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Diagenetic density inversions and the deformation of shallow marine chert beds in Israel

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ABSTRACT

Chert folds and 'dyke'-like boudinage in the Senonian Mishash Formation of Israel have orientations consistent with contemporaneous tectonic patterns whereas their amplitudes are anomalously high relative to strains calculated for adjacent layers. We suggest several means by which density inversions associated with chert diagenesis might amplify gentle structures whose wavelengths and orientations were determined by regional stresses.

INTRODUCTION

Chert layers in shallow marine sedimentary sequences are commonly deformed into folds and boudinage with much larger amplitudes than structures in the overlying and underlying layers. Such structures have been described from shallow marine chert beds throughout the world, including the United States (Goodwin, 1956; Rigby, 1958; Hoge, 1976), Australia (Bryan & Jones, 1962), Poland (Kutek, 1962), Oman (Hudson, McGugan & Morgan, 1954), Iran (Gray, 1949), Jordan (Reuf, 1967) and Israel (Lees, 1928; Steinitz, 1970, 1974). In the Mishash Formation of Israel, the amplification of the chert structures is roughly proportional to the total amount of chert at a given locality (Steinitz, 1981), suggesting that the deformation was at least partially controlled by properties or processes inherent in the deposition of chert. Axial trends of the same folds and boudinage of the Mishash Formation show a regional coherence over distances of hundreds of kilometres. Furthermore, these trends are consistent with the regional tectonic stresses acting at the time of chert deposition. It thus appears that in the Mishash Formation, deformation of chert layers was influenced by both sedimentary, diagenetic processes and tectonic forces. In this paper we investigate the possible interaction between chert diagenesis and regional tectonic events.

OBSERVATIONS

The Mishash Formation of Senonian Age is part of the widespread Upper Cretaceous chert-bearing formations in North Africa and the Middle East. The petrology (Kolodny, 1967, 1969; Kolodny, Tarablus & Frieslander, 1980), stratigraphy and structure (Steinitz, 1974; Reuf, 1967) of its chert beds are well documented. In addition to chert, the Mishash Formation contains chalk, porcellanite, phosphorite, siliceous limestone and minor amounts of evaporites (Kolodny, 1969; Steinitz, 1977).

Chert occurs either as massive layers up to 2 m thick or as multilayers composed of thin layers interbedded with chalk and porcellanite. The massive chert layers are embedded in thick chalk and siliceous chalk sequences and show a relative uniformity of thickness. Local syndepositional unconformities, rapid variations of thicknesses and facies, and the occurrence of sand, bioclastic limestone, phosphorites and dolomites, all indicate that the Mishash Formation was deposited in shallow water, the salinity of which varied from hypersaline to brackish (Steinitz, 1974; Kolodny, 1967; Kolodny *et al.*, 1980). The chert layers of the Mishash Formation display a variety of small-scale structures such as breccia, micro-veins

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and nodules (both linear and irregular). These features were described and classified in detail by Steinitz (1981) and Steinitz & Kolodny (1978). Here we choose to investigate only the relatively simple folds and boudinage, which are the most conspicuous structures found in the chert layers in the field.

Folds and boudinage in the Mishash cherts

Folds occur in the Mishash Formation in both single layers of chert and in multilayers consisting of chert, porcellanite and chalk. In both cases, the fold amplitude decreases upward and downward, vanishing at distances up to one wavelength from the chert (Fig. 1). Steinitz (1981) noted that the amplitude of the folds increases with cumulative thickness of the chert beds within the sequence. He also noted that within the multilayers individual chert layers may be thicker in synclines than in adjacent anticlines. Both multilayer and single layer folds have a wide distribution throughout most of Israel and Jordan (Steinitz, 1981; Reuf, 1967) (Fig. 2). Boudinage or pinch and swell structures have a more restricted distribution, occurring primarily in the southern part of Israel, near Eilat (Fig. 2).

We selected single layer folds and boudinage for detailed study because their geometric simplicity requires the fewest assumptions in modelling. The folds which we have mapped are located about 15 km north-west of Jericho in the Jordan Valley (Fig. 2, location A). Plane table maps and cross-sections were constructed to determine the geometry of the structures. Figure 3 shows a downplunge profile of a folded chert layer. The folds have a wavelength ranging from 8 to 13 m; the wavelength to thickness ratio is 6–10. Maximum fold amplitudes are 3 m with limb dips up to vertical, and there is a slight clockwise asymmetry. Most folds have an irregular form with appreciable thickening in the hinges. Folding is prominent in the chert layers with only gentle contortion of bedding in the adjoining chalks and limestones.

We also mapped chert dykes exposed in an isolated

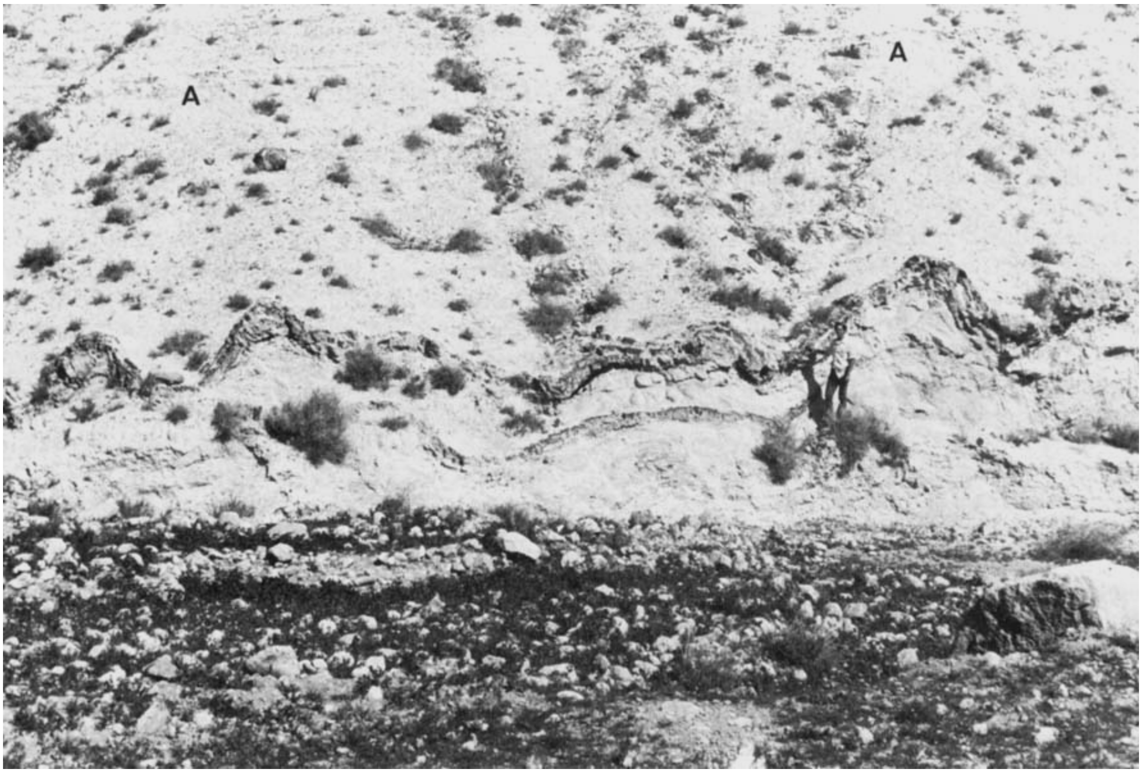


Fig. 1. A folded chert layer embedded in chalk, limestone and porcellanite layers. Senonian age Mishash Formation, north-east of Jerusalem, Israel. Note thickening of hinge zones and lack of visible deformation of the limestone layer, A–A.

chert layer near Nahal Etek, about 20 km north of Eilat (Fig. 2, location B). Here the upper halves of the boudins intruded and fractured the overlying limestone concretions (Steinitz, 1970), giving rise to the term 'chert dykes'. The dykes have a regular spacing of about 3 m (Figs 4 and 5) within a layer about 50–75 cm thick; thus the ratio of dyke spacing to layer thickness is about 4–6. The overlying limestone layers are deflected and intruded by the chert dykes but this effect rapidly dies out vertically in the section.

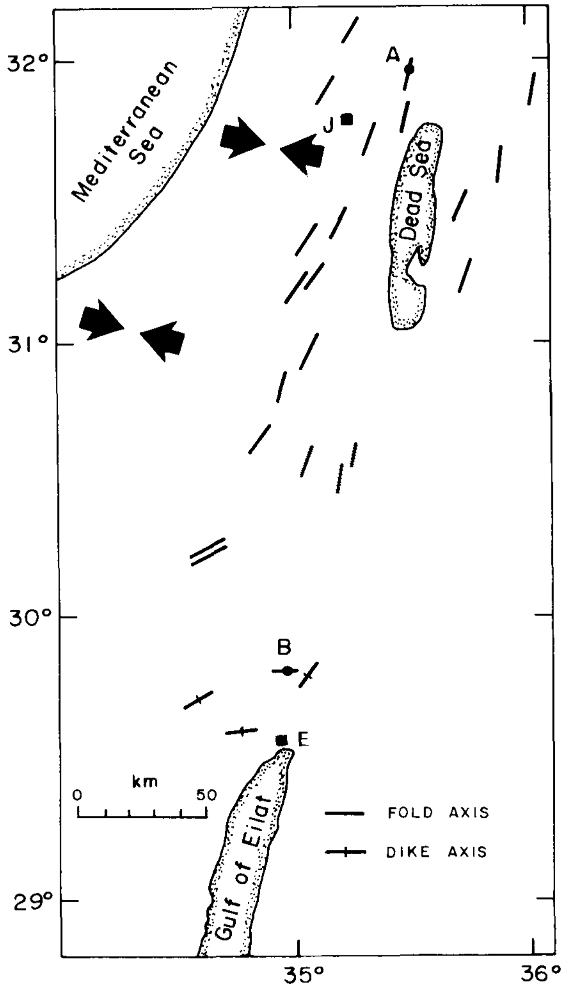


Fig. 2. Orientation of chert folds and dykes in Israel and Jordan (modified after Steinitz & Kolodny, 1978). Each axis represents tens to hundreds of measurements. A—area of detailed mapping of folds (Fig. 3). B—area of detailed mapping of dykes (Fig. 5). J—Jerusalem. E—Eilat. Arrows indicate directions of maximum horizontal compressive stress for the upper Cretaceous based on tens of measurements (from Eyal & Reches, 1982).

At least three types of observations indicate that the folds and dykes developed when the chert layers were still ductile. First, abrupt thickness variations occur without any faulting of the chert layers. For example, in fold number 1 of Fig. 3, the thickness of the left limb is about 0.80 m whereas the thickness of the hinge zone exceeds 2.0 m; the upper and lower contacts as well as the internal lamination are continuous without any apparent faulting. Second, the chert can be tightly folded without any fracturing. Cherts and other siliceous rocks are usually highly brittle materials that fracture under small amounts of strain (e.g. Johnson, 1977). Thus, siliceous rocks which are deformed after lithification show intense fracturing (e.g. Johnson, 1977, chapter 9). In contrast, the tightly folded layers of the Mishash Formation, which correspond to shortening of some tens of per cent, are conspicuously continuous. Similarly, the chert dykes (Fig. 4) intrude overlying and underlying sediments, and even break and displace cemented calcite concretions (Steinitz, 1970), yet their surfaces rarely exhibit fractures. A third factor is the nature of brecciation within chert layers. The folded layers are commonly composed of breccia-like chert fragments embedded in a cherty matrix (e.g. Kolodny, 1967). Flow structures and preferred orientation of the *c*-axes of quartz crystals in the matrix (Kolodny, Nathan & Sass, 1965; Wenk & Kolodny, 1968) indicate that the matrix flowed around the fragments while they were partly lithified. Steinitz (1981) presents a few tight folds of breccoidal chert layers in which the disconnected fragments are aligned and tilted on both limbs, whereas the matrix appears to have undergone continuous folding due solely to flow.

Orientations of folds and boudinage within the Mishash Formation

The orientations of thousands of chert folds throughout the Judean and Negev deserts were measured by Steinitz (1981). The fold axes have consistent orientations over large regions with a prominent trend of NNE-SSW (Fig. 2). The folds which we mapped lie along the NNE-SSW-trending East Ramallah monocline. The 28 measured fold axes have a mean orientation of N08°E, which is similar to the trend of the monocline and to the fold orientations measured by Steinitz in this area. In a related study, Eyal & Reches (1982) measured several types of small-scale structures including tectonic stylolites, small faults, slickensides and calcite twins at tens of outcrops throughout Israel. They used these structures to determine the palaeostress directions for several stratigraphic intervals. Eyal & Reches found that subhorizontal compression trending E–W to WNW–ESE prevailed throughout Israel from the Turonian (Upper Cretaceous) to the Eocene, including the period of deposition of the Mishash Formation (Fig. 2). The trend of the maximum compression axis determined by Eyal & Reches is generally perpendicular to the trends of the chert folds mapped by Steinitz (1981) as well as those mapped by us.

Chert dykes have a more restricted distribution than the folds (Steinitz, 1970). In our map of the dykes (Fig. 5), 30 measured ridge axes had a mean azimuth of N85°W. This is nearly perpendicular to the extension direction of N03°E determined by Eyal & Reches from small faults and slickensides in the siliceous limestone layers immediately overlying the chert layer. Furthermore, Eyal & Reches (1982) found that in the Eilat region, unlike the northern part of Israel, the subhorizontal compression of E–W to WNW–ESE did not prevail, and a N–S to NNE–SSW subhorizontal extension was the dominant tectonic stress.

These spatial relationships between the syndepositional tectonic palaeostress and the orientations of structures in the Mishash Formation suggest a strong tectonic influence on the deformation. This Formation originally consisted of a sequence of unlithified siliceous sediments, chalk and micritic limestone. When such a sequence of thin, soft layers of different competencies is subjected to layer-parallel compression or extension it is most likely to deform into folds or boudinage (Johnson, 1977, chapter 1). The observation that chert layers were the dominant units in both folding (Fig. 1) and boudinage (Fig. 4), indicates that at the time of deformation they were more competent than their neighbours. Therefore, the layer-parallel tectonic compression during the Sen-

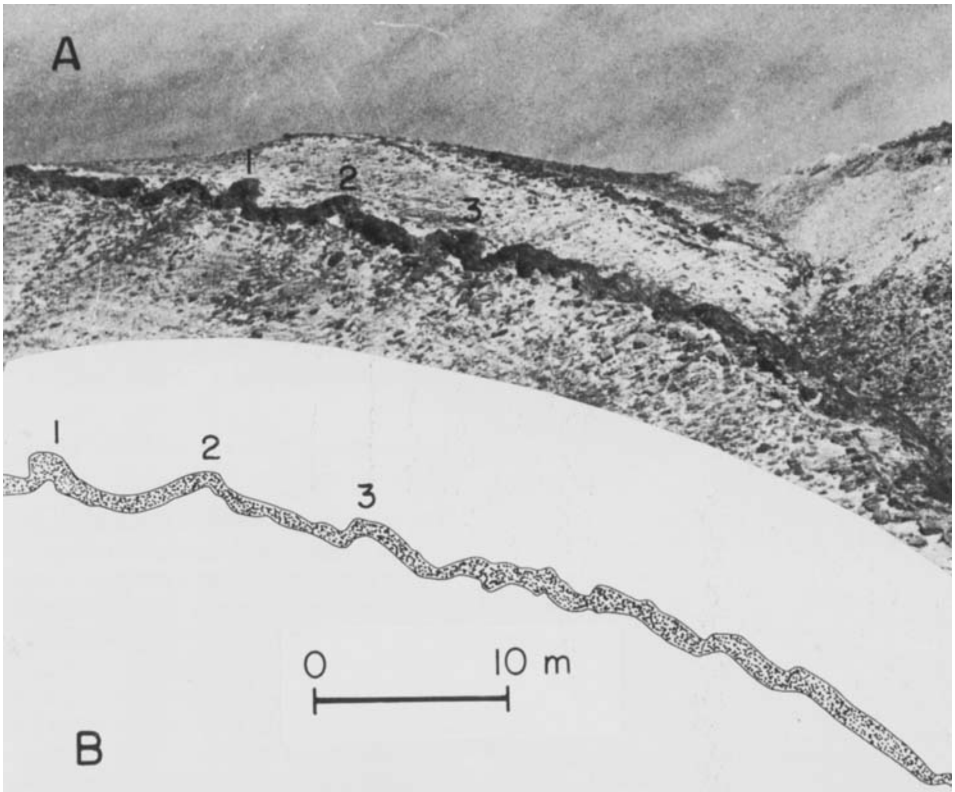


Fig. 3. A fold train of a chert layer embedded in chalk and limestone (location A in Fig. 2). (A) Photograph of the area; chert layers are dark. (B) Accurate profile based on plane table mapping. Mean fold axis plunges 6° to N12°E. The folds developed within layers dipping 30° eastward on the limb of a large anticline. The numbers 1, 2, and 3 correspond to three anticlinal folds.

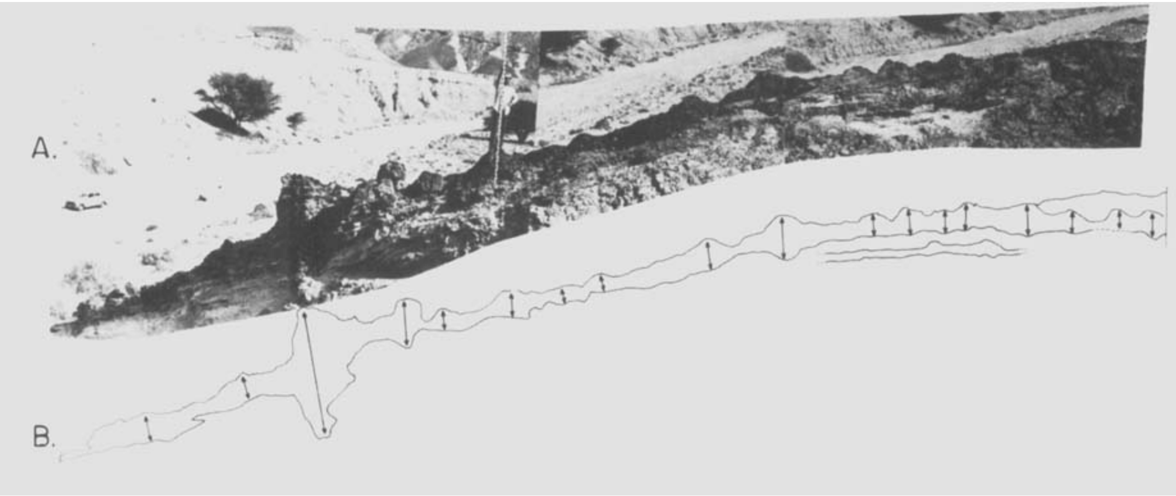


Fig. 4. (A) Cross-section view of dykes in the chert layer mapped in Fig. 5. (B) Tracing of photograph of dykes in (A). Largest dyke apparently formed through the coalescence of several smaller dykes (see Steinitz, 1970).

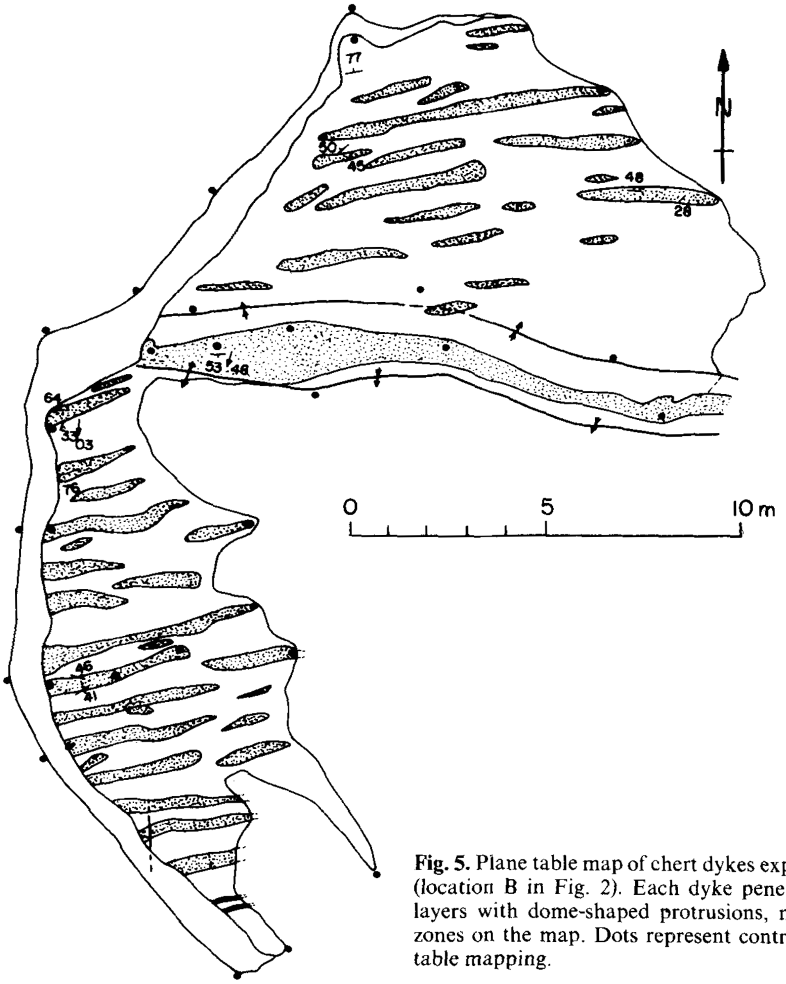


Fig. 5. Plane table map of chert dykes exposed north of Eilat (location B in Fig. 2). Each dyke penetrates the adjacent layers with dome-shaped protrusions, marked as stippled zones on the map. Dots represent control points for plane table mapping.

onian could form regularly spaced folds throughout the major part of Israel. If the same sequence of soft layers were subjected to layer-parallel tectonic extension, the result could be regularly spaced boudinage (Ramberg, 1955) leading to the development of chert dykes like those in the Eilat area. Although our observations suggest a tectonic imprint on the fold and dyke orientations, they do not account for the large amplitudes of these structures within the chert layers. In the next section we will consider several different explanations for this amplification.

DISCUSSION

Intraformational structures in chert layers from shallow marine sequences throughout the world have been explained by a variety of mechanisms. These include deformation due to diagenetic volume changes (Lees, 1928; Steinitz, 1981), diapiric rise of cherty sediments into more dense overlying sediments (Bryan & Jones, 1962), gravity sliding following submarine uplift (Hudson *et al.*, 1954; Rigby, 1958; Kutek, 1962), giant wave action on freshly deposited sediments (Lees, 1928), upwelling of groundwater (Goodwin, 1956), movement of thrust sheets (Gray, 1949), earthquakes near strike-slip faults (Reuf, 1967; Hoge, 1976) and tectonic compression or extension (Bryan & Jones, 1962).

The large amplitudes of structures within the Mishash Formation have been explained by three main models: downhill slumping of relatively soft chert layers (e.g. Fairbridge, 1942), folding due to horizontal tectonic compression (e.g. Kolodny *et al.*, 1965), and preferential shortening of the chert layers through volume increase associated with an influx of silica (Fig. 6) (Steinitz, 1981). In the following discussion we will consider evidence for and against these models and propose a fourth which accounts for the growth of folds and dykes through a combination of diagenetic and tectonic processes.

Any mechanism which explains the folds and boudinage in the Mishash Formation must be consistent with the following observations (after Kolodny, 1967; Steinitz, 1981; Steinitz & Kolodny, 1978):

(a) Chert layers are folded intensively with respect to adjacent layers. The folds attenuate quickly both upward and downward.
(b) Intense thickness variations and flow features indicate that the chert layers were soft during deformation.
(c) The trends of chert folds and dykes are coherent over large regions.
(d) Faults, overturned layers, detachment surfaces, consistent asymmetry and thrusting are rare, if not absent, in the chert folds and dykes.

Intraformational folding is frequently explained as a downslope slumping of a sedimentary pile which occurs preferentially within the softest layers (Fig. 6A). The Mishash chert folds are incompatible with several aspects of this model. Consistent asymmetry of the folds is rare. Fold axes are oblique or even parallel to the syndepositional palaeoslope in several

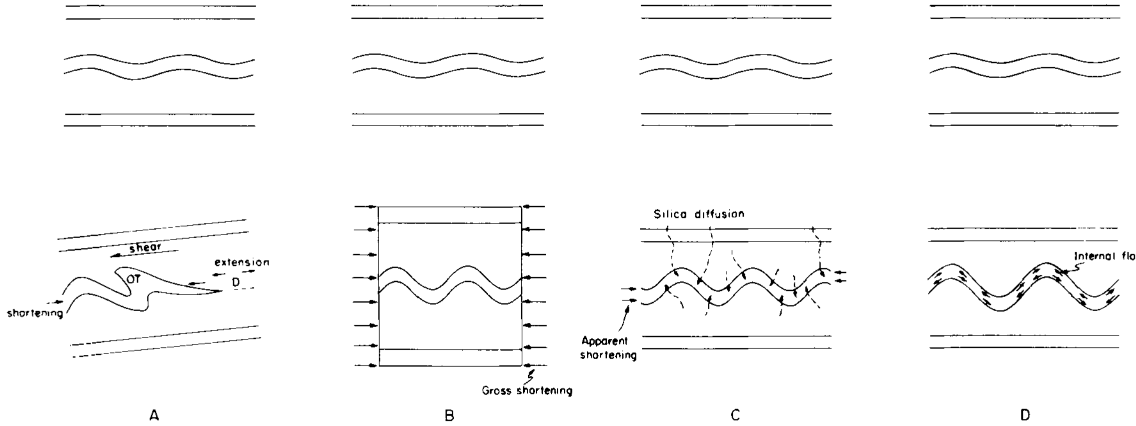


Fig. 6. Four models of the folding of Mishash Formation chert layers. (A) Downhill slumping model. OT—zone of overturned layers; D—detachment zone. (B) Tectonic model. Note the uniform overall shortening. (C) Steinitz' (1981) model of volume growth due to inward flux of silica. (D) Folding due to vertical flow (present model).

locations (Steinitz & Kolodny, 1978, fig. 13). Overturned layers, detachment zones (OT and D in Fig. 6A) and thrust faults were observed in only a few folds out of the thousands examined (Steinitz, 1981). Furthermore, slumping cannot explain the development of the regularly spaced dykes within the chert layers.

The second proposed mechanism, folding due to tectonic shortening, is initially appealing since the chert fold axes consistently trend perpendicular to the compressive stress direction for the Senonian. This model implies that the dolomite and limestone layers below the chert underwent the same shortening as the folded chert layers (Fig. 6B). These chert folds require a considerable amount of shortening. For example, the gentle folds in Fig. 3 represent approximately 9% shortening; Steinitz (1981) calculated that chert folds in some basins in the Judean Hills and Negev required more than 20% shortening. The unfolded layers above and below the chert lack conspicuous evidence of intense deformation, although they could have been shortened by small faults, pressure solution, plastic flow (e.g. calcite twinning), or recrystallization. All of these deformation mechanisms have been studied in Israel. The measured shortening due to shear along small faults in the Negev is about 1·5% (Reches, 1976). The shortening associated with the other mechanisms was estimated at 2–3% (Eyal & Reches, 1982). Since no field evidence indicates that the rocks underlying the Mishash Formation underwent more than a few per cent of internal shortening, we must reject tectonism as the sole source of chert folding.

The third model (Steinitz, 1981; Steinitz & Kolodny, 1978) proposes that folds are amplified through selective shortening of the chert layers (Fig. 6C). According to this model, the volumes of the chert layers increase due to an influx of silica, while the trends of the growing folds are influenced by the prevailing tectonic stresses. This is the only model of the above three that addresses the origin of the chert dykes. Presumably the same volume expansion that produces folds could cause dykes to form under the proper tectonic conditions. There are several problems in applying this model to the Mishash structures. First, it is not clear how tectonic stresses can control the direction in which a chert layer expands. More importantly, there is no known mineralogic process which may cause a volume increase during chert diagenesis. Furthermore, it is very unlikely that mobile silica could be driven into the already silica-laden chert layers from either the overlying water or from other sediments across a sequence of sediment layers without obliterating the fine-scale layering still observed today.

Considering the inherent problems of the above three models, we propose a fourth: that regional tectonic stresses produce gentle folds and boudinage structures which are simultaneously or subsequently amplified by vertical flow within the soft layers to form large amplitude folds and dykes (Fig. 6D). This vertical flow is caused by density differences associated with the diagenesis of siliceous sediments. The density contrasts cause internal flow, diapirism and slumping of the chert layer which amplify the gentle initial structures without additional regional shortening or extension. Thus the orientations of both folds and dykes would be controlled by regional tectonic stresses whereas their amplitudes would reflect the density variations of the layers during diagenesis. Let us briefly consider some mechanical properties of likely chert precursors before looking more carefully at the model.

Mechanical properties of the Mishash sediments

What was the rheology of the soft Mishash sediments when the folds and boudinage formed? Available measurements of the mechanical properties of recent marine sediments provide only partial answers. Most of these measurements are made for geotechnical purposes and thus include bulk density, porosity, shear strength and acoustic velocity (e.g. Hamilton, 1971). Despite the evidence for viscous behaviour in shear strength tests (e.g. Moore, 1964), we have no data concerning the viscosity of undisturbed sediments. Viscous behaviour would be especially significant during slow deformations such as those associated with tectonic events or density inversions.

Due to the lack of direct evidence, we make the assumption that the soft siliceous and calcareous sediments of the Mishash Formation behaved as a sequence of viscous or visco-plastic layers with contrasting viscosities. We cannot specify if the layers had linear (Newtonian) or non-linear rheologic behaviour (cf. Allen, 1977). Chert is the dominantly folded layer in the Mishash Formation, as described earlier, which indicates that the chert precursor was relatively more viscous than its neighbours (e.g. Johnson, 1977). However, one must distinguish between the viscosity and the shear strength of the chert precursor. These sediments might have a relatively high viscosity and low shear strength, similar to high temperature igneous melts in which the settling of small heavy crystals indicates negligible shear strength, despite their high viscosities. We will now discuss some measured properties of the chert precursors.

There are no present-day equivalents of the shallow marine cherts of the Mishash Formation (Kastner, 1982). As long as no siliceous fossils had been found in the Mishash Formation cherts, it had been hypothesized that, unlike deep sea cherts, these had been formed by non-biogenic replacement of calcareous sediments (e.g. Steinitz, 1981). However, the recent discovery of opaline siliceous fossils in the Mishash Formation (Soudry, Moshkovitz & Ehrlich, 1981) suggests that the chert layers were deposited as biogenic siliceous oozes, similar to deep sea cherts.

In the case of deep sea cherts, the original amorphous biogenic opal is transformed in several steps into a more structured form called opal-CT which may further transform to microquartz or chert (Jones & Segnit, 1971; Kastner, Keene & Gieskes, 1977). The rates of these transformations depend primarily on the temperature and chemistry of the sediments (Kastner, Keene & Gieskes, 1977). In deep sea sediments observed in cores of the Deep Sea Drilling Project (DSDP), one can distinguish between opal-CT-rich porcellanites and quartz-rich cherts, which are hard, vitreous rocks, and siliceous oozes, which have a 'soupy' consistency (M. Kastner, 1979 and P. Knauth, 1980, personal communications). Davie, Fenske & Serocki (1978) summarized the geotechnical properties of marine sediments as measured in DSDP cores. They presented the bulk density and water content of 65 samples of calcareous, clayey and siliceous oozes collected from the seafloor to depths of 200 m (Davie *et al.*, 1978, Table 1 and Fig. 4). Typically, the siliceous sediments have more than twice the water content and correspondingly lower bulk density than calcareous and clayey sediments. For calcareous, clayey and siliceous oozes, respectively, the average ratios of water content to solids are 0·75, 0·85 and 1·64, and the average bulk densities at the seafloor are 1·60, 1·54 and 1·35 g cm^{-3}. Typically, siliceous sediments have lower shear strengths than other sediments and diatom ooze has negligible shear strength close to the seafloor (Davie *et al.*, 1978, fig. 5).

We thus infer that the siliceous sediments from which the Mishash chert developed behaved essentially as strengthless viscous fluids similar to these siliceous oozes. Furthermore, at the time of deformation the Mishash cherts were significantly less dense, yet more viscous than the enclosing sediments.

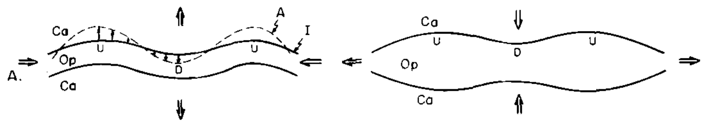
Density inversions and chert diagenesis

Gravity instabilities resulting from density inversions are a principal source of vertical flow within any sedimentary sequence (Anketell, Cegla & Dzulynski, 1970; Allen, 1977). The relatively low density of siliceous oozes can cause a gravitationally unstable configuration to develop when these layers are buried by more dense clayey or calcareous oozes. Diapirs of siliceous ooze could then rise into the overlying layers and slumps of the heavier material could sink into the siliceous ooze.

Both field and experimental observations indicate that diapirs develop as ridges or domes which are separated by characteristic wavelengths (e.g. Ramberg, 1967). It is generally accepted that the gravity forces significantly amplify initial perturbations which possess these wavelengths. The wavelengths depend on the viscosity of the layers and their geometry.

In the case of the Mishash Formation, the initial perturbations are the upper halves of very gentle folds and boudinage which developed within the chert layers due to the regional tectonic stresses (Fig. 7A). These stresses, as determined by Eyal & Reches (1982), had a coherent regional pattern with maximum compression trending in an E–W to WNW–ESE direction (Fig. 2). The orientations of the initial folds and boudinage are consistent with these stresses.

At the upper interface of the gently folded opaline layer (Fig. 7A), the less dense opaline ooze is overlain by more dense calcareous sediment. Calculations of the buoyant stresses across this interface indicate that at higher zones (marked 'U' in Fig. 7A) the opaline layer exerts upward stresses, whereas at lower zones (marked 'D' in Fig. 7A) downward pushing stresses occur (e.g. Ramberg, 1967). These buoyant stresses are proportional to the density contrast and the amplitude of the initial folds. The upper and lower interfaces deform in response to these stresses with velocities which are also proportional to the amplitude. Hence the rate of vertical deformation will accelerate while the original wavelength and orientation are maintained. Such amplification, which requires some local, lateral flow (small arrows in Fig. 7B), would lead to thickening of the hinge zones, thinning of the limbs, and would be roughly proportional to the amount of siliceous sediment present. Later, when the deformed siliceous oozes had transformed into chert, they would preserve the deformed shape. Thus vertical movement within the layers could amplify tectonic structures by causing the crests



TECTONICALLY CONTROLLED WAVELENGTH SELECTION

GRAVITY DOMINATED AMPLIFICATION

Fig. 7. Schematic diagram showing flow within a transforming layer which is initially perturbed by gentle tectonic stresses. (A) Layer with initial boudinage due to layer-parallel extension (right) and layer with initial folds due to layer-parallel shortening (left). (B) Amplification of the initial perturbation by internal flow of lighter and more dense materials (arrows). Op—opaline ooze; Ca—calcareous ooze; I—initial surface; A—amplified surface; small vertical arrows indicate relative movements of interfaces.

of anticlines and boudins in the siliceous layers to extend upward causing an *apparent*, but unreal, shortening. However, the downward growth of synclines and the lower halves of chert dykes require an additional explanation.

Density differences may also develop during the transition of opal into quartz. The transformation of biogenic opal to opal-CT and quartz probably begins at many sites within the opaline ooze as a process of opal ooze solution and opal-CT and quartz precipitation (Kastner, 1982). The particles of opal-CT or quartz have much higher specific gravities than the opaline ooze and, since the sediment behaves as a viscous material, these particles may settle through the layer. The specific gravity of opal-CT is 2·00–2·16 and that of quartz is 2·65. In contrast, the bulk density of biogenic opal is only 1·00–1·50 g cm^{-3} (Demars & Nacci, 1978; Davie *et al.*, 1978). This difference may cause the solid particles to settle, forming a sublayer of denser material at the base of the opaline ooze.

Such a settling process operating in an opaline ooze could transform a gravitationally stable sedimentary sequence into one with two unstable density inversions (Fig. 8). The lighter upper sublayer (layer 2A) would then rise diapirically into the overlying layer (layer 1), while the denser lower sublayer (layer 2B) would sink into the underlying layer (layer 3). Superimposed on an episode of folding or dyke formation (boudinage), this vertical movement of material would induce some lateral flow and would amplify the final shape of the structures, as observed in the Mishash Formation chert beds (Fig. 8).

The settling of dense quartz crystals or opal-CT in a soft siliceous ooze and the development of two sublayers is analogous to the more familiar settling of dense crystals in a liquid magma and the development of layered igneous intrusions (e.g. Wager & Brown, 1968). Igneous crystal settling has been supported by field, theoretical, and experimental studies. Gravitational segregation in sedimentary layers has the same theoretical and experimental justification as its more familiar analogue; however there is at present no direct field evidence for the settling of quartz or opal-CT in their precursory amorphous oozes. The reason for this lack of field evidence is that quartz is the only stable mineral that precipitates from an opaline ooze under most conditions so that there is generally no detectable gradation in mineral composition preserved within a chert layer, unlike the conspicuous gradations seen in layered intrusions.

We measured the opal content in 12 chert layers of the Mishash Formation and found that they contain less than 1% opal, probably due to the complete transformation of opal to quartz. Our inability to detect variations of opal content within these layers may have proved fruitless due to the limited accuracy of our techniques. We suspect that fresh siliceous layers, which have not transformed completely to quartz, might preserve the gradation of opal to quartz; however, we are not aware of any published data

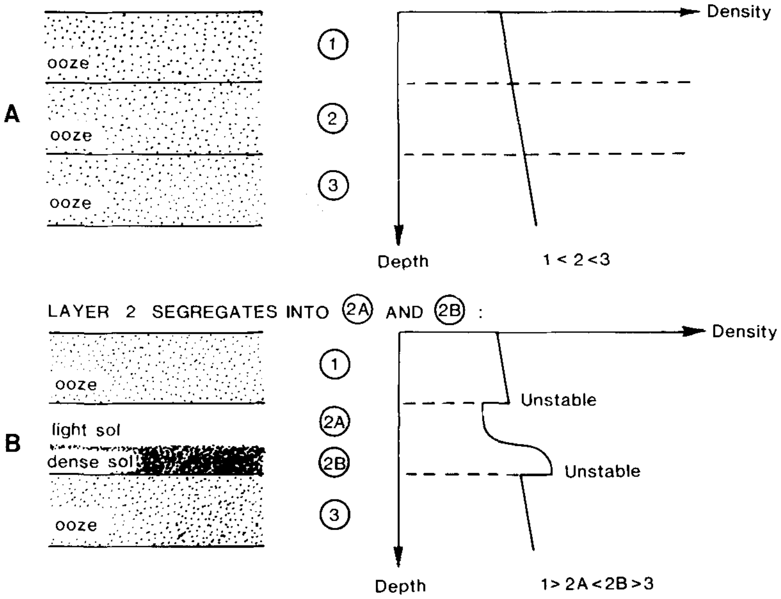


Fig. 8. Schematic representation of possible density variations in the vicinity of an opaline ooze locally transforming to more dense opal-CT. (A) Initial layering, with assumed density gradient (arbitrary units). Density increases slightly with depth due to compaction. (B) Density relations after segregation of central layer of ooze into light and dense phases. Upper sol (2A) is now less dense than the overlying ooze (1), and lower sol (2B) is more dense than underlying ooze (3); hence two density inversions result. Initial density differences between opaline and surrounding oozes are not taken into account here.

showing such mineralogical segregation within a single siliceous layer.

The model that we propose—amplification of folds and boudinage in chert layers due to gravity instabilities—is compatible with all field observations outlined above. In particular it explains well the thickening of hinge zones, thinning of limbs, lack of overturned layers, selective amplification of chert structures and the regionally consistent trends of chert folds and dykes. However, our incomplete knowledge of the rheology of siliceous sediments during diagenesis limits the accuracy of the present model.

SUMMARY

There are several ways that density inversions can develop during the evolution of chert from a siliceous ooze. If superimposed on a gentle regional deformation, such inversions could amplify structures within the chert layers, leaving the surrounding non-siliceous layers less deformed. Orientations and spacings of folds and boudinage would then be determined by the tectonic stresses, whereas the amplitudes of these structures would be controlled by diagenetic processes.

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DISCUSSION

Diagenetic density inversions and the deformation of shallow marine chert beds in Israel

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The diagenetic chert structures in the Senonian bedded cherts of Israel attracted the attention of many investigators. Of the chert structures the three most widespread are the heterogeneous structures (Steinitz, 1981a, cf. 'breccoidal' chert of Kolodny, 1965, 1969), the linear cherts (Steinitz, 1981a) and the chert folds (e.g. Blanckenhorn, 1914, Kolodny, 1967, Reuf, 1967 and Steinitz, 1981b). Studies in recent years have enabled certain conclusions to be drawn regarding their origin. Fink & Reches (1983) have presented a model for the formation of these structures, but their scientific method seems to be questionable. The authors present data on the structures, but many are derived from the literature, with some observations of their own. In citing data from previous publications they have been highly selective or misleading. Some of the more important cases are:

(a) They have preferred to disregard stratigraphic and petrographic evidence presented by Steinitz (1974, 1981a) that the 'dykes' represent rare end members of a large spectrum of widespread linear chert structures. The latter are generated through diagenetic replacement and cementation by microquartz, generally without any deformation.

(b) Fink & Reches 'choose to investigate only the relatively simple folds and boudinage', assuming that a common model can be suggested for their origin. It was shown (Steinitz, 1974, p. 104; 1981b, p. 32) that when linear structures (including 'dykes') and chert folds are developed in the same beds, the former are folded by the latter, i.e. two distinct diagenetic events are represented. Fink & Reches may dispute the basic notion that the 'dykes' represent a certain 'facies' of a larger widespread group of structures, and they may, on the other hand, claim that they are a variation of the folds, but to do so without clearly saying it, and without substantiating it with data or arguing previously presented data seems to be bad procedure.

(c) In fig. 2 of Fink & Reches, showing the orientation of chert folds and dykes, the reader perceives that one system of oriented chert structures is being considered; but this is wrong. Only part of the existing data for the area west of the Eilat–Dead Sea line (collected by Steinitz, 1970, 1981a, b) is presented. They state that the 'chert dykes have a more restricted distribution than the folds' simply by citing Steinitz (1970). This ignores later work (Steinitz, 1981a, fig. 18) which showed an intrusive linear structure, i.e. a 'dyke' half-way between Jerusalem and the Dead Sea. This is an area in which chert folds are also extensively developed. In fact, of the 'dykes' presented by Fink & Reches in the map, only a few are really intrusive features. Most of the features cited are replacement linear structures of the type they ignore. A correct generalization of the regional distribution of the linear chert structures (including 'dykes') and the fold structures is given in Fig. 1, where it can be seen that the linear structures are much more abundant than the chert folds and that there are two systems of diagenetic chert structures.

In a similar manner Fink & Reches cite loosely and incorrectly published interpretations. According to them, in Steinitz's (1981a, b) model 'the trends of the growing folds are influenced by the prevailing tectonic stresses' which 'can control the direction in which a chert layer expands'. On the contrary, Steinitz (1981b) concluded that the orientation of the fold axes does not conform to the synchronous tectonic pattern.

One of the basic arguments presented by Steinitz (1974, 1981a, b) was the relation of the linear and fold structures to the concurrent tectonic pattern. The analysis indicated: that (a) the chert structures have a diagenetic age; (b) the synchronous tectonic pattern can be well described by a set of palaeogeographic maps; and (c) the tectonic pattern started to develop before the chert structures formed and prevailed after

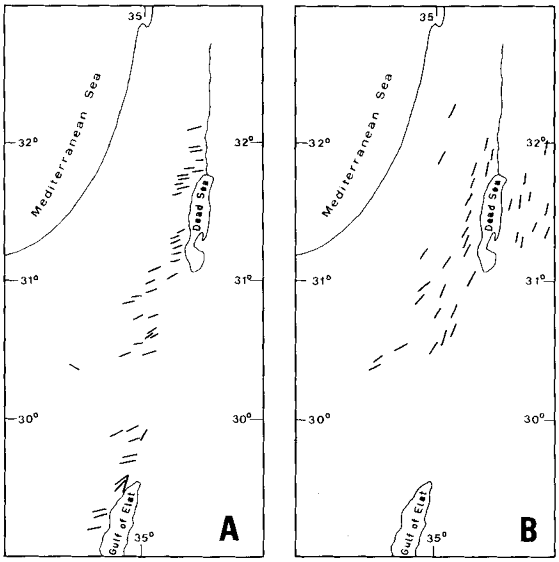

Fig. 1. A correct citation from Steinitz (1974) and Steinitz (1981a, b) of the generalized distribution of the linear chert structures—including among them the chert 'dykes' (A) and the distribution of the chert fold structures (B). From this representation it is evident that two systems of structures, both of diagenetic age, are being dealt with.

their lithification. As a result it could be shown, on a local scale as well as on a regional scale, that there is no simple causal relation between the oriented (linear, fold) chert structures and the synchronous palaeogeographic configuration, i.e. the coexisting tectonic regime. Fink & Reches disregard these data and in order to substantiate their model they cite Eyal & Reches (1983) and state that substantial compression prevailed throughout Israel in an E-W to WNW-ESE direction. It is not clear how this compression can be related to the oriented diagenetic chert structures:

(a) The compression was deduced from measurements on rocks of Turonian to Eocene age. Do they really know that it was active during that part of the Senonian relevant to our diagenetic problem?

(b) The trend of the maximum compression of Eyal & Reches (1982) is roughly perpendicular to the trend of the chert folds, but there are regions where it is not perpendicular, e.g. in the western Negev.

(c) This compression certainly cannot explain the linear chert structures, including the 'dykes', as they are almost parallel to each other.

As to Fink & Reches's gravity density inversion model itself:

(a) Their model assumes the opal—opal CT—microquartz transformations which should be accompanied by density transitions. To date, the most detailed petrographic studies on the Senonian cherts and associated porcellanites, including SEM, do not indicate that such a transformation took place and Fink & Reches do not present evidence for it.

(b) Steinitz (1974, 1981a, b) presented ample evidence showing that the development of the structures is directly connected with the precipitation of silica as microquartz within the sediment. In the case of the linear structures this is basically a replacement and cementation process, leading only in extreme cases to displacive growth and the formation of the chert 'dykes'. Fink & Reches present a density inversion model, without any petrographic justification and only for an extreme end member structure, disregarding the fact that their model does not explain the majority of the structures for which carbonate replacement by microquartz was shown to be the dominant process.

In addition to data from other contributions, Fink & Reches also present their own data on the discussed chert structures:

(a) Photographs of the discussed structures have been presented previously, some of precisely the same structure. New Structures, or new features (field evidence or petrography) have not been shown.

(b) They constructed detailed maps and cross-sections of a group of folds in the Judean Desert and of the best known chert 'dykes' described by Steinitz (1970). It is not clear what these contribute to the model and argumentation which they used.

The development of the terminology for the heterogeneous, linear and fold structures in the Senonian cherts of Israel, based on petrographic criteria, can be traced through the contributions of Kolodny (1965, 1967, 1969) and Steinitz (1967, 1970, 1974, 1981a, b). Fink & Reches rather prefer to use loose, new and undefined terms, while renaming previous structural terms, without justification. This approach results in unnecessary confusion, particularly for any reader who is not familiar with the complex structures:

(a) For one of the structures Fink & Reches use the term 'boudinage' without defining clearly what they mean by it. They chose to use this term, which has a specific connotation in the context of metamorphic structures as well as genetic implications (extension perpendicular to their length, e.g. Ramsay, 1967). It is unwise to use a well-established metamorphic-structural term for a diagenetic structure without having good grounds for taking such an attitude.

(b) Steinitz (1967, 1970) first described the chert 'dykes'. In further work (Steinitz 1974, 1981a), it was suggested that the term chert 'dyke' be amended to the term linear structure. Fink & Reches adhere to the old term. Could it be that they intentionally deal only with the 'abnormal' end-member type of structure in order to refrain from having to deal with the limitations which the general case, i.e. the linear chert structure, imposes on their model?

(c) Fink & Reches (1983) use their own terms in an inconsistent manner. Are the following terms attributed to the same structure or not: 'dyke like boudinage'; 'boudinage'; 'boudins'; 'boudinage or pinch and swell structures'; 'dykes'. These differences call for an explanation!

(d) Fink & Reches state: 'Chert layers display a variety of small scale structures such as breccia, microveins and nodules (both linear and irregular)'. They supposedly follow Steinitz (1974, 1981), but this makes complete havoc of the classification cited.

The scientific method used by Fink & Reches (1983) is highly questionable. They propose a model to solve a geological problem, specifically for a well-documented case. Data previously collected relevant to the problem are wrongly cited or partly ignored, or new data, which would support Fink & Reches' model, are not presented. It is therefore concluded that the density inversion model is incompatible with both the field and petrographic evidence.

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REPLY

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The criticisms raised by Steinitz (1985) in his discussion of our paper on chert deformation (Fink & Reches, 1983) seem to arise largely from fundamental differences in our ways of explaining geologic structures. Steinitz's view, as demonstrated in his chert studies (1981a, b, 1974), is that pure geometric description constitutes a sufficient means of explaining the development of chert structures. Through careful and detailed documentation of dozens of types of these features, he hints at processes described as emplacement, replacement, cementation, expulsion, and intrusion. However, he seems to have forgotten that scientific method requires not only the recognition of a problem and the collection of data but also the formulation of testable hypotheses.

In contrast to Steinitz, we think that explaining a geologic structure requires a model which is based on known processes and which can be tested by relevant field observations. In our study of chert folds and dykes, we invoke the well-accepted opal-quartz transition as a source of mechanical energy necessary to amplify gentle, tectonically induced structures that originate in accordance with the equally well-tested theory of folding. This model arises from a synthesis of field measurements and mathematical analysis of structures, and appears to be consistent with more of the documented observations of deformed chert layers than any other currently available model.

Steinitz's comments seem to fall into four general categories which we will address:

(1) disagreement with our decision to analyse only chert folds and chert dykes;
(2) objections to our model because it disregards Steinitz's claims to have proven his own model;
(3) questions about the validity of our correlation between palaeostress directions and the orientations of fold and dyke axes;
(4) arguments with our use of terminology.

In his initial comments, Steinitz says that our distinction between chert dykes with and without deformation is invalid. Steinitz (1981a) proposed that dykes were just a rare end member of a large spectrum of linear structures that all formed by silica replacement constrained to a linear geometry by some 'non-mechanical' factor. The large amplitudes of the intraformational folds were also attributed to this undocumented process of replacement.

In our study we focussed on structures with relatively simple geometry that had deformed the surrounding layers, because analysis of structures like these folds and dykes provides the best mechanical constraints for the general problems of chert emplacement and deformation. Based on our analysis we concluded that the dykes and intraformational folds formed by a different process from the linear structures. Even though both dykes and non-deforming linear structures have parallel, elongate geometry, they differ significantly in their ratios of spacing (or wavelength) to original layer thickness. This ratio is of the order of 2–4 for both the chert dykes and folds (Fink & Reches, 1983), whereas the ratio for almost all other linear structures is less than 1 (Steinitz, 1981a, figs 7, 12, 13, 17, 23 and 29). Rheologic arguments based on folding theory (Smith, 1977) indicate that the geometry of chert folds and dykes are consistent with known properties of siliceous sediments subjected to mechanical instabilities. In contrast, the low ratios for the non-deforming linear structures preclude an origin related to mechanical instability and require some other process.

Steinitz claims (1985, comment c) that we presented only part of his data set in constructing our map of fold and dyke locations (Fink & Reches, 1983, fig. 2). Our figure in fact shows those linear structures which have associated deformation (dykes), because these are the features that we analysed. Steinitz (1985, fig. 1) presents a new map but includes the axes of non-deformed linear structures along with the axes of dykes (Fig. 1A). If one omits the axes of the non-intrusive linear structures, which make up the majority of the data points in Fig. 1A, and plots only the axes of the dykes, the resulting map would be essentially the same as our fig. 2. The only difference would be a single exposure of dykes east of Jerusalem.

A second set of Steinitz's comments suggest that we have ignored the evidence that proves his model. We take exception with Steinitz's claims to have *proven* that all of the linear structures could only have formed by replacement. As an example, upon finding preserved laminae or fauna in a chert sample, Steinitz concludes that 'emplacement of microquartz chert is [here] due only to a replacement process' (Steinitz, 1981a, p. 16). Other plausible explanations are ignored, such as that the original sediment contained a mixture of opaline and carbonate sediment in which the opal was subsequently transformed into microquartz. Steinitz fails to tell us the exact process of replacement, the source for the silica, or the process by which the silica migrated through several tens of metres of sediment (Steinitz, 1985) without disturbing the layering. He totally ignores the process of chert deposition and again calls for an ad hoc 'hypothesis' of silica replacement that is controlled by an *unknown* 'non-mechanical factor' which determined the site and shape of the chert structure.

Steinitz repeatedly argues that his previous works have proven relationships that in fact have merely been alleged. For instance, he (Steinitz, 1985, comment b) asserts that linear structures, including dykes, preceded the folding. However, Steinitz (1974, 1981a, b) only *stated* this relationship; he did not present any data, such as a fold test on a stereoplot, cross-cutting structures, or twisted linear features, to prove his point. Furthermore, even if there were two events, development of linear structures followed by folding, both could have occurred in unlithified sediments, and thus do not unambiguously support his model.

Another context in which Steinitz invokes a replacement process is in his criticism of our proposed deformation mechanism. He points out that we did not show direct evidence for the opal-microquartz transition in the Senonian cherts of Israel and again mentions his evidence for a 'replacement and cementation process' leading to the development of the linear structures. The lack of direct petrographic evidence for the opal-microquartz transition in the Mishash cherts is likely due to the intense subsequent crystallization of microquartz, which obliterated earlier microstructures in the soft siliceous sediments. However, with only a few exceptions, biogenic siliceous oozes are the principal known source for massive shallow marine cherts of Mesozoic age or younger. We prefer to consider the effects of this reasonable and known mineralogical process, rather than a highly speculative massive replacement by silica-rich solutions at depths up to tens of metres.

Steinitz' third group of comments deals with the relationship between tectonics and chert structures. Steinitz (1981a, b) found no correlation between what he calls the 'tectonic pattern' or 'tectonic regime' and the orientation of chert structures. We, on the other hand, found very good correlation between the tectonic palaeostress and the trend of the chert folds and dykes. The main source for this disagreement between Steinitz' conclusions and ours may be due to the way we define the tectonic field. Steinitz (1985) claims that the 'tectonic pattern can be well described by a set of palaeogeographic maps'. The latter present thickness variations, facies changes, biofacies analysis, etc., which depend on topography, sea-water influx, water chemistry, biological conditions, and palaeostructure. These parameters are related to the structural development, but they are *not* indicators of the tectonic stress orientations.

It is commonly accepted (see references in Eyal & Reches, 1983) that tectonic palaeostress can be determined from the analysis of small-scale structures, such as small faults, stylolites, or veins, all of which were measured by Eyal & Reches. The good agreement between results of these palaeostress analyses and the trends of chert dykes and folds is striking, as also admitted by Steinitz (1985). However, he points out that in one region, the western Negev, this agreement is poor. Indeed, the generalized palaeocompression axes here trend about 60° from the orientations of the chert folds, while they are perpendicular to each other elsewhere. Such a local 30° deviation requires an explanation, but it in no way discredits the excellent correlation over hundreds of square kilometres on both sides of the Dead Sea rift.

Steinitz also raises the question of the age of the palaeostress field. The stress field is uniform in rocks of Turonian through Eocene age (Eyal & Reches, 1983). This field was not measured in Senonian rocks due to the lack of suitable structures. However, as the Syrian–Arc folding event initiated during the Senonian and as well-defined, gentle structures developed during the Senonian (e.g. Steinitz, 1974), we conclude that the palaeostress indicators in Turonian rocks formed primarily during the Senonian. Furthermore, the uniformity of the palaeostresses from the Turonian to the Eocene strongly suggests that the Senonian stress field did not differ significantly.

Finally, Steinitz questions the value of our data and the accuracy of our terminology. He claims that the purpose of the maps and cross-sections we present is not clear. Their purpose is to provide geometric data necessary to construct a mechanical folding model. The accurate shape of a fold train or set of boudinage which includes thickness variations, wavelength to thickness ratios, and the shape of hinge zones, are essential components of folding analysis. This type of information was not available in any earlier chert studies.

Steinitz also appears disturbed about our use of terminology, particularly in our descriptions of chert dykes. Steinitz prefers to use the term 'linear structures' instead of dykes. We have already explained why 'dyke' is a more appropriate term for structures that deformed the surrounding layers. The term 'boudinage' has a strictly geometric meaning, and even though such structures are common in metamorphic rocks, the term may also be applied to sedimentary structures. The terms 'dyke' and 'boudinage' were used in several forms in our paper; all refer to the same geometry: an elongated body of chert intruded into the overlying and underlying layers.

In summary, we feel that deformation of the chert layers of the Mishash Formation constitutes a resolvable puzzle, rather than the 'enigma' referred to by Steinitz (1981a, b). The structures seem to have been formed by a complex mechanism which combines known sedimentary and tectonic processes. We do not wish to suggest that replacement never occurred, nor that our model can explain all linear structures; rather our study pertains to those structures with relatively simple geometry that deformed adjacent layers. In contrast to Steinitz's replacement model with its 'non-mechanical factor', the model we propose appears to conform to all available field observations as well as to known mineralogical processes.

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