Pergamon

Journal of Structural Geology, Vol. 17, No. 7, pp. 997 to 1010, 1995

0191-8141/95 $9.50+0.00

0191-8141(95)00009-7

Dike intrusion into unconsolidated sandstone and the development of quartzite contact zones

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(*Received* 27 *September* 1993; *accepted in revised form* 23 *November* 1994)

Abstract—Shallow, near-surface magma emplacement into a porous, unlithified sandstone occurred by forceful dike dilation and was accompanied by a localized hydrothermal event. Petrographic fabric, authigenic mineralogy and petrophysical data, grade smoothly through the quartzite contact zone outward into the friable Inmar sandstone of Makhtesh Ramon, Israel. Quartz grain deformation, fracturing and rehealing of grains, and pressure solution constitute overwhelming evidence of a compressive environment adjacent to dike margins, albeit with temperatures and pressures insufficient to fully recrystallize detrital grains. Dikes were accommodated primarily by the repacking of the sandstone with both brittle and elastic grain interaction. Post emplacement heating together with elastic compressive stress dissipation, lead to fracture healing and pressure solution. The occasional columnar-jointing must be related to thermal contraction of the quartzite during later cooling and resulting mode I cracks. The alteration of both contact zone and dike material occurred via a transitory and confined hydrothermal seepage up dike margins. Elsewhere around the world highly altered intrusions bordered by indurated sometimes uniformly jointed sediments, may also be the result of forceful magma emplacement and hydrothermal alteration at near-surface levels.

INTRODUCTION

Igneous intrusion into unlithified materials may proceed by displacement, assimilation, and mass transfer of wall rock material. Because of this variety of processes, examples of shallow intrusion exhibit a wide spectrum of contact metamorphism; from melting and recrystallization to contact zones with low-grade mineralogy. Low-grade contact zones with columnar jointing are found around the world and appear to represent the results of shallow intrusive processes (Summer 1993). Comprehension of the processes by which dikes are emplaced at shallow levels, and their range of deformation and alteration phenomena in unlithified sediments are critical for understanding the process of magma ascent and arrest.

This paper aims to determine the processes active in forming the low-grade contact zones of the Jurassic Inmar Formation exposed in south-central Israel. Field, microstructural, petrological and petrophysical data are presented to support a model of dike emplacement, to document the response of poorly consolidated material to magmatic intrusion, and to illustrate the relationship between shallow magmatism and induced hydrothermal flow.

Geological background

Makhtesh Ramon in south-central Israel (Fig. 1) is an erosional feature exposing a subhorizontal sedimentary succession hosting basaltic and trachytic intrusions (Fig. 2). The sediments include Triassic carbonates and shales (Mohilla Formation), lower-Jurassic formations including a flint–clay (Mishor Formation), a thinly layered carbonate and shale sequence (Ardon Formation), a friable and porous sandstone (Inmar Formation), and an overlying mixed carbonate siliciclastic sequence (Mahmal Formation), as well as Cretaceous formations such as the Arod conglomerate and the Hatira sandstone.

The geological history of the area includes a lower Jurassic–early Cretaceous depositional hiatus during which about 350 m of section was removed (Fig. 3). The widespread magmatic activity in Makhtesh Ramon coincides with both this unconformity (Garfunkel & Derin 1988) and a thermal event that extended over 10–25 Ma. During the thermal event, the rocks experienced geothermal gradients of 45–55°C km^{-1}, and subsequently the rocks have cooled, despite reburial during lower Cretaceous times (Feinstein *et al.* 1989). Since the Neogene, extensive erosion resulted in the cirque-like morphology of Makhtesh Ramon, exposing three chronologically and chemically distinct dike systems (Lang *et al.* 1988). Some dikes did not cross the unconformity and formed sills, others crossed the unconformity and the Arod Conglomerate possibly associated with the vents and calderas in Makhtesh Ramon (Baer *et al.* 1989). Also, the Arod conglomerate fills altered dike furrows, indicating that erosion and alteration of some of the early dikes must have occurred before deposition of the Arod conglomerate and the final surges of magmatism (Fig. 3). These data imply that intrusion took place whilst the Inmar Formation was either exposed or close to the surface.

The Inmar Formation in Makhtesh Ramon is a quartzose, well-sorted sandstone, showing little diagenesis or compaction due to burial (Richardson & Goldbery 1988). Maximum burial depth was 500–1000 m (Feinstein *et al.* 1989), and primary shallow-burial authigenic minerals are preserved in these friable sediments away

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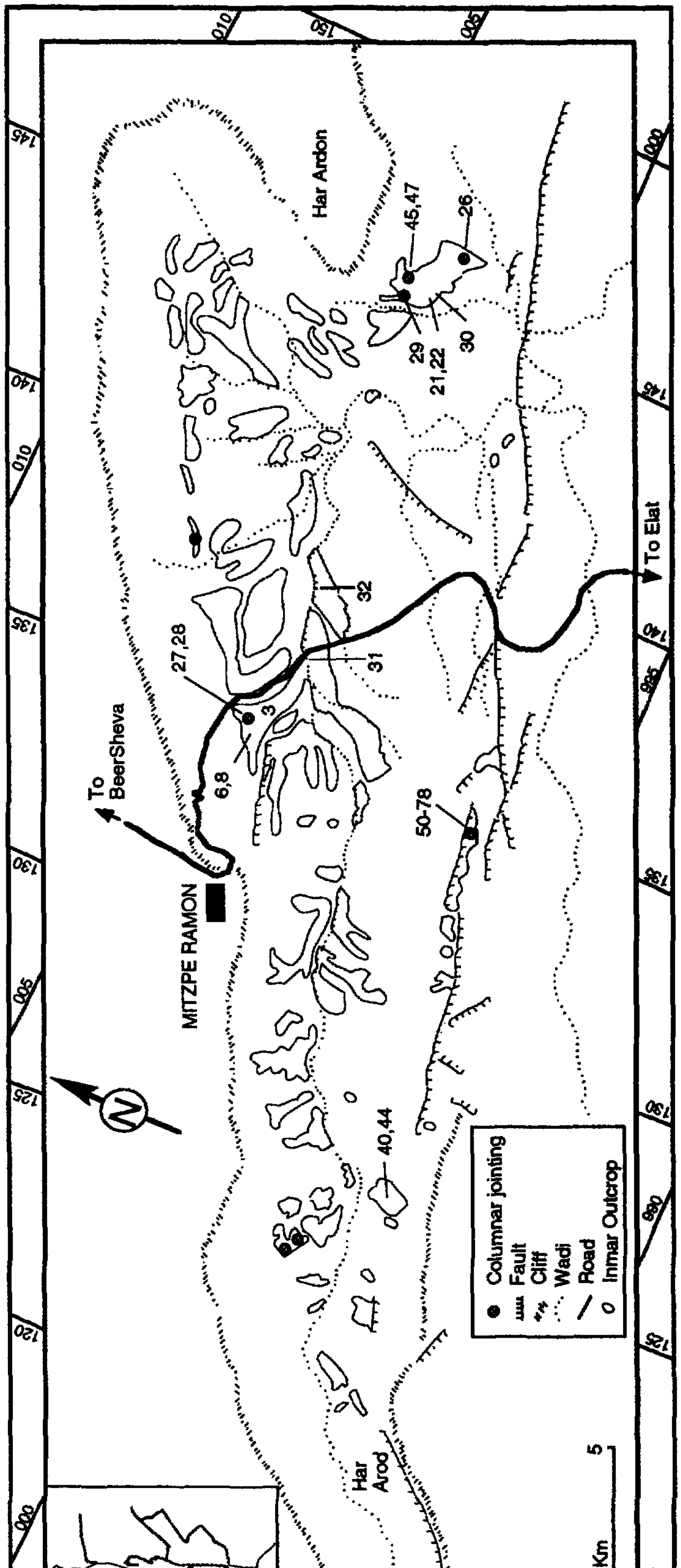

Fig. 1. Location map of Makhtesh Ramon, Israel, showing sampling sites.

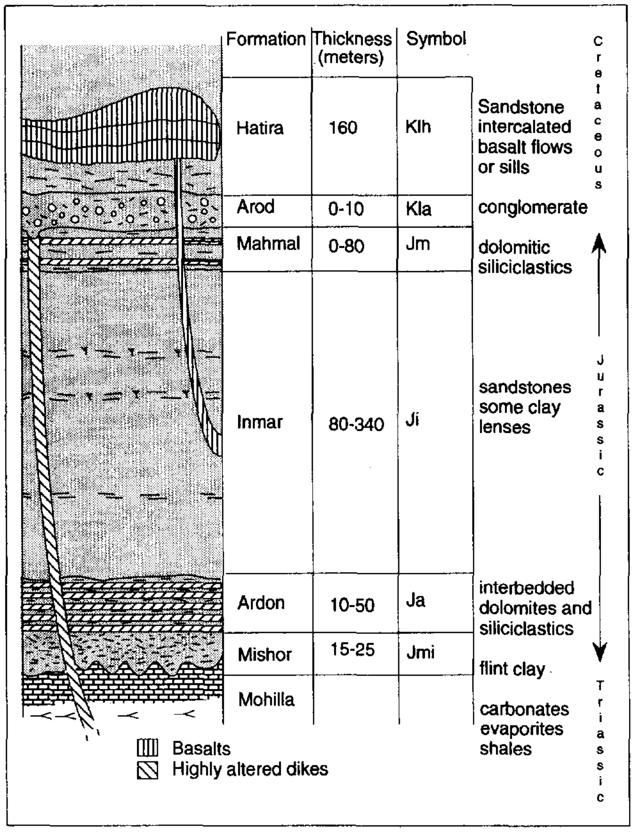

Fig. 2. Generalized stratigraphy and magmatic relationships of Jurassic and lower Cretaceous formations, Makhtesh Ramon.

from the intrusions (Figs. 4a–c) (Katz 1971, Goldbery 1978). Near the intrusions the sandstone is altered to a resistant quartzite which serves to delineate the highly altered and otherwise undistinguishable dikes. Accordingly, the friable sandstone can be easily compared to the indurated contact zone quartzite.

Previous work

Previous studies have suggested several mechanical and hydrothermal processes to form these contact zones. Contact zones have been described that consist of embayed quartz grains with primary and secondary interstices filled with quartz, chalcedony and K-feldspar (Bentor *et al.* 1966). Baer (1991) noted that contact zones consisted of corroded, shattered, angular and rounded quartz grains in an iron-oxide cemented kaolinite matrix. Garfunkel & Katz (1967) attributed these contact zones to quartzification with some brecciation, and described how quartzification graded outwards into friable sandstones. Elongation of clastic quartz grains and welding of the sandstone grains in the contact zones was cited as evidence for recrystallization (Itamar *et al.* 1983). The formation of columnar-joints, however, was attributed to the influence of steam or 'hot solutions', triggered by intrusive activity (Mazor & Cohen 1987). Similarly, dike alteration has long been thought to be due to hydrothermal activity (Bentor *et al.* 1966) as the dikes are altered inward from their margins with kaolinite at dike margins enclosing montmorillonitic cores (Garfunkel & Katz 1967). However the dikes must have remained only partially altered after a short-lived hydrothermal event, as recent work shows a weathering-related overprint (Teutsch *et al.* 1993).

OBSERVATIONS

Outcrop features

The Makhtesh Ramon dikes are 10–15 km in length with dike widths averaging 1 m. The widths of individual dikes fluctuates, with occasional 'dike buds' up to 5 m across. All dikes are altered and eroded leaving parallel quartzite walls with a 1–3 cm layered iron oxide crust (Figs. 5a & b). The contact itself is usually stained yellow–red with sometimes plentiful calcite, while the quartzite away from the dike margin is blue–grey and usually free of iron oxide.

Narrow (1–2 m) indurated contact zones prevail, but in six localities, broader (up to 12 m wide) columnar-jointed contact zones are present. These changes in contact zone thickness correspond to dike buds along strike of predominantly meter-wide dikes with narrow

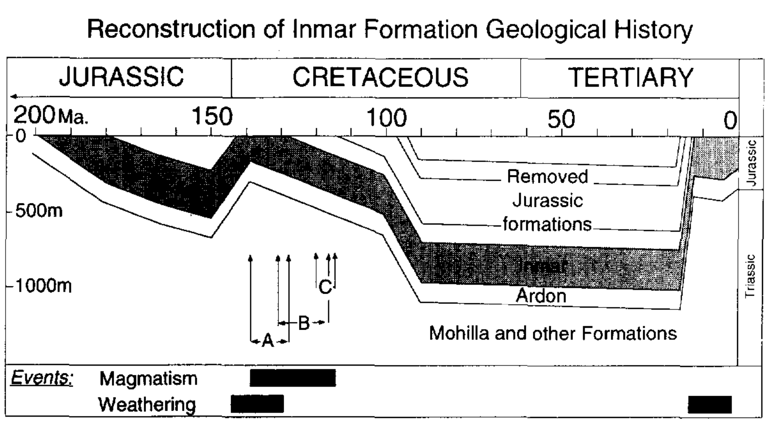

Fig. 3. Burial-depth chart reconstructing the burial and magmatic history of the Inmar and adjacent formations in Makhtesh Ramon, adapted from Feinstein *et al.* (1989). The burial curve for the Inmar Formation was calculated using actual formation thickness, while the timing of the three distinct magmatic events (A,B,C) is based on radiometric ages. Weathering occurred when the formation was exposed at the surface.

contact zones. Quartzite columns are either vertical or horizontal, forming fans and chevrons with columns lengths of up to 10 m and cross-sections of 5 cm. These discrete columnar-jointed sections of contact zones are found through Makhtesh Ramon, but they are confined to the upper Inmar Formation (Mazor & Cohen 1987). Bedding can be traced through the columns as the contact zone quartzite grades outward into friable sandstones (Figs. 5c & d). In the country rock sandstones adjacent to columnar-jointed contacts, there is no heterogeneity in bedding, detrital composition or alteration, indicating that column formation was controlled by the ballooning of the adjacent dike.

Petrography

At some distance from intrusive dikes, the Inmar sandstone is fine–medium grained (0.3–0.9 mm), with a bimodal grain-size (fine grains amongst predominantly coarser grains). The sandstone is grain-supported and highly porous, with point contacts and floating grains (Fig. 4a). Grains are usually well rounded monocrystalline quartz, with rare polycrystalline quartz grains, and accessory minerals include chalcedony, altered potassium feldspars, zircon, tourmaline and leucoxene. Diagenetic minerals include delicate quartz overgrowths with minor calcite and alunite encrustations (Fig. 4b).

In the contact zones, the most abundant neoformed minerals are quartz, kaolinite and iron oxide cements. The quartz overgrowths grew outward into open pore space, without closing pores (Fig. 6a). Coarse-grained vermicular kaolinite partially fills the remaining irregular shaped pores (Fig. 4d), locally cemented by iron and titanium oxides (Fig. 7). Kaolinite forms directly upon quartz, especially in the etched areas along sutured grain boundaries (Fig. 6d), along the quartz overgrowth/grain boundary, and on the surface of grains. The amount of authigenic minerals, especially kaolinite, increases toward contacts (Fig. 8).

Accessory authigenic minerals are also present in the contact zones. Iron-oxides are found as a layered red-brown crust at the actual contact, with embedded quartz, kaolinite and calcite. Geothite cements quartz overgrowths and kaolinite, and fills pores adjacent to the actual contact. These observations, together with microprobe analyses which show that kaolinite has structural iron, imply that the iron-oxide crust formed after intrusion and induraction, probably during or after kaolinite precipitation in both dike and quartzite contact zone. The patchy hematite cement present in both altered and unaltered sandstones is probably related to Neogene/contemporary weathering. Calcite is also present in grain coating and fracture filling modes, as well as an irregular pore-filling cement. Illite/smectite grows out into available pore space off the ends of kaolinite flakes, and together with gypsum, alunite and halides were the last minerals to precipitate. Thus the sequence of authigenic mineral precipitation in the contact zones was: quartz, kaolinite, Fe-oxides, illite/smectites, Ti-oxides, anhydrite, alunite and calcite; while in friable sandstones, different quartz overgrowths, kaolinite and calcite formed during burial (Fig. 9).

The former basaltic or trachytic dikes emplaced within the Inmar Formation have been pervasively altered to kaolinite and montmorillonite. At one location where the host rock is the Ardon Formation, relatively fresh basaltic cores of original dike material can be found consisting of plagioclase, olivine, augite and ilmenite phenocrysts in a matrix of fine grained albitized plagioclase. The paragenetic sequence of alteration minerals in dikes appears to be: quartz–calcite veins, feldspars, albite, chlorite, clays, Fe and Ti-oxides, calcite and gypsum.

Petrographic fabrics

As igneous contacts are approached, a systematic variation in the petrographic fabric of the sandstone becomes obvious. The number and type of grain contacts were counted for 50–85 grains from 13 thin sections over three contact zone profiles and grain contacts ranged from point, long, concavo-convex, to sutured (Fig. 10). Flattened grains, elongated parallel to dike contacts, with aspect ratios of $\approx 3:1$ with long grain contacts and sutured boundaries are common adjacent to dikes (Fig. 7a), while grains in distal samples exhibit largely tangential contacts (Fig. 7d). Grain-to-grain indentation and penetration is common and is probably due to pressure solution (Fig. 7b). There is little or no evidence for recrystallization and triple-junctions between grains are rare.

Quartz grains in the friable sandstones are predominantly clear monocrystalline grains, while those in contact zones are entirely milky, filled with both large and small fluid inclusions: this suggests either a pervasive fabric of microcracks or decrepitation of pre-existing fluid inclusions. Fractures within grains are often intergranular radial concentrations at grain contacts (Fig. 7c) and sometimes transgranular cracks involving a number of grains. Contact zone grains exhibit undulose extinction and Boehm lamellae suggesting some crystal-plastic deformation. Overall, the petrographic fabrics typical for the contact zone increase in intensity toward contacts.

Petrophysical data

Unconfined compressive strength tests show that intrusion-affected sandstones become more competent toward contacts (Fig. 11). Directly at the contact, however, the rock is less indurated due to grain fracturing and patchy iron-oxide cementation. Density of the samples determined by a Corelab mercury densitometer, smoothly increases toward the contact from background levels of 1.76 g cm^{-3} to almost 2.45 g cm^{-3}. Such a density increase is mirrored by a porosity decrease from more than 32% in unaltered sandstones, to less than 3% at contacts (Fig. 11). Permeability also decreases from more than 3700 mD to less than 1 mD at contacts (Fig. 11). All petrophysical data exhibit trends

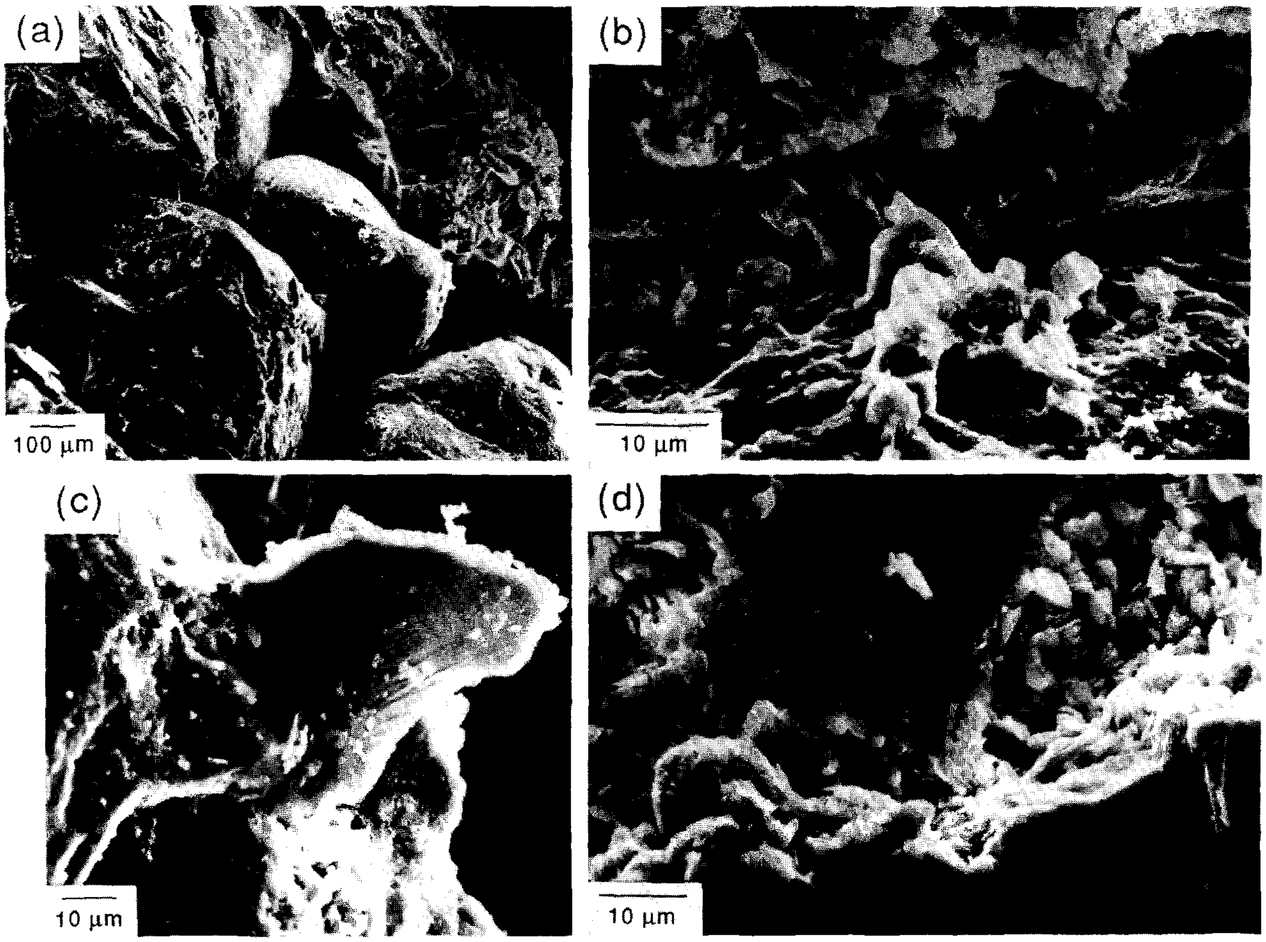

Fig. 4. SEM photomicrographs of Inmar sandstones: (a)–(c) are unaffected while (d) is affected by intrusion. (a) The grains are well rounded and sorted with little or no intergranular matrix. Grains of about 700 μm in size are in point contact. (b) Higher magnification shows that the grains are cemented in a minor fashion with a mixture of fine calcite and alunite cubes. (c) Quartz overgrowths are fin-like and delicate, growing out unimpeded into open pore space. (d) Quartz overgrowths surround detrital grains, growing in a euhedral prismatic form, 50 cm from dike margin. Later etching, both in front and behind the overgrowth occurred during kaolinitization, and vermicular kaolinite now coats the pores.

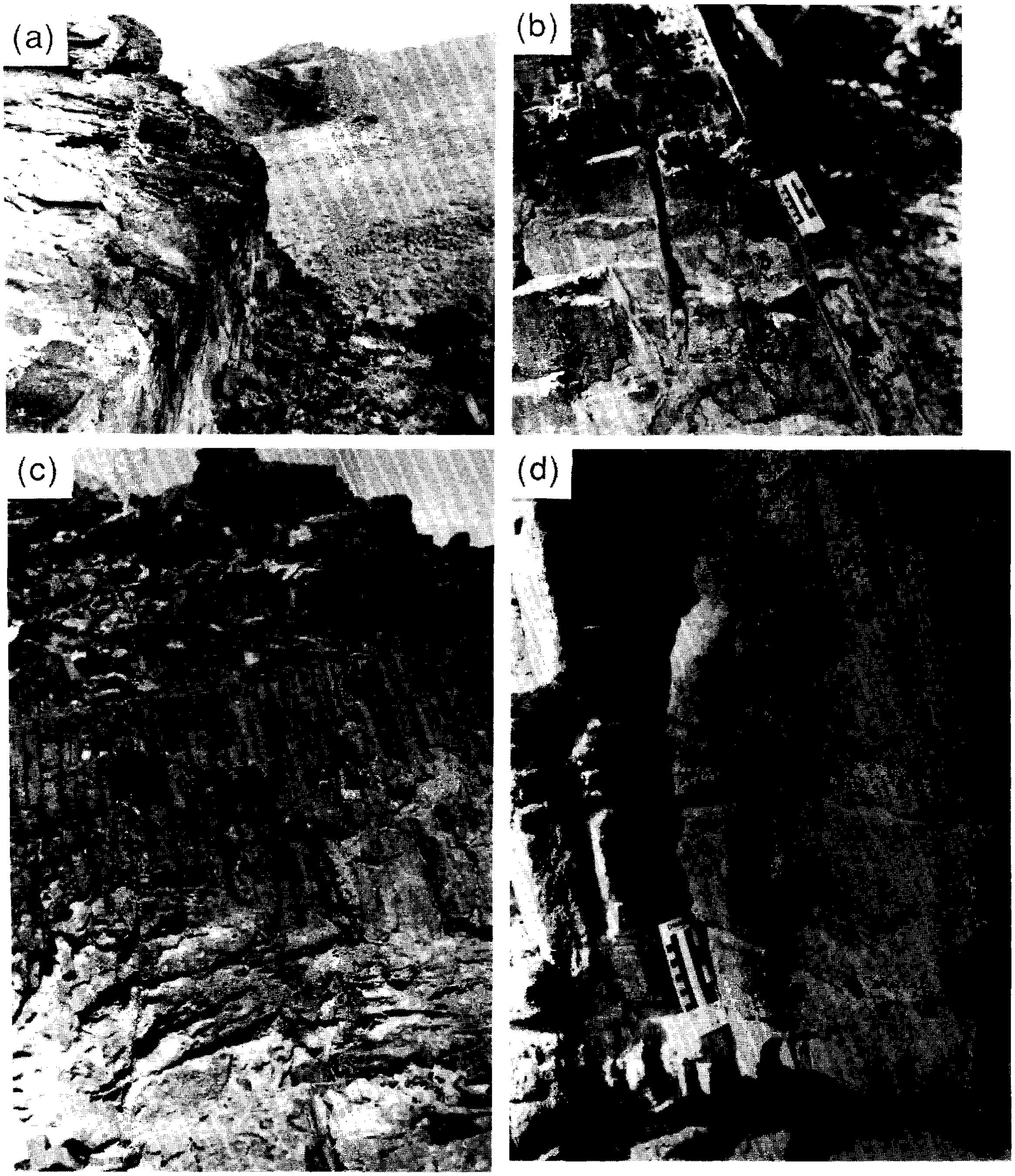

Fig. 5. Outcrop dike contact zone and columnar-jointing relationships. (a) Altered and eroded dike with remnant quartzite wall. (b) 5 cm wide iron-oxide crust between altered eroded dike and quartzite contact zone. The contact is inclined and quartzite columns are near-vertical. (c) Sub-vertical columns grading downward into friable bedded sandstone. Dike contact is 50 cm to the left of the photo. (d) Close-up of the base of photo (c) showing how primary bedding relics are undisturbed by the columnar joint formation and how columns grade into friable sandstone.

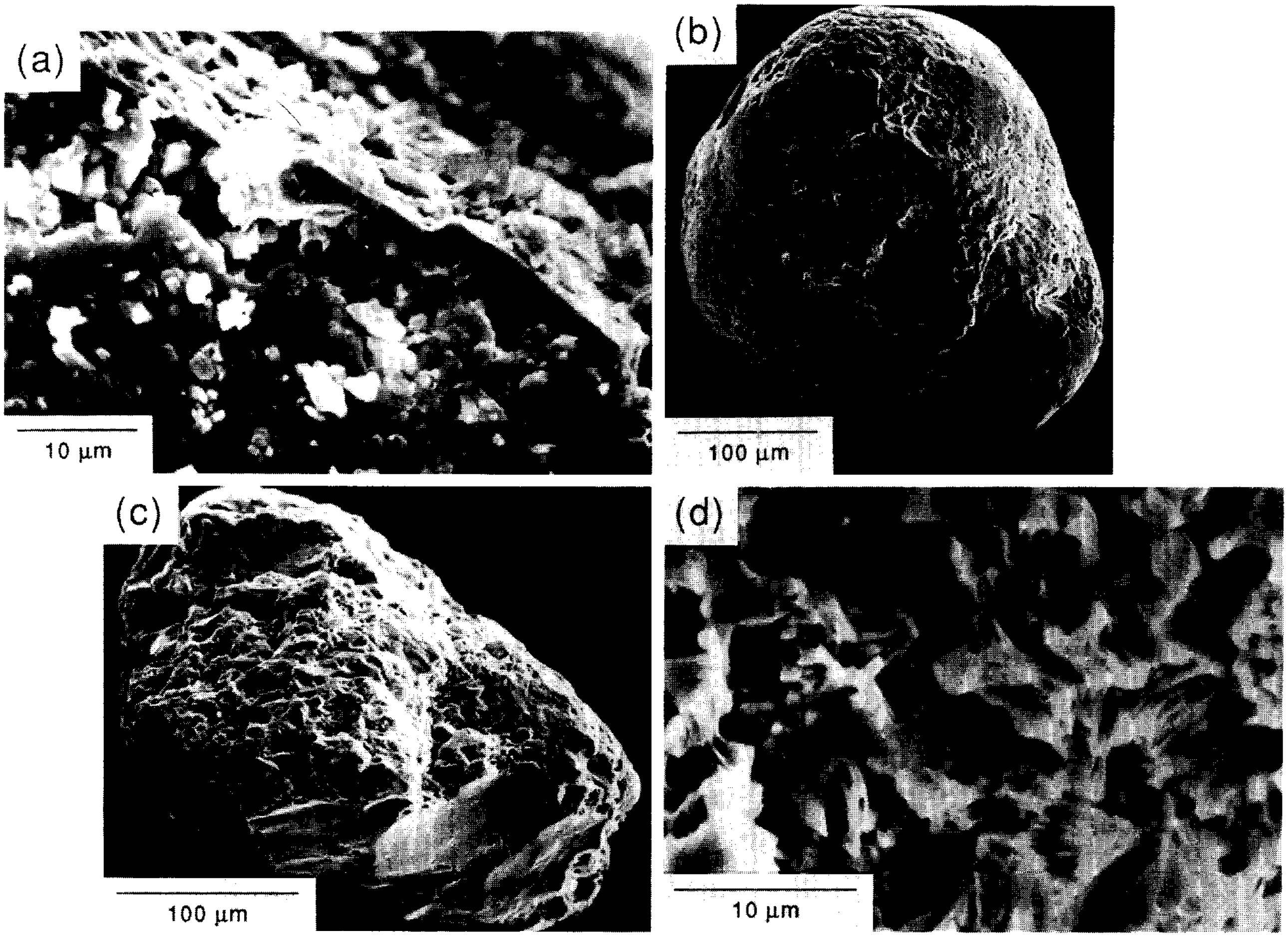

Fig. 6. SEM photomicrographs. (a) Euhedral prismatic quartz overgrowth in contact zone. Later etching occurred between overgrowth and host grain during kaolinitization. (b) Unaffected rounded detrital sandstone grain showing some minor etching due to overgrowth removal treatment. (c) Detrital grain from a contact zone quartzite, with quartz overgrowths removed. Smooth pits are places where adjacent grains indented this quartz grain. Major etching damage occurred during kaolinitization. (d) Interior surface of a separated quartz overgrowth, showing molds of kaolinite flakes remaining after clay removal.

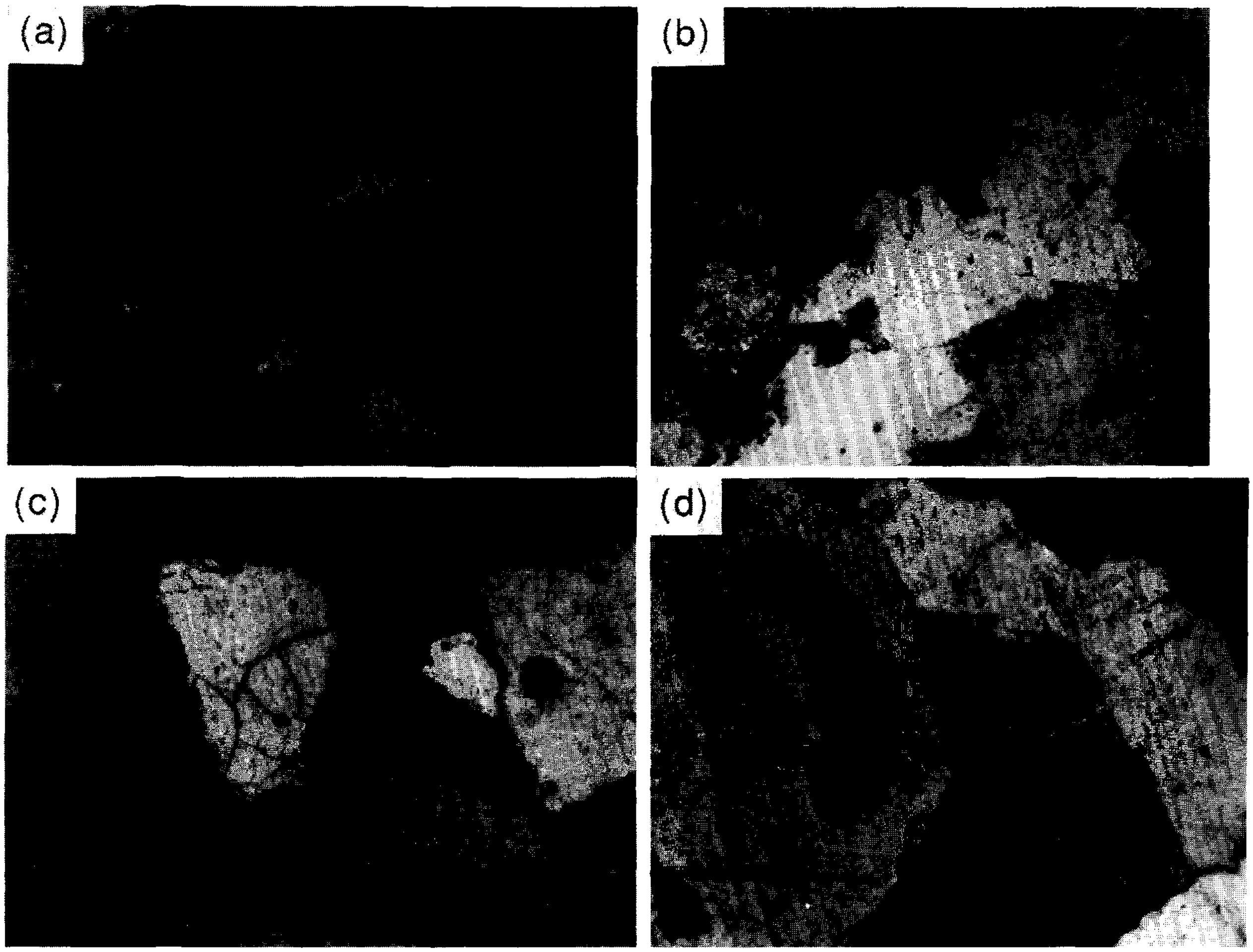

Fig. 7. Photomicrographs of thin sections from the lower Inmar contact. (a) At the contact repacked, flattened, sutured grains predominate. Nearly all primary porosity has been obliterated. Grains have been flattened with long axes parallel to the dike contact. (b) 10 cm away from the contact the grains are less compacted, suturing is common with interpenetrating grains and concavo-convex contacts. (c) 50 cm away from the contact the grains are much less compacted, ductile deformation is rare and brittle deformation is common. Point contacts are common, with transgranular microcracks. Long and concavo-convex contacts are also common. (d) 1 m from the contact the grains are in point contact and long contacts. The grains are not deformed and remain well rounded. Quartz overgrowths and clay pore coating is present. Porosity is high.

toward contacts which are similar to those derived from mineralogy and petrological fabrics.

DISCUSSION

Outcrops of altered, easily eroded dikes paralleled by narrow zones of hardened sandstone are common to intruded sandstones (e.g. Sitte 1954, Buist 1980, Poole & Hutton 1986). Such sandstone contact zones form in a wide range of settings. Ackerman (1983) describe high-grade metamorphic rocks with a glassy matrix forming from lithic-rich sandstones under intrusion temperatures exceeding 1000°C and plentiful water. Low-grade contact zones forming under low temperatures and restricted amounts of water from arkosic sands also occur (Braukmann & Füchtbauer 1983, Aldeham 1985, Hudson & Andrews 1987). Field observations, together with microstructural and diagenetic evidence suggest a two stage process in the formation and alteration of these quartzite contact zones. The first stage occurred during intrusion and formed the contact zone quartzite; the second stage followed dike emplacement and produced the mild alteration of both quartzite contact zone and dike material.

Formation of secondary minerals

The active geological history of the region has resulted in a wide variation of burial conditions in the Inmar sandstones (Fig. 3). The afore-mentioned paucity of burial diagenesis and retention of high porosity supports maximum burial depth of 1 km. However, volcanological studies (Garfunkel & Katz, Baer *et al.* 1989) indicate that dike intrusion of the Inmar sandstones took place when burial depth was less, possibly several tens of meters below the surface (Fig. 3). Temperatures in the sandstones would have been elevated by intrusion during the 6–10 months that a one meter wide dike could take to cool by conduction to ambient levels (Furlong *et al.* 1991). Maximum temperatures of 500–700°C could have been present at the contact over a period of days, decreasing sharply over time (Delaney 1987). Given such temperatures and the regional geological history, it is possible to account for the paragenesis of neoformed minerals in both the contact zone and the background sandstone.

The authigenic minerals of the contact zones and the friable sandstone show major morphological differences. Delicate 'fin-like' quartz overgrowths of the friable background sandstones (Fig. 4b) must have formed during burial diagenesis in open meteoric fluid saturated pore space. In contrast, the pore-coating and equant quartz overgrowths of the contact zones formed in the reduced pore space adjacent to sutured quartz grains, during the process of pressure solution in the presence of thermal fluids. The kaolinite and calcite of the friable sandstones are mere encrustations on grains, while in the contact zones, iron-rich kaolinite almost completely fills pores, finally closed up by geothite and calcite cement. The authigenic minerals in the friable sandstones must have formed as a response to slowly changing fluid and temperature conditions with increasing burial depth. In the contact zone, quartz forming via pressure solution could have precipitated over a wide range of temperatures below 700°C. The kaolinite that followed these higher temperature quartz overgrowths had to form below 300°C, as above this temperature pyrophyllite would form (Frey 1978, Hemley *et al.* 1980). In turn illite followed kaolinite, possibly at 120–150°C (Bjørlykke 1988). Therefore the authigenic minerals of the contact zone most likely formed sequentially from an evolving fluid as the dike cooled and contact zone temperatures decreased.

Argillitization of both contact zone quartzite and dike material must have involved intrusion-heated formation water derived from the deeper buried formations underlying the Inmar sandstone. The iron oxides and Ti-rich phases concentrated at the actual contact in the iron crust indicate that the fluids were oxidizing (Bjørlykke 1989), suggesting that the fluids were meteoric derived and not deep basinal brines. Since volumetrically kaolinite decreases away from the contact, the source of the required aluminium appears to lie within the dike.

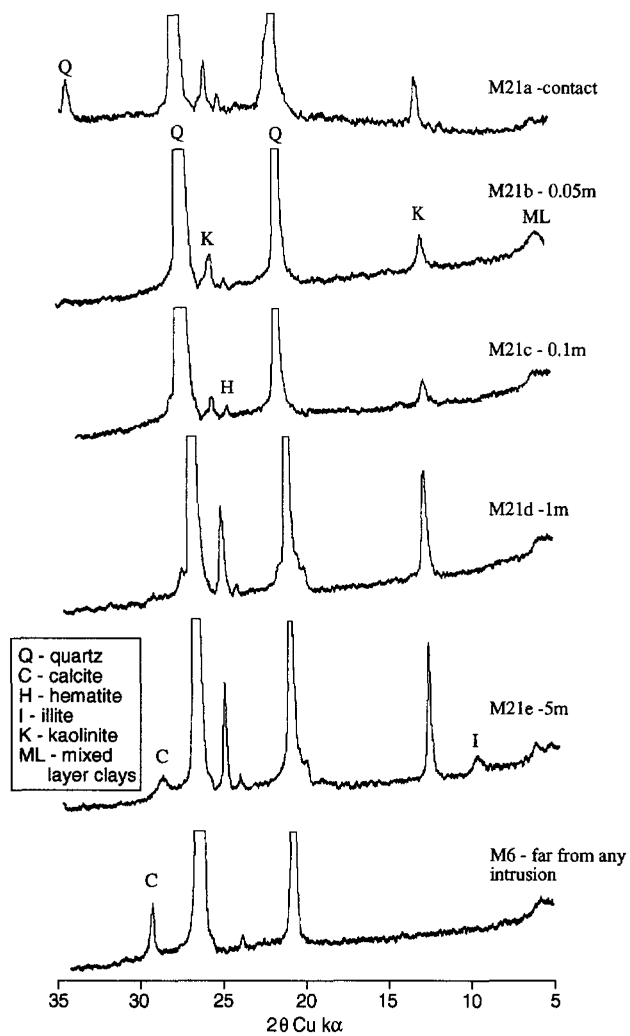

Fig. 8. XRD profiles of contact zone (M21) from the lower Inmar member. Quartz and kaolinite are most abundant with traces of accessory minerals. M6 is distal unaffected sandstone.

Accordingly, the kaolinitization of quartz observed in the contact zones could be related to acidic Al-enriched fluids seeping into the quartzite from the dike margins. Iron present in solution was incorporated into the kaolinite structure and as the fluid further evolved, geothite precipitated, effectively sealing the walls and building a crust. This crust and the concentration of kaolinite and geothite suggest that fluid seepage was concentrated along the dike/quartzite interface.

Only a small fraction of the fluids would have managed to seep through the semi-permeable quartzite contact zone, thus the major part of the flow was directed alongside the dike resulting in the preferential alterations of the dike material at the contact. Therefore the fluids associated with intrusion and incipient dike and quartzite alteration, must have been meteoric, acidic, oxidizing and hot, similar to those involved for the alteration of underlying sedimentary units (Rozenson *et al.* 1982). The fluid evolved as it cooled, mixed with background formation water and precipitated minerals. Thus as the dike-induced transient hydrologic regime decayed, pH increased to levels where illite–smectite clays and even calcite formed in both dike and contact zone. Thus alteration of contact zone and dike material can be attributed to mild hydrothermal conditions compounded by extensive weathering.

Formation of contact zone fabrics

Microstructures within the quartzite contact zone appear to extend only a meter away from contact (Fig. 10), however the effects of dike intrusion are discernible throughout the transition into friable sandstone (Fig. 11). Induced fabrics such as grain fractures and long contacts are present in the final transition but occur at a low frequency (Fig. 10). In contrast, the frequency of neoformed minerals is sharply curtailed within the first meter. Thus even though the two stages of alteration may have had similar effects on petrophysical parameters, textural alteration is by far more prevalent than any neoformation of minerals in the Inmar contact zones.

Detrital grain fracturing and pressure solution are most intense adjacent to dike margins and decrease outwards into the background sandstones. Pressure solution, a material transfer process whereby a mineral dissolves at areas of high normal stress and precipitates on surfaces with lower normal stress, is known to be a major cause of induration in sandstones over increasing depth of burial (e.g. Taylor 1950, Palmer & Barton 1987). Pressure solution occurs from temperatures as low as 75°C (Trurnit 1968), and generally has been found to intensify with increasing burial and lithological pressures (e.g. Deboer *et al.* 1977). The observed trends in grain contacts, induration, density and porosity from these contact zones are comparable to those reported from buried sandstones, thus these meter-scale contact zones imitate kilometers of burial.

The trends in grain contacts (Fig. 10), observed grain deformation and evidence for strain, and lack of any evidence of pore filling quartz cementation, indicate that the contact zone sandstones experienced a compressive environment. Contact zone temperatures and pressures were not sufficient to fully recrystallize detrital grains as no coarsening of grain size and no triple junctions common to recrystallized sandstones were found. Compressive stresses were sufficient only to cause fracturing and pressure solution. However, healing of fractures into planar splays of fluid inclusions directly at dike contacts suggest the effect of local high temperature. The simplest interpretation of these observations and inferences is that the indicated compressive stresses were induced in the sandstone by the forcible dilation of adjacent dikes and that healing of fractures and flattening of grains took place in the ensuing high temperature domain directly adjacent to dike margins.

The contact zone petrography is not unprecedented, as similar flattened detrital grains, common near the contact area and becoming rarer distally, are found in contact zones in Greenland (Brauckmann & Füchtbauer

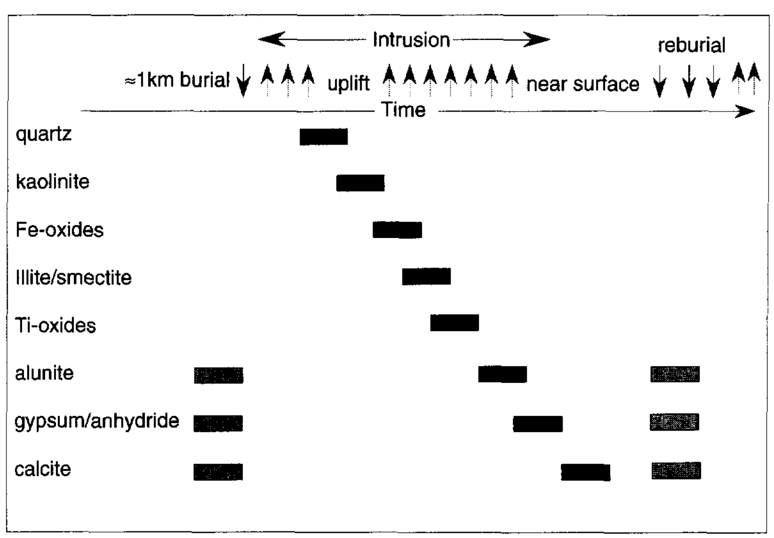

Fig. 9. Order of authigenic mineral precipitation. Time scale is relative and indicates order of formation. Shaded areas and dashed lines indicate tentative assignment of some minerals forming with burial or possibly at all times.

1983). The smooth progression from friable sandstone to quartzite observed in outcrop, was confirmed by petrophysical analyses of tensile strength, permeability and porosity (Fig. 11). Similar porosity reduction in intruded sediments has been attributed to the way dikes and sills wedge apart host rocks as they propagate (e.g. Delaney *et al.* 1986, Duffield *et al.* 1986). Such forceful expansion or dilation of an igneous body, inflating

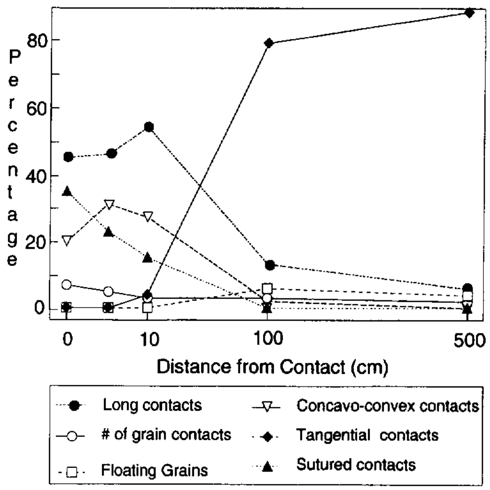

Fig. 10. Semi-log plot of the frequency of different grain contacts in a contact zone.

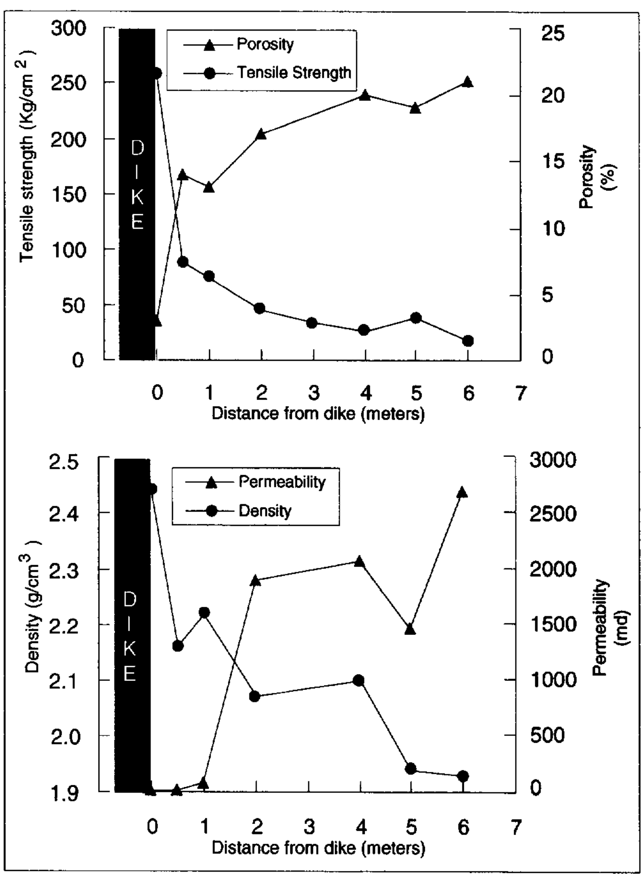

Fig. 11. Petrophysical data on tensile strength, density, porosity and permeability. The induration or unconfined compressive strength of samples was assessed using a Robertson Research Rock Strength Index log. Porosity, permeability and density measurements were made using a Corelab mercury apparatus.

against a relatively ductile or elastic host rock has been invoked to account for textural and structural deformation around plutons (e.g. Holder 1979) as well as dikes (Delaney & Pollard 1981). This study confirms that forcible intrusion occurs into porous unconsolidated sediments and reaffirms the importance of material transfer processes (i.e. pressure solution) as a major factor accompanying forceful intrusion (Paterson & Fowler 1993).

Laboratory compression experiments on sandstones duplicate many of the fabrics of these contact zone quartzites including: milky quartz grains (Blacic & Christie 1984), the interpenetration of one quartz grain into another, radial fractures from point contacts, and pressure solution and suturing of grains (Gallagher *et al.* 1974, Carter *et al.* 1964, Sprunt & Nur 1977). The increase in induration of the contact zone sandstone is similar to the strain hardening induced in laboratory samples during compression experiments (Tullis 1990) and adjacent to faults (e.g. Hippler 1993). In the laboratory, intergranular crystal plastic deformation was induced in an indurated sandstone, whereas in these friable sandstones, similar partial crystal-plastic deformation expressed by undulose extinction and Boehm lamellae of flattened and strained detrital quartz grains was induced adjacent to dike contacts. Accordingly, this induration of a friable sandstone may be attributed to the progressive increase in grain contact area due to the high states of packing obtained via a combination of plastic, brittle and pressure solution processes rather than to intergranular phenomena such as cementation.

In laboratory studies of deformation and fracture processes in sandstones, stresses of 0–400 MPa on sandstones evoke a gradual transition from localized brittle fracture to dislocation creep with increasing stress, both at room and at elevated temperature (e.g. Wong 1990, Luan & Paterson 1992). Even though quartz is a competent material, notable weakening of quartz grains does occur due to trace impurities, and water weakening (Luan & Paterson 1992). Since a heated fluid mixture is thought to have accompanied dike intrusion (Baer 1987) and pre-heated the sandstone, detrital quartz grains would more readily deform in a ductile manner when the magma followed, filling and dilating the fracture. Moreover the time required for crack healing in quartz at such elevated temperatures (400–700°C) and pressures (30–80 MPa) (Summer 1993), is on the order of hours (Brantley *et al.* 1990). Thus the observed plastic deformation of quartz could have occurred in the temperature field adjacent to dikes, under dike-induced compression, in the short time available.

The observed petrographic fabrics strongly interrelate to illustrate how a friable sandstone responds to dike intrusion. Fractures in grains must have occurred during initial compression due to dike expansion, when individual grains underwent physical rotation as the sandstone was repacked. Healing of the fractures occurred as temperature increased via heat conducted from the adjacent magma. Such fracture healing is less prevalent outward from the contacts, expressing the steep thermal

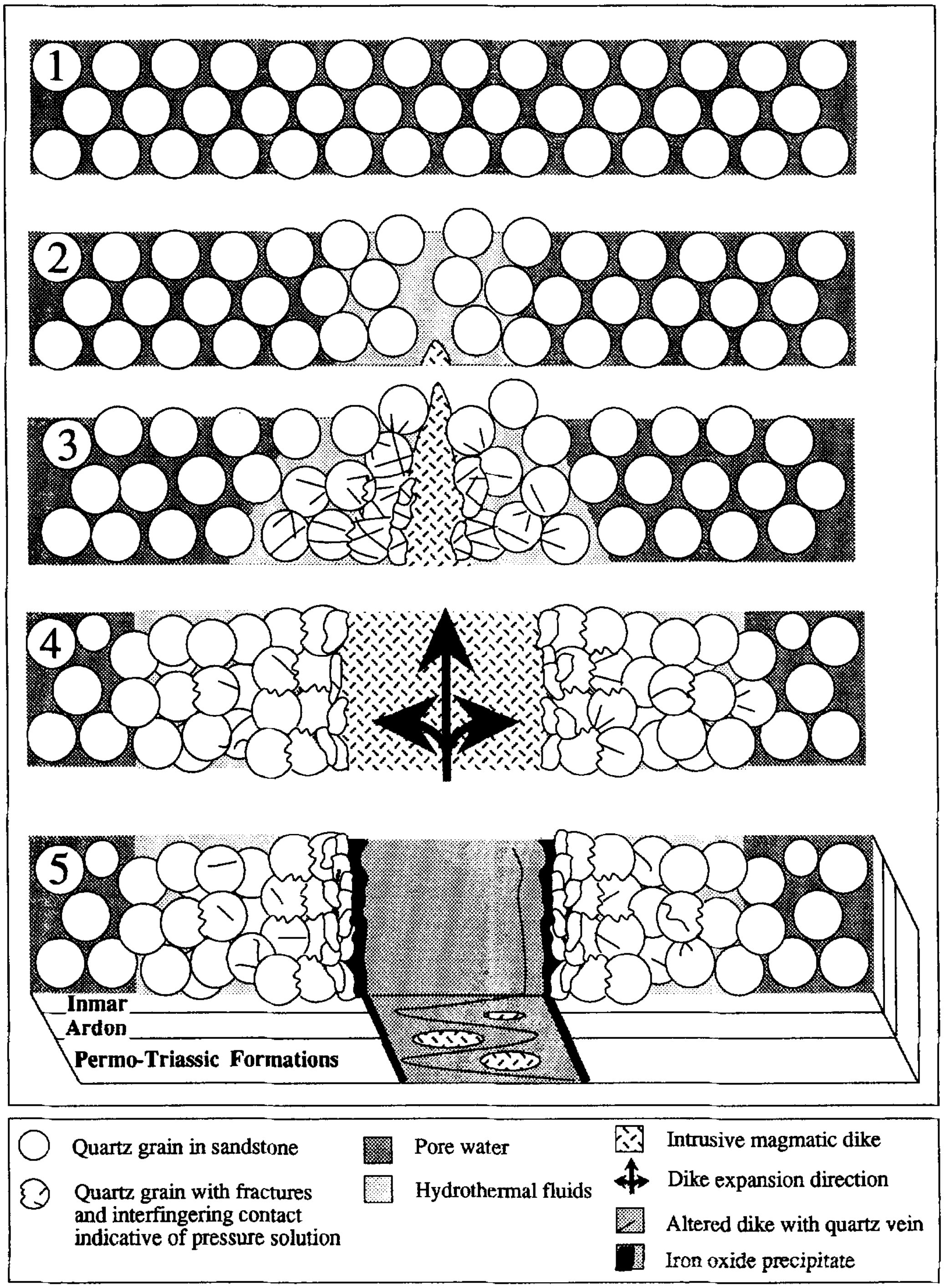

Fig. 12. Cartoon of the overall model for the dike/sandstone interaction. (1) The country sandstone prior to intrusion. (2) Hydraulic fracturing of the sandstone ahead of the dike tip. (3) Dike tip enters fracture, wedging through the sandstone and repacking and fracturing quartz grains. (4) As this wedging continues, or as the dike dilates, the sandstone on each side of the dike is compressed and heated with fracture healing and pressure solution. Thus the sandstone is indurated to a quartzite in the contact zone. (5) As the dike cools it is partially altered to a clay-rich matrix. Veins are emplaced in the altering dike. Iron oxides precipitate between the altering dike and quartzite, and within the quartzite along fractures and adjacent microporosity.

gradient adjacent to dikes. In the presence of this thermal gradient, pressure solution occurred as a result of very slow elastic compressive stress dissipation. Thus in a response to dike dilation, an agglomeration of individual detrital grains was welded together, or 'sintered' in the metallurgical sense. Sintering is a process common to industrial ceramics and is not to be confused with siliceous sinter which describes cementation. Instead the process envisaged is whereby a bonded mass of particles is generated by pressure and heating below the melting point of the constituent particles. In summary, the deformation of the sandstone began under strain induced by the dike tip resulting in grain flow, reorientation and repacking (Fig. 12). Grains swept aside by the dike tip, pressed back against adjacent grains as increasing stress lead to grain fracturing, as temperatures increased, fractures were annealed and pressure solution began to slowly weld grains together. Thus the dike accommodation process involved brittle, elastic and grain repacking mechanisms, while the sediment induration process involved sintering and pressure solution mechanisms.

Columnar joint formation

Columnar jointed or 'prismatic' sandstones have been reported from around the world (Summer 1993). The rocks are enigmatic, since in many instances undisturbed sedimentary structures such as bedding and ripple marks can be traced from unjointed sandstone through the columns. This type of columnar jointing clearly differs from superficial features such as polygonal mud-cracks and patterned ground, formed during drying or freeze–thaw cycles. The most spectacular outcrops of columnar-jointing of this type rivals that of colonnade basalts. Considering that columnar-jointing is usually derived from cooling-related shrinkage of a basalt, the mechanism of columnar-joint formation in sediments can be inferred: it may form when sediments are first heated and are then allowed to cool and fracture in a manner reminiscent of cooling lava. Thus the mystery lies not in the formation of the joints, but rather in the manner in which sediments are amalgamated and the physical and chemical conditions under which such phenomena occur.

In the Inmar sandstones, repacking and microcracking of quartz grains must have absorbed most of the mechanical compaction induced by dike intrusion. Any remaining intrusion-induced elastic stress was relaxed by the ductile deformation of grains, fracture sealing and pressure solution as heating progressed. Accordingly, as the contact zone cooled, subsequent jointing must have relieved only the thermoelastic stress induced during the heating. Thus the columnar joints produced were not parallel to the contact as they would be if the quartzite was releasing intrusion-induced elastic stress, but rather normal to isotherms developed in the cooling igneous body and quartzite contact zone.

The columnar jointing appears to have only occurred in the shallowest buried sandstones where vent geometry and aquifer conditions were perhaps optimal (Summer 1993). Since uniform cooling is required for columnar joints in basalt, similar joint formation in sandstones must occur in the vadose zone, above the quenching effects of aquifers. Accordingly, the presence of such joints in a sandstone contact zone may be an indication of shallow intrusive phenomena.

CONCLUSIONS

Intrusion of individual dikes in the friable Inmar sandstone was accommodated primarily by the repacking of the sandstone accompanied by brittle and elastic grain interactions. Once emplaced the dikes provided heat that healed the earlier induced micro-fractures and sintered quartz grains together by pressure solution thus forming a quartzite. Columnar joints developed in the contact zone quartzite by the release of thermoelastic stresses during cooling at the near-surface. Later as the magma and contact zone cooled, heated formation water from underlying strata must have seeped up the contacts, leaching and altering both dike material and quartzite.

Acknowledgements—This work benefited from discussions with Y. Kolodny, G. Baer and N. Teutsch. Invaluable help in the field and laboratory were provided by the staff of the Israel Geological Survey, and faculty and staff of the Geology Department, Hebrew University. This research was supported by the Basic Research Foundation administered by the Israel Academy of Sciences and Humanities. The critical reviews of Tom Fowler and an anonymous reviewer greatly improved the manuscript.

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