds that are asymmetric, and poles to S_2 fill a NW-SE vertical π-girdle, but are mostly subvertical indicating predominantly horizontal stretching. The D_2 features may thus have been produced by gravitational sliding down the dip of preexisting S_1 planes during late regional extension (e.g., see Dewey, 1988).

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LIST OF FIGURES

Fig. 1. Geologic and location map of Trinidad and the Tompire Bay study area. Geology simplified from Kugler (1961). With the exception of the Sans Souci basalt, rocks in the Northern Range are metasedimentary with Mesozoic protolith ages and Cenozoic metamorphic ages. Sediments and sedimentary rocks of Quaternary (Qal), Cenozoic (Cz), and Mesozoic (Mz) ages cover the rest of the island. Fault traces and major fold axes are shown as heavy dark lines; names are given for some of the major faults. The fault at the southern boundary of the Northern Range is shown schematically and referred

to as the Arima Fault after Kugler (1961), Flinch et al. (in press), and Weber et al. (in review).

Fig. 2. Map showing location of the study area, marked 0-340 m, along Tompire Bay. UTM Zone 20 coordinates, which define a one square kilometer grid, are also given.

Fig. 3. Sketch cross-section of the 250-270 m segment of the Tompire Bay outcrops illustrating mostly representative D_1 structures in metasandstone rocks. Explanation: metasandstone (stippled), metamudstone (not stippled), S_0 bedding traces (thick black lines in metasandstone; thin black lines in metamudstone), fault traces (thick black lines marked f), S_1 cleavage traces (gray lines) in metasandstone, stratigraphic younging (way up) directions (arrows) determined from graded- and cross-beds. Scale at the bottom of diagram is in meters south of reference zero (see text and Fig. 2).

Fig. 4. Sketch cross-section of the 90-100 m segment of the Tompire Bay outcrops illustrating mostly representative D_1 structures in metamudstone rocks. Explanation: slate (not stippled), metasandstone and metacarbonate (stippled), S_0 bedding traces (thick black lines), S_1 cleavage (thin black lines inclined to north), S_2 cleavage (gray lines inclined to south). Scale at the bottom of diagram is in meters south of reference zero (see text and Fig. 2). Note tight to isoclinal F_1 folds with boudinaged limbs and approximately axial planar S_1 slaty cleavage.

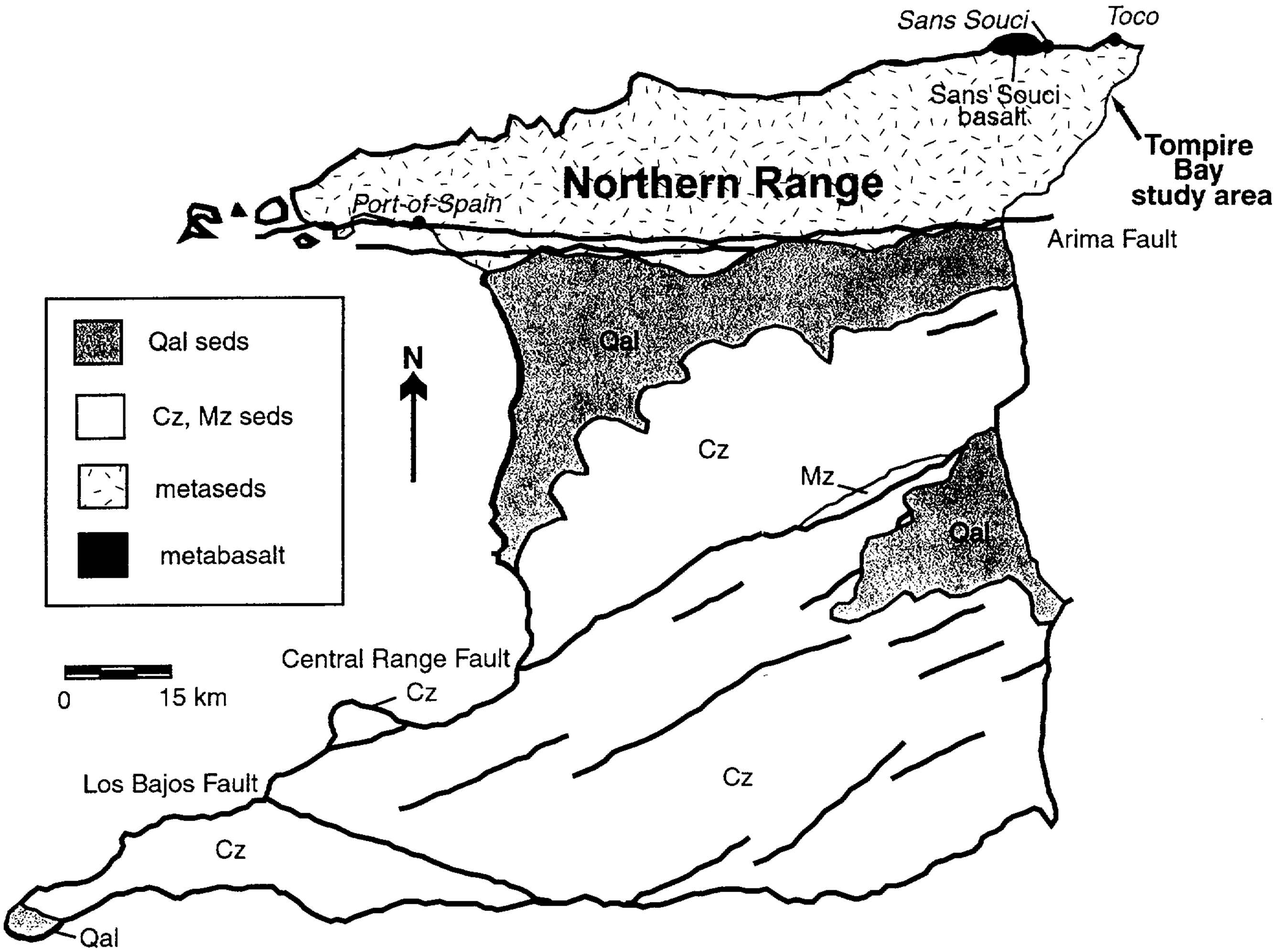
Fig. 5. Sketch cross-section of the 190-200 m segment of the Tompire Bay outcrops illustrating mostly representative D_2 structures. Explanation: metamudstone (not stippled), metasandstone (stippled), S_0 bedding traces (thick black lines), S_1 cleavage traces (thin black lines), S_2 cleavage traces (subhorizontal or southward-inclined gray lines), fault traces (thick black lines marked f). Scale at the bottom of diagram is in

meters south of reference zero (see text and Fig. 2). Note association of forced F_2 folds with S_1-parallel detachment fault, and also isolated intrafolial F_1 hinges in metamudstone, and tight to isoclinal F_1 folds of metasandstone beds.

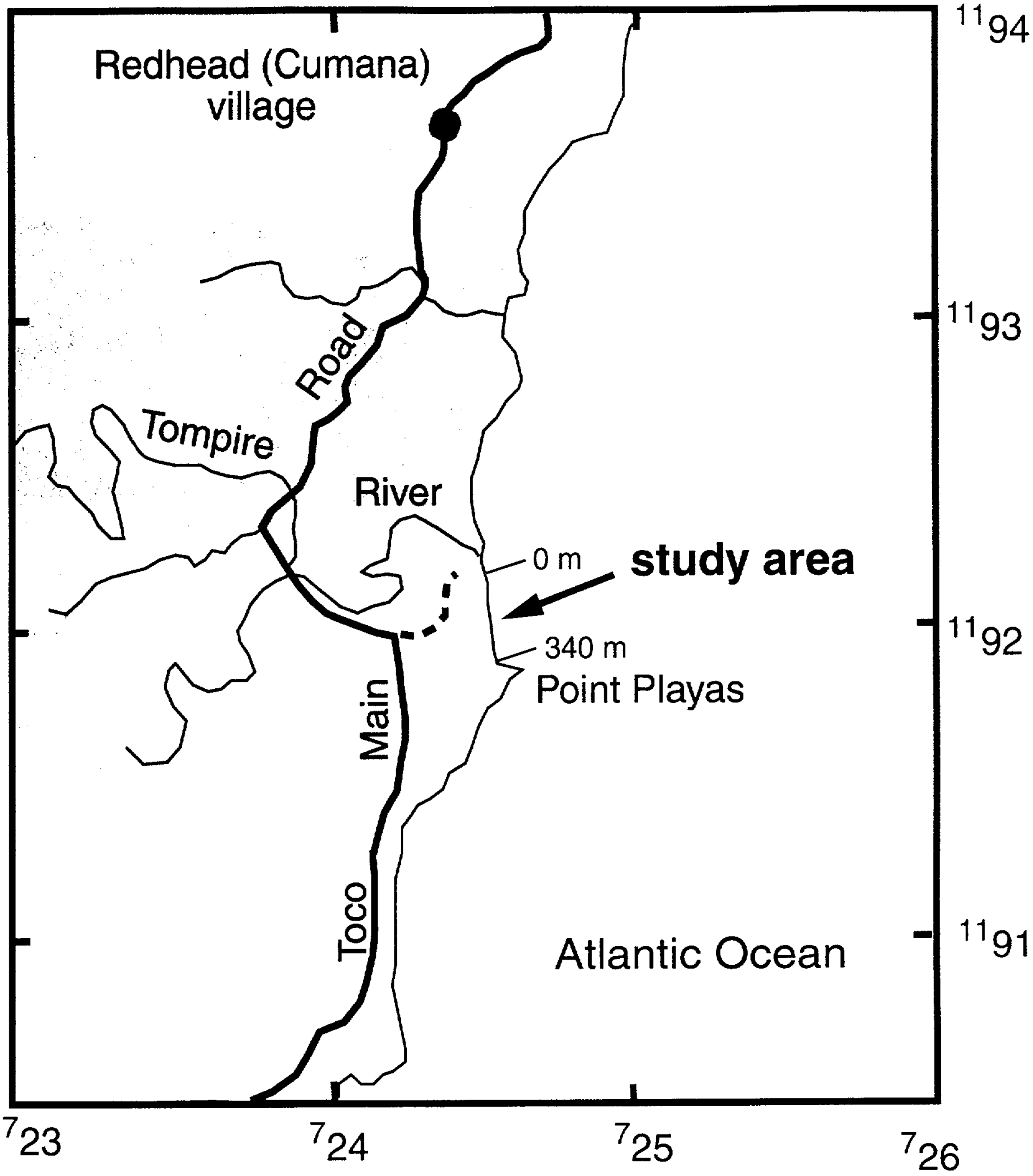
Fig. 6. Lower-hemisphere, equal-area stereoplot of Tompire Bay structural data collected from 0-340 m. Explanation: poles to S_0 bedding (open circles), poles to S_1 and F_1 axial surfaces (filled circles), poles to S_2 and F_2 axial surfaces (filled squares), poles to fault planes (open squares), F_1 hingelines (open triangles), F_2 hingelines (filled triangles). See text for further explanation and discussion.

Table 1. Summary of deformation phases and structures in the Tompire Bay outcrops, eastern Northern Range. The D_i, S_i, F_i, and L_i nomenclature refers respectively to deformation phases, planar fabric elements (e.g., foliation, cleavage), folds, and lineations; i = successive phases and generations.

	S_0	-cross-bedding and graded-bedding well preserved in part -sedimentary layering generally easily recognizable in metasandstone; highly strained, modified, and transposed in metamudstone
D_1	F_1	-generally symmetric, upright, minor and major folds -NW-SE striking subvertical axial surfaces -subhorizontal hinges
	S_1	-spaced to slaty cleavage -dominant layering in metamudstone -generally axial planar to F_1
	f_1	- dextral-contractile faults -normal faults that accommodated F_1 hinge-parallel stretch
D_2	F_2	- symmetric and asymmetric minor folds of S_1 -forced folds in fault-bounded panels -detached from adjacent homoclinal panels of S_1
	S_2	-axial planar to F_2 mesofolds -NE-SW strikes; full spectrum of dip angles and directions
	f_2	-detachment faults (see F_2 above)



Weber and Ferrill, Fig. 1



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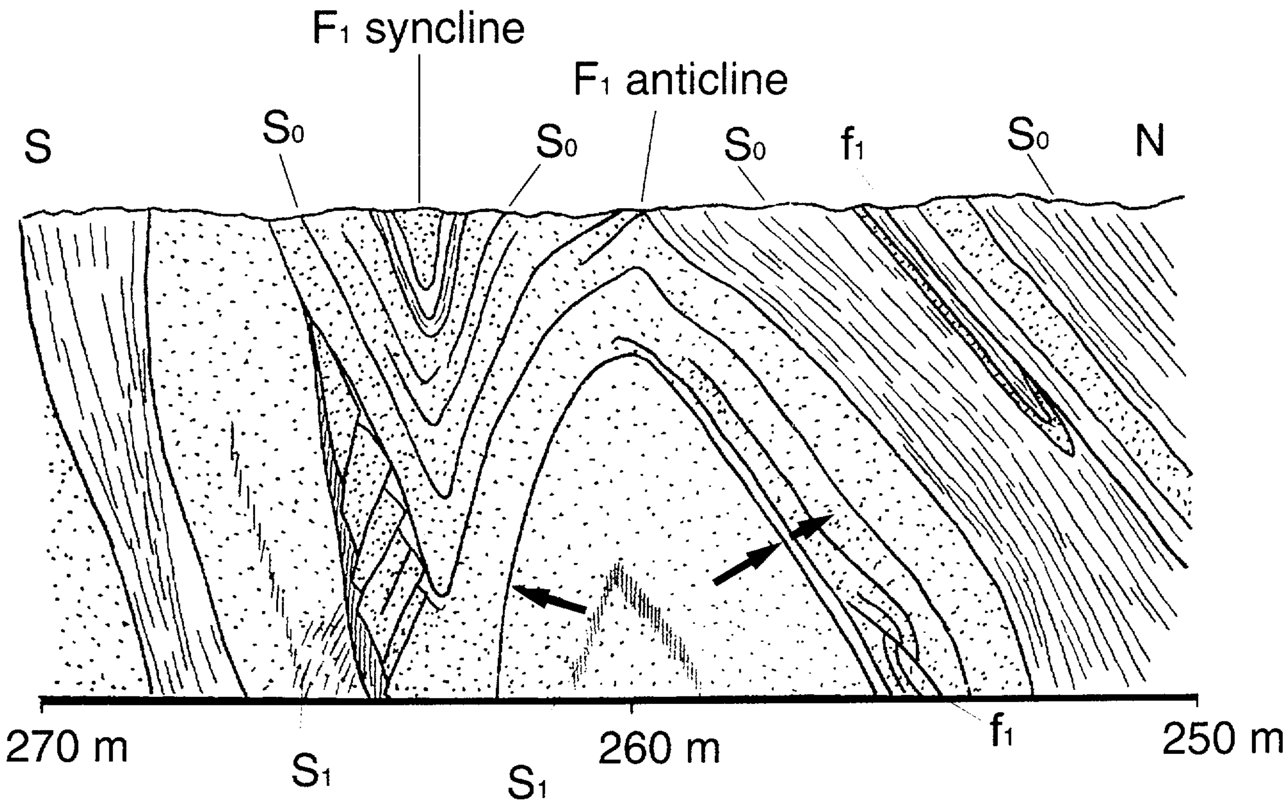

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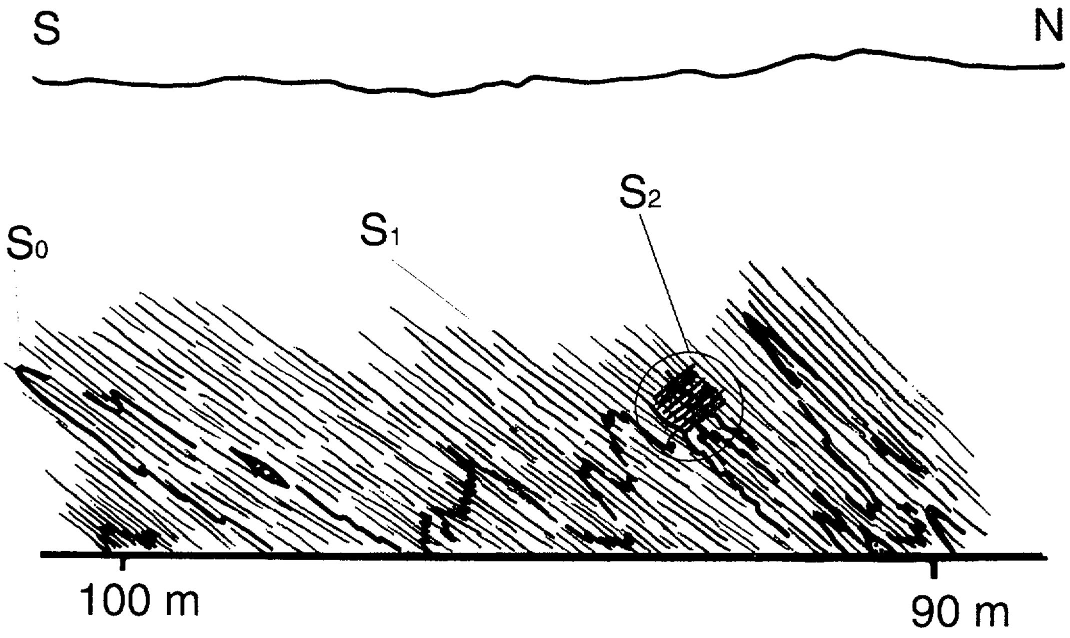

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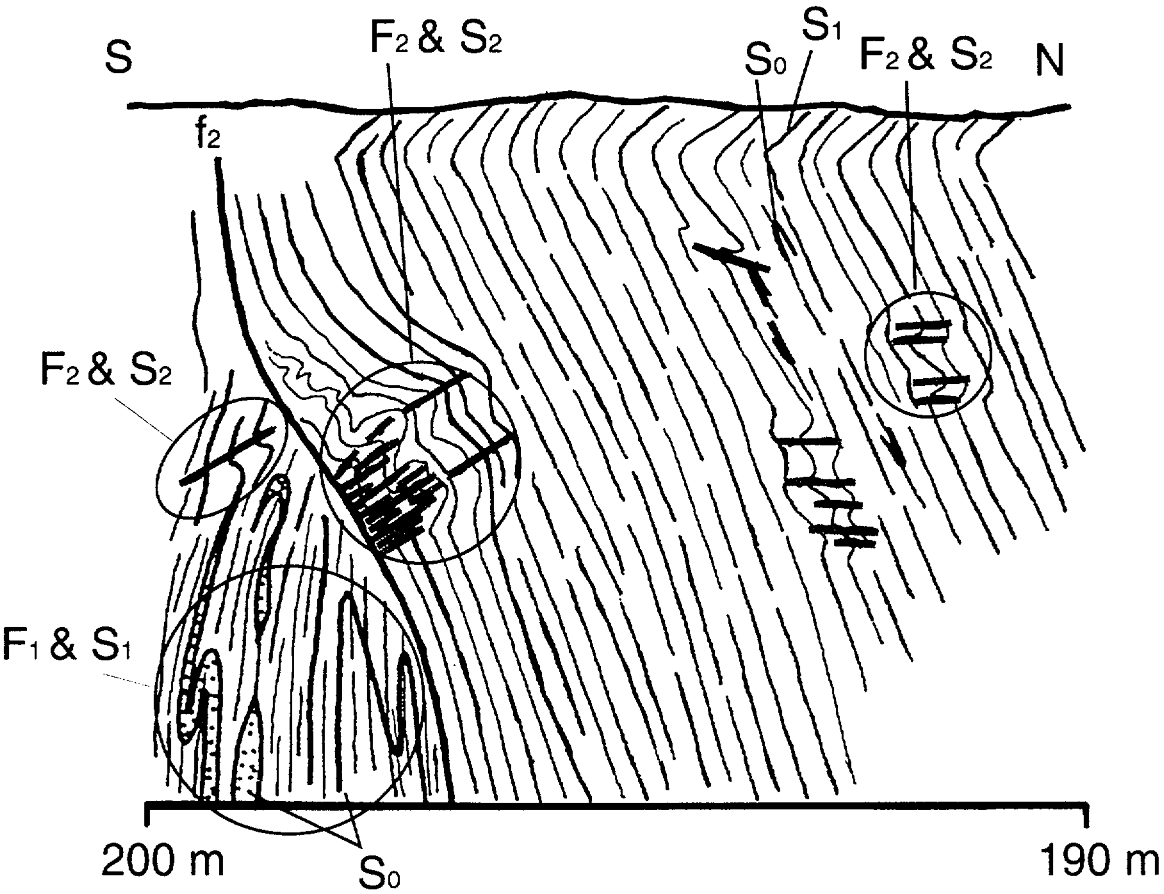
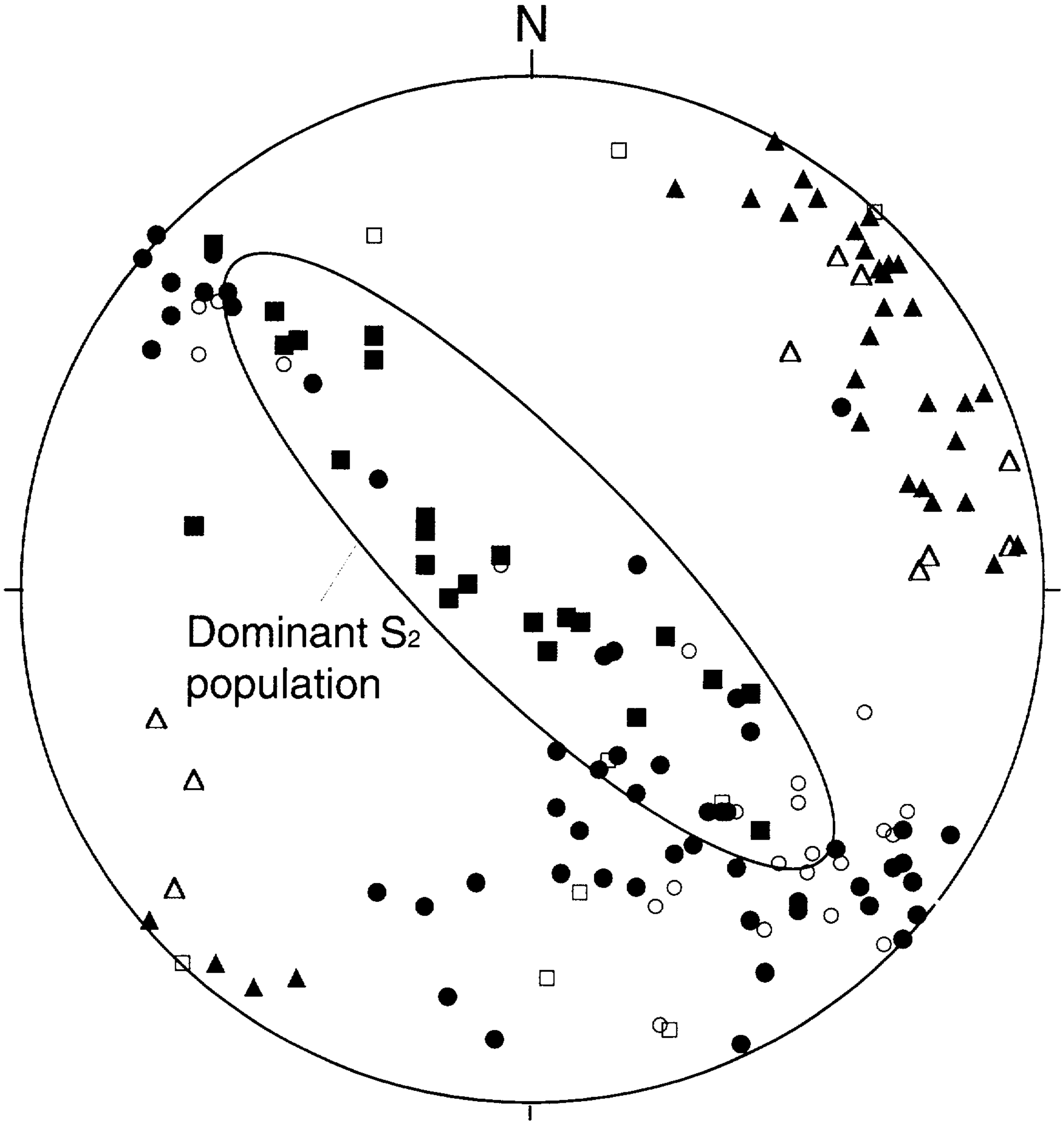


Weber and Ferrill, Fig. 5



Weber and Ferrill, Fig. 6