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DESICCATION OF MUD IN THE TEMPERATE INTERTIDAL ZONE: STUDIES FROM THE SEVERN ESTUARY AND EASTERN ENGLAND

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Field studies, including the close temporal monitoring of selected sites, allow desiccation cracks in the hypertidal subzone to be classified on the basis of (i) degree of desiccation, (ii) overall shape of individual cracks, (iii) shape of crack margins, (iv) the angle at which cracks join and the number of sides to a desiccation pillar, and (v) the degree and kind of preferred orientation of cracks. In the Severn Estuary and The Wash, and on the north Norfolk coast, these properties are controlled by the thickness, lithology and degree of stratification of the exposed muds, and by the history of drying as determined by positional, tidal and climatic factors. The cracks are initiated at such defects as bird's footprints, plant stems, and pebbles and shells, and grow slowly along mainly orthogonal paths under the influence of principal stresses that change in orientation with the spread of the fractures they themselves have caused. Hypertidal desiccation cracks commonly open and fill more than once; filling may be accomplished by either a repetition of the same material or a succession of different ones (for example, mud, sand, mud clasts, bivalve shells). The closely monitored sites reveal that hypertidal cracks develop chiefly during the late spring and summer on time scales of hours to months, but that significant fracturing may also occur during the winter, when periods of dry windy weather coincide with relatively weak tides.

Because of the nature of the controls, the degree of desiccation and the type and pattern of the cracks varies stratigraphically within the hypertidal zone in a systematic manner which is similar in all the areas studied. Late- and terminal-stage cracks are most prevalent in the upper hypertidal subzone, whereas early-stage forms predominate in the lower subzone. Non-orthogonal patterns predominate in the upper subzone, where various factors promote the destratification of the sediment. Orthogonal fractures are best developed in the middle subzone, where thick muds can be accumulated but where exposure can be lengthy. As an assemblage, and taking into account their stratigraphical variation, temperate-zone hypertidal desiccation cracks appear to be distinct from the associations developed in other marginal and continental environments.

1. INTRODUCTION

Desiccation cracks, commonly developed in atmospherically exposed muddy sediments, are incompletely to fully joined fractures that form mainly normal to the sedimentary surface, as the result of a moisture loss to the stage where the affected material fails in tension. These structures attracted the early attention of Hall (1843), who noted their abundance in certain facies of the Devonian rocks of the Appalachians. Although the cracks have since been frequently and widely reported from both modern environments and the rock record, their deceptively simple meaning has by and large discouraged the systematic study of their variety (considerable) and controls (partly environmental). Some insights have come from the rather generalized field and laboratory work of Kindle (1917, 1923, 1926), Longwell (1928), Bradley (1933), Kindle & Cole (1938), Beppu (1971), and Soleilhavoup & Bertouille (1976). The theoretical work of Lachenbruch (1961, 1962, 1963) on thermal contraction cracks, and the incisive experimental study by Corte & Higashi (1964), however, are essential reading for subsequent workers concerned with desiccation, but neither work receives from sedimentologists the attention it merits, perhaps because of its apparent restriction to the problems of frozen ground. What is at present lacking are satisfactory field descriptions of desiccation structures, to which the advances in general theory, especially that of fracture mechanics, may eventually be applied.

Here I therefore give an account of the geometry, the environmental controls on, and the preservation of desiccation cracks in the temperate intertidal zone, to understand better these structures and to refine our ability to use them in environmental interpretation. This zone is one of the more important for the desiccation of muddy sediments. The areas chosen are the Severn Estuary, where work included a year-long monitoring of five sites at two localities, and The Wash and the Norfolk marshes of the East Coast of England.

At the outset of the work, it was intended to associate descriptions of the desiccation features with measurements of relevant physical properties of the sediment, such as water content and shear strength, to establish the thresholds governing the development of drying cracks. It speedily became apparent that critical data on these thresholds could not be reliably obtained in the field, chiefly because of the substantial blurring effects of rewetting by the tide and by rainfall. This aspect of desiccation is consequently being explored through a programme of controlled laboratory experiments, which will be separately reported. The present paper stresses the form and distribution of intertidal desiccation features and analyses their occurrence in purely environmental and stratigraphical terms.

2. Setting

The Severn Estuary (see figure 1*a*), expanding toward the SW, ranges for approximately 80 km from Gloucester to a line joining Lavernock Point (Cardiff) with Sand Point (Weston-super-Mare) (Kirby & Parker 1983). It is rock-bound in places but fringed in others by extensive intertidal mudflats and broad grazed salt marshes. An extreme macrotidal régime (Davies 1964) typifies the estuary (see figure 2*a*, *b*). The intertidal zone, here defined as the extreme range of the astronomical tide in any period of at least one year, measures 13.9 m at Avonmouth (1982–3; slight variation from year to year), the standard port for the estuary (Hydrographer of the Navy 1981, 1982). Desiccation occurs supratidally but mainly in the hypertidal subzone, defined in any tidal year or longer period as lying between the lowest of the neap-tide high waters (LNHW) and the highest of the spring-tide high waters (HSHW). At Avonmouth its range is 5.5 m (1982–3). Desiccation features were examined chiefly at Rodley, Arlingham, Awre, and Slimbridge in the middle and upper estuary, where mud and very fine sand become interlaminated on a millimetre to centimetre scale and, occasionally, thick extensive sheets of mud accumulate. At two places in the middle estuary, Berkeley (two sites) and Oldbury-upon-Severn (three sites), the progress of desiccation in homogeneous muds with millimetre-scale silt laminae was monitored over a period slightly exceeding one year (5 July 1982 to 8 July 1983). Localities between Chepstow and Cardiff on the Welsh bank were also visited, the hypertidal sediments here varying from thick muds to muddy very fine sands.

The Wash (Kestner 1975) is a rectangular gulf measuring approximately 20 by 30 km opening northeastward into the North Sea (see figure 1*b*). The coastline is mainly low-lying and chiefly underlain by Flandrian deposits. Intertidal sands and mudflats some kilometres wide grade upward into accreting salt marshes which have periodically been reclaimed (Inglis & Kestner 1958; Kestner 1962, 1975; Evans 1965). The Wash is also macrotidal (see figure 2*c*, *d*), but with a somewhat narrower tidal range than the Severn Estuary. At Immingham, the standard port, the zone measures 7.9 m (1983) and the hypertidal subzone 2.8 m. The pattern of tides in the two areas is similar, however, except for two features. The immersion curve for the Severn Estuary is comparatively skewed and annually the spring-tide high waters show only one clearly defined period of diminished values (late spring to summer). Desiccation

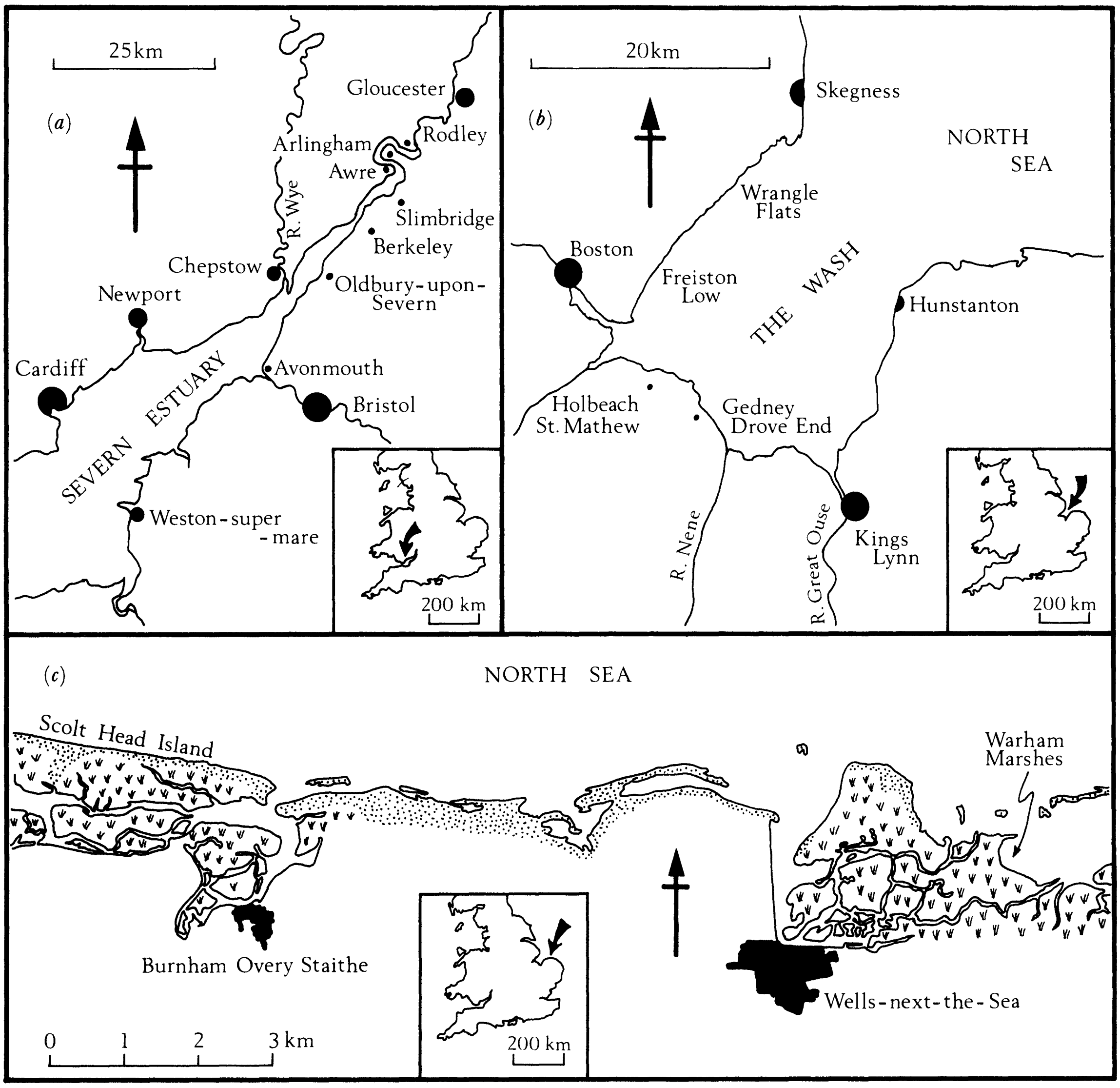

FIGURE 1. General locality maps. (*a*) Severn Estuary. (*b*) The Wash. (*c*) The north Norfolk coast, Scolt Head Island to Wells-next-the Sea.

structures were examined in muds with millimetre- and some centimetre-scale sand and silt laminae near the Great Ouse and Nene outfalls, at Gedney Drove End, and at Holbeach St Matthew. On Wrangle Flats, and southwestward to Freiston Low, they occurred in laminated sandy muds and muddy very fine sands.

Immingham is also the standard port (see figure 2*c*, *d*) for the north Norfolk coast (see figure 1*c*). Here desiccation structures were examined on the sheltered marshes of Scolt Head Island and Burnham Overy Staithe (Steers 1934) and on the more open Warham Marshes (Steers 1964; Bayliss-Smith *et al.* 1979) east of Wells-next-the-Sea. The affected sediments were sandy muds grading to mud and sand interlaminated on a millimetre to centimetre scale. Salt-marsh pans are a distinctive feature of the Norfolk saltings and of the older marshes bordering The Wash.

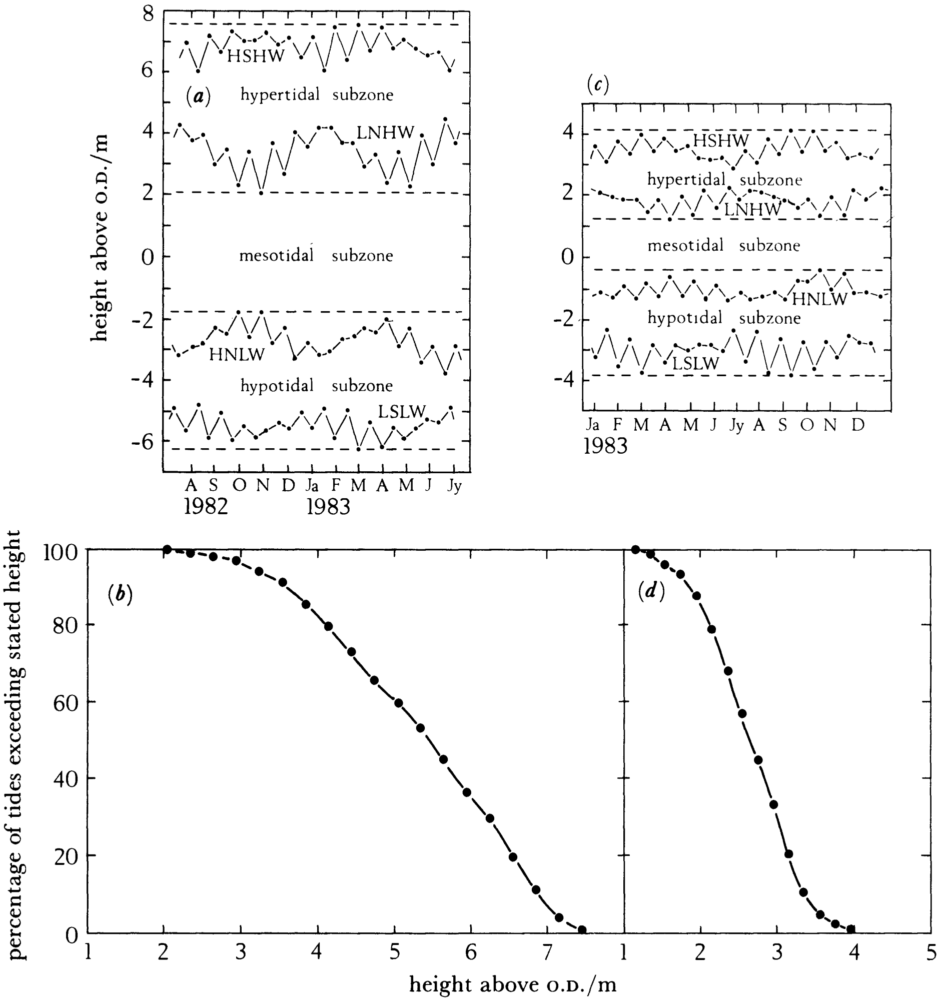

FIGURE 2. Tidal regimes in the Severn Estuary and the west-central North Sea. (*a*, *b*) Tidal sequence and immersion curve for Avonmouth (5 July 1982 to 8 July 1983 inclusive). (*c*, *d*) Tidal sequence and immersion curve for Immingham (Humberside) (1983). HSHW, highest spring-tide high water; LNHW, lowest neap-tide high water; HNLW, highest neap-tide low water; LSLW, lowest spring-tide low water.

3. DESCRIPTION AND CLASSIFICATION OF DESICCATION FEATURES

Lachenbruch (1961, 1962, 1963) sketched a classification of thermal contraction cracks in frozen ground which Allen (1982) found could be readily expanded to cover drying cracks in muddy sediments (see figures 3 and 4). A few points require additional explanation.

The chief components of a set of desiccation features are: (i) the vertical and, in some instances, also horizontal *cracks* cutting the affected sediment; (ii) the *pillars* of sediment defined by the vertical cracks, ranging from wide and low to tall and narrow, and (iii) the horizontal *storeys* into which the pillars may be divided by horizontal fractures developed within or at the boundaries of silt or sand laminae. Figure 3 summarizes the characteristics of cracks seen in plan and the various patterns to which sets of them may give rise. Fracture patterns are classified chiefly on the basis of the degree to which component cracks are joined and on the angle, or angles, at the join, or joins, between two (or more) ruptures.

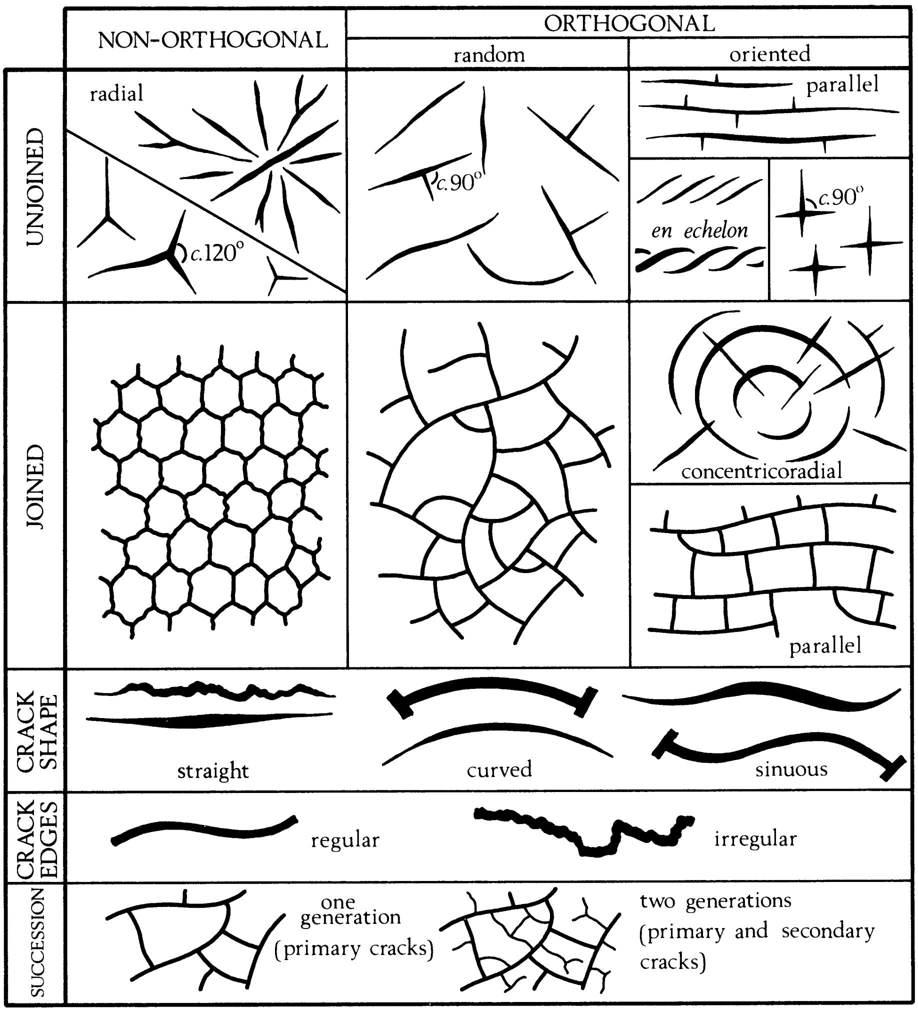

FIGURE 3. Outline classification of desiccation cracks viewed in plan.

Figure 4 relates partly to pillars and storeys. Each vertical fracture has a characteristic width (w) and depth (d). Similarly, each pillar has a characteristic width (W) at the top. The horizontal *contraction* involved in a set of desiccation cracks is conveniently measured in the field over a suitably long traverse as $100w/(W+w)$, where the widths are understood to be characteristic averages. Some storeys curl up as they dry. The degree of curvature is conveniently measured by the *angle of curl* (α), defined as the angular rotation of the bedding at the edge of the storey from its original position. Various plumose markings (Cegla & Dzulynski 1967; Ernston & Schinker 1986) can be found on the sides of some pillars and storeys, but are difficult to see and record in the field. The rest of figure 4 covers the infilling and preservation of intertidal desiccation cracks.

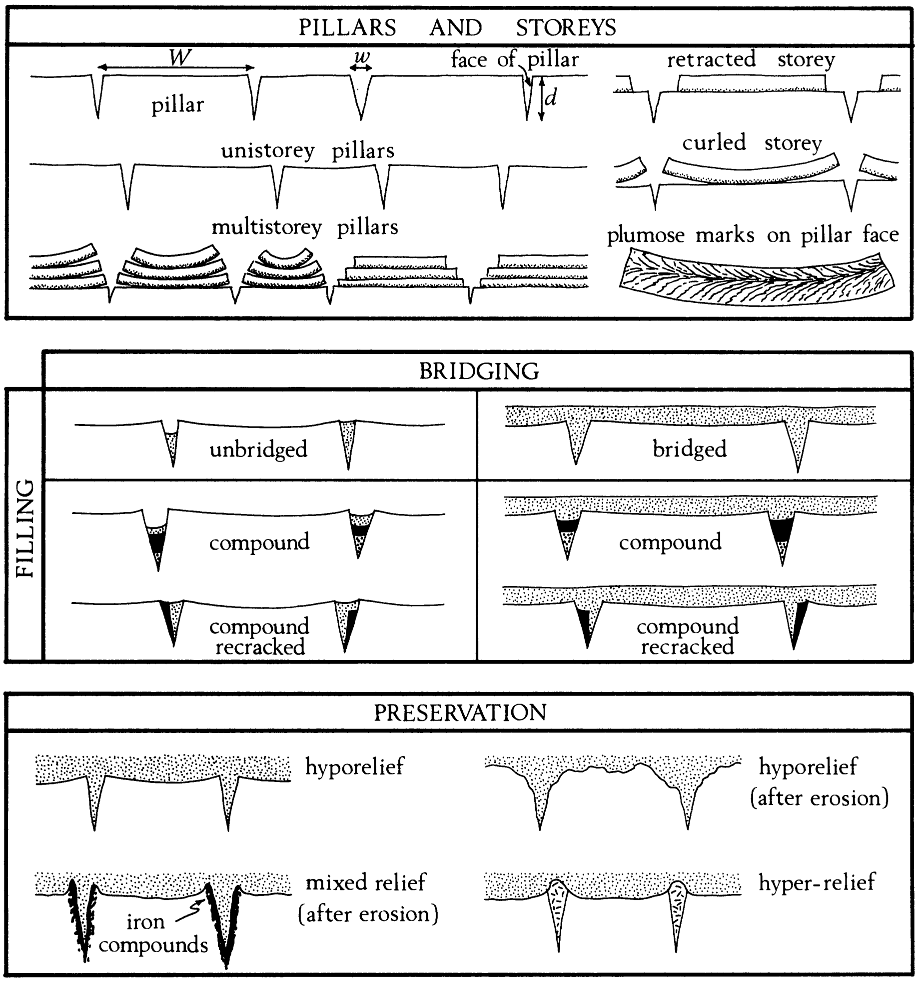

FIGURE 4. Characterization and outline classification of desiccation cracks, their fillings, and modes of preservation as seen in section.

4. GENERAL CHARACTER OF THE DESICCATION FEATURES

(*a*) *Initiation*

Although theoretically cracks should spread from defects in a drying muddy sediment (Lachenbruch 1961, 1962, 1963; Allen 1982), it is seldom possible in the field to establish the location and nature of those initiating flaws. Occasionally, however, the parent defects are clearly evident.

Commonest in the Severn Estuary, The Wash and the Norfolk coast is initiation at the footprints left by feeding birds (see (1) of plate 1). The process, favoured by warm weather and by tides moving from springs to neaps, is reported from river as well as other tidal environments (Wuest 1934; Schäfer 1953; Soleilhavoup & Bertouille 1976; Mason & Von Brunn 1978). Less common is the spread of cracks away from plants growing up through the sediment (see (2) of plate 1), either in the spring, when new growth appears, or at any time where an already-vegetated surface can receive fresh mud. A few instances were noticed of fractures initiated at bivalve shells, especially encrypted cockles on the northwestern shores of

The Wash (see (3) of plate 1), as observed by Kues & Siemers (1977) from the Florida Keys. In the upper and middle Severn, cracks occasionally form at scattered, concealed mud pebbles, a situation comparable to their initiation by Corte & Higashi (1964) at buried stones and similar objects. In rare instances in the Severn Estuary and on the Norfolk coast, cracks arise at scattered points on the clifflets limiting partly eroded but previously unfractured mud layers (see (4) of plate 1), and along the floors of shallow drainage runnels into which mud layers thin (see (5) of plate 1). In all three areas visited, new cracks can be triggered in identical positions to earlier ones, provided that the older cracks are not buried too deeply (see §4*h*).

Elsewhere desiccation cracks have been localized by such defects as surface trails (worms, gastropods, beetle larvae) (Hughes 1884; Baldwin 1974; Soleilhavoup & Bertouille 1976; Metz 1980), and above the crests and other raised parts of buried sand ripples (Häntzschel 1936; Picard 1966; Karcz & Goldberg 1967; Picard & High 1969, 1973; Donovan & Foster 1972; Karcz 1972; Soleilhavoup & Bertouille 1976). These inhomogeneities appear to play little or no role in the areas here discussed.

(*b*) *Plan shape of individual cracks*

Individual desiccation cracks within the intertidal zone vary considerably in overall shape (see figure 3). Although none are strictly straight over any distance of many crack widths, the term seems appropriate for those of little overall curvature, such as commonly appear in thick, relatively homogeneous muds (see (6) and (7) of plate 1). Some more obviously curved fractures, however, invariably accompany these straight ruptures. Particularly extensive layers

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DESCRIPTIONS OF PLATES 1 AND 2

PLATE 1. Initiation of cracks and character of individual fractures. (Scale box in (1–7) measures 0.05 m square; spade blade in (8) measures 0.14 m wide.)

(1) Cracks growing from bird footprints, upper hypertidal subzone, Oldbury-upon-Severn.

(2) Cracks initiated at grass stems (*Spartina*), middle hypertidal subzone, Oldbury-upon-Severn.

(3) Cracks growing from the sites of encrypted cockle shells, low middle hypertidal subzone, Freiston Low.

(4) Cracks spreading from the edge of an eroded mud layer, middle hypertidal subzone, Oldbury-upon-Severn.

(5) Crack growing along the axis (mud thinnest) of a mud-draped runnel, middle hypertidal subzone, Oldbury-upon-Severn.

(6) Straight regular late- to terminal-stage cracks, low upper hypertidal subzone, Berkeley (see also figure 6*h*).

(7) Straight irregular teminal-stage cracks, upper hypertidal subzone, Burnham Overy Staithe.

(8) Curved regular late-stage cracks, middle hypertidal subzone, Arlingham (see also figure 6*i*).

PLATE 2. Character of individual cracks. (Scale box measures 0.05 m square.)

(1) Curved regular to irregular early- to intermediate-stage cracks, upper hypertidal subzone, Scolt Head Island.

(2) Circular to subcircular teminal-stage cracks, middle hypertidal subzone, Oldbury-upon-Severn.

(3) Irregular intermediate-stage cracks developed in mud infested with *Nereis* and *Corophium*, low upper hypertidal subzone, Oldbury-upon-Severn.

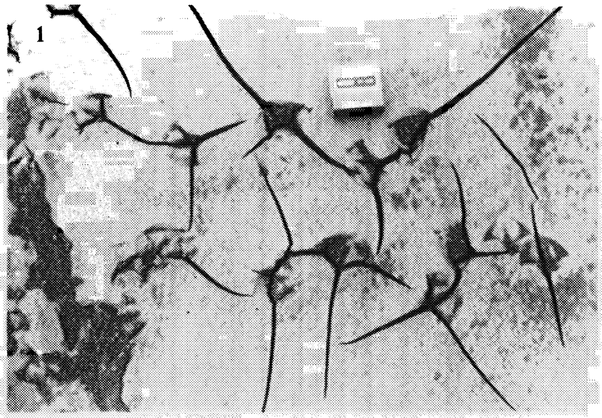
(4) Irregular late-stage cracks developed in crumb-textured mud, high upper hypertidal subzone, Berkeley (see also figure 6*a*).

(5) Irregular teminal-stage cracks in crumb-textured mud, upper hypertidal subzone, Scolt Head Island.

(6) Irregular early- to intermediate-stage cracks developed in muddy sand, lower hypertidal subzone, Freiston Low.

(7) Irregular late-stage cracks developed in deposit of mud clasts, upper hypertidal subzone, Oldbury-upon-Severn.

(8) Irregular intermediate-stage cracks with *en echelon* gashes developed in organism-infested muds, middle hypertidal subzone, Holbeach St Matthew.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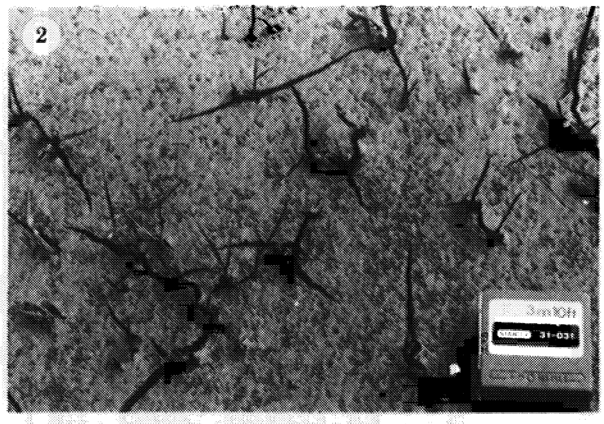
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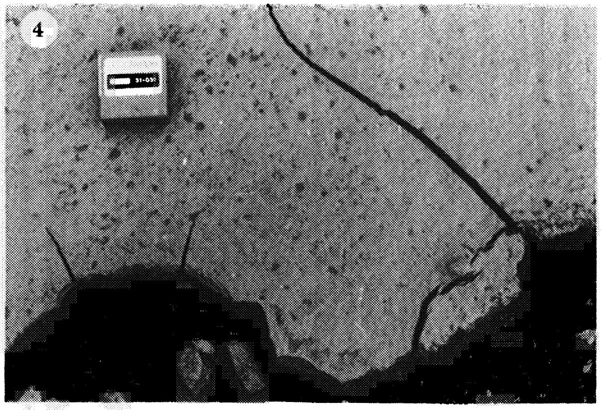
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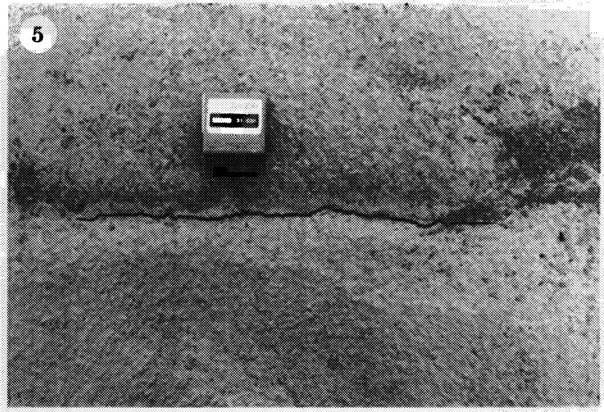
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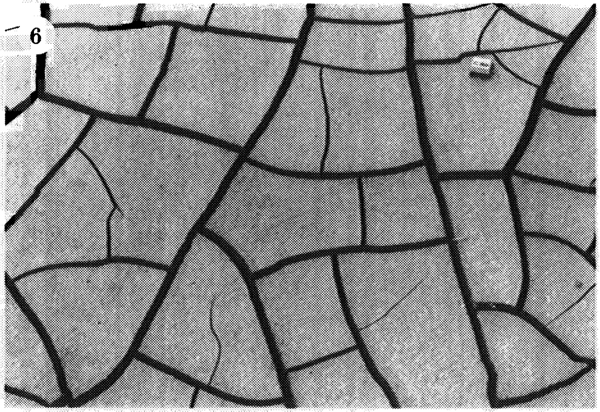
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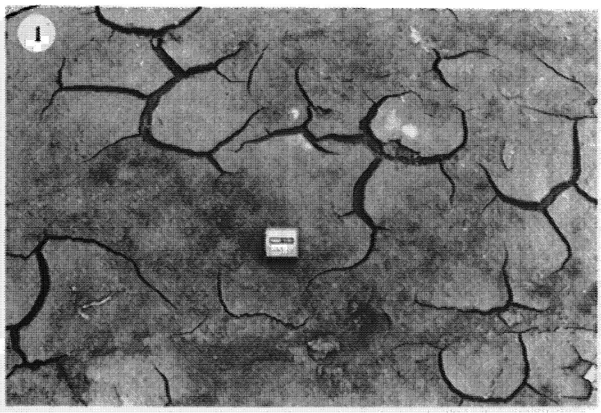
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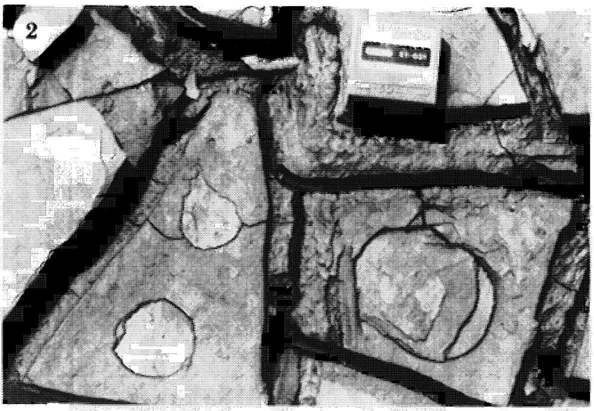
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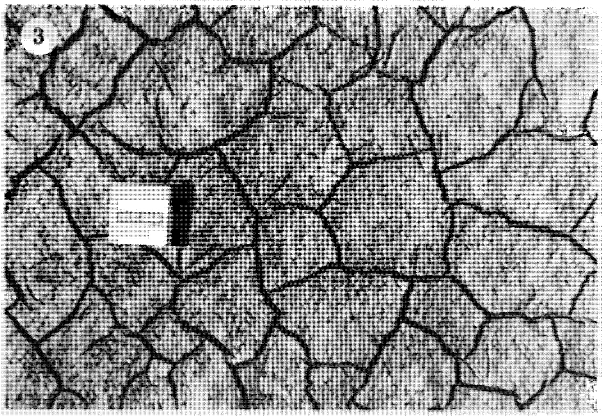
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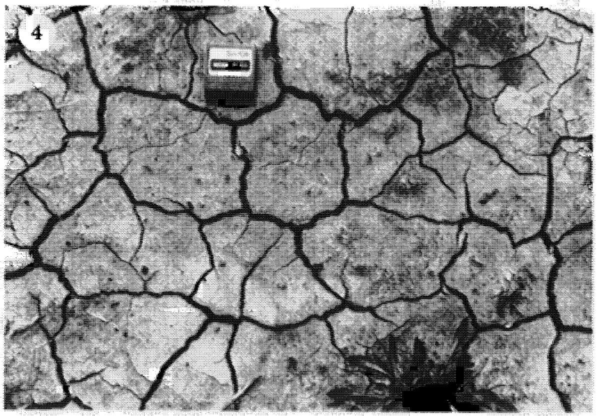
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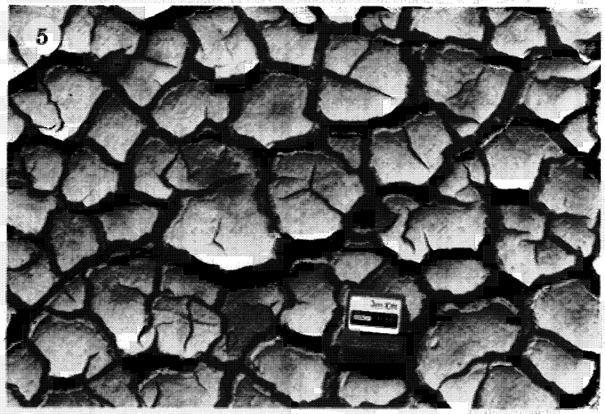
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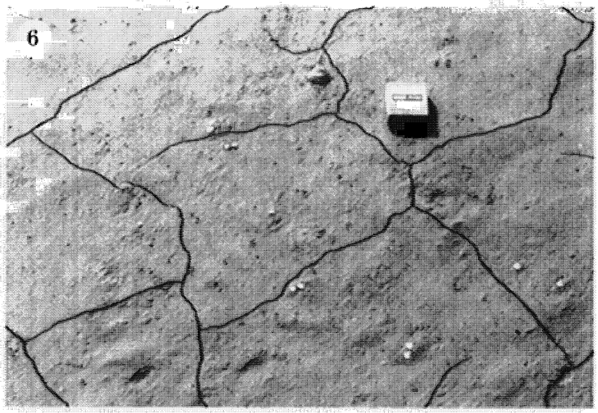
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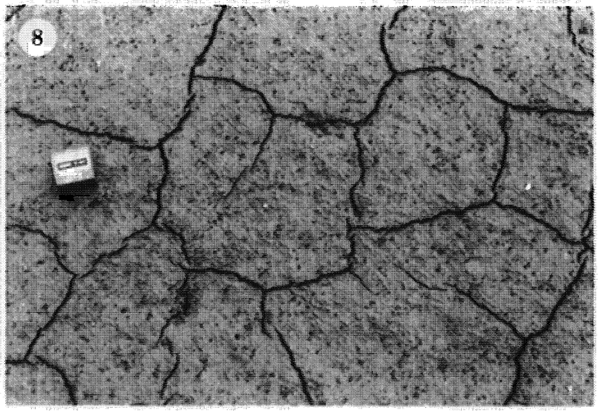
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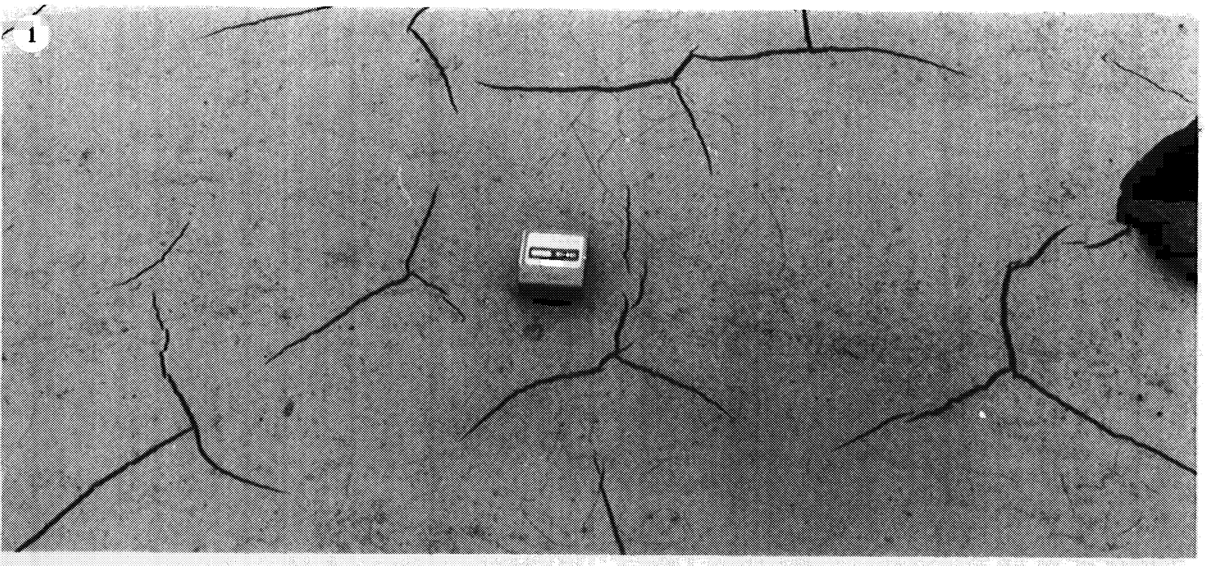
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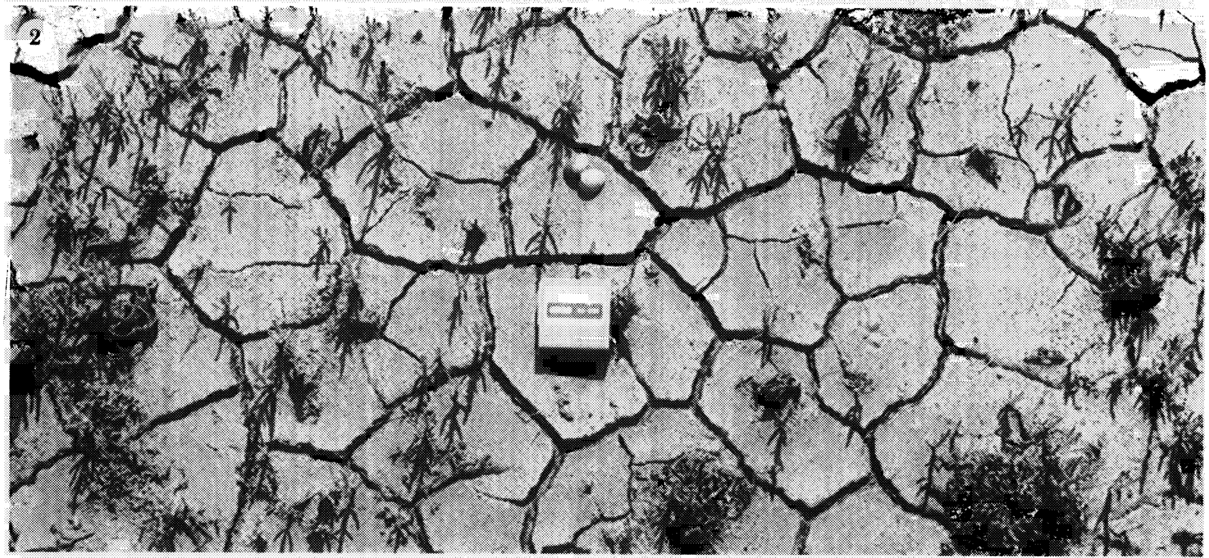
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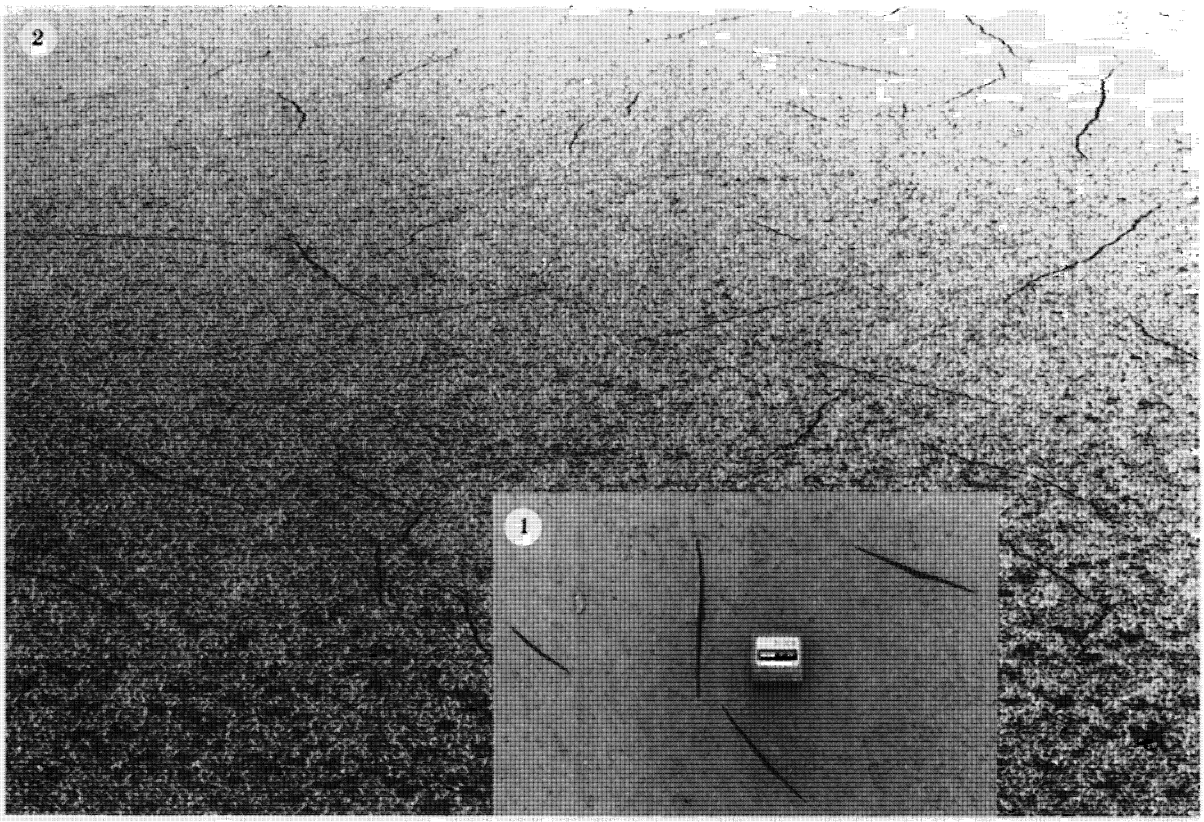

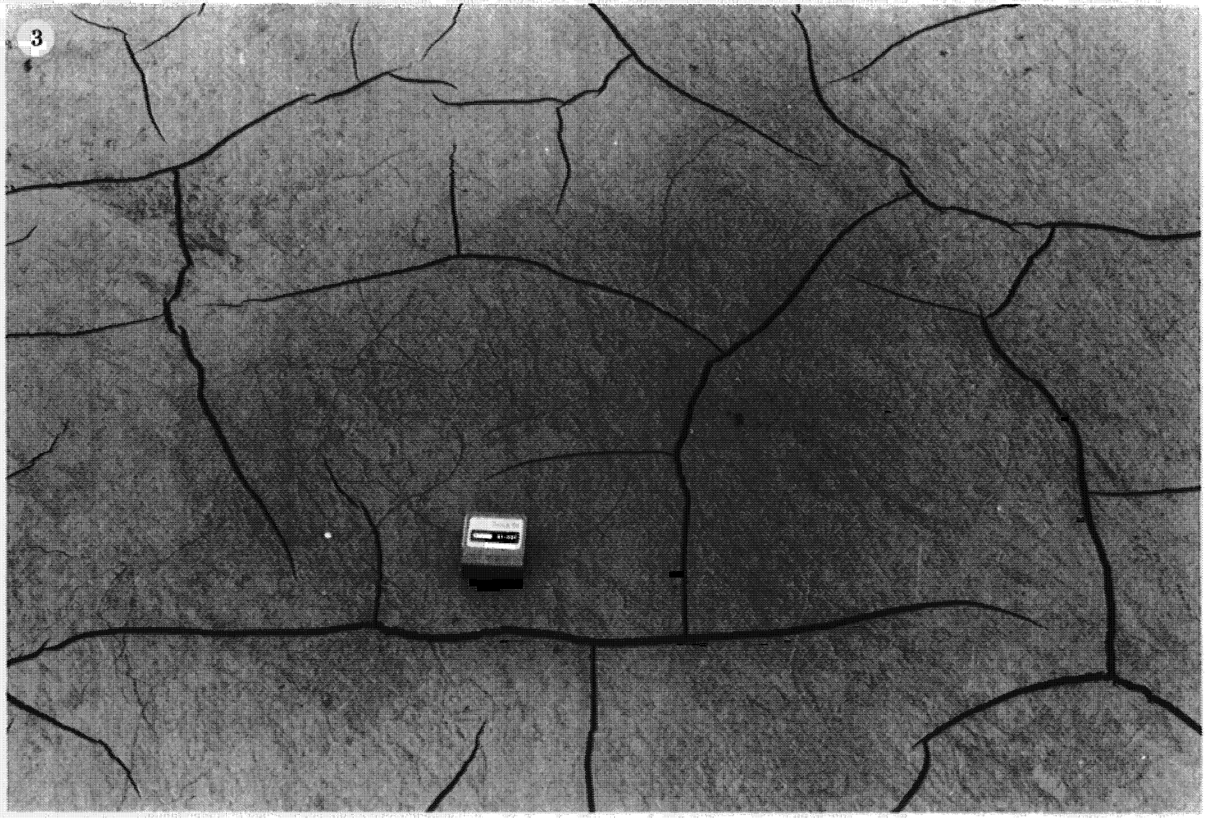

For description see opposite.

of thick uniform mud frequently form on the meander-enclosed bars at Rodley, Arlingham and Awre in the Severn Estuary. These sheets when quickly dried invariably give rise to long, strongly curved, and commonly winding cracks associated with relatively few straight elements (see (8) of plate 1). Similar cracks were made by Corte & Higashi (1964) in thin layers of mud deposited on a smooth bottom, a combination of circumstances partly corresponding to conditions on these bars. Like intertidal cracks figured by Plummer & Gostin (1981), the fractures shown in (1) of plate 2 are even more curved, and again arose in a comparatively thin, uniform layer. Picard (1966) and Soleilhavoup & Bertouille (1976) recorded similar forms, but from non-marine environments.

Roughly circular complete cracks (see (2) of plate 2) are not uncommon within the cores of pillars formed in thick, well-dried muds. These internal fractures, one or more to a pillar depending on the latter's shape, mark the inward limit of a storey crack and, from that limit, reach steeply downward in the form of a tapering cone. The dislocation either dies out unevenly downward at a tip in moist mud or terminates at a single deep-lying coarse lamina. The tapering 'cores' defined by these cracks resemble bath plugs or corks. They are readily detached and strewn by currents over the tidal flat. Circular cracks of this kind are not known outside the upper and middle Severn Estuary.

(*c*) *Crack margins and the sides of pillars*

The margins of cracks in a given set tend to be closely similar, either regular or variously irregular (see figure 3). Regular cracks typify the rapid desiccation of homogeneous muds which are little or not at all affected by either burrowing invertebrates or the long-repeated action of rain combined with plant growth (see (6) and (8) of plate 1). Such cracks are commonest in the middle and upper Severn Estuary, an area relatively poor in mud-dwelling invertebrates, where they can occur in all but the low hypertidal subzone. Fractures of this sort in the Norfolk marshes and The Wash are largely restricted to the upper subzone.

Plumose markings can usually be found on the faces of pillars bounded by regular cracks. Their pattern tends to vary with the vertical distribution of grain size within the pillar (see figure 5).

The irregularity of most cracks is of various scales with several rarely independent causes. On the north Norfolk coast, the muddier shores of The Wash, and in parts of the Severn Estuary, the middle and lower hypertidal sediments are more or less heavily infested with burrowing organisms, generally some combination of the amphipod *Corophium volutator*, the polychaete *Nereis diversicolor*, and the bivalves *Macoma balthica* and *Scrobicularia plana*. The cracks triggered

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DESCRIPTIONS OF PLATES 3 AND 4

PLATE 3. Non-orthogonal crack patterns. (Scale box measures 0.05 m square.)
- (1) Early-stage cracks, high middle hypertidal subzone, Berkeley.
- (2) Intermediate- to late-stage cracks, middle hypertidal subzone, Warham Marshes (see also figure 6*c*).
- (3) Late- to terminal-stage cracks, upper hypertidal subzone, Burnham Overy Staithe (see also figure 6*b*).

PLATE 4. Orthogonal crack patterns. (Scale box in (1) and (3) measures 0.05 m square; cracks in (2) are about 0.75 m apart.)
- (1) Early-stage cracks, middle hypertidal subzone, Oldbury-upon-Severn.
- (2) Early-stage cracks, lower hypertidal subzone, Berkeley.
- (3) Early- to intermediate-stage cracks, high middle hypertidal subzone, Berkeley.

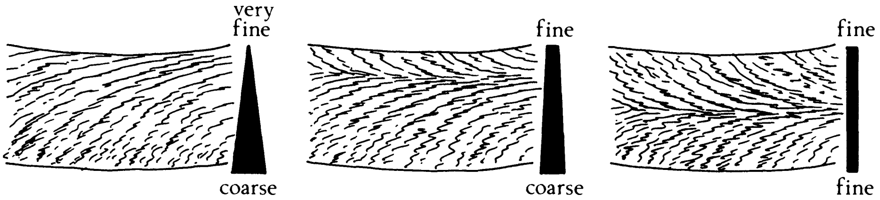


FIGURE 5. Common patterns of plumose markings observed on the faces of desiccation pillars, in relation to the vertical profile of grain size.

as these muddy sediments dry out tend to spread from one burrow or siphon to an adjacent one, and hence to advance along an irregular sequence of defects (see (3) of plate 2). In the upper hypertidal zone, and especially in salt-marsh pans, the main cause of irregular cracking is the destratified, almost crumb-like character of the sediment, acquired through some combination of (i) repeated drying and wetting by rain, (ii) the intermittent spread of plant roots, and (iii) temporary infestation by burrowing invertebrates, especially *Corophium* and *Nereis* and occasionally by *Arenicola* (see (4) and (5) of plate 2). The most irregular of all cracks due to this general cause were formed during a drought on the high marshes of the lower Severn Estuary, chiefly at Rumney Great Wharf and the mouth of the Rhymney River. A relatively coarse primary lithology also favours irregular cracking, as witness the muddy sands of the Wrangle Flats, Butterwick Low and Freiston Low in The Wash (see (6) of plate 2). Autumn and winter storms in the lower and middle Severn often severely erode the mudflats and spread far and wide in the middle and upper hypertidal subzone a thick blanket of mud clasts. These blankets also crack irregularly (see (7) of plate 2), on account of the large size of the particles among which the fractures spread. Plumose markings are never seen on the rough, uneven faces of pillars defined by irregular cracks.

A frequent contributory cause of local irregularity is the spread of a crack over one or more portions of its lengths as a series of step-like dislocations, expressed at the surface in the shape of *en echelon* gashes (see (8) of plate 2).

(*d*) *Patterns of cracks*

Cracks joined at an angle of 120° or so are called non-orthogonal (see figure 3) and give rise intertidally to various fracture patterns.

Some muds during early drying break along isolated biradiate and triradiate non-orthogonal cracks associated with few orthogonal junctions (see (1) of plate 3). The centres of these fracture systems are seldom less than 0.2 m apart and can be separated by as much as 1.2 m. The contraction is invariably small, of the order of 0.1–1 %.

Much more common are joined non-orthogonal fractures (see figure 6*a–d*). This pattern dominates the dried-out layers of mud pebbles (see (7) of plate 2) that are seasonally plentiful in the Severn Estuary. Fairly regular patterns involving five- and six-sided elements and chiefly non-orthogonal junctions are common in the partly bioturbated muds accumulating on the lower fringes of the East Coast salt marshes (see (2) of plate 3; also (4) of plate 2). The pillars tend to be small, about 0.15 m across, and contractions rarely exceed 10 %. Closely comparable fractures occur in high intertidal carbonate muds of Florida (Gebelein 1977), and on the salt flats of King Sound, Western Australia (Semeniuk 1981). As Van Straaten (1954) noted from the Wadden Sea, patterns of joined non-orthogonal fractures are especially common in the

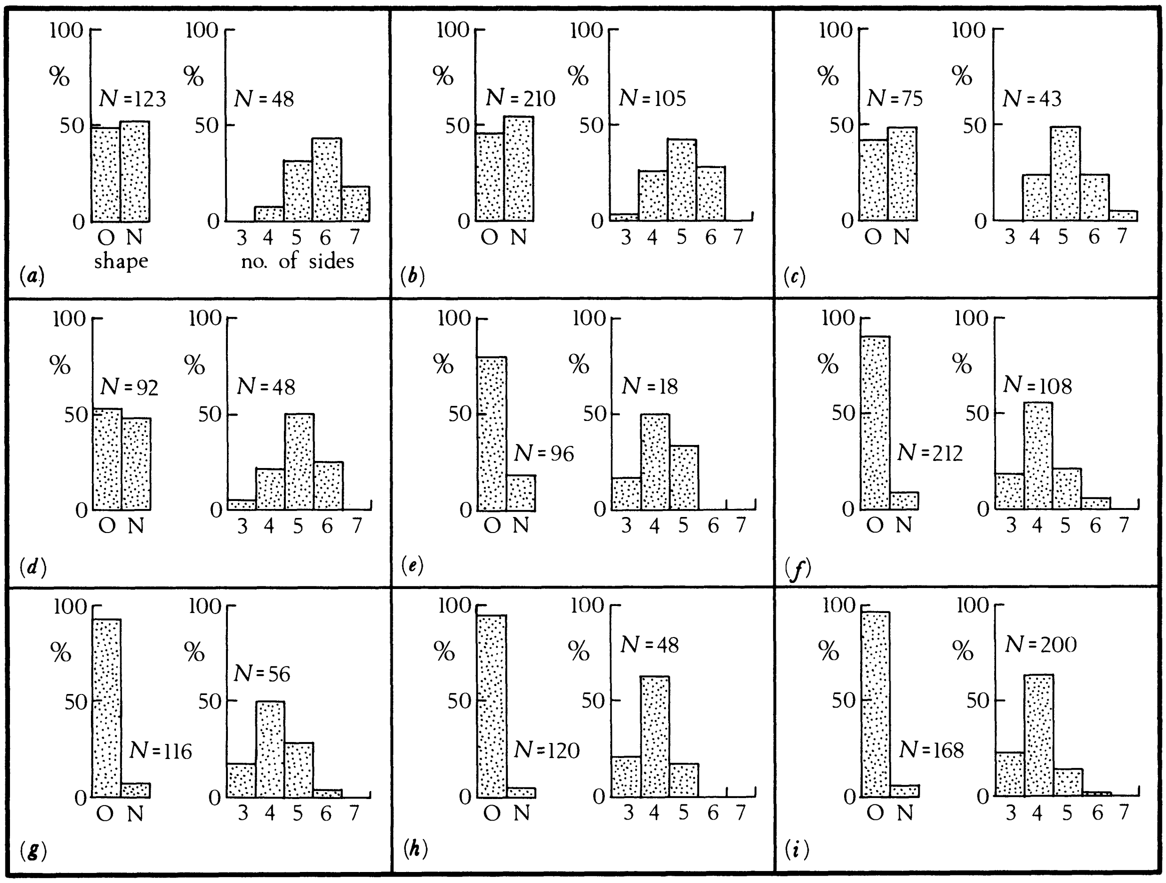


FIGURE 6. Statistical summary of representative patterns of desiccation cracks from the intertidal zone. The left-hand plot in each case shows the percentage of orthogonal (O) and non-orthogonal (N) junctions in the assemblage. The right-hand plot gives the percentage of pillars with a specified number of faces. (*a*) Upper hypertidal subzone, Berkeley (see (4) of plate 2). (*b*) Upper hypertidal subzone, Burnham Overy Staithe (see (3) of plate 3). (*c*) Middle hypertidal subzone, Warham Marshes (see (2) of plate 3). (*d*) Teminal-stage, non-orthogonal pattern, middle hypertidal subzone, Scolt Head Island. (*e*) High middle hypertidal subzone, Berkeley (see (1) of plate 5). (*f*) Low upper hypertidal subzone, Berkeley (see (3) of plate 5). (*g*) Low upper hypertidal subzone, Berkeley (see (2) of plate 5). (*h*) Lower upper hypertidal subzone, Berkeley (see (6) of plate 1). (*i*) Middle hypertidal subzone, Arlingham (see (8) of plate 1).

partly to thoroughly disturbed sediments of salt-marsh pans (see (3) of plate 3; also (5) of plate 2). Pillars here range up to 0.25 m wide and vary greatly in regularity from one set to another. Substantial numbers of orthogonal junctions are invariably present, especially where the pillars are uneven in size. Extreme contractions of 15–20% have been recorded from cracks in fully dried-out pans.

Sets of orthogonal cracks (see figure 3) comprise fractures that in the main either face or join each other at right angles, depending on the extent of desiccation. Such patterns typify rapidly dried muds in the middle and to a lesser extent the lower hypertidal subzone, provided that the layers accumulated quickly, are thick and homogeneous, and suffered little or no destratification. Orthogonal fractures were seen at all the localities described, but proved to be best developed in the Severn Estuary, where short-term deposition rates are comparatively high and where the infauna is only locally and intermittently dense.

In their earlier stages (see (1) and (2) of plate 4), orthogonal patterns are represented by scattered, wholly unjoined to partly joined cracks with little obvious preferred orientation. Contractions measure as little as 0.01–0.5 %.

A more advanced stage of drying sees many to most cracks joined up mainly orthogonally (see (3) of plate 4 and (1) of plate 5). A contraction of a small percentage is typical. Any irregularity of the fracture margins is mainly attributable to *en echelon* gashes.

Few or no ruptures remain unjoined in orthogonal sets at late and terminal drying stages, when contractions of 5–15 % are attained (see figure 6*e*–*i*). The cracks have no preferred orientation in some sets (see (2) of plate 5 and (8) of plate 1), weak to moderate preferred trends in others (see (6) of plate 1), and two strongly preferred directions in a minority of cases (see (3) of plate 5). Typically most pillars are four-sided, but substantial numbers of three- and five-sided ones also occur (see figure 6*e*–*i*). Five-sided pillars are commonest in poorly oriented sets dominated by short, mainly straight fractures (see (2) of plate 5) rather than by long, winding ones (see (8) of plate 1). The pillars tend to be on the large side, with a typical width of several decimetres and a greatest span up to 1 m. Crack depths could not be measured with much confidence but seemed to lie between three and eight times the width. Similar joined orthogonal sets were described from the intertidal muds of Florida (Kindle 1923; Gebelein 1977), the Atlantic Coast of France (Bajard 1966; Mathieu 1966; Verger 1968; Plummer & Gostin 1981), and the tidal flats of the Mahakam delta in Indonesia (Allen *et al.* 1979), as well as from various freshwater deposits (Kindle 1926; Keller & Foley 1949; Glennie 1970; Picard & High 1973; Donovan & Archer 1975; Soleilhavoup & Bertouille 1976; Bishop *et al.* 1984).

Radial (non-orthogonal) and concentricoradial (orthogonal) sets of cracks (see figure 3) are very rare intertidally. The former (see (1) of plate 6) are restricted to the middle and upper Severn Estuary, where uniformly thin, slow-drying mud sheets are occasionally spread during the winter and spring over the higher salt marshes. The sets mainly consist of short, irregular cracks tending to join radially inward at Y-shaped junctions. The irregularity derives largely from the presence of *en echelon* gashes. In some radial clusters one crack is much longer than any other and traverses the whole pattern through its centre. Large areas can be uniformly covered by these clusters, which typically have a centre spacing of 0.5–1.25 m. Kindle (1926) recorded similar sets from a recently flooded Nevada playa. Only one concentricoradial set was observed. Like Scherber's (1931), it arose in mud partly filling a deep, roughly circular depression, in the present case a scour hollow.

(*e*) *Features associated with crack growth*

Corte & Higashi (1964) found in their laboratory that desiccation cracks in orthogonal sets grew slowly as individuals, increased gradually in areal density, and tended either to face or to join at right-angled intersections. The present widely cast study yields no field evidence discordant with these conclusions.

Part (1) of plate 7, from a set of partly unjoined orthogonal cracks, is typical of the field evidence supporting the above statement. Regardless of shape, individual cracks are seen to be both spreading from orthogonal junctions and, at their sharply pointed tips, approaching nearby ruptures orthogonally.

It is at an intermediate stage of drying, when cracks begin to join in some number, that tension gashes begin to form singly or in groups along primary ruptures. The gashes enhance the irregularity of many cracks (see (8) of plate 2), but are of most interest as indicating shear, and in some cases actual shear displacements, across fractures as shrinkage proceeded. The displacements appear to be rare, as such features as trails and feeding traces practically never prove to have been displaced when compared across the width of the cracks. Gashes appear at two scales and in various patterns (see figure 7).

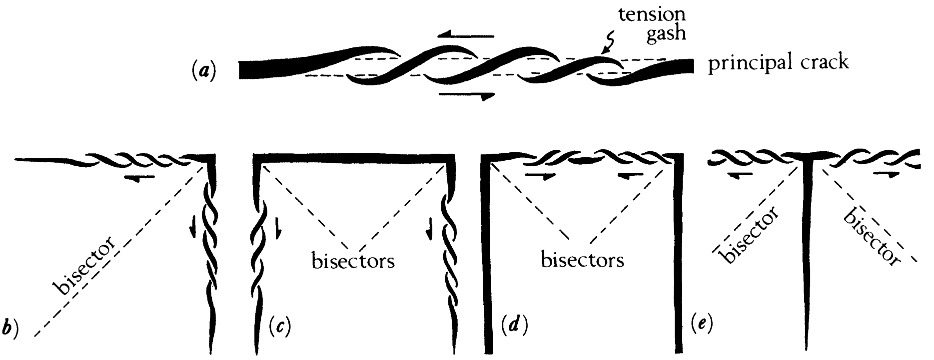


Figure 7. *En echelon* tension gashes associated with desiccation cracks. (*a*) General morphology and sense of shear (arrows). (*b–e*) Association of gashes with various patterns of cracks.

Some gashes take a scale only one order of magnitude smaller than the pillars that they accompany. Isolated pairs of oppositely curved fractures (see (2) and (3) of plate 7) tend to arise as roughly parallel but offset straighter cracks grow toward each other. Such pairs either define large step-like features on the faces of the adjoining pillars or range downward to much the same depth as the main cracks. Long sequences of comparatively large offset fractures, to which the term tension gash is perhaps more appropriate, affect the more uniform and extensive mud sheets that dry in the middle and upper Severn Estuary (see (2) and (3) of plate 6). The rows course for many metres through these sheets, dividing up the sets of straight to curved orthogonal cracks into large domains.

The commonest *en echelon* gashes, observed at most of the sites, are small to very small in scale relative to the principal fractures and the pillars. At the surface (see figure 7*a*) they are seen as rows of as many as ten sigmoidal gashes along the line of a principal crack. The gashes define step-like features that twist slightly and fade out downward into the principal cracks represented by the faces of the pillars, as figured by Pollard *et al.* (1982) from fractured rocks. In one pattern (see figure 7*b* and (4) of plate 7) the gashes lie along two essentially orthogonal principal ruptures. A second arrangement (see figure 7*c* and (5) of plate 7) shows gashes with a common sense of shear ranged along opposite sides of a trough-shaped pattern of three principal cracks. In a third pattern (see figure 7*d* and (6) of plate 7), the gashes are again associated with a trough-shaped set of principal cracks, but are restricted, with a symmetrical change in the sense of shear, to the side joining the remaining two. By far the commonest pattern is associated with an orthogonal junction (see figure 7*e*; (7) and (8) of plate 7), particularly that formed as one principal crack grows away from another initiated at a similar time. Diametrically opposed shear displacements can be inferred along the two parts of the cross-piece of the arrangement.

(*f*) *Features of late desiccation*

Late and terminal stages of intertidal desiccation normally see the formation of secondary (and even tertiary) cracks, which may be either vertical or horizontal (storey cracks) or both (see figures 3 and 4).

These late-stage features are restricted to one or more generations of vertical cracks in the thick, sparsely laminated sediments of open mudflats (see (1) of plate 8) and in the destratified muds of salt-marsh pans (see (2) of plate 8). Mathieu (1966) found similar intertidal forms. Better laminated deposits, such as occasionally form in the outermost marsh pans, normally become split both vertically and horizontally by secondary fractures (see (3) of plate 8), in a similar manner to many river muds (Kindle 1926; Soleilhavoup & Bertouille 1976). A distinctive feature of intermediate to late desiccation in salt-marsh pans and along marsh edges is the inception and growth of secondary cracks away from the centres rather than the edges of the tops of pillars (see (3) and (4) of plate 8).

Storey cracks predominate as secondary fractures in muds with plentiful laminae, particularly where sand is present, as in the middle and upper Severn Estuary. Thick layers of sediment yield wide pillars and, therefore, storeys of substantial moist mass. These tend to remain flat as they shrink differentially and slide on the silt or sand layers (see (5) of plate 8), becoming retracted from the planes of the primary cracks to an extent decreasing downward, as Kindle (1923) noted from intertidal carbonate muds dredged up from the Florida Keys. Storeys less than about 0.2 m across, however, curl up at the edges, the amount of bending increasing as the affected sediment becomes thinner (see (6), (7) and (8) of plate 8). These storeys prove to grade from coarse up to fine, consistent with Bradley's (1933) explanation of curling by differential contraction (Allen 1986). The curl seldom exceeds 120°, and nothing has been seen or reported (Häntzschel 1936; Bajard 1966) to match the thin, tightly rolled storeys (mud curls) so prevalent in river environments (Longwell 1928; Karcz & Goldberg 1967; Picard & High 1969, 1973; Glennie 1970; Soleilhavoup & Bertouille 1976).

(*g*) *Filling of cracks*

The intertidal desiccation cracks of the Severn Estuary, north Norfolk coast, and The Wash can be infilled at any stage after initiation, in a variety of ways, and by many materials.

Although mud is the commonest material introduced into hypertidal fractures, a single tide is rarely enough to see their complete infilling and bridging. Hence most cracks have a compound fill (see figure 4), involving either a repetition of mud deposits, or a sequence of contrasting sediments. Typically, a new accretion of mud in the first instance drowns the cracks virtually to the top (see (1) of plate 9), as Mathieu (1966) observed, but as the deposit is liquid and subject to later contraction, the eventual depth of filling is generally less (see (2) of plate 9). The advent of fresh watery sediment permits burrowers once more to inhabit the surface. If a long interval separated the start of desiccation from crack infilling, however, a significant difference in the density or kind of animal, or both, may be detectable between the old and the new sediments (see (3) of plate 9; also (6) of plate 10). Such differences were seen in all the areas visited, except the upper Severn Estuary. Occasionally, a single tide drops enough mud to bury completely any pre-existing desiccation cracks. The few ruptures that subsequently become evident (see (4) of plate 9) owe their visibility to the drainage of liquid mud and consolidation-released water off the surface. Few cracks appear to become infilled in less than two or three episodes.

Quartz sand is a common infilling in the middle and upper Severn Estuary, the northeastern shores of The Wash, and on the margins of the sandy creeks within the Norfolk marshes. The evidence of trenches, together with the character of the sedimentary surfaces (see (5) of plate 9), suggests that the infilling of cracks by sand in a single stage is also infrequent. A compound fill which includes one or more mud layers seems instead to be typical. A few mud clasts may also be present, as in the sand drifting over the fractured surface shown in (5) of plate 9. In muddier settings, some sets of cracks become partly or even wholly infilled with such debris (see (6) of plate 9), especially during stormy periods, when layered muds are prone to break up (see, for example, Nossin 1961). Thus it is not uncommon to find the larger cracks tightly jammed with vertically arranged flakes and plates of dried mud. A scattering of *Macoma* or *Scrobicularia* shells may also be present. In places on the northwestern shores of The Wash, the larger desiccation cracks are filling up with alternate layers of mud and cockle shells (see (7) of plate 9) drifted up from eroding sand flats to seaward.

(*h*) *Overlap of desiccation and filling*

It is often the case at the sites mentioned that desiccation and rupture infilling overlap in time, particularly in the middle and upper hypertidal subzone. Complex structures result where desiccation and filling were extensively repeated before final burial.

An early and relatively simple stage in this process appears in (1) of plate 10. The wide cracks that spread through a thick homogeneous mud dried to an intermediate to late stage became partly infilled with further mud, the combination then shrinking further. The younger cracks grew partly in the pillars defined by the first fractures and partly in the mud incompletely filling those ruptures, which in consequence partly reopened. The younger fractures are either orthogonal to the older ones or follow the surface of contact between the original pillars and the subsequent infill. Locally the whole infill adheres to a pillar, but in other places a vertical plate of mud is separated from the pillars by a crack on each side. In other cases of this type of reopened crack, and particularly from the salt-marsh pans of the Norfolk coast and The Wash, the younger crack approximately bisects the first, so that each pillar clasps approximately one-half of the infill. The firm adherence of infills to all the faces of pillars formed in this setting is perhaps due to the considerable roughness of those faces.

A wide variety of crack–infill relationships is to be expected within desiccated intertidal muds, to judge from the character of surfaces such as that described (see (1) of plate 10), and the results of a layer-by-layer dissection of partly dried sequences. Figure 8 illustrates the simpler and more confidently established of these relationships. They represent preservation in hyporelief (see figure 4) and involve no more than two episodes of cracking and either two or three episodes (or sequences of episodes) of filling. Some dissections revealed quite complex relationships, the sediment for a number of decimetres being riven by several generations of cross-cutting and both horizontal and vertical infills, giving the deposit a brecciated appearance.

(*i*) *Erosion of desiccated surfaces and infilled cracks*

The readiness with which dried intertidal mud layers break down into clasts under wave and tidal action is well known (see, for example, Häntzschel 1939; Nossin 1961; Mathieu 1966; Le Gall & Larsonneur 1972; Augustinus 1978; Semeniuk 1981). Much less is known about the effects of erosion on the sediments that remain.

Muds accumulated in salt-marsh pans and over the uppermost hypertidal mudflats may dry out completely at times during the spring and especially the summer. They are then prone to erosion as the result of rain-wetting (slaking) and impact, as well as through wetting and current effects associated with changes in the tide. The normal consequence, in The Wash and the Norfolk coast, is the rounding of the tops of the pillars. In the least affected cases, only the upper edges become smoothed, as Kindle (1926) and Longwell (1928) observed from certain playa cracks, the flakes and scales of liberated mud falling into the fractures below. A more extreme but not uncommon result is the rounding of the whole of the top of a pillar, and the creation of either an irregularly scalloped (see (2) of plate 10) or a deeply pitted and gnarled surface (see (3) of plate 10). Some pillars even become undercut, as in (3) of plate 10. Less commonly, erosion only affords a central cluster of coarse pits (see (4) of plate 10).

The deep erosion of a desiccated mud leads to various effects. An irregular surface formed of intersecting conchoidal fractures is an occasional winter feature (see (5) of plate 10), but more common is one that steps unevenly up and down through a sequence of laminae (see (6) of plate 10). When thinly buried and further dried, infilled cracks in this kind of surface commonly localize additional fractures (see figure 8*d*). These effects abound in the Severn Estuary and on the open mudflats of The Wash and the Norfolk coast, but rarely appear in the marsh environments.

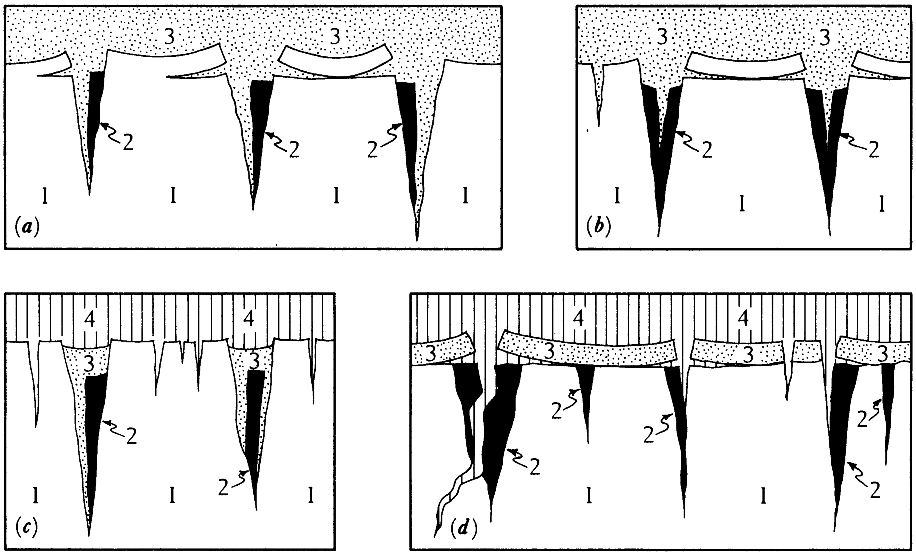


FIGURE 8. Schematic representation of the simpler crack-infill relationships observed from the intertidal zones of the Severn Estuary and the east coast of England. (*a*, *b*) Two episodes each of cracking and filling. (*c*) Two episodes of cracking and three of filling. (*d*) Two episodes each of cracking and filling with an episode of erosion followed by deposition (sediment 3) intervening.

Erosion may lead under two circumstances to the preservation of desiccation cracks in hyper-relief (see figure 4). One is where the infilling mud is more resistant to erosion, because of its homogeneity and greater water content, than the drier, intricately fractured or laminated, or both, sediments of the pillars. As seen on the margins of channels crossing the Norfolk marshes, and on the open mudflats of the Severn Estuary and The Wash, the pillars may then be eroded to lower levels than the infills, which stand as ribs on the surface (see (7) of plate 10). A potential mode of preservation in hyper-relief restricted to the northwestern shores of

The Wash appears in (8) of plate 10. Here erosion roughly to the depth of encrypted *Scrobicularia* (*ca.* 0.2 m) has picked out resistant impregnations of iron compounds into the permeable sides of large sandy pillars. These impregnations form paired ribs (compare (7) of plate 10).

5. Seasonal and tidal controls

(*a*) *Experimental sites*

Five hypertidal sites divided between two contrasted localities were established on the English bank of the Severn Estuary and visited at fortnightly to monthly intervals over a period of about a year beginning on dates in July 1982. Apart from their suitability on sedimentological grounds, the localities were chosen mainly for their all-season accessibility and minimal human and animal interference.

The northern locality is at the neck of the lowermost point bar of Berkeley Pill (British National Grid Reference SO 674 002) (see figure 9*a*). Here a profile roughly parallel with the bar axis was levelled from the marsh cliff across the mud (see figure 9*b*). At each of two sites on this profile, a pair of long metal stakes 1 m apart along a contour on the surface was driven vertically into the mud leaving only short portions visible. Site BA lies at approximately 6.3 m O.D. and, referring to the immersion curve (see figure 2*b*) after positional and seasonal correction, was inundated by nominally 41 % of the tides that occurred during the observation period. Site BB lies 0.2 m lower and was wetted by nominally 46 % of the tides. Both sites are

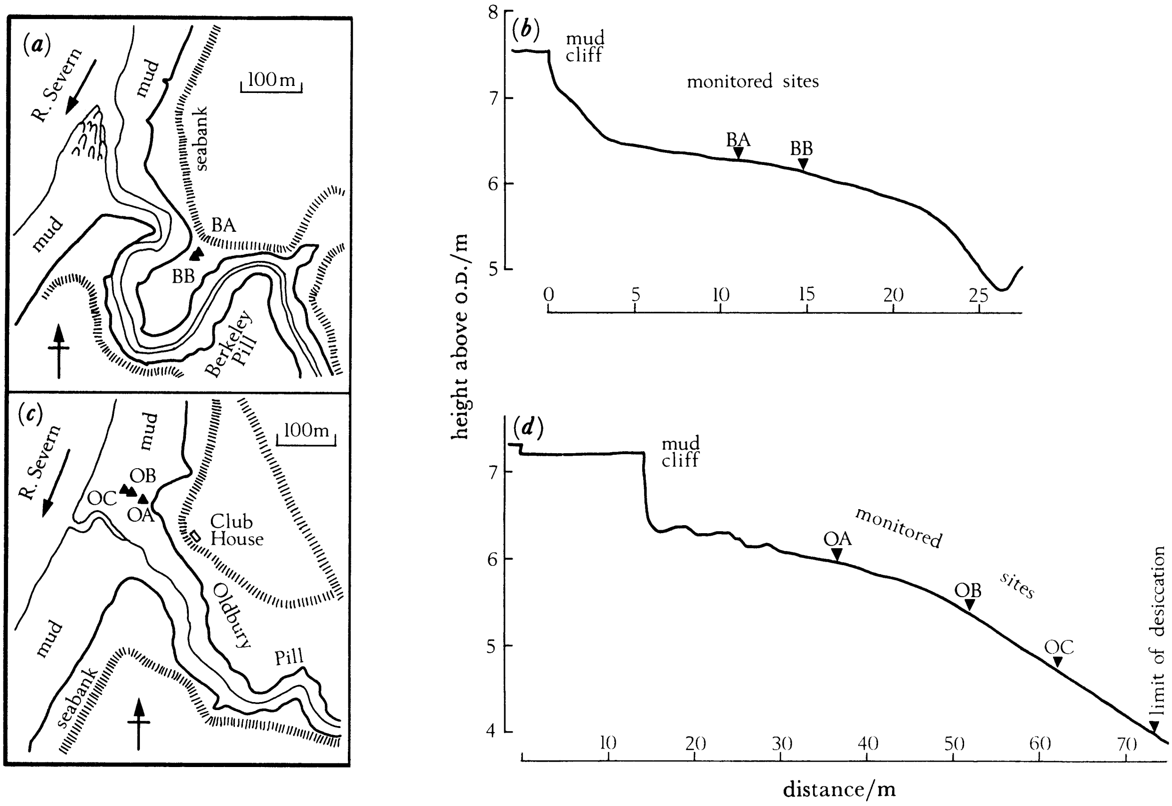


Figure 9. Location maps and profiles for the intertidal sites monitored at (*a*, *b*) Berkeley Pill and (*c*, *d*) Oldbury Pill. See also figure 1*a*.

stable in the long term but accretionary, primarily because the muds of the bar are creeping and, at the margins, slumping under their own weight into the adjacent channel. Accretion was so substantial during the year of observation that, about half-way through, the original pair of stakes had to be replaced. Lying within the pill, the Berkeley sites are sheltered from wave action, with the result that little mud is resuspended.

By contrast, the southern locality, on the open mudflats northeast of Oldbury Pill (ST 600 929) (see figure 9*c*), experiences the normal tidal and wave régime of the middle estuary, and is subject to both erosion and deposition. Three sites were established here in the previous manner on a profile across the salt marshes and mudflats starting near the yachting club house (see figure 9*d*). Site OA lies at approximately 6.0 m O.D. and, referring to figure 2*b* after corrections, received nominally 43% of the tides during the observation period. It therefore compares in exposure with sites BA and BB. Sites OB (5.4 m O.D.) and OC (4.7 m O.D.) experienced nominally 58% and 74% of the tides, respectively.

(*b*) *Tidal and seasonal factors*

The degree of desiccation shown by a hypertidal mud depends on the cumulative effects of (i) exposure to wind and sun and (ii) wetting by tide and rain.

None of the sites was exposed to the atmosphere for more than one whole spring-neap cycle, but sites BA, BB and OA were covered by clusters of fewer tides in a cycle than site OB, which in turn was drowned by a shorter sequence of high waters in a cycle than site OC (see figures 10–12). The extent of exposure was slightly more in late spring and early summer than in early winter, but was greater at each of these times than in the autumn and the late winter/early spring, the equinoctial periods. Tidal surges due to meteorological causes – positive ones were the more frequent – slightly modified the predicted immersions given above.

The drying of wet mud through moisture loss into the atmosphere involves a change of state, demanding a supply of heat, followed by mass transfer by forced convection. Hence the drying rate should increase with the meteorological factors (i) air temperature, (ii) extent of exposure to sunlight, and (iii) wind speed, but decrease with (iv) rainfall. The effect of wind speed is with little doubt approximately linear (Verma & Cermak 1974*a*, *b*). The effects of air temperature and exposure to sunlight are less certain, because the (unknown) properties of the affected mud are also involved, but may also be expected to be roughly linear. Weather data were not available for the Oldbury and Berkeley sites themselves, so that recourse was made to information available at the Meteorological Office (Bracknell) for the Bristol Weather Centre. This low-level urban station lies 20–30 km SSW of the sites and 10 km from the nearest shore of the Severn Estuary. Because of the comparatively distant position and nature of the Bristol station, the influence of the above factors considered to affect drying is summarized in a single drying or weather index, calculated *inter alia* as the sum of (i) the daily maximum temperature divided by the long-term mean, (ii) the daily hours of sunlight divided by the long-term mean, and (iii) the daily mean wind speed divided by the long-term mean, less (iv) the daily precipitation divided by the long-term mean. These quantities have been evaluated (see figures 10–12) for the period 5 July 1982 to 8 July 1983.

(*c*) *Assessment of response at the sites*

The response at each site to the factors controlling desiccation may be summarized under four headings (see figures 10–12). 'Sedimentation' refers to the net sedimentary effect of the

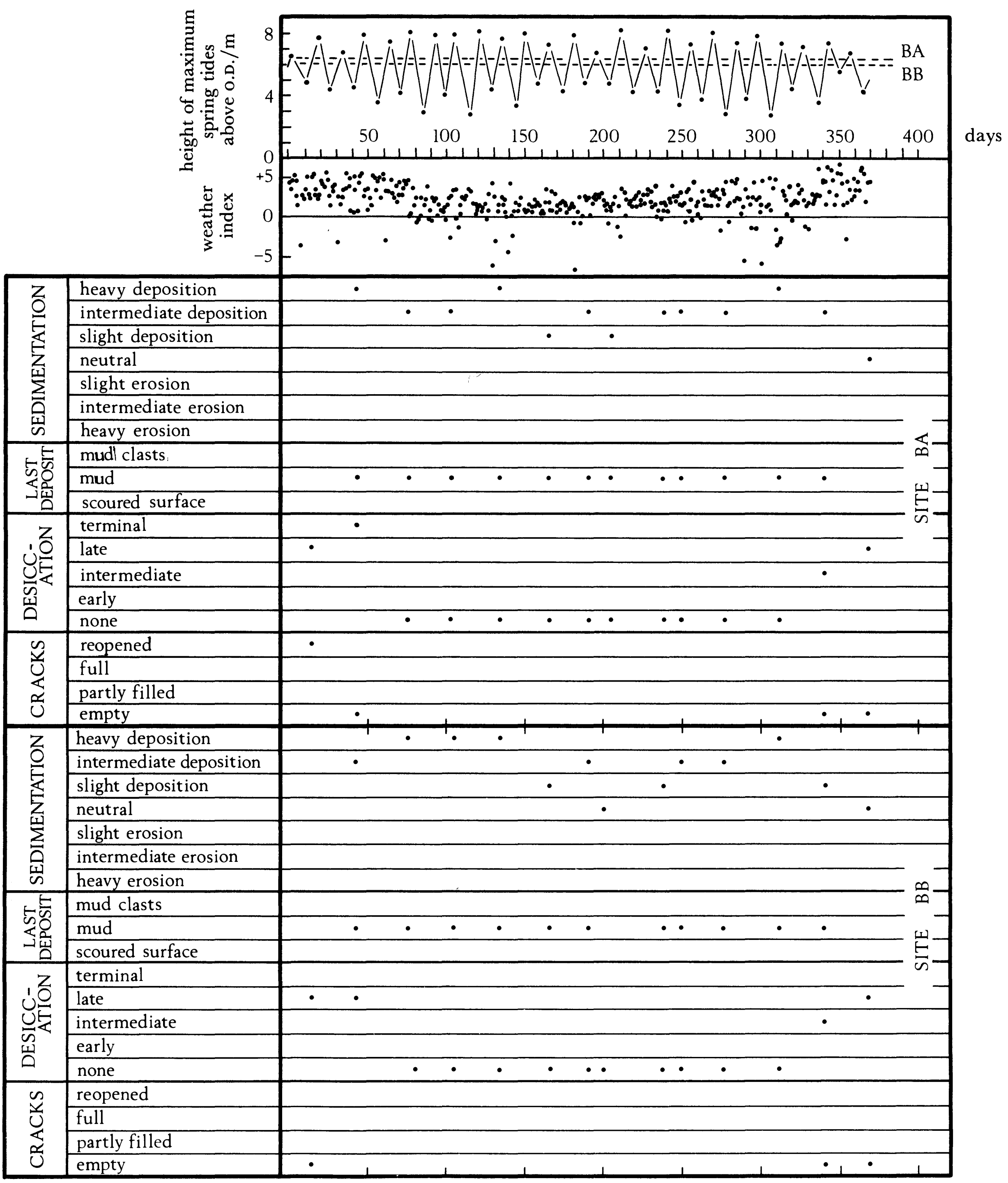


FIGURE 10. Development of desiccation features at the Berkeley Pill sites (see also figure 9*a*, *b*) as a function of tidal and weather régimes. The period covered is from 19 July 1982 to 8 July 1983.

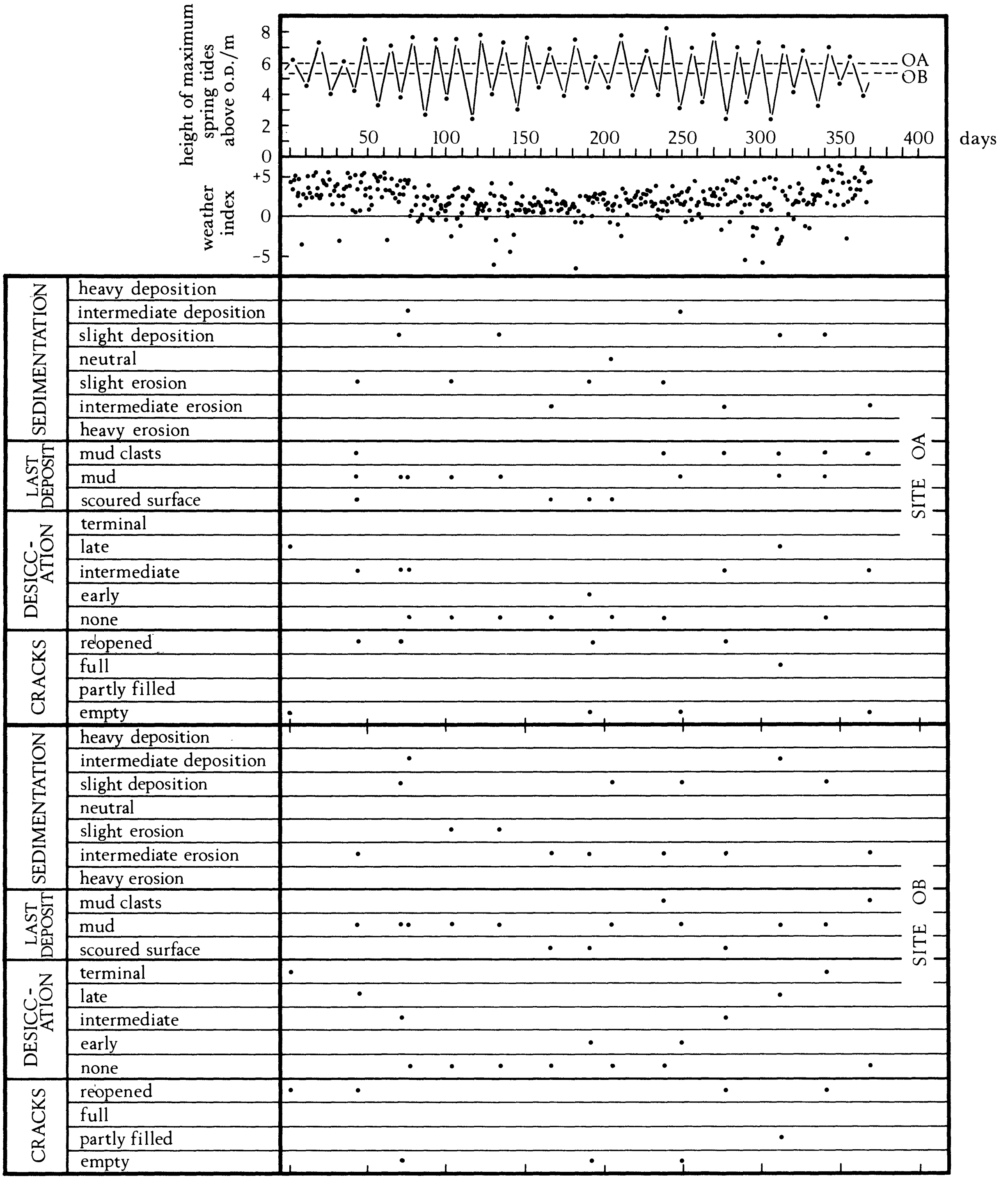


FIGURE 11. Development of desiccation features at sites OA and OB at the mouth of Oldbury Pill (see figure 9*c*, *d*) as a function of tidal and weather régimes. The period covered is from 5 July 1982 to 8 July 1983.

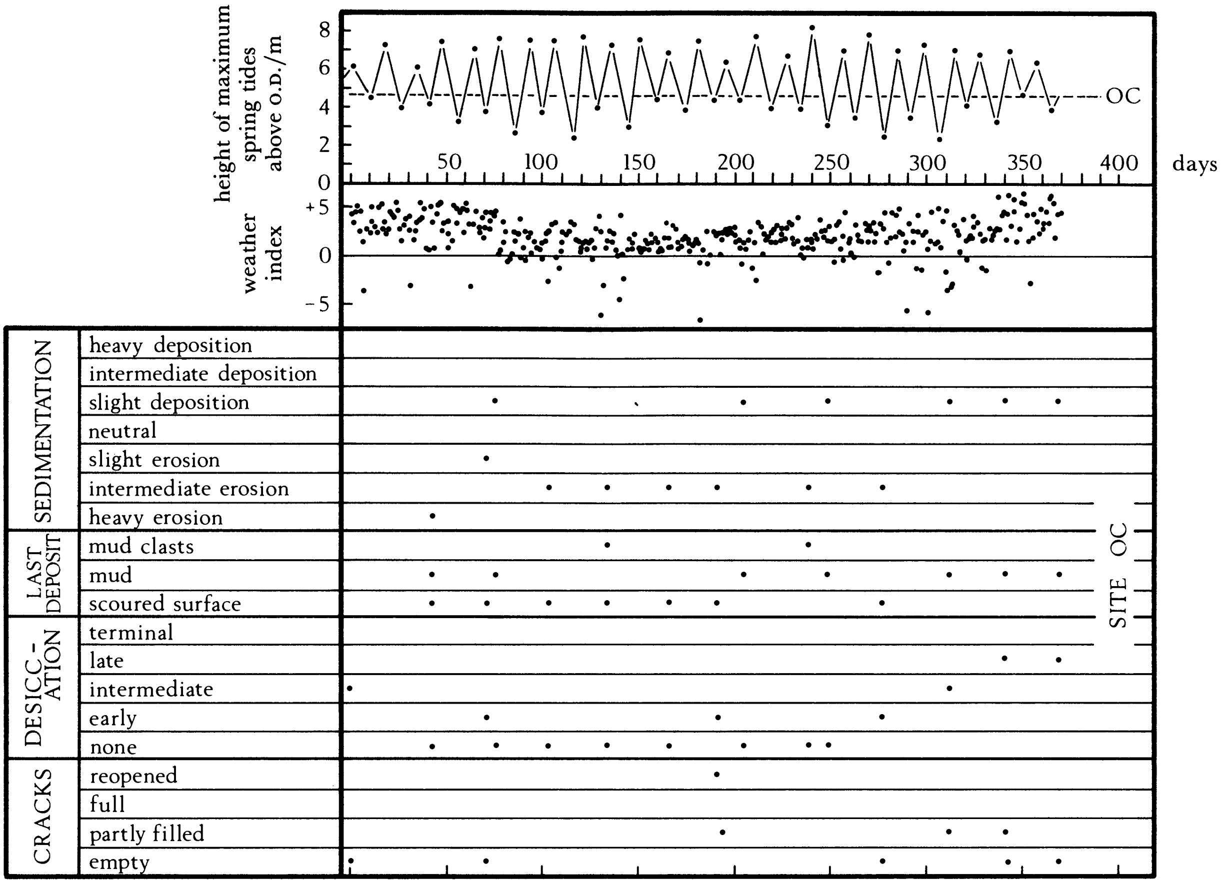


Figure 12. Development of desiccation features at site OC at the mouth of Oldbury Pill (see also figure 9*c*, *d*) as a function of tidal and weather regimes. The period covered is from 5 July 1982 to 8 July 1983.

tides (and to some extent the rain) that wetted a site since the previous visit. At a neutral site there was neither detectable erosion nor measurable deposition, in terms of the character of the mud surface and its level relative to the datum furnished by the stakes. Slight deposition (erosion) refers to a vertical change of 0.01 m or less, intermediate deposition (erosion) to a difference of more than 0.01 m up to 0.05 m, and heavy deposition (erosion) to a shift in excess of 0.05 m. The rows in figures 10–12 grouped under 'Last deposit' refer to the last effect at the site, either the production of a scoured surface, or the deposition of a layer of either mud or mud clasts. Two entries appear in cases where the new deposit covered the surface incompletely. 'Desiccation' refers to the extent of drying and rupturing, either none (no visible cracks), early (most cracks unjoined, contraction less than about 1 %), intermediate (most cracks joined but no secondary cracks, contraction a small to medium percentage, late (all primary cracks joined, some to many secondary cracks, contraction about 10 %), or terminal (like late desiccation but with surface mud completely dry and contraction commonly in excess of 15 %). 'Cracks' refers to visible fractures, classified as either empty, partly filled (either mud or mud clasts), full (mouths just detectable but not true bridging), or reopened after having been partly filled (see 2 of plate 9).

(*d*) *Responses at Berkeley*

The sites were levelled in on 19 July 1982, day 15 of the sequence of observations at Berkeley–Oldbury as a whole. Fracturing at these accretionary sites occurred only during the late spring and summer periods, in response to warm dry weather combined with comparatively low tides (see figure 10).

Site BA accreted by approximately 0.26 m (wet mud basis) over the period ending on 8 July 1983, when the station was sampled using a 0.3 by 0.4 m Reineck box. The large, reopened late-stage cracks (see (1) of plate 11) present on day 15 (19 July) were by day 43 (16 August) replaced after heavy accretion by a new system of terminal fractures (see (2) of plate 11), owing nothing to the first set. By day 76 (18 September) the cracks had become thickly smothered by fresh mud, the surface of which, except for the occasional erosion of faint rills, remained smooth until the following spring. Fresh cracks (see (3) of plate 11) appeared some time between day 312 (12 May 1983) and day 341 (10 June). These continued to grow until, by day 369 (8 July), they closely resembled in all but position the fractures of day 15 (see (1) of plate 11). The box sample (see figure 13*a*), starting at the surface that existed on day 43, reveals the cracks of that day, the fractures of day 15, and a lower set probably dating from the spring–summer of 1981.

The responses at site BB 0.2 m lower in the hypertidal subzone were similar in their timing but the degree of desiccation was noticeably less extreme (see figure 10). The large cracks (see (4) of plate 11) present on day 15 (19 July) were replaced by new cracks by day 43 (16 August)

DESCRIPTIONS OF PLATES 5–8

PLATE 5. Orthogonal crack patterns. (Scale box in (1) and (2) measures 0.05 m square; spade blade in (3) measures 0.14 m wide.)

(1) Intermediate-stage pattern with some unjoined cracks, high middle hypertidal subzone, Berkeley (see also figure 6*e*).

(2) Late- to terminal-stage random pattern, low upper hypertidal subzone, Berkeley (see also figure 6*g*).

(3) Late- to terminal-stage parallel pattern, low upper hypertidal subzone, Berkeley (see also figure 3*f*).

PLATE 6. Desiccation crack patterns. (Spade blade measures 0.14 m wide.)

(1) Late-stage radial pattern, high upper hypertidal subzone, Slimbridge.

(2) Late-stage orthogonal pattern divided into domains by connected sequences of *en echelon* gashes, middle hypertidal subzone, Arlingham.

(3) Detail of gash sequence in (2).

PLATE 7. Orthogonal growth and *en echelon* gashes. (Scale box measures 0.05 m square.)

(1) Cracks growing orthogonally toward each other.

(2, 3) Isolated pairs of gashes in a (2) intermediate and (3) late stage of development.

(4–8) Sequences of *en echelon* gashes along various patterns of principal crack (see also figure 7). Early- to intermediate-stage cracks, all from the middle hypertidal subzone, Berkeley.

PLATE 8. Features of late or terminal desiccation. (Scale box measures 0.05 m square.)

(1) Late- to terminal-stage secondary cracks, middle hypertidal subzone, Berkeley.

(2) Secondary cracks associated with terminal-stage pattern, upper hypertidal subzone, Holbeach St Matthew.

(3) Secondary cracks in terminal-stage pattern, upper hypertidal subzone, River Great Ouse outfall.

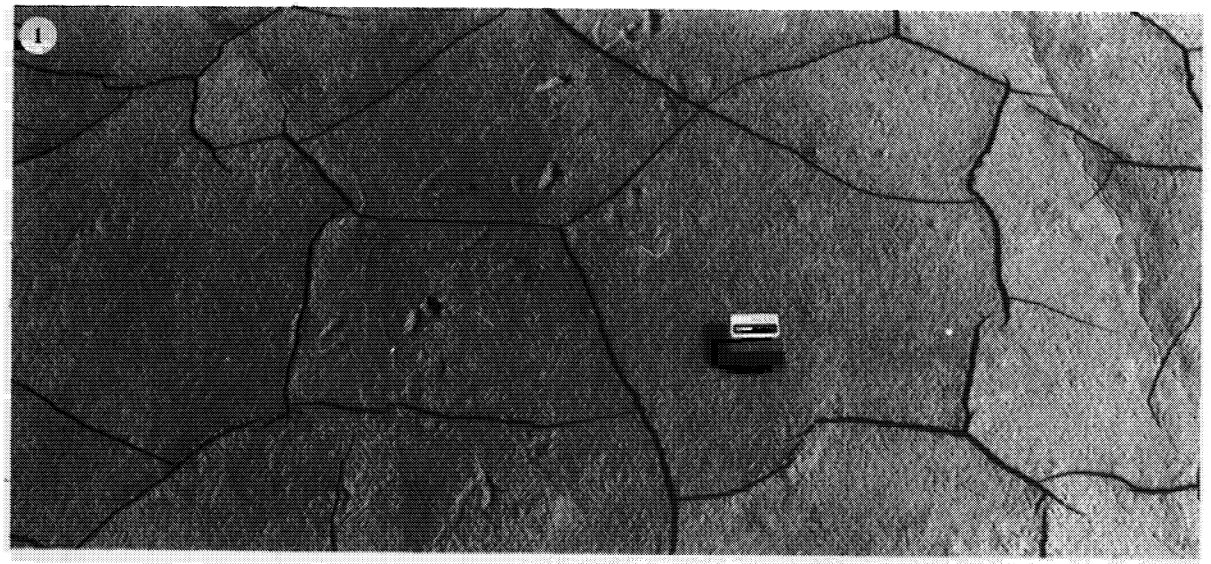
(4) Secondary cracks initiated at centres of tops of pillars, upper hypertidal subzone, Scolt Head Island.

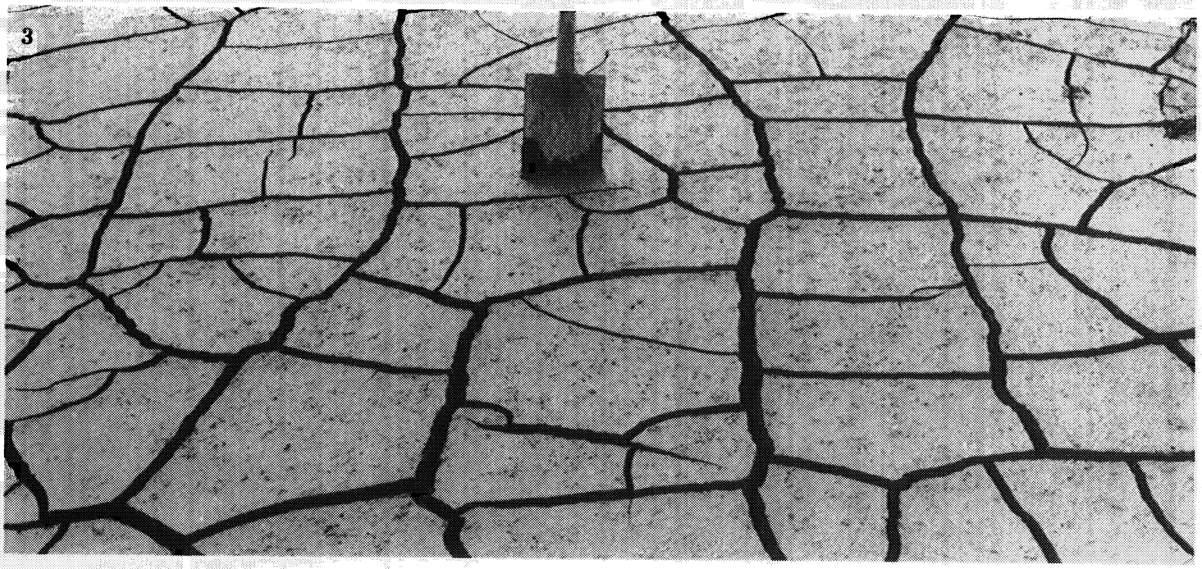
(5) Retracted storeys associated with late-stage cracks, middle hypertidal subzone, Rodley.

(6) Slight retracted and curled storeys associated with terminal-stage cracks, middle hypertidal subzone, Oldbury-upon-Severn.

(7) Moderately curled storeys accompanying terminal-stage cracks, middle hypertidal subzone, Rodley.

(8) Moderately to strongly curled storeys associated with late- to terminal-stage cracks, high middle hypertidal subzone, Scolt Head Island.





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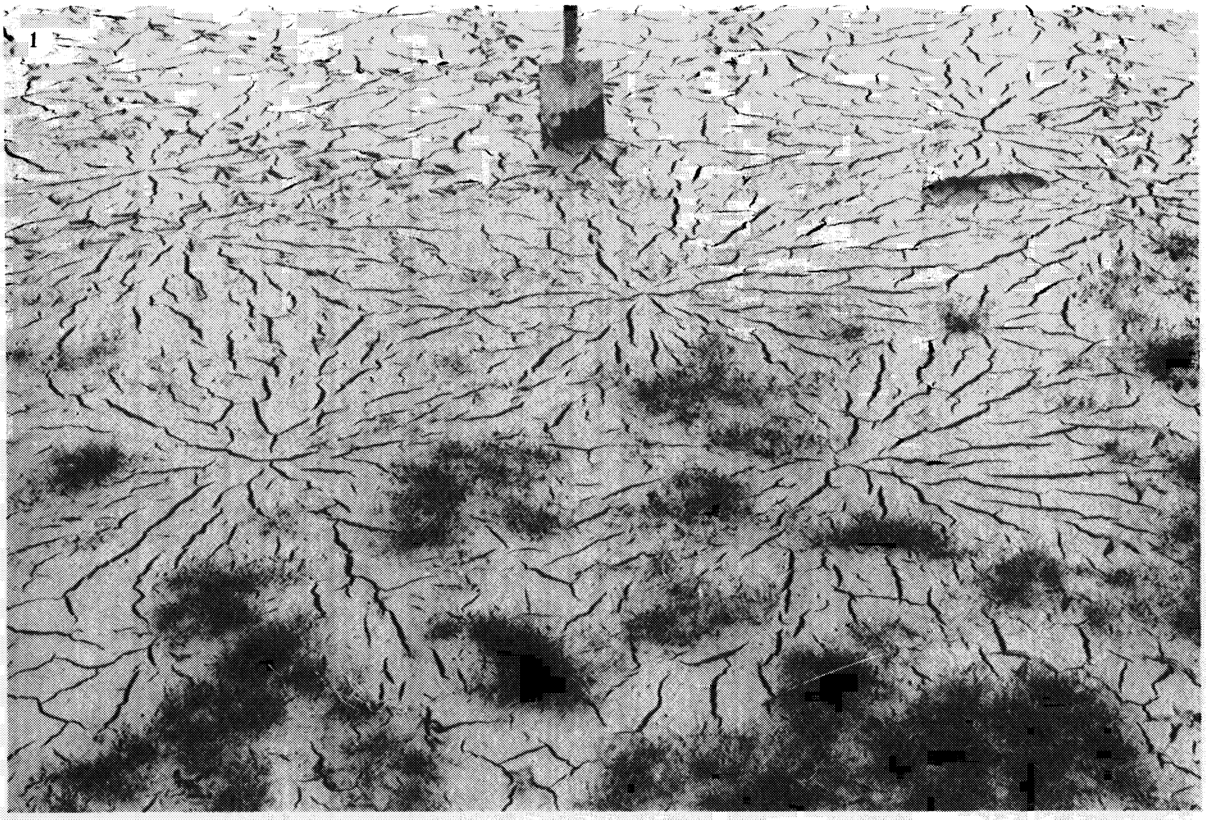

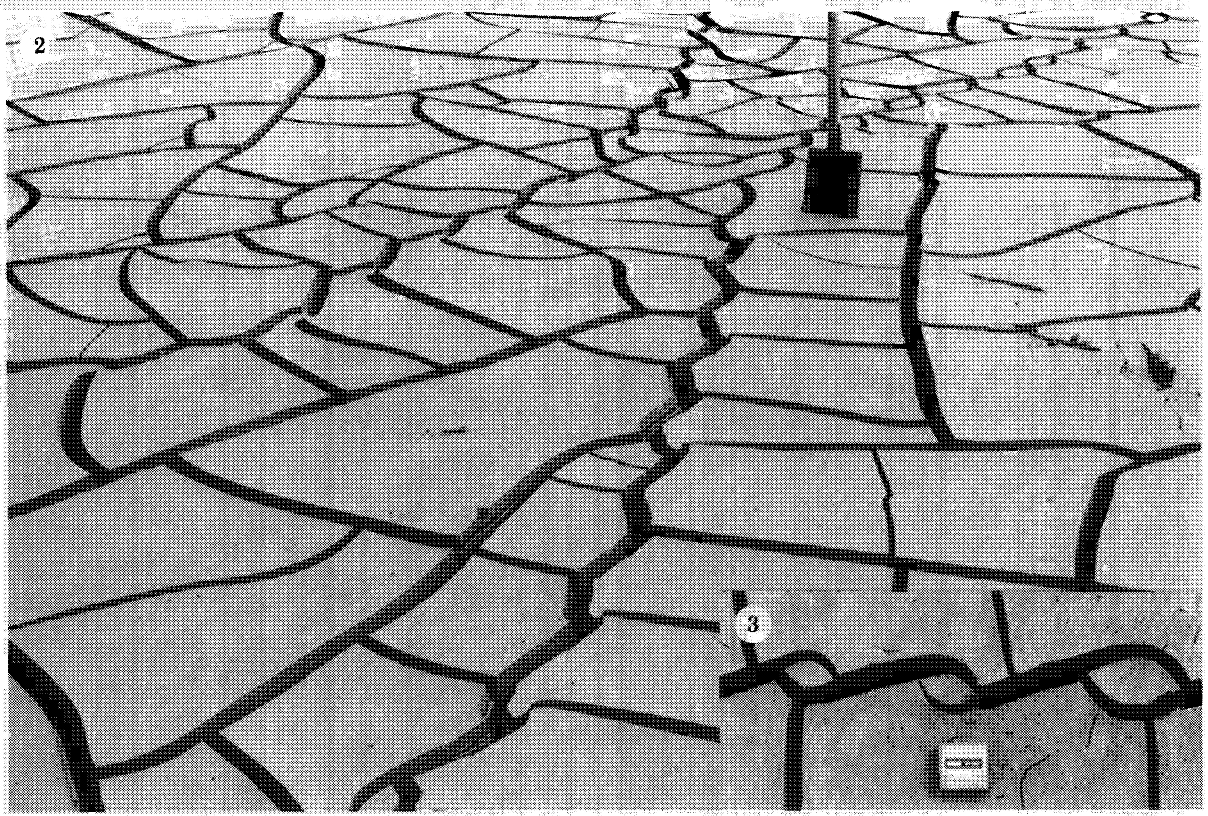

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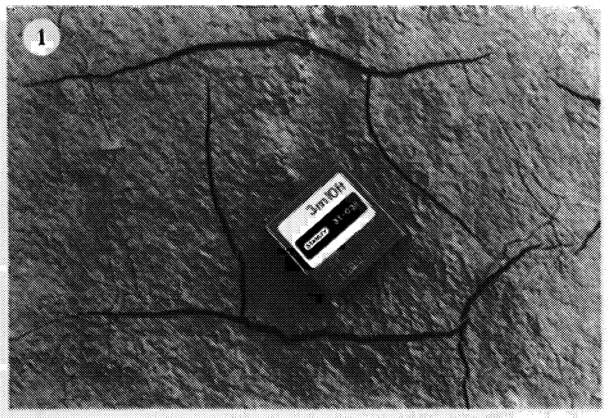
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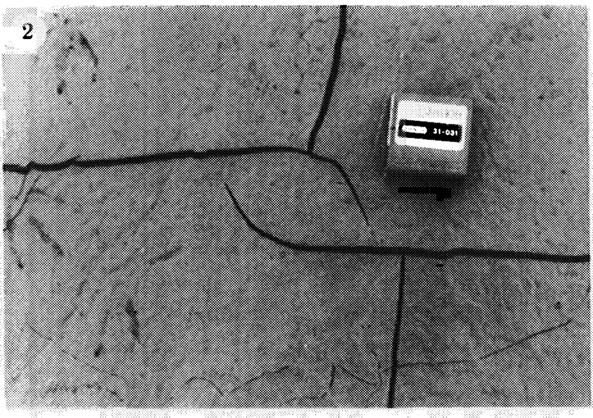
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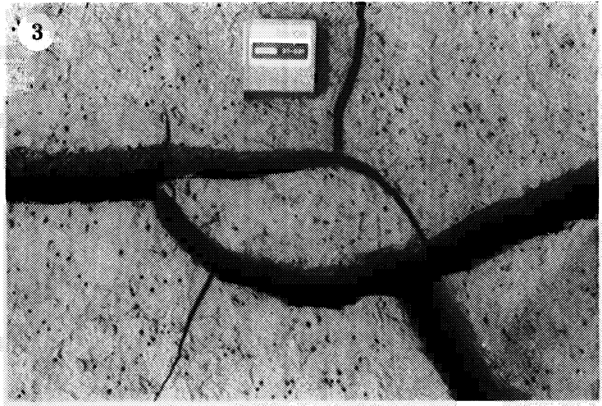
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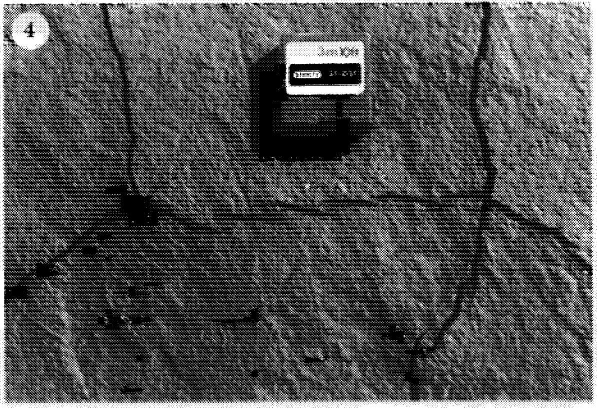
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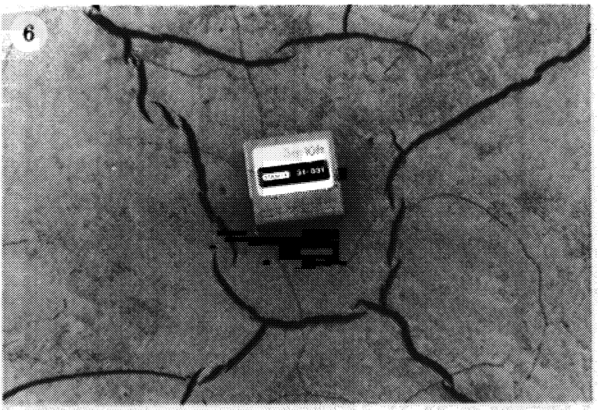
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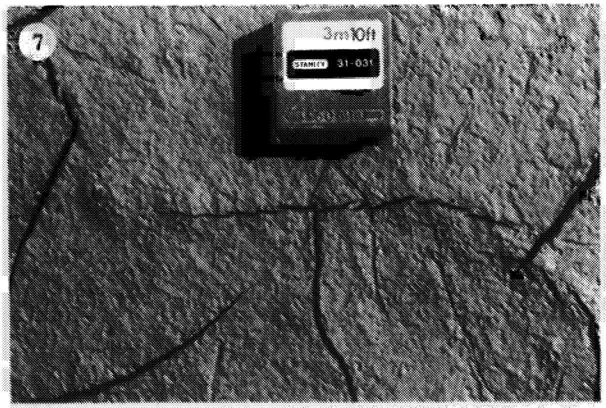
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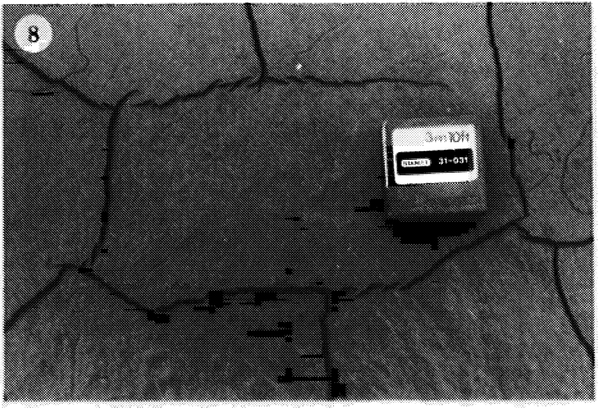
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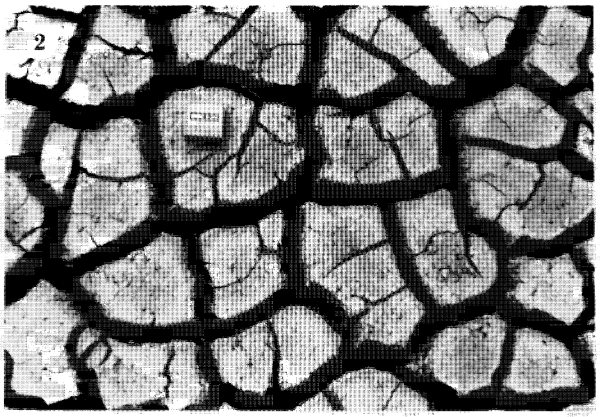

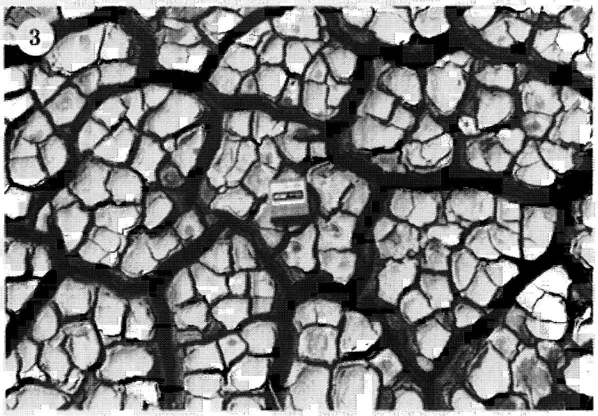

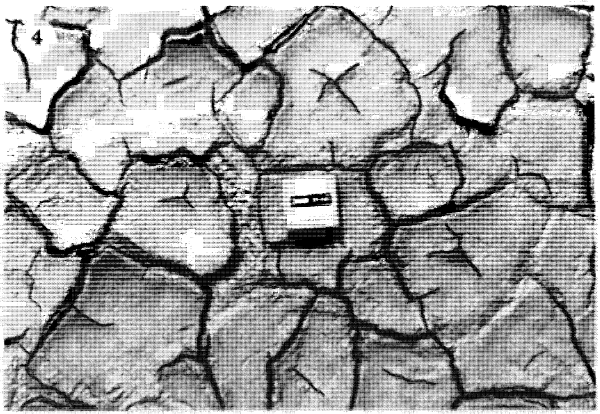

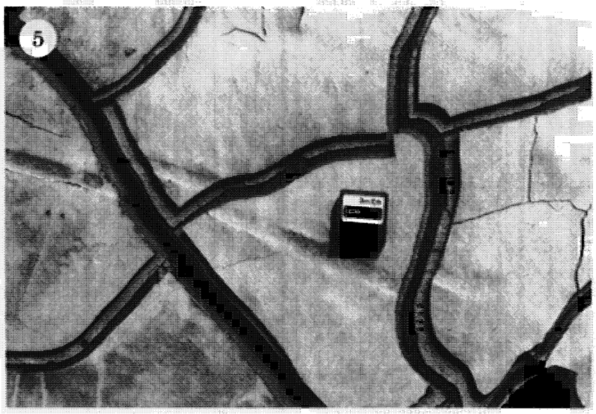

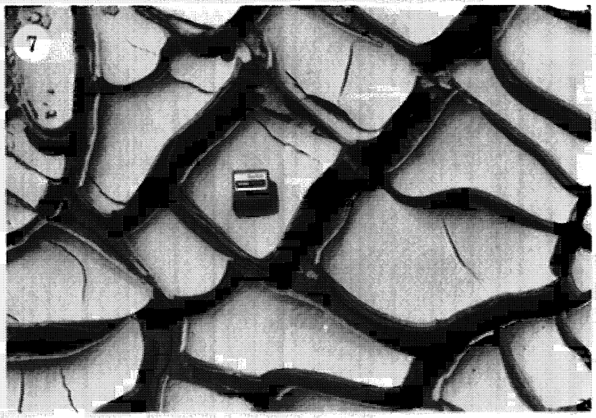

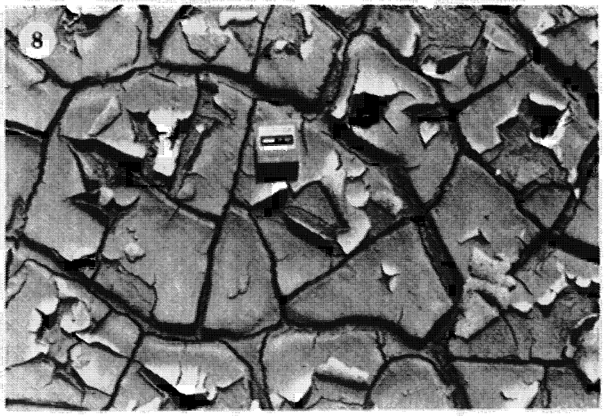

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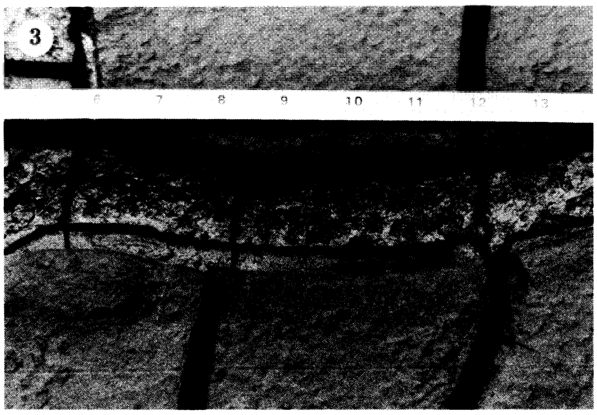

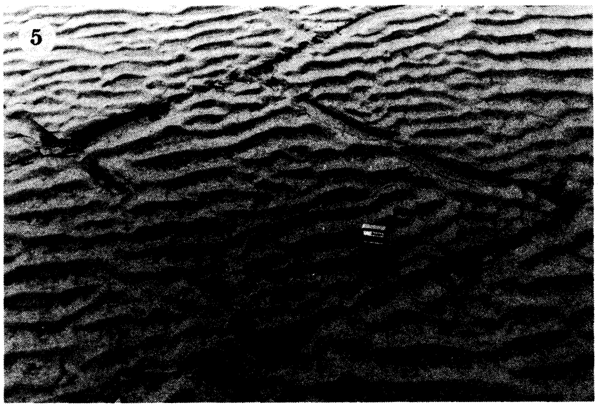

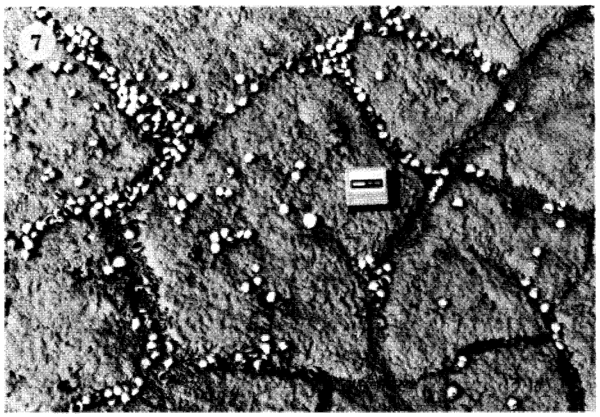

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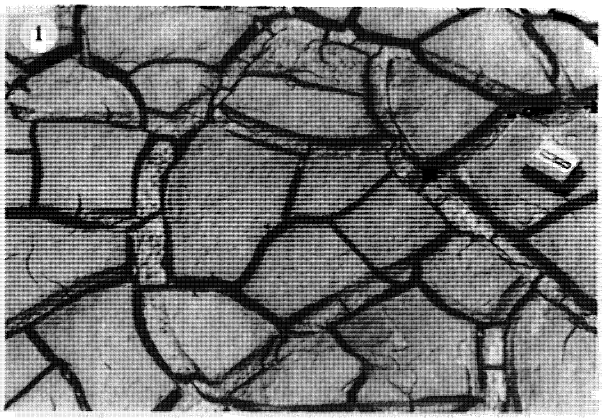

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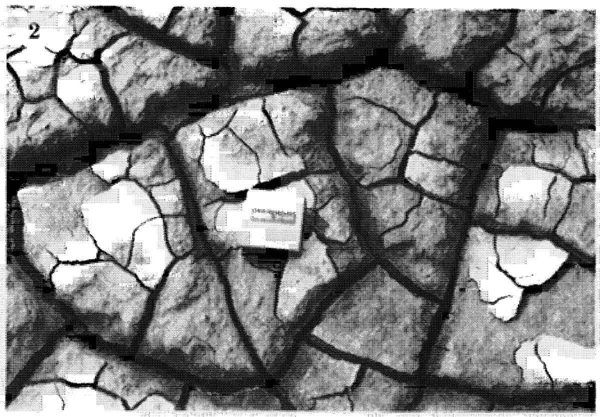

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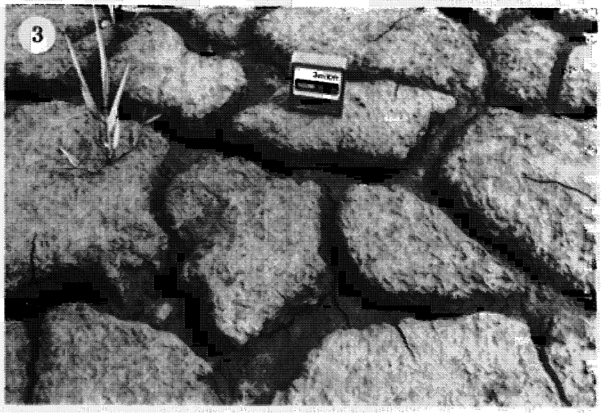

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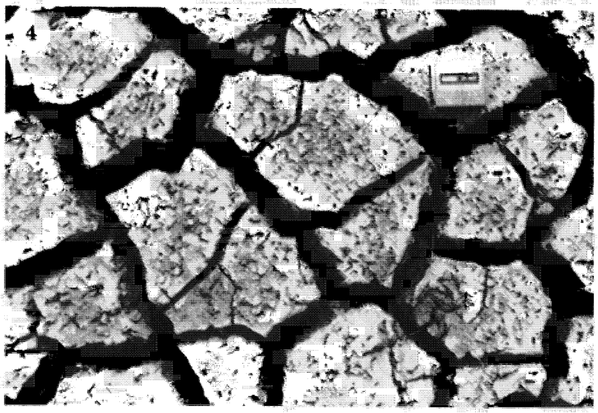

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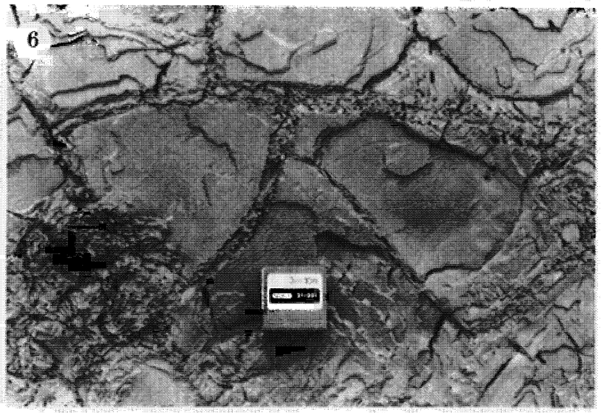

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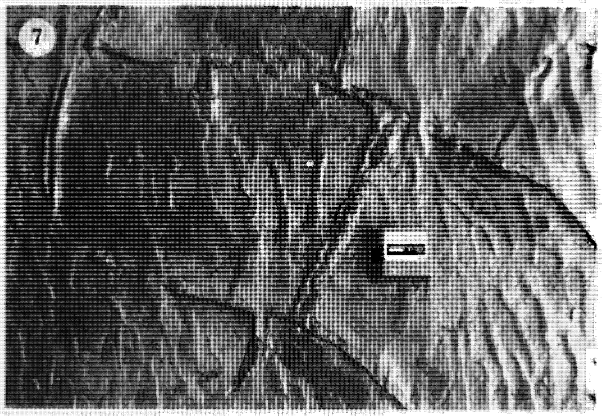

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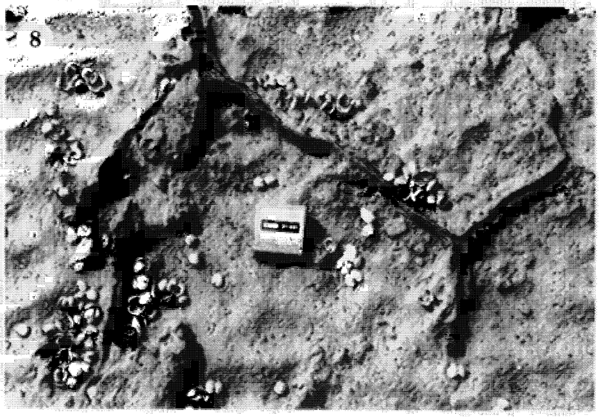

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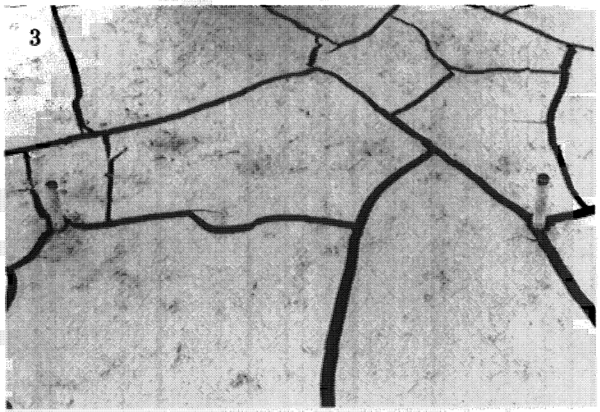
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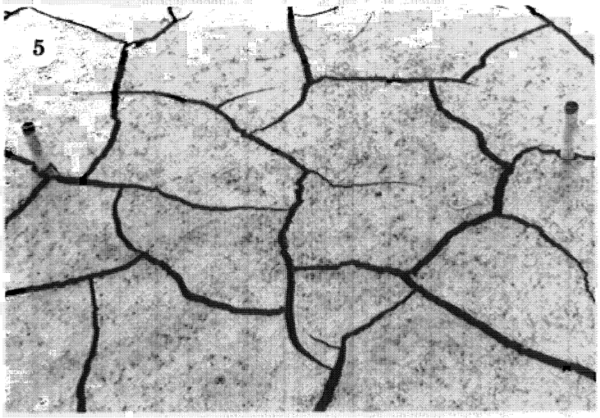
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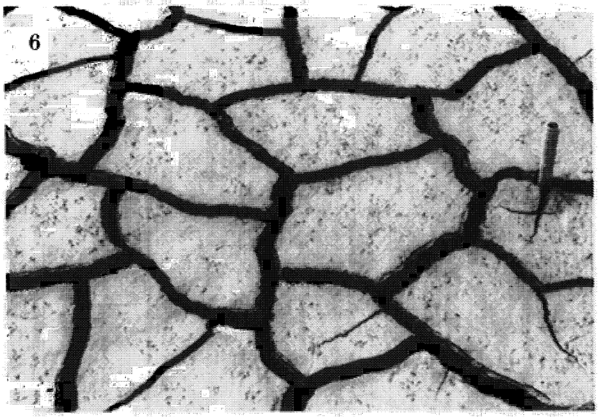
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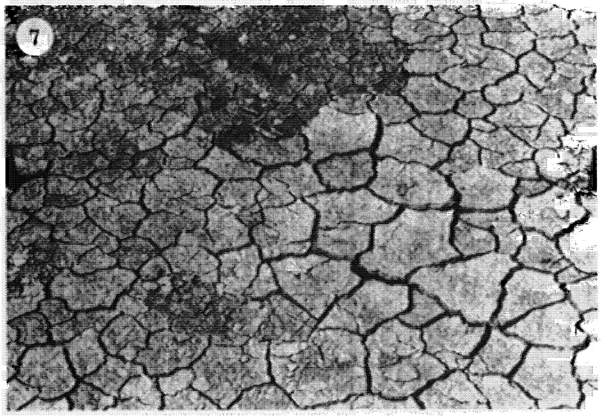
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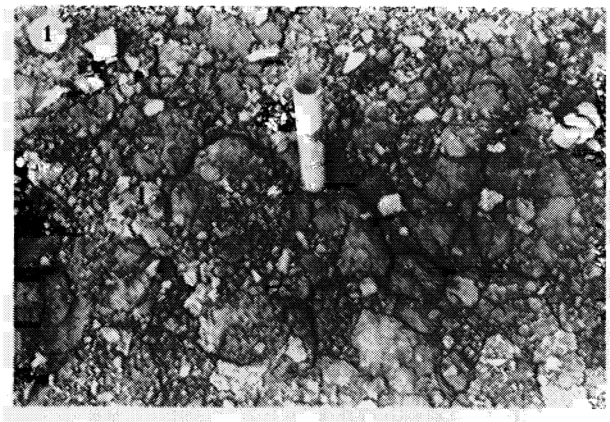
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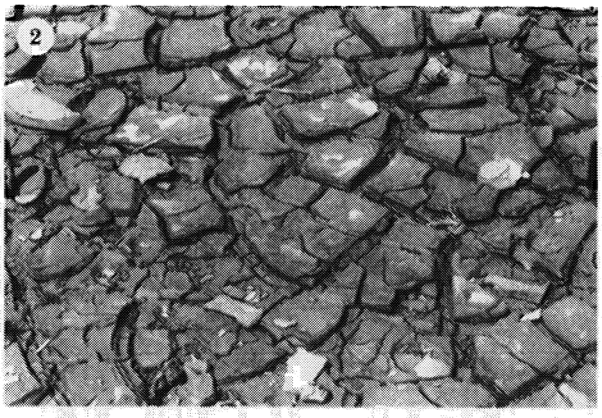
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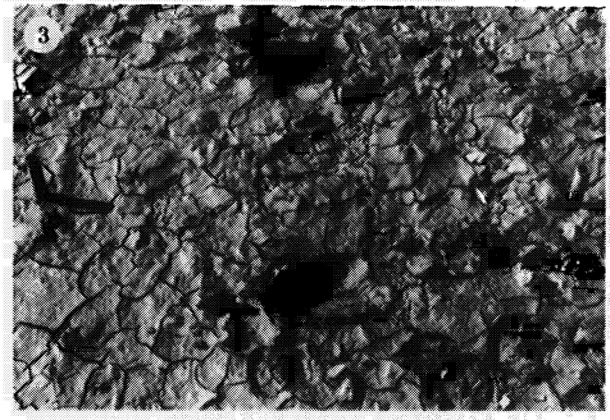
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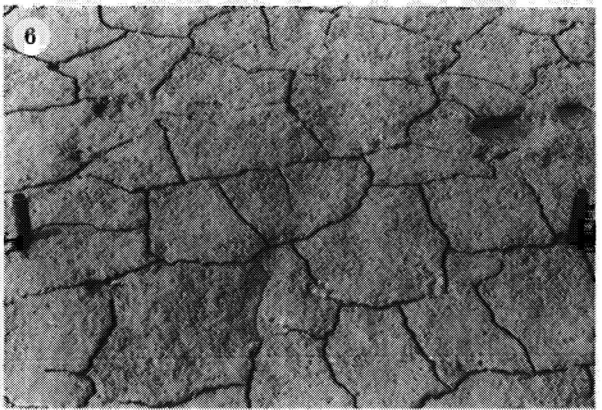
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but all were smothered by day 76 (18 September). The earlier cracks, however, lacked the partial infill noted at site BA (see (1) of plate 11), suggesting that they had opened after cracks first appeared at the higher station. Heavy accretion ensured that no more cracks were seen until day 341 (10 June 1983) (see (5) of plate 11). By day 369 (8 July) desiccation had reached a late stage (see (6) of plate 11). The box-sample taken then (see figure 13*b*) just reached a horizon that could be dated to the spring of 1982, but intersected no cracks. More than 0.3 m of wet mud had accreted.

By the subsequent 12 September (day 435 of the sequence), the large cracks at both sites had become thickly smothered, just as their predecessors at much the same time in the previous year (day 76, 18 September).

(*e*) *Responses at Oldbury*

Levelling-in of the three sites took place on 5 July 1982 (day 1). Fracturing occurred not only in response to warm dry weather and low tides in the late spring and summer, but also

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DESCRIPTIONS OF PLATES 9–12

PLATE 9. Filling of desiccation cracks. (Spade blade in (1) and (4) measures 0.14 m wide; tape in (3) marked in inches and centimetres; scale box in remainder measures 0.05 m square.)

(1) Late-stage cracks partly infilled with liquid mud deposited by immediately preceding tide, high middle hypertidal subzone, Berkeley.

(2) Terminal-stage cracks with fractured incomplete infill of mud, middle hypertidal subzone, River Great Ouse outfall.

(3) Late-stage crack with fractured incomplete infill of mud infested by *Corophium*, middle hypertidal subzone, Oldbury-upon-Severn.

(4) Bridged to incompletely mud-filled late-stage cracks, high middle hypertidal subzone, Berkeley.

(5) Late-stage cracks incompletely filled with sand and mud chips, middle hypertidal subzone, Arlingham.

(6) Terminal-stage cracks incompletely filled with mud chips over mud, high middle hypertidal subzone, Berkeley.

(7) Late-stage cracks filled with cockle shells alternating with mud, the last deposit of shells being visible on the surface, upper hypertidal subzone, Freiston Low.

PLATE 10. Infilling and erosion of desiccation cracks. (Scale box measures 0.05 m square.)

(1) Terminal-stage cracks with incomplete mud fill subsequently cracked, middle hypertidal subzone, Oldbury-upon-Severn.

(2) Terminal-stage incompletely filled cracks, and pillars with erosively rounded and scalloped tops, high middle hypertidal subzone, River Great Ouse outfall.

(3) Late-stage cracks incompletely filled and pillars with gnarled tops and undercut flanks, middle hypertidal subzone, River Great Ouse outfall.

(4) Terminal-stage cracks and pillars with pitted tops (central areas), upper hypertidal subzone, Holbeach St Matthew.

(5) Conchoidally fractured surface produced by erosion of desiccated mud, middle hypertidal subzone, Oldbury-upon-Severn.

(6) Stepped erosion surface produced in desiccated laminated mud, middle hypertidal subzone, Oldbury-upon-Severn. Note *Corophium* burrows in mud infill.

(7) Mud-infilled intermediate- to late-stage desiccation cracks undergoing preservation in hyper-relief beneath a sand cover, middle hypertidal subzone, Arlingham.

(8) Potential preservation in hyper-relief of resistant impregnations of iron compounds into the faces of pillars (muddy sand) defined by intermediate-stage desiccation cracks, low middle hypertidal subzone, Freiston Low.

PLATE 11. Desiccation features observed at monitored sites, Berkeley and Oldbury Pills. (Portion of surface shown in (1–7) is approximately 1 m wide; an area about 0.4 m wide appears in (8).) (1) Site BA, day 15. (2) Site BA, day 43. (3) Site BA, day 341. (4) Site BB, day 15. (5) Site BB, day 341. (6) Site BB, day 369. (7) Site OA, day 1. (8) Site OA, day 277.

PLATE 12. Desiccation features observed at monitored sites, Oldbury Pill. (Portion of surface shown in (2–6) and (8) is approximately 1 m wide; an area about 0.4 m wide appears in (1) and (7).) (1) Site OA, day 369. (2) Site OB, day 1. (3) Site OB, day 71. (4) Site OB, day 277. (5) Site OB, day 312. (6) Site OC, day 1. (7) Site OC, day 277. (8) Site OC, day 369.

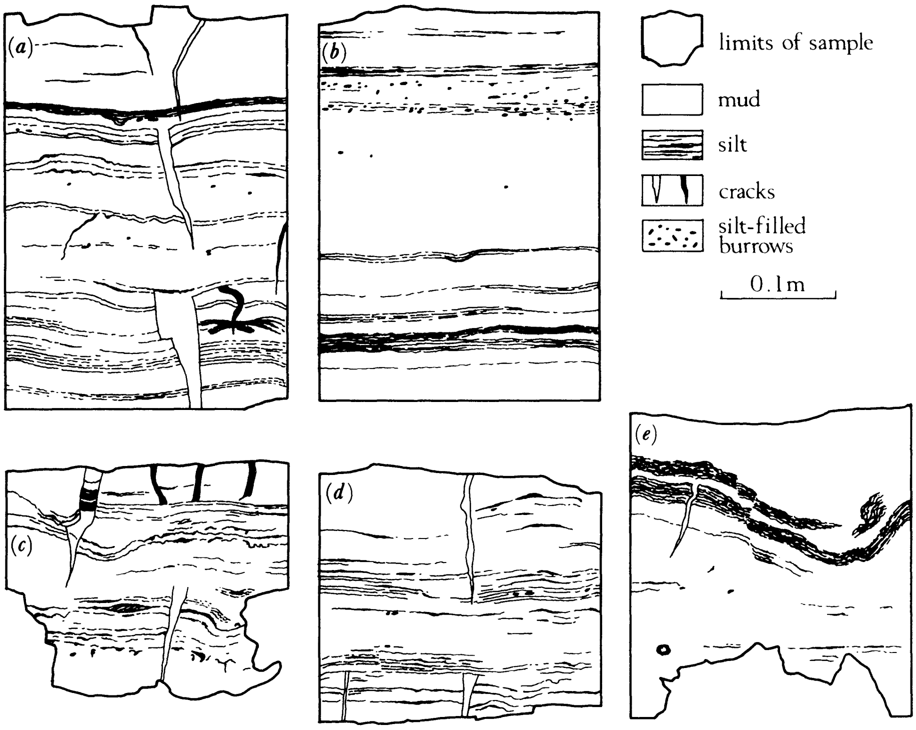

FIGURE 13. Features of stratification and desiccation recorded from Reineck-box samples taken at the monitored sites on 8 July 1983. (*a*, *b*) Sites BA and BB, Berkeley Pill (see also figure 9*a*, *b*). (*c*–*e*) Sites OA, OB and OC, Oldbury Pill (see also figure 9*c*, *d*). The top of the sample in (*a*) lies at the sedimentary surface as seen on day 43. The tops of the remaining samples are defined by the surface at the time of collection (day 369).

during the winter when the tides were again relatively low and the weather for periods comparatively fair (see figures 11, 12).

Site OA at 6.0 m O.D. (see figure 11) experienced a net loss of roughly 0.08 m of firm mud over the period 5 July 1982 to 8 July 1983. The late-stage cracks present on day 1 (see (7) of plate 11) grew in a layer of mud-bound mud clasts. By day 43 (16 August) this layer had been eroded off, a clast-strewn surface of firm mud with reopened older cracks remaining. This set was still evident on day 71 (13 September), but by day 76 (18 September) was mud-smothered. Cracking did not recur until day 191 (11 January 1983), when a set of widely dispersed, short, unjoined fractures was visible on an irregular scoured surface. Swelling of the mud had sealed these cracks by day 205 (25 January). The surface was covered by mud clasts and then mud by day 249 (10 March). Cracks were beginning to spread from the footprints of duck and geese that had fed on the sediment. Subsequent erosion had by day 277 (7 April) once more exposed firm muds in which old cracks had re-opened (see (8) of plate 11). These ruptures on day 312 (12 May) were full of a mixture of mud clasts and fresh mud. Continued deposition of mud and mud clasts had bridged the cracks by day 341 (10 June). Subsequent erosion re-exposed firm muds and led to the development by day 369 (8 July) of new fractures and round-topped pillars (see (1) of plate 12). A box-sample collected then gave evidence of frequent cracking before the observation period (see figure 13*c*).

Site OB at 5.4 m O.D. (see figure 11) also experienced a total net loss of about 0.08 m of firm mud. Large, terminal, orthogonal cracks were visible on day 1 (5 July), the surface having already lost numerous loose mud storeys (see (2) of plate 12). A new mud layer introduced before day 43 (16 August) was seen on that day to be cracked, as was a further deposit on day 71 (13 September) (see (3) of plate 12). As at site OA, deposition had by day 76 (18 September) smothered these fractures, and no further ruptures were seen until day 191 (11 January 1983). Fracturing was not again evident until day 249 (10 March), by which time fresh mud and mud clasts formed the surface. Erosion followed, with the result that by day 277 (7 April) old firm mud had been re-exposed and its fractures reopened (see (4) of plate 12). New ruptures unrelated to earlier ones were present on day 312 (12 May) (see (5) of plate 12) and again on day 341 (10 June). In contrast to site OA, by day 369 (8 July), a thick layer of mud clasts had smothered any cracks present. The box-sample showed a certain amount of fracturing in the deposits antedating the observation period (see figure 13*d*).

Site OC at 4.7 m O.D. (see figure 12) was more erosional than the two higher stations, losing in total approximately 0.12 m of firm mud. The cracks seen on day 1 (5 July) (see (6) of plate 12) were much less advanced than at the higher sites OA and OB (see (7) of plate 11, (2) of plate 12); fracturing could be traced outward over the mud surface down to a level of about 4.4 m O.D. By day 43 (16 August) the cracks at site OC were no longer visible, although a clean scoured surface was locally exposed. Renewed mud deposition led to a new set of cracks by day 71 (13 September) but caused their burial by day 76 (18 September). During the long subsequent period dominated by scour, ruptures were visible only on day 191 (11 January 1983), as at the higher sites, when the fractures of day 1 were found to have been re-opened. A return to mainly depositional conditions led to the finding of new sets of cracks on each of days 277 (7 April) (see (7) of plate 12), 312 (12 May), 341 (10 June), and 369 (8 July) (see 8 of plate 12). Mud clasts filled the ruptures on day 341. From day 277 desiccation cracks were visible on the mud outward to a level of 4.0 m O.D. reached by nominally 84 % of the tides (see figure 9*d*). The fractures became increasingly narrow, wider apart, and less frequently joined outward over the mudflats. The box-sample afforded unexpectedly little sign of desiccation in the muds antedating the observation period (see figure 13*d*).

Oldbury was revisited on 12 September, 435 days after the start of observations. Sites OA and OB lay beneath soft mud with some mud clasts. Only at site OC were fractures visible. They proved to be the set of day 369, with an almost complete infilling of mud-bound mud clasts.

6. Discussion and conclusions

(*a*) *Spatial distribution and typology of intertidal desiccation cracks*

Figure 14 summarizes the spatial variation in the character of hypertidal desiccation cracks formed under temperate conditions. As a change of level occurs across the hypertidal subzone, the diagram also indicates the stratigraphical variation in desiccation to be expected in high intertidal sediments, thereby furnishing another criterion for the recognition of such deposits.

The maximum of the frequency of formation of new sets of desiccation cracks lies in the middle hypertidal subzone, in consequence of the interaction between the (i) downward-increasing frequency of tidal siltation; and (ii) the upward-increasing frequency and duration of exposure. Tidal inundation not only remoistens the mud but may also contribute a new layer of sediment, which may on subsequent exposure become fractured. Whereas the frequency with which such new layers are added decreases upward across the subzone (see figure 2*b*, *d*), the effectiveness of exposure falls off downward.

Speaking generally, desiccation declines in severity downward across the hypertidal subzone, because of increasing tidal inundation (see figure 2*b*, *d*). The drying stage to which particular fractures advance, however, depends not only on their position within the subzone but also

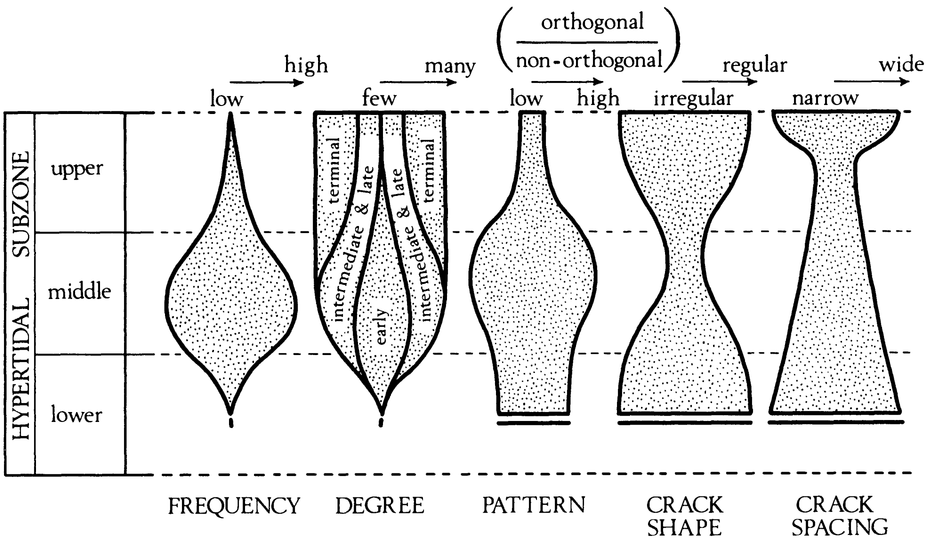

FIGURE 14. Stratigraphical variation within the hypertidal subzone in the characteristics of desiccation features. Summary based on all visited localities in the Severn Estuary and on the east coast of England (The Wash, north Norfolk).

on how soon they become buried. The relative importance of cracks of each stage therefore changes systematically across the subzone. Terminal cracks, for example, range from the middle of the middle subzone upward, but predominate only in the upper subzone, where they are especially characteristic of marsh pans. Only early-stage cracks occur below the middle of the middle subzone, and fractures are totally lacking downward from the level of mean high-water neaps, exceeded by 85–90 % of tides.

Crack pattern also varies systematically across the subzone. Joined non-orthogonal sets typify the upper part, where periods of exposure are long and a variety of mechanisms (burrowing, root growth, pedoturbation) destratify the sediment and introduce many large defects. Non-orthogonal sets rapidly decline in abundance downward, but can occur in the middle subzone, particularly in layers of mud clasts left after storms or where burrowers proliferated. Typical of the low upper and middle subzone are sets of orthogonal fractures which include few non-orthogonal junctions. Non-orthogonal joinings increase slightly in relative abundance down into the lower levels of the subzone, but the sets of cracks developed here are invariably less regular than those formed in the upper part.

In the field, the volumetric density of large defects appears chiefly to control the form of individual desiccation fractures, as Corte & Higashi (1964) and Beppu (1971) noticed experimentally. Cracks are irregular, in many cases extremely so, in the upper hypertidal subzone, where several mechanisms of destratification create an abundance of large defects. Again, in the low middle and lower subzone, burrowers produce numerous fracture-deflecting flaws. Irregular cracks can often be found in the middle subzone, but straight to curved regular ones are more common here.

The scale of desiccation showed broadly the same trend everywhere. Crack spacings of the order of 0.5–1 m are restricted to the surfaces of the highest salt marshes in the upper subzone and to the lower subzone. The pillars at intermediate levels are rarely more than 0.3 m across and commonly much less. The smallest are no more than a few centimetres wide.

As represented by the three areas described, the temperate intertidal zone is characterized by a distinct assemblage of desiccation patterns, the elements of which appear in a definite spatial and stratigraphical order. No one kind of pattern, however, is typical of this environment.

Sets of orthogonal cracks similar to those typical only of the middle hypertidal subzone appear overwhelmingly to predominate in river floodplain and allied environments (Scherber 1931; Keller & Foley 1949; Glennie 1970; Williams 1970; Butzer 1971; Burkham 1972; Picard & High 1973; Soleilhavoup & Bertouille 1976; Plummer & Gostin 1981). Non-orthogonal sets involving irregular cracks are rare and reported only by Picard & High (1973) and Soleilhavoup & Bertouille (1976). In at least one case, the pattern can be linked to the presence of coarse debris in the mud. Thin storeys of an extreme curvature are common in floodplain and allied environments (Longwell 1928; Scherber 1931; Karcz & Goldberg 1967; Glennie 1970; Williams 1971; Picard & High 1973; Soleilhavoup & Bertouille 1976), but are lacking intertidally. River floodplain and temperate intertidal environments seem, therefore, to be distinct as regards the balance of desiccation features they contain.

Playas in warm semi-arid and arid regions are perhaps the best known intermittently drying lakes. As Kindle (1926) and Longwell (1928) were early to find, their characteristic desiccation features are remarkably regular systems of predominantly six-sided pillars, commonly with rounded tops due to slaking and erosion, separated by irregular cracks (see also Neal *et al.* 1968; Krinsley 1970; Stoertz & Ericksen 1974; Sharp & Carey 1976). No patterns as regular as these have so far been recorded from an intertidal environment, temperate or otherwise. It is only occasionally that playas afford either well-developed orthogonal sets (Kindle 1926; Longwell 1928) or non-orthogonal patterns of the modest regularity found in the hypertidal subzone (see, for example, Neal *et al.* 1968). Intertidal and playa muds appear, therefore, to be readily separable in terms of desiccation features.

(*b*) *Timing and time scales of desiccation*

Desiccation in the temperate intertidal zone is everywhere most advanced during the late spring and summer, when comparatively low tides combine with warm and dry but seldom windy weather (see figures 10–12). The winter tides, however, are also comparatively low, and less-advanced desiccation may occur at this time if high winds arise to offset the effects of low temperature and little sunlight. At the heavily accretionary Berkeley sites (see figure 10) there was no sign of winter cracking, but on 11 January 1983 all the Oldbury sites revealed fractures (see figures 11, 12). The mudflats at approximately 6.8 m O.D. in the upper hypertidal subzone NNE of Berkeley Pill showed drying effects throughout the winter of 1983 (11 and 25 January, 10 March, 7 April). Sets of cracks were initiated on at least three occasions and found on two (27 February, 12 May) to have been buried. Intermediate-stage (see (1) of plate 5, (7) of plate 7) as well as early features (see (1) of plate 3, (3) of plate 4, (1) of plate 7) were noted. Indeed, similar effects were widely observed during this period at roughly this level on the open coast of the Severn Estuary.

There can therefore be little doubt that the time scales associated with the development of desiccation patterns in the intertidal zone are those of hours to weeks and, in some cases, even months. The presence on mud of unjoined cracks (see (1) of plate 4), of joined combined with unjoined fractures (see (1) of plate 3, (2) and (3) of plate 4, (1) and (2) of plate 7), and of narrow combined with wide cracks (see (1) and (2) of plate 8) make it clear that rupturing is both slow and progressive, as Corte & Higashi (1964) found in the laboratory. The first cracks are short, narrow and scattered; some spread from visible defects. As these ruptures lengthen, further cracks grow from them, until the whole surface becomes consumed by a mesh of joined fractures. Orthogonal-type junctions overwhelmingly predominate in crack sets described as orthogonal, but even in non-orthogonal sets appear in substantial numbers (see figure 6). Actual rates of fracture growth have yet to be measured from the field, but may be expected to vary with both season and position in the hypertidal subzone. Summer weather and a high position should favour more rapid growth. Frequent mud deposition in the middle subzone may also favour comparatively rapid growth, as only a thin layer of sediment has on each occasion to yield up its moisture. The Berkeley sites, however, suggest that frequently repeated heavy accretion inhibits growth.

(*c*) *Fracture mechanics*

Lachenbruch (1961, 1962, 1963) saw the rupture of brittle plastic geological materials as gradually passing from the control of the disposition and quality of defects in the material to that of the material's 'small-sample' strength and the local stress field. The cracks first to develop are guided as regards path and spacing by the distribution of the larger flaws in the affected layer. Only in the immediate vicinity of these cracks is the stress relieved, the material in the intervening areas remaining stressed. As more cracks appear, however, chiefly if not exclusively at orthogonal junctions, zones of stress relief begin to overlap and the paths of fractures are guided by local patterns of stress. A feedback mechanism now operates, for the cracks change the stress field by the very act of growing. Evidence for this should be present among desiccation cracks.

The field observations reported here combine with Corte & Higashi's (1964) laboratory results fully to support Lachenbruch's model as regards both the role of defects (see (1–5) of plate 1) and the progressive orthogonal growth of cracks (see §6*b*). The field evidence also bolsters the theory in its further requirement that, in the later stages of the development of a fracture pattern, spatio-temporal changes in the stress field must occur. Especially persuasive are the *en echelon* gashes accompanying many early- to intermediate-stage sets (see figure 7 and plate 7). Pollard *et al.* (1982), building on the work of Lawn & Wilshaw (1975), demonstrated that such structures record a substantial rotation during growth of the remote bedding-parallel principal stress. The gashes associated with intertidal desiccation cracks cannot yet be interpreted quantitatively, but it is clear from plate 7 that the remote principal stress was normally rotated toward the bisector of the smaller angle defined by any pair of joined principal fractures with gashes (see also figure 7). Such rotations are consistent with the interaction of the zones of stress relief associated with joined orthogonal cracks spreading at much the same time.

Lachenbruch's model envisages non-orthogonal crack growth only under special circumstances, when the material is highly homogeneous and capable of little plastic behaviour, so that fractures spread simultaneously and extremely rapidly. It is doubtful that these are the conditions associated with the formation of the more common non-orthogonal intertidal patterns. Not only do these sets include large numbers of orthogonal intersections (see figure 6*a*–*d*), but the muds involved carry the largest sizes and highest densities of defects anywhere in the intertidal zone. Their non-orthogonal junctions are perhaps merely macroscopically non-orthogonal and, as Lachenbruch (1962) himself suggests, due to a truly orthogonal branching on the convex sides of bends too small to be generally detectable on the opened cracks. This explanation, however, may not be available for playa cracks, of far greater regularity than any intertidal forms.

Although very rare both intertidally and in freshwater environments, radial cracks (see (1) of plate 6) represent another non-orthogonal pattern of fracturing that appears not to conform to Lachenbruch's model. Geometrically, these cracks seem to be the inverse, by rotation of the fractures through a right-angle, of a regular hexagonal set. In terms of a system of stresses, they could have arisen if each affected sheet of consolidating mud had collapsed upon a surface that was locally updomed, so as to create a series of foci of tension. In the Severn Estuary, however, sets of radial fractures are rather regularly distributed over the affected surface, and there is no sign of any associated positive relief on the substrate. It therefore remains unclear why radial rather than either orthogonal or subhexagonal fractures should at times arise.

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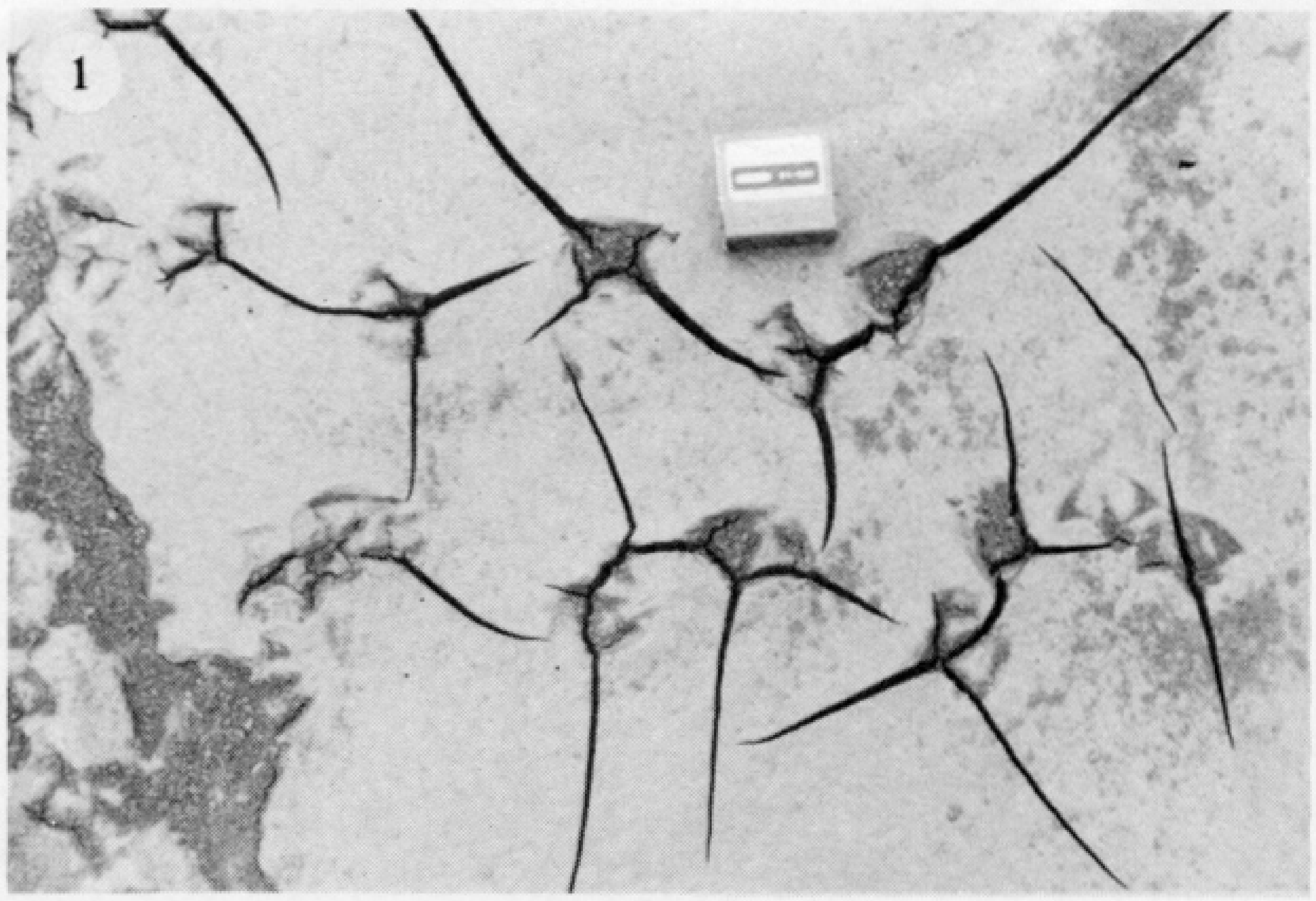
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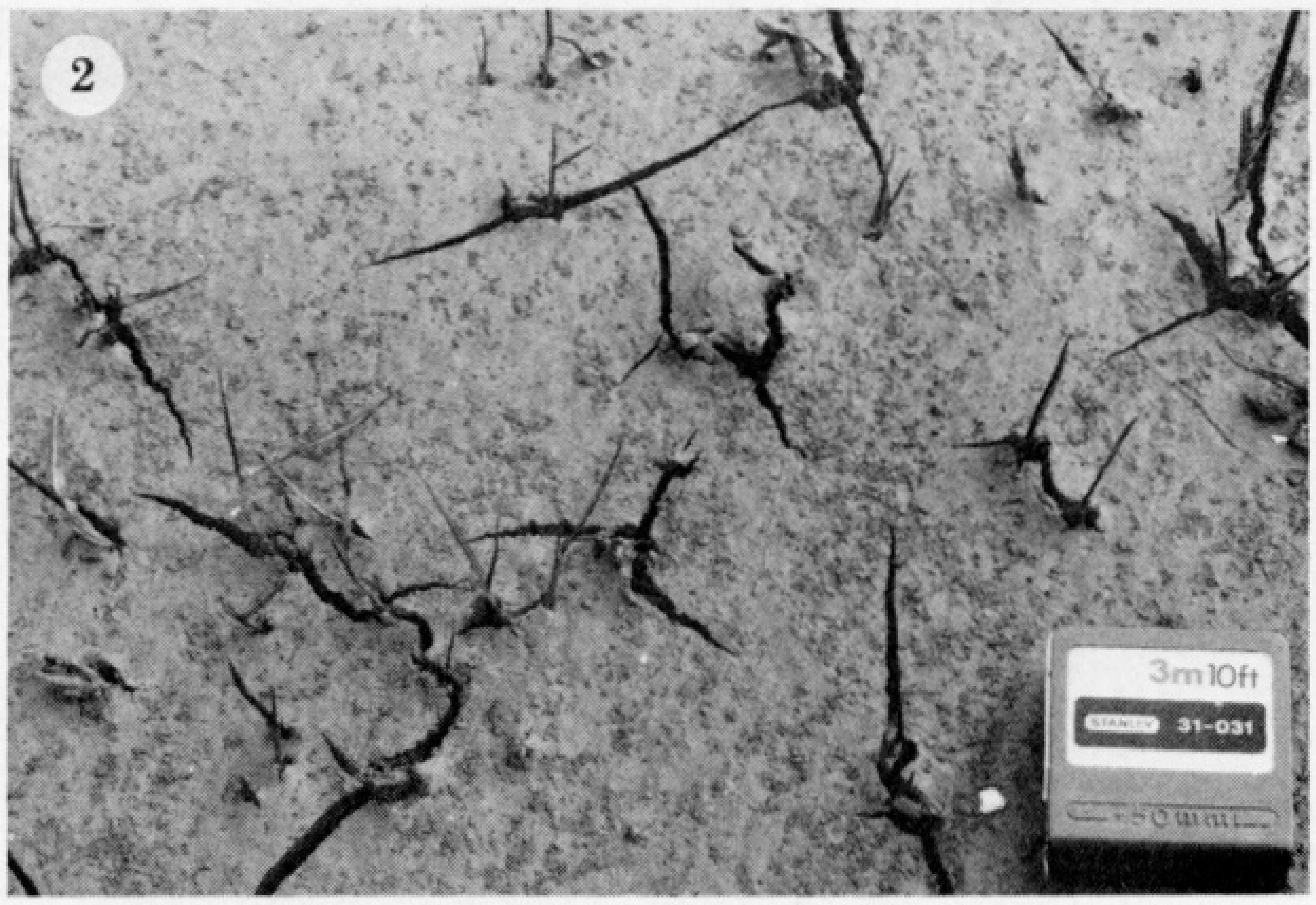
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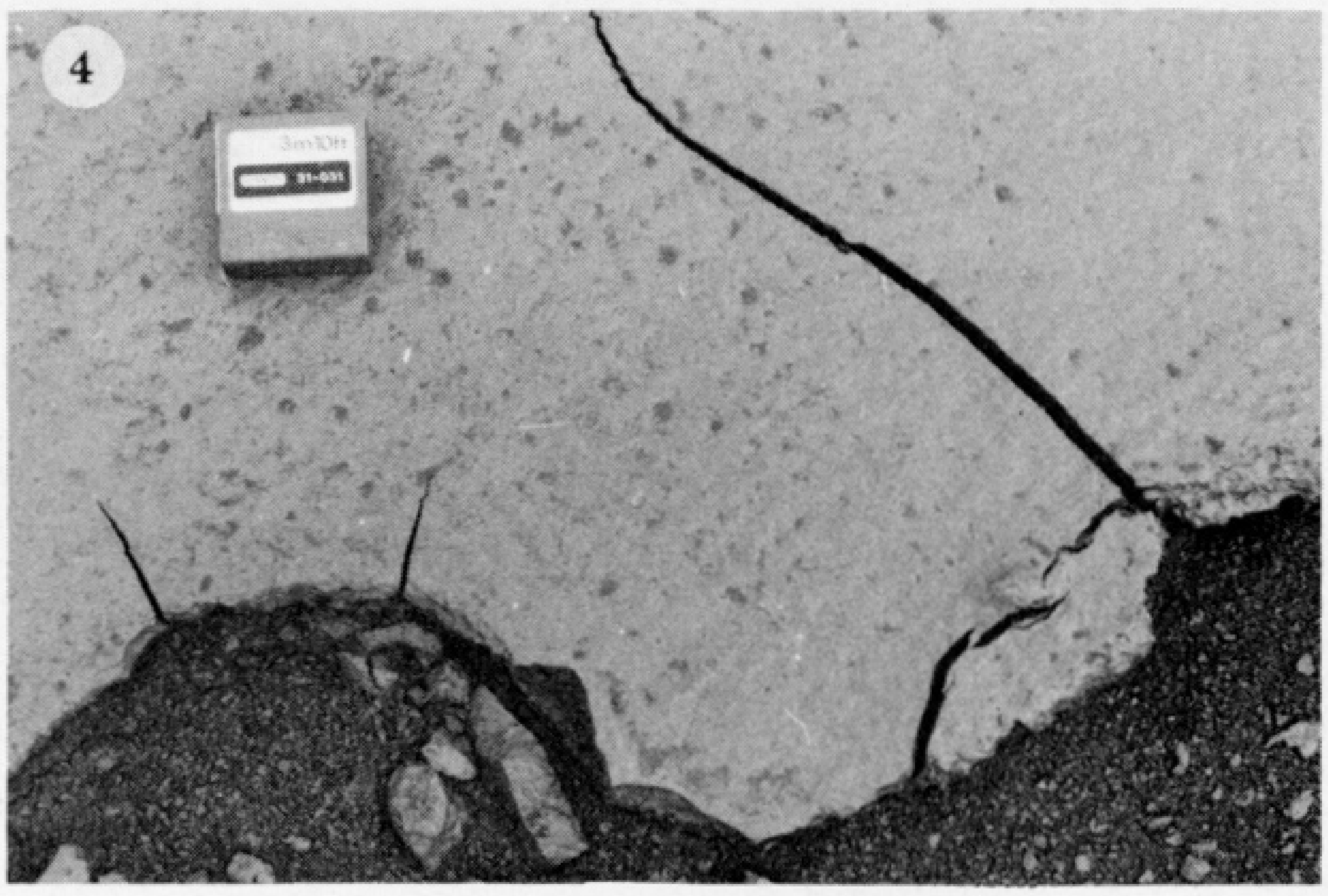
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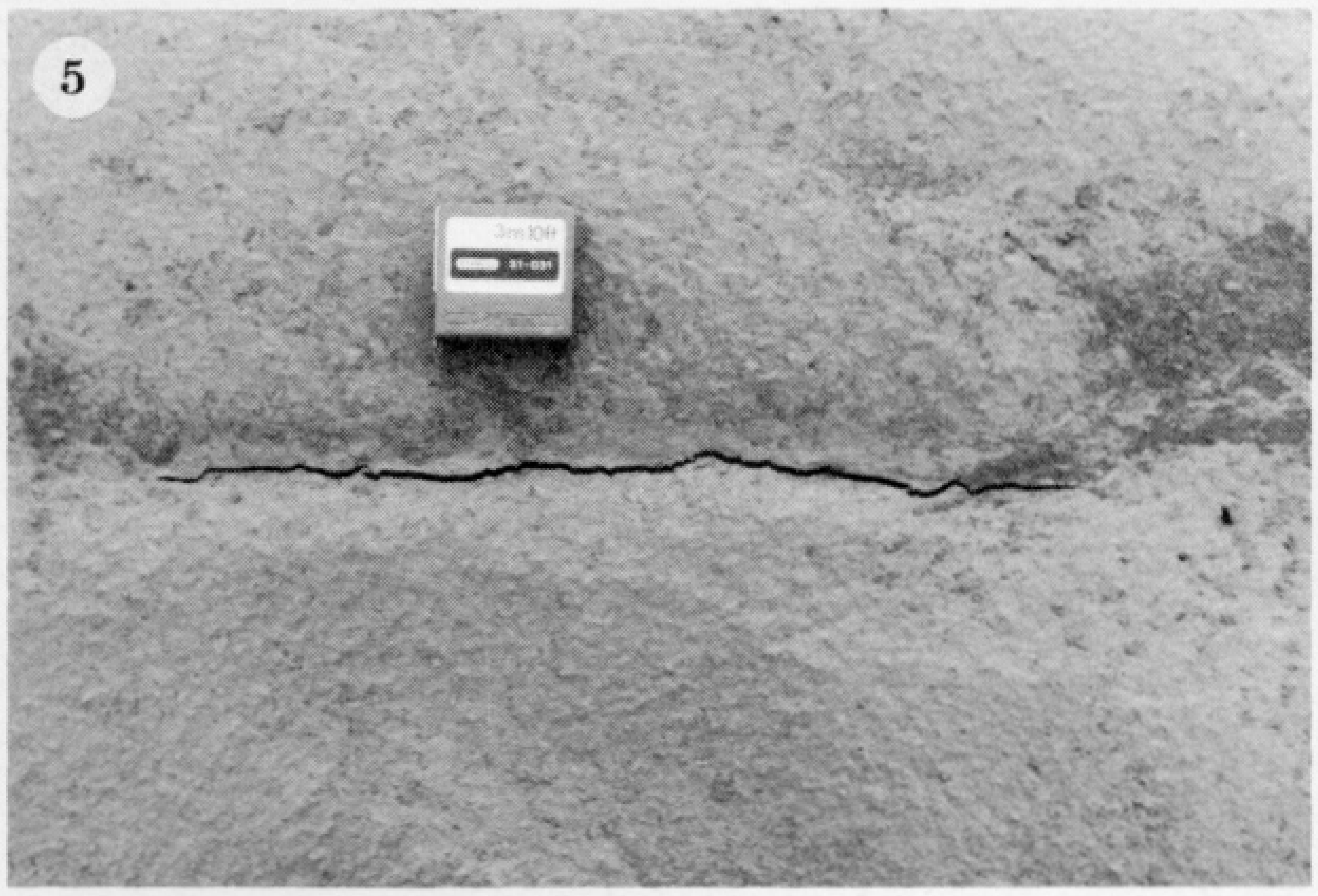
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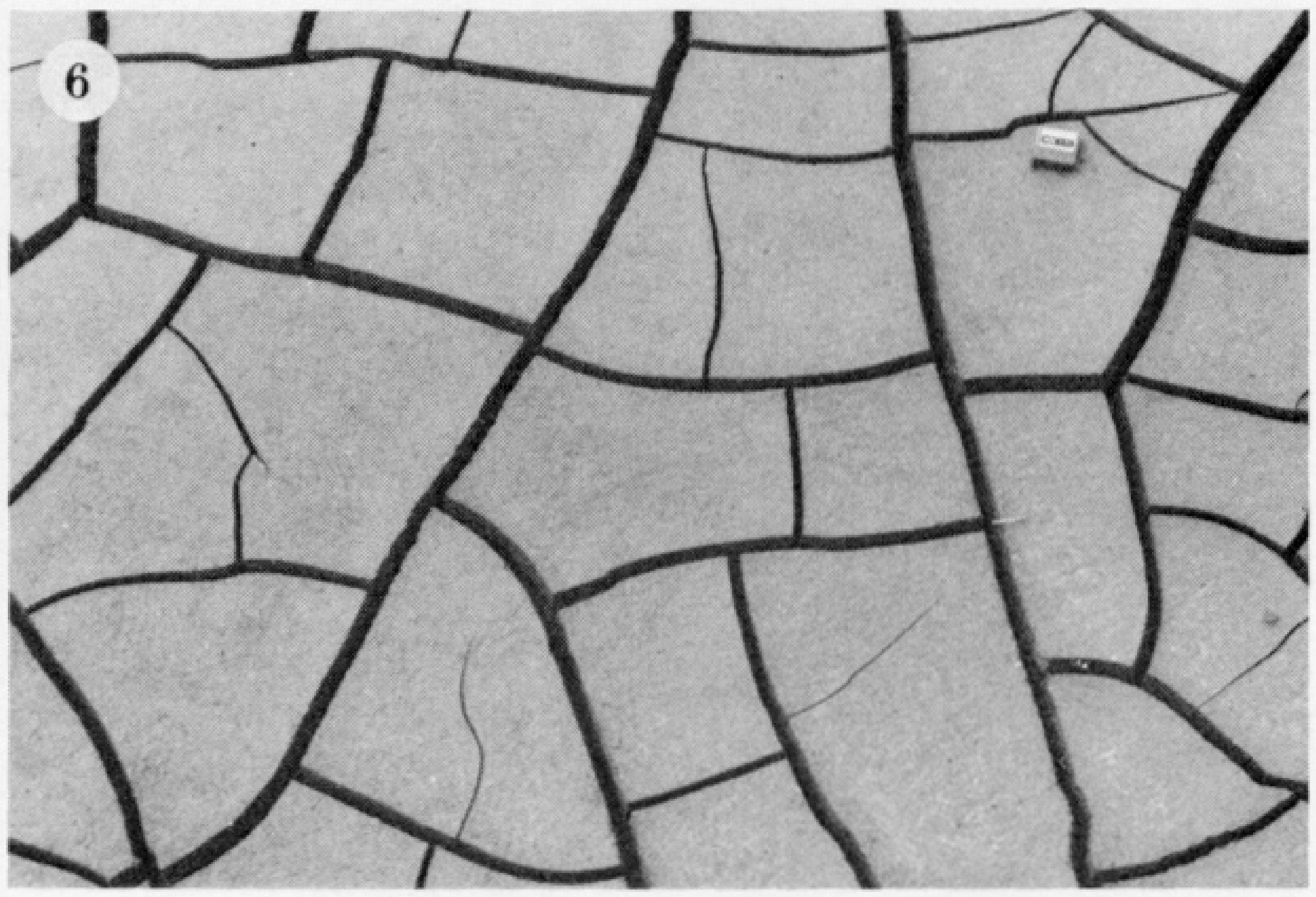
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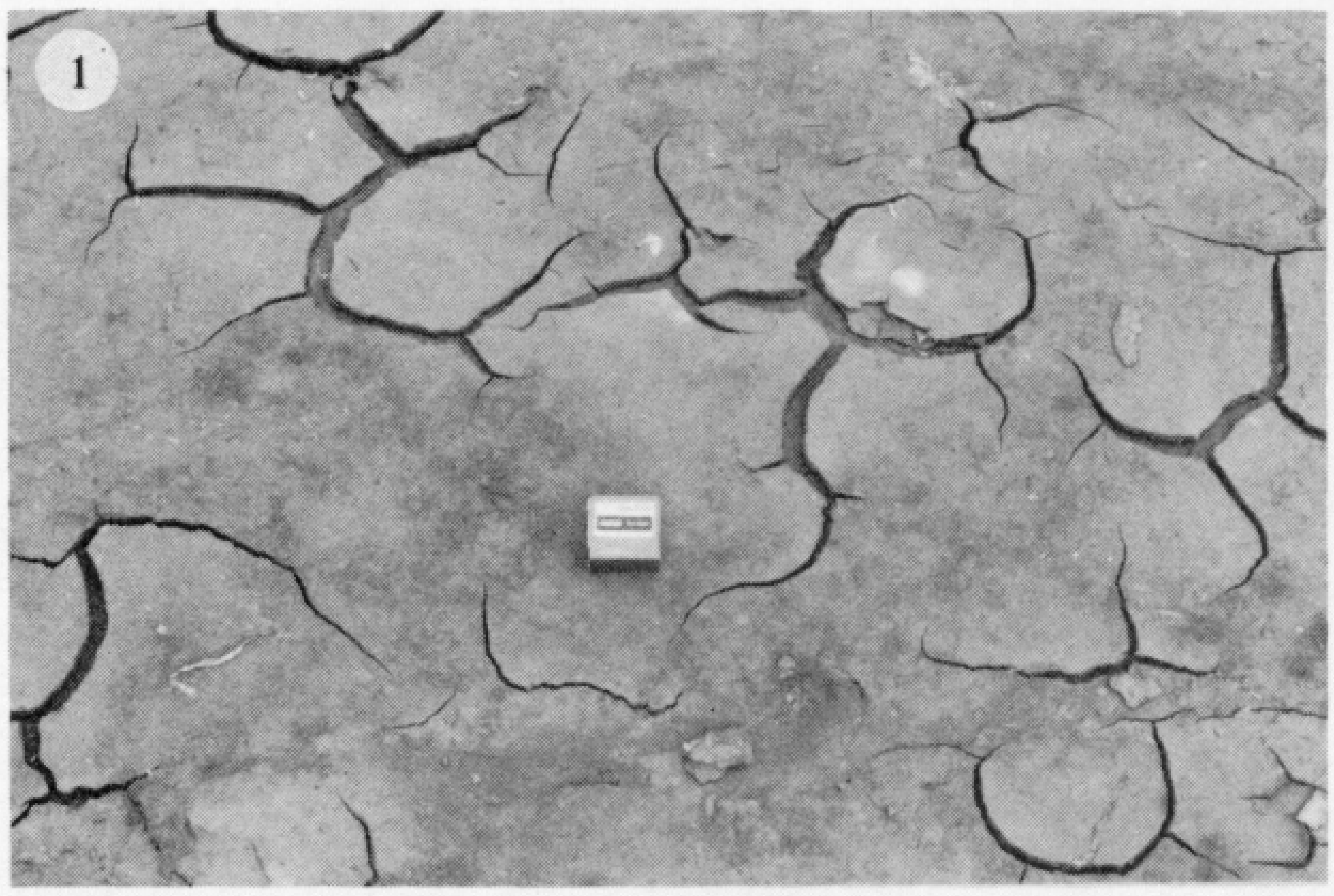

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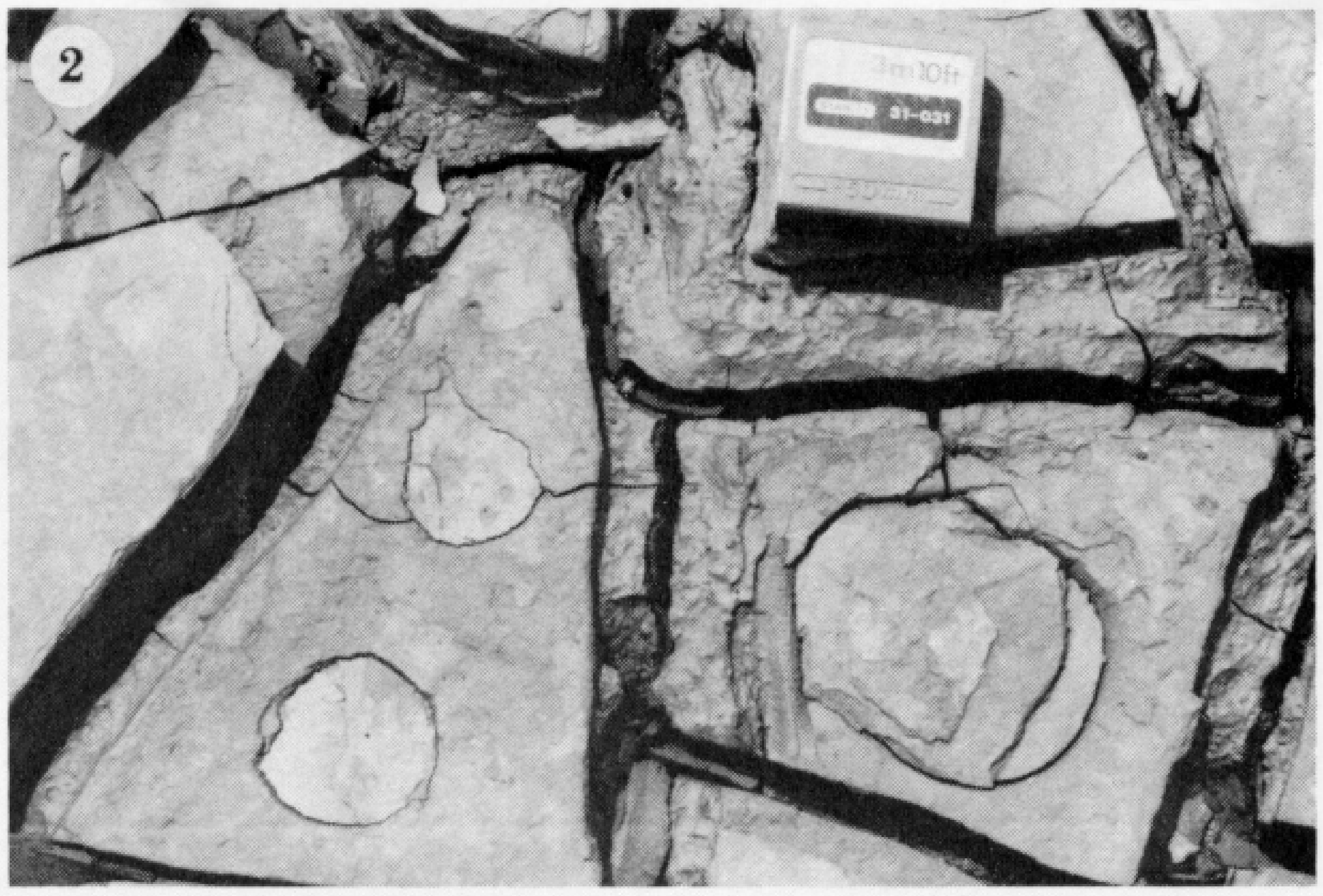

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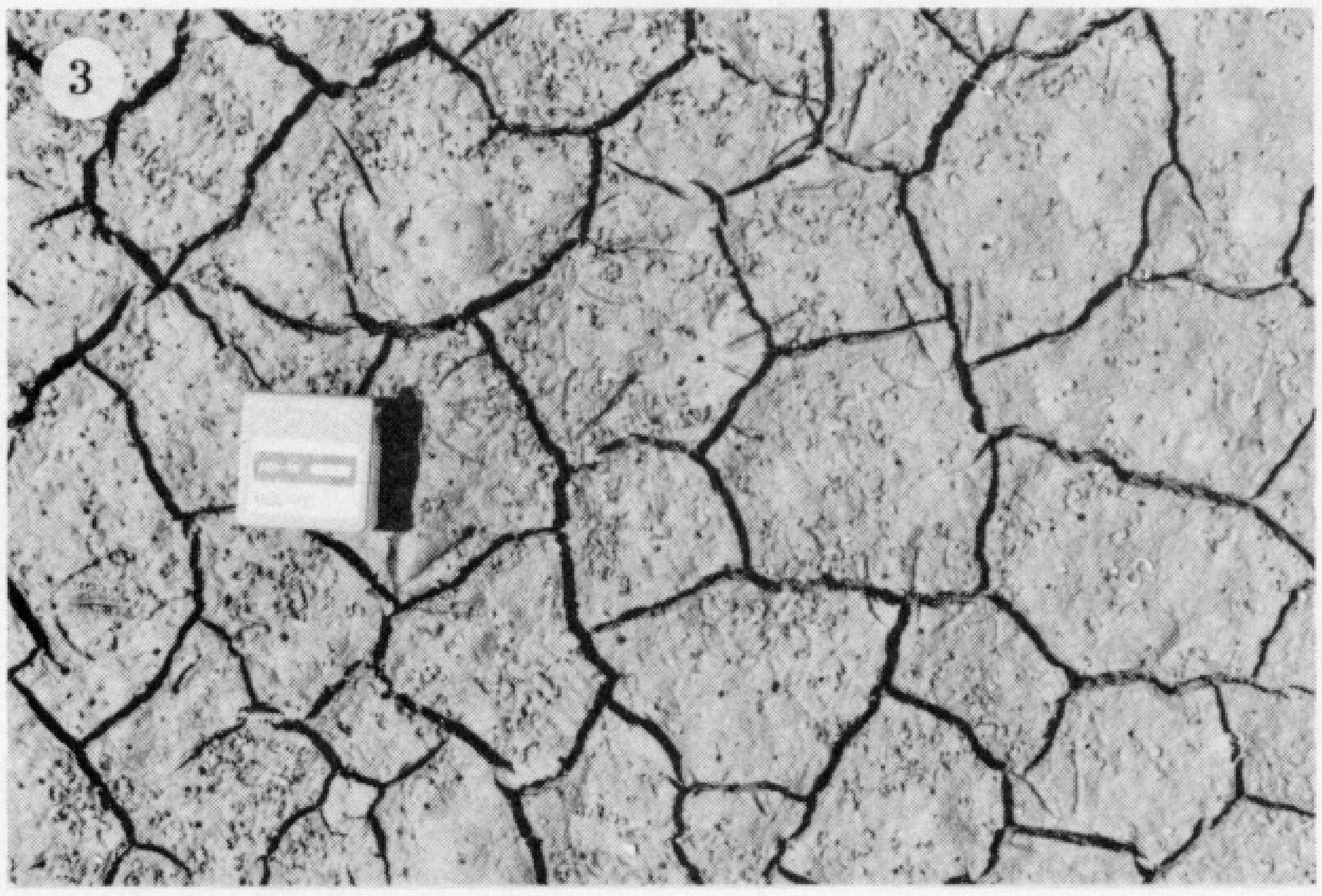

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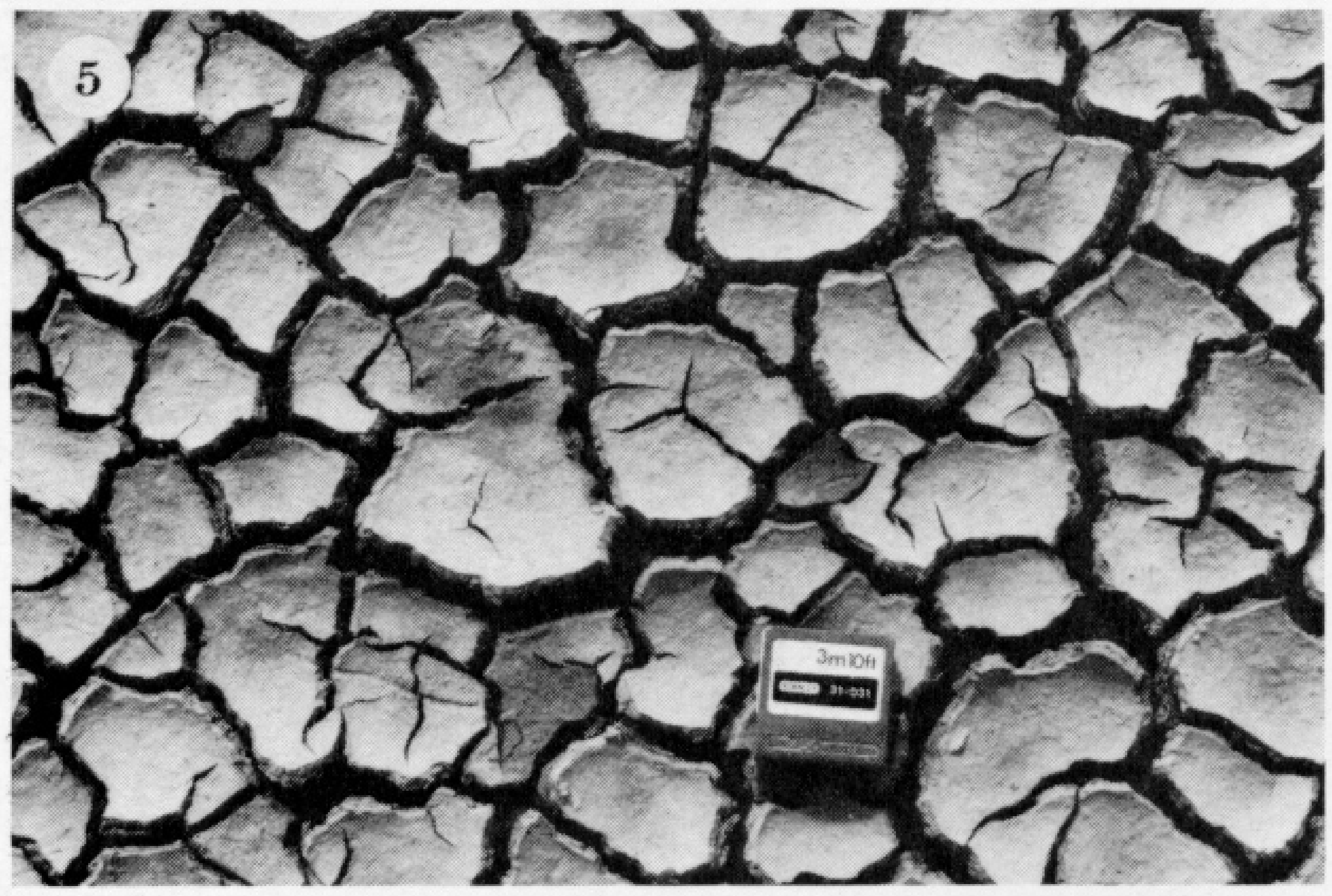

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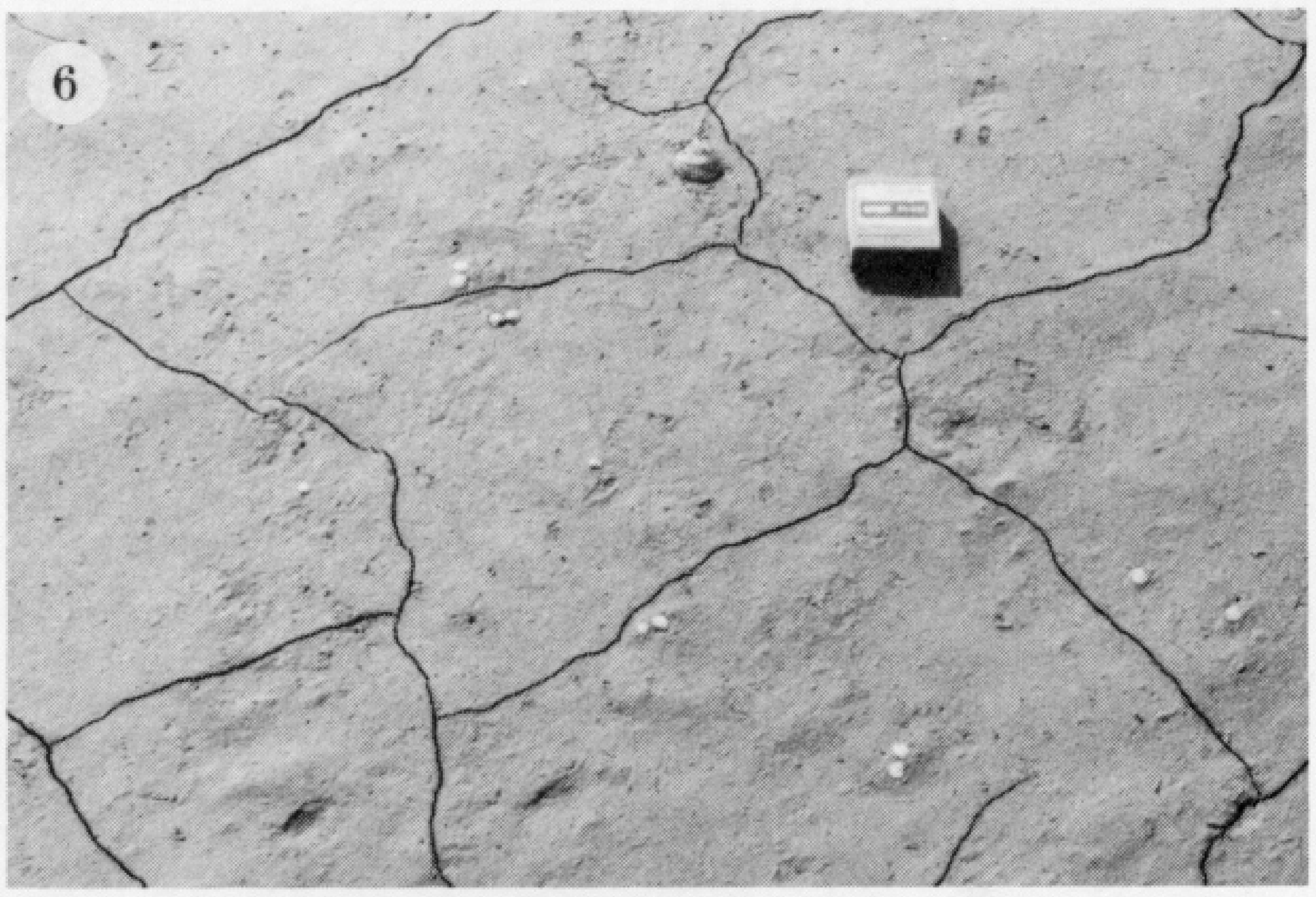

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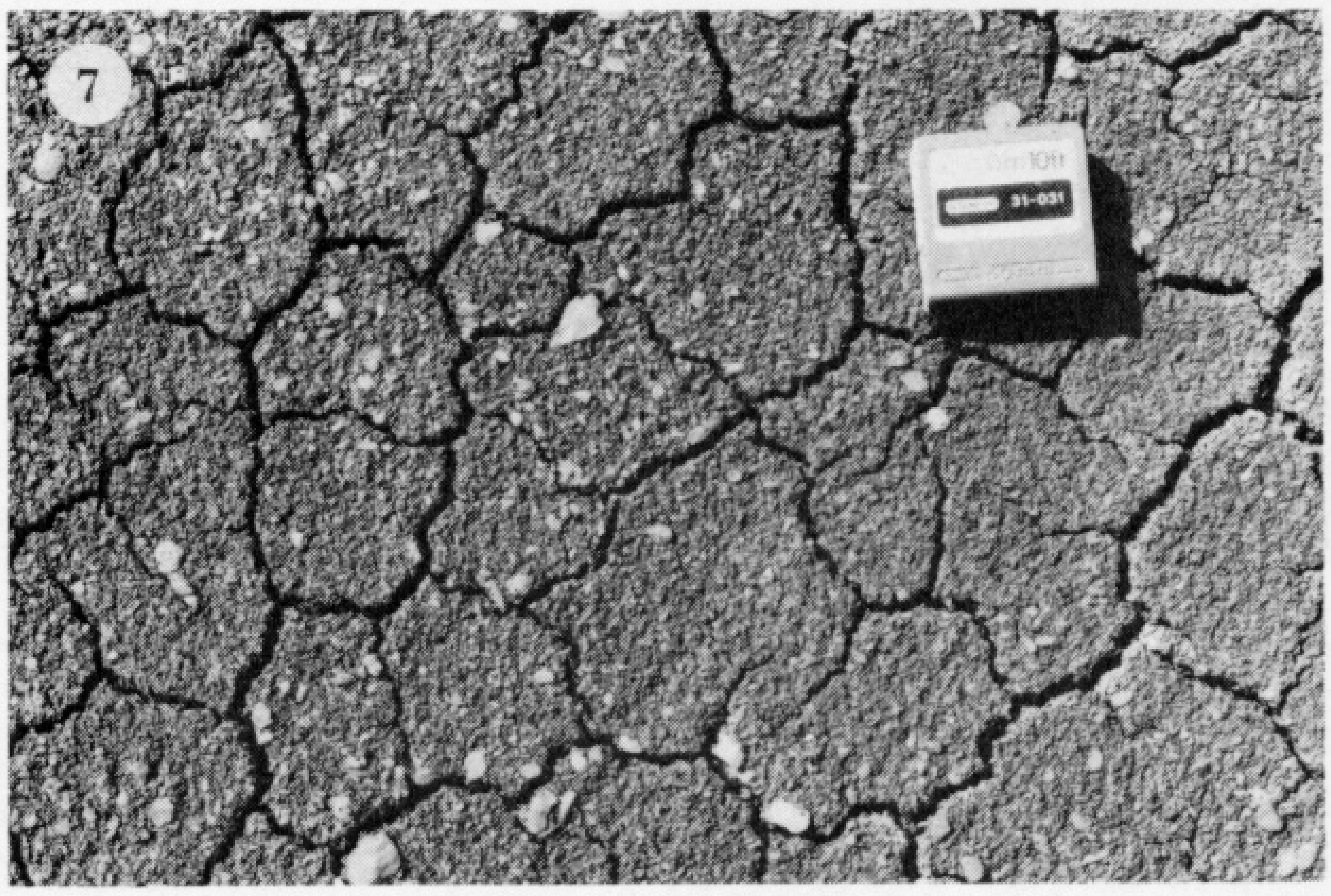

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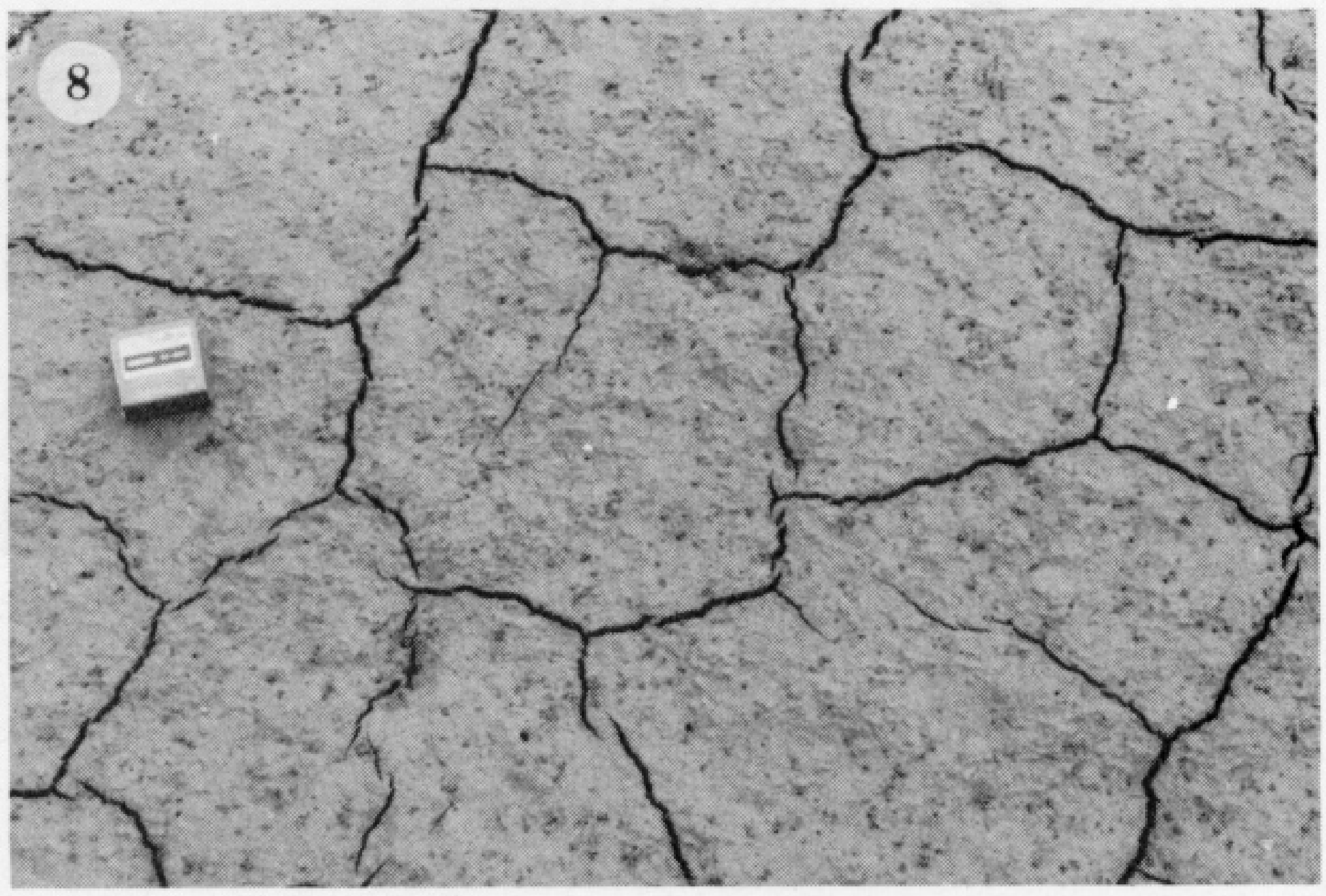

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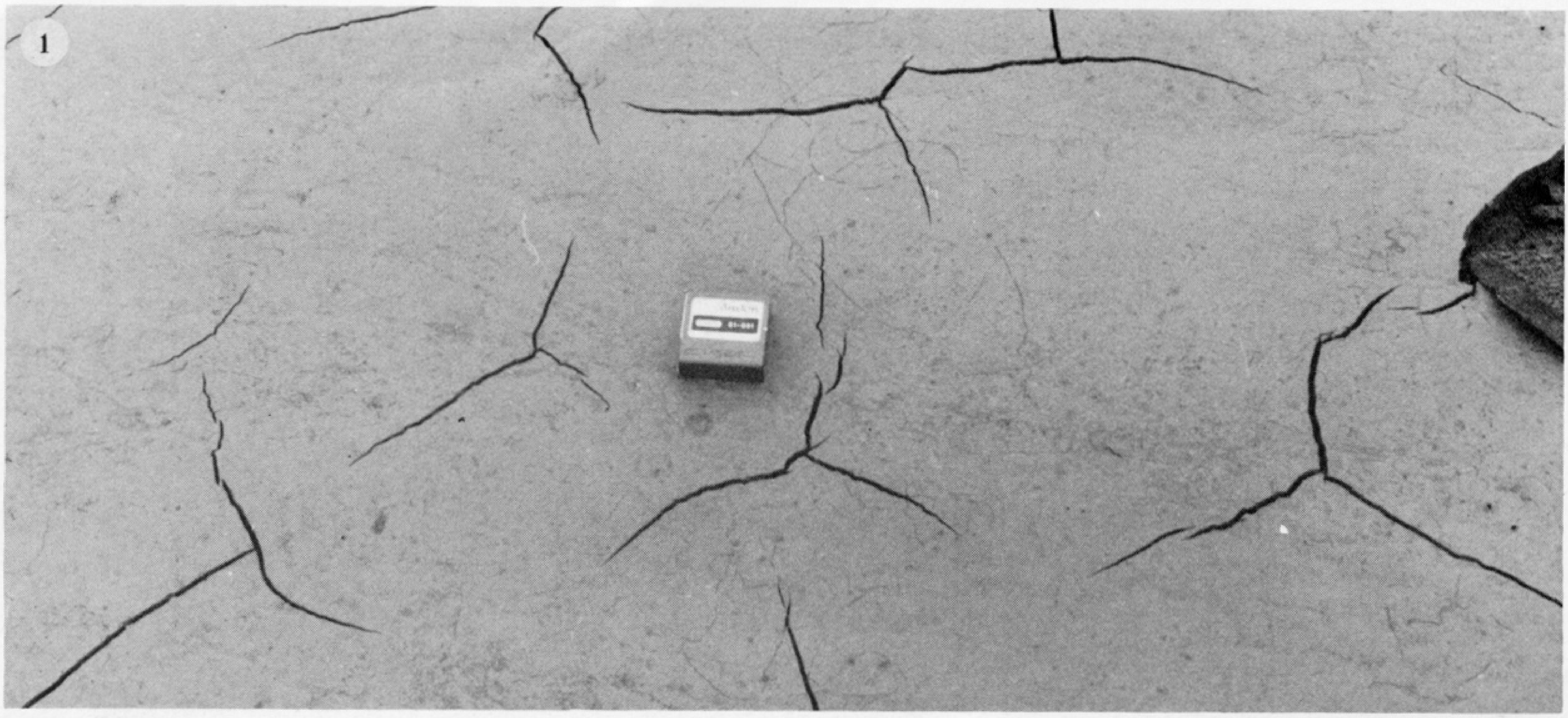
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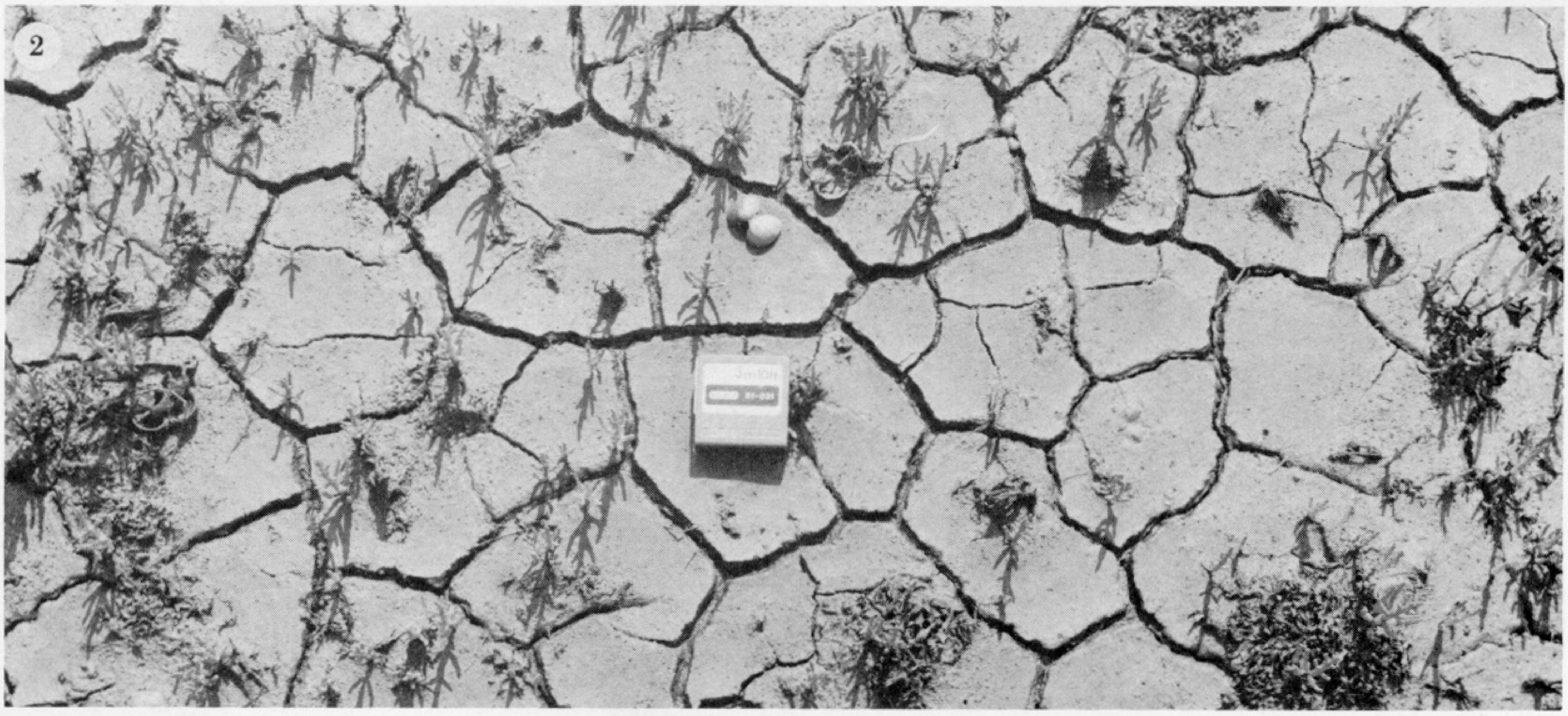
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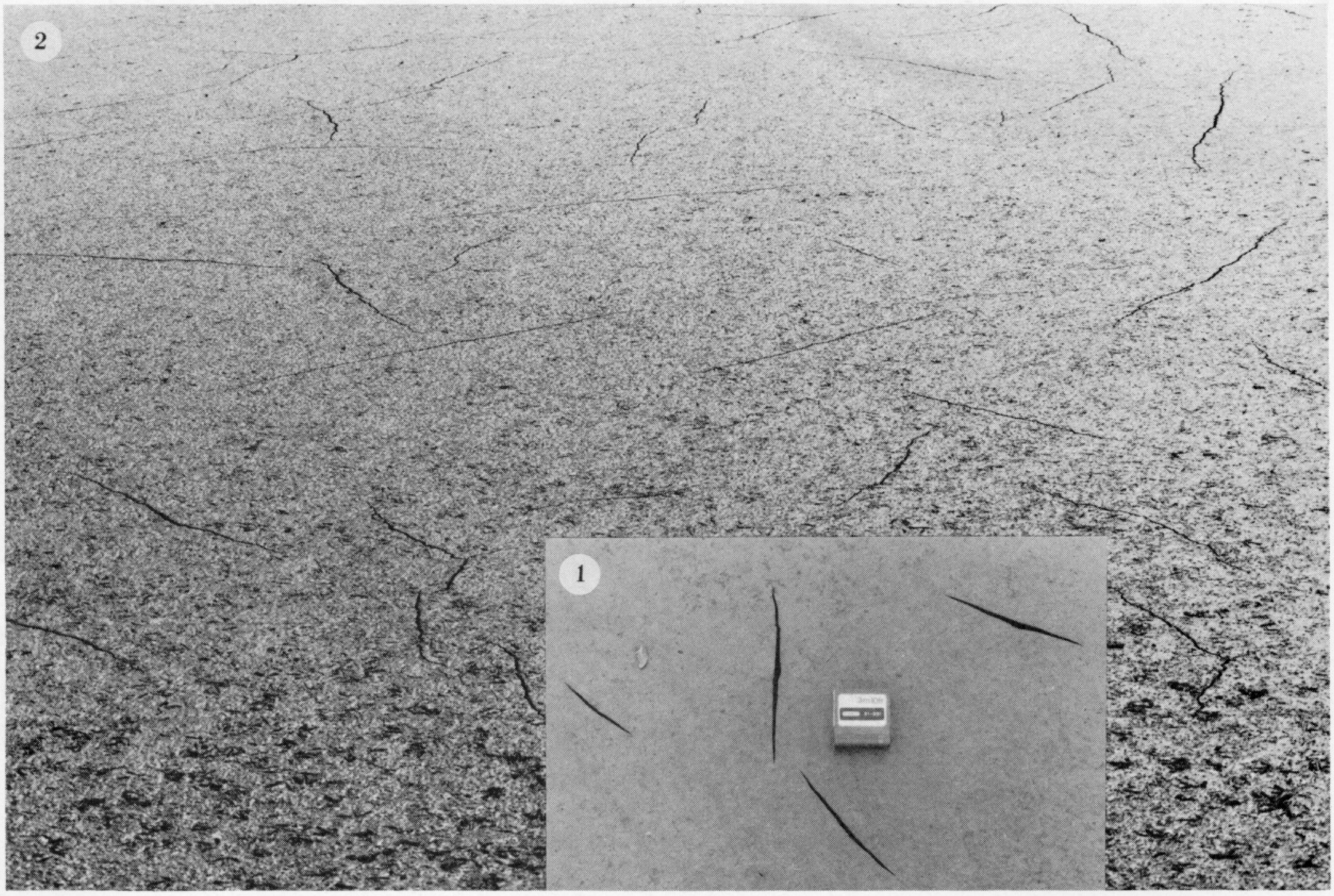

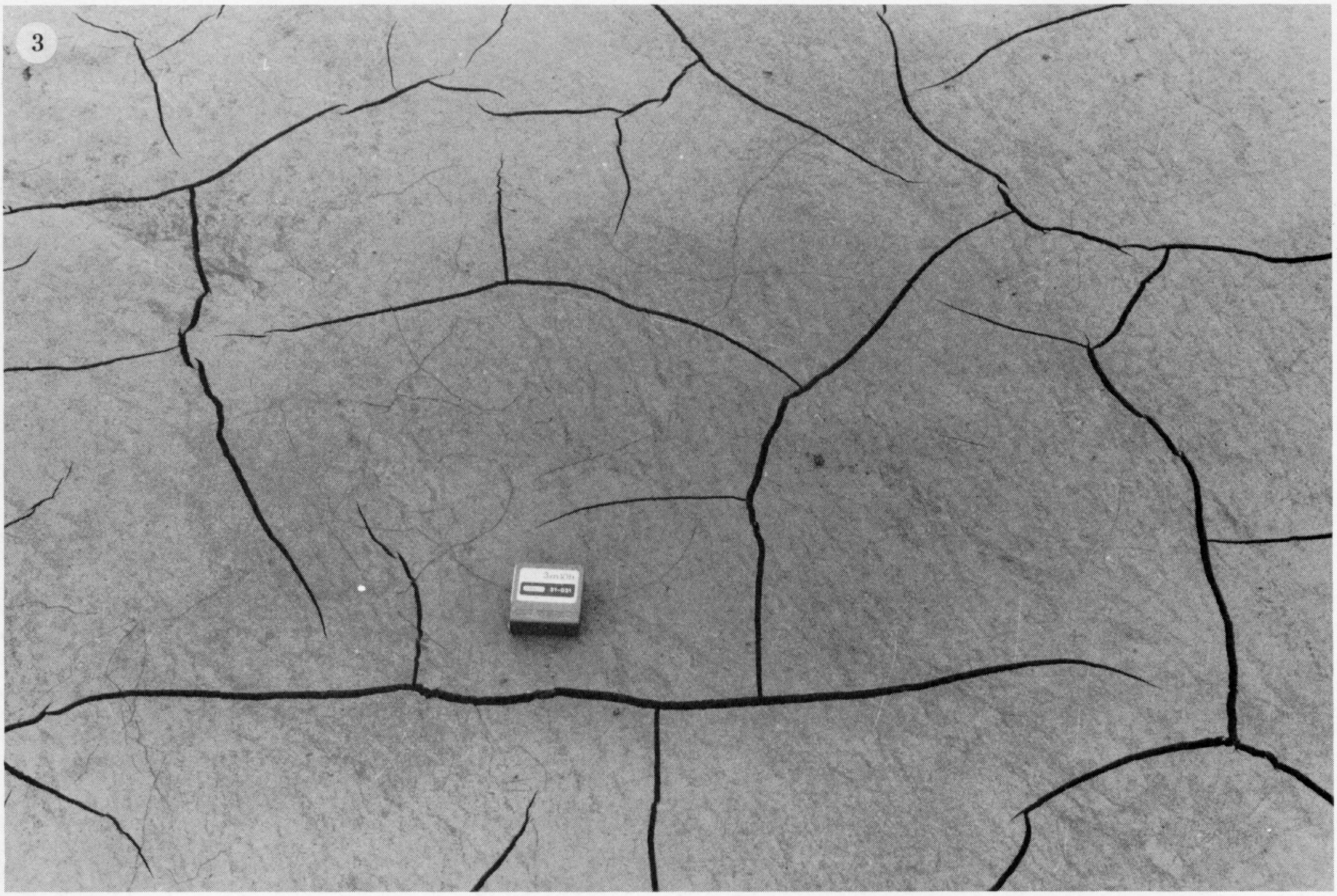

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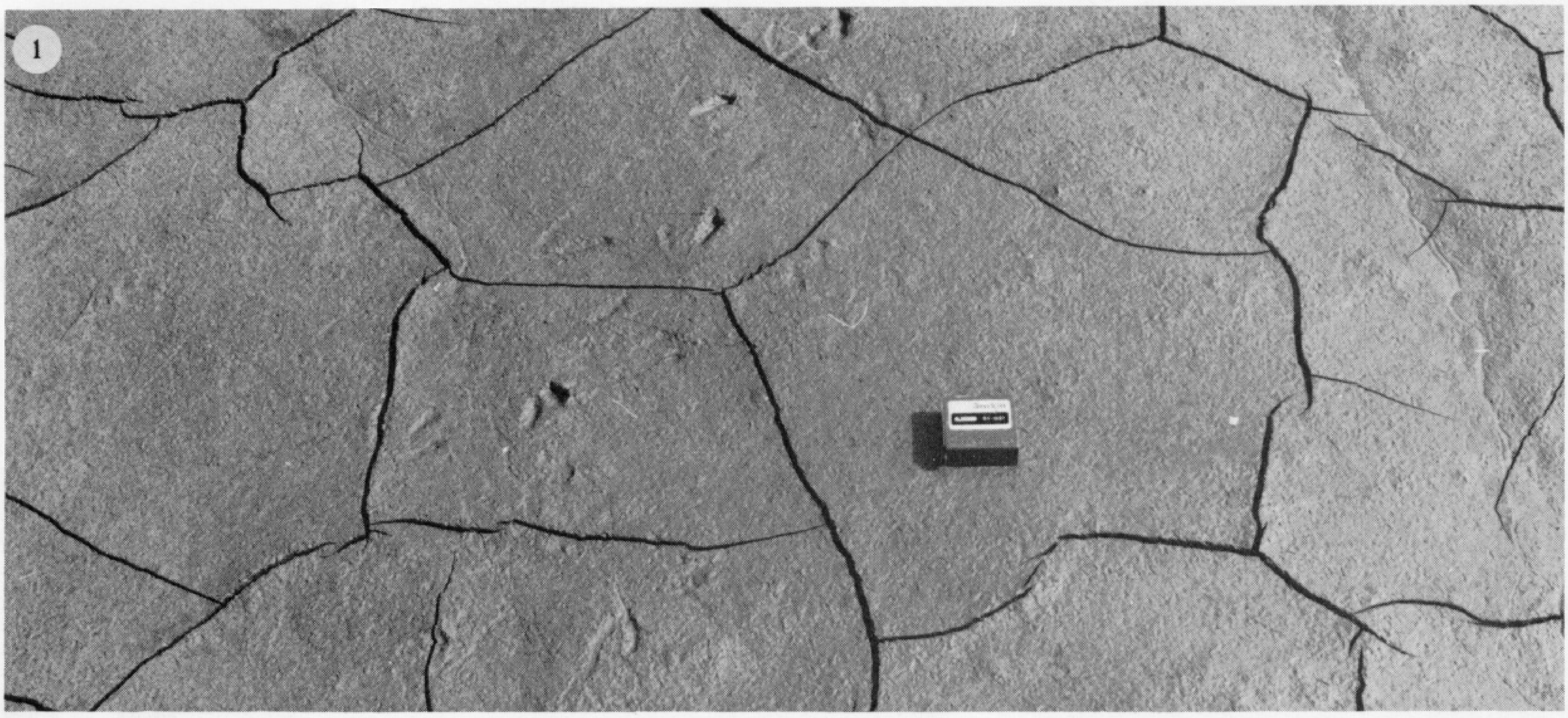

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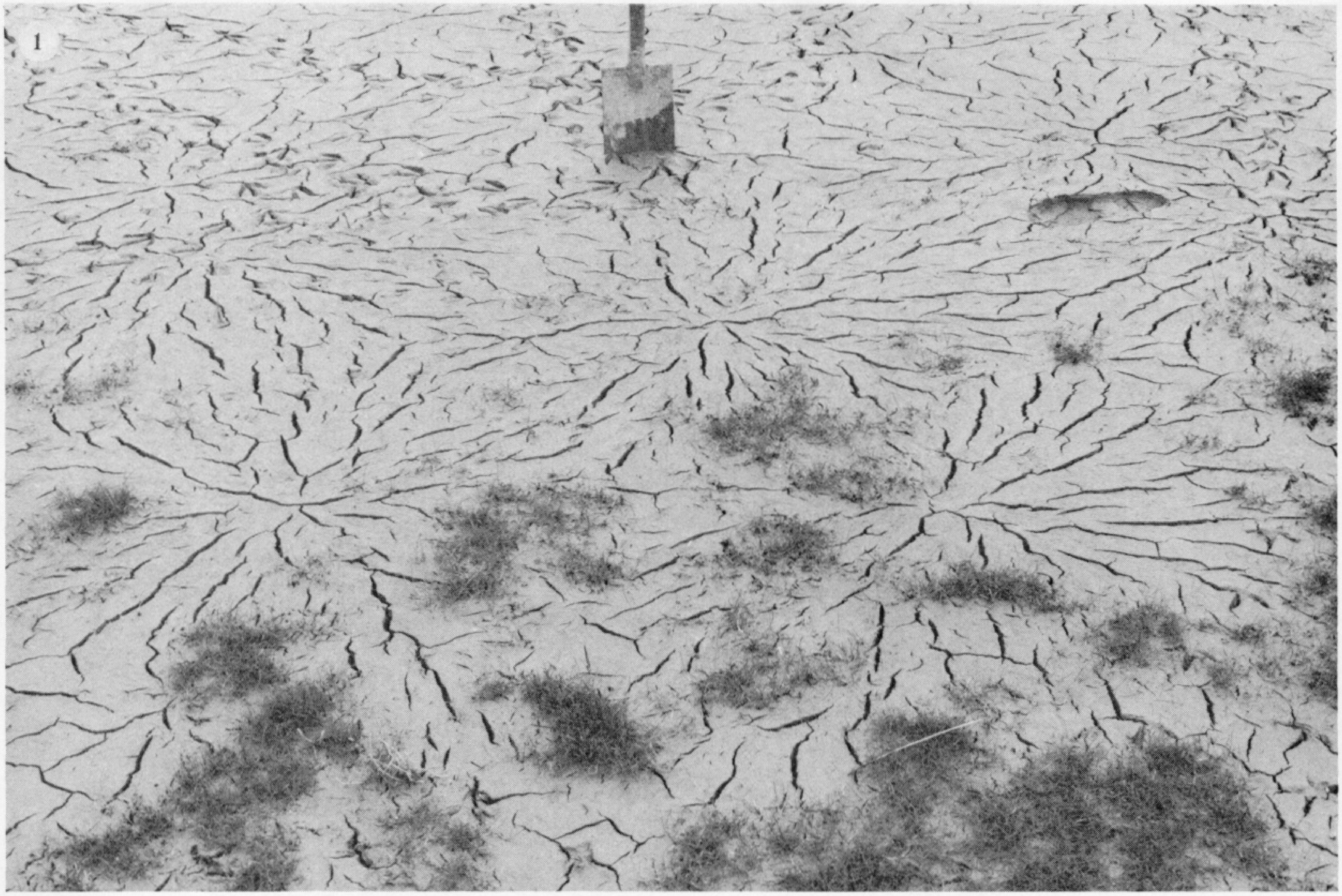

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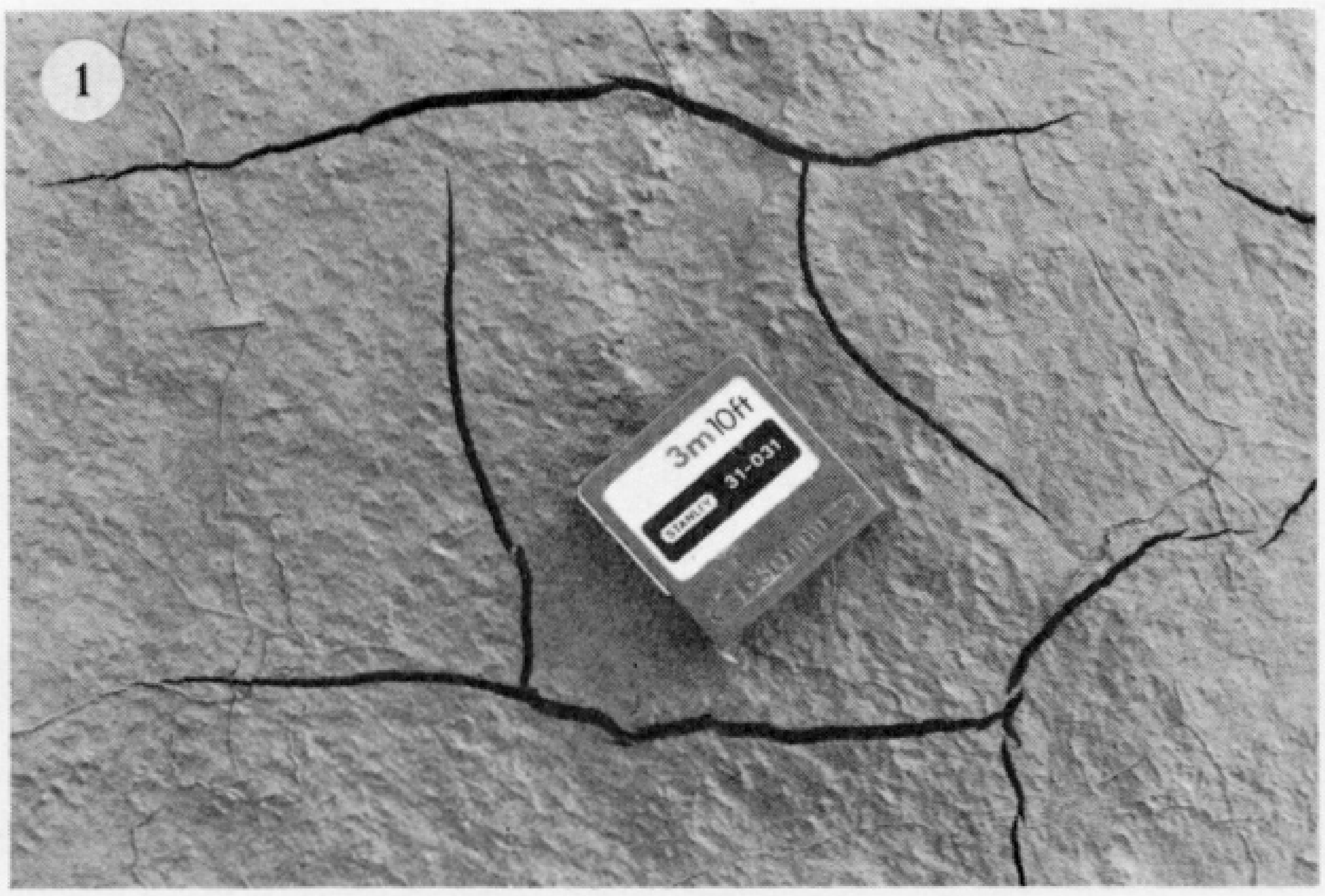

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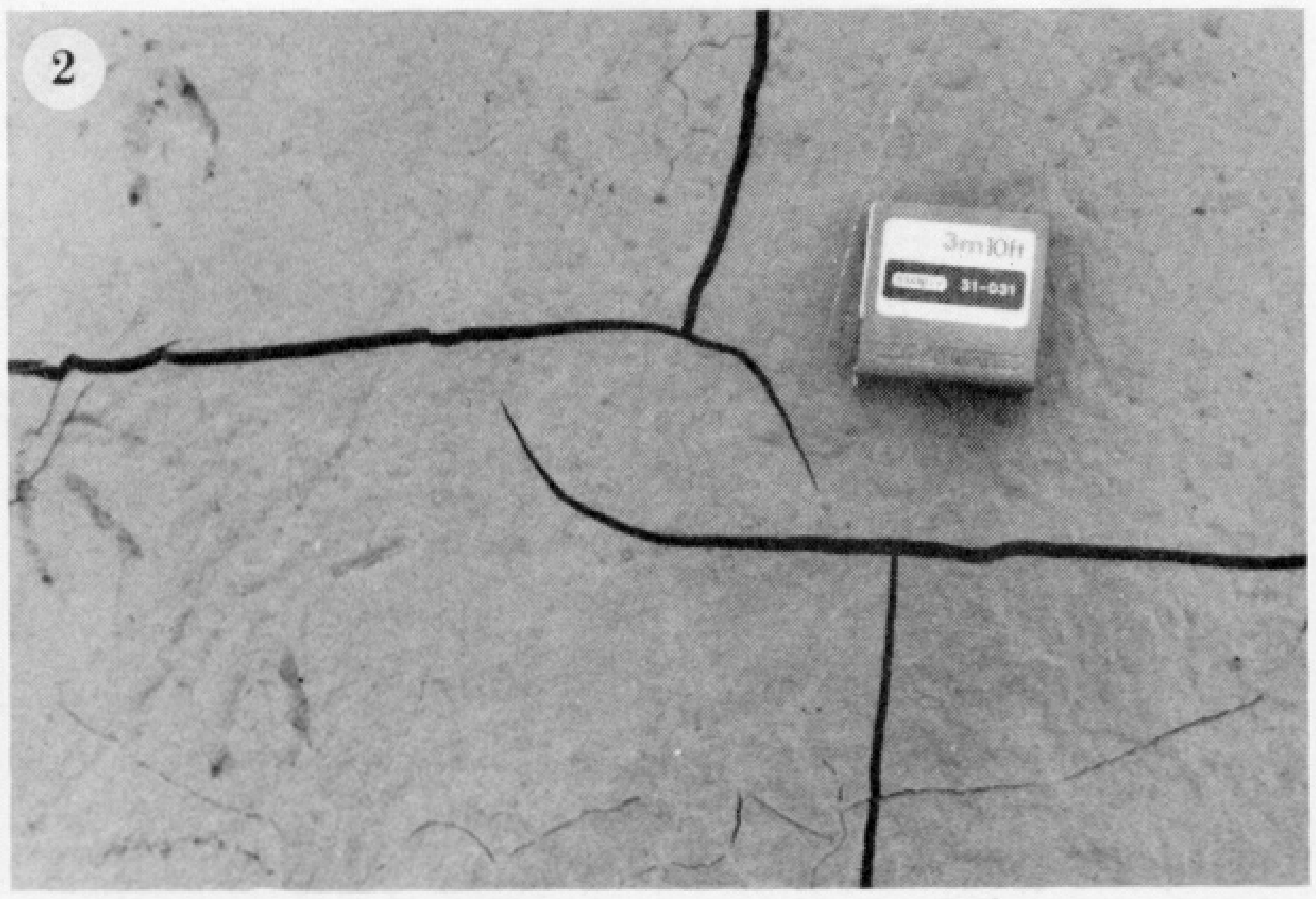

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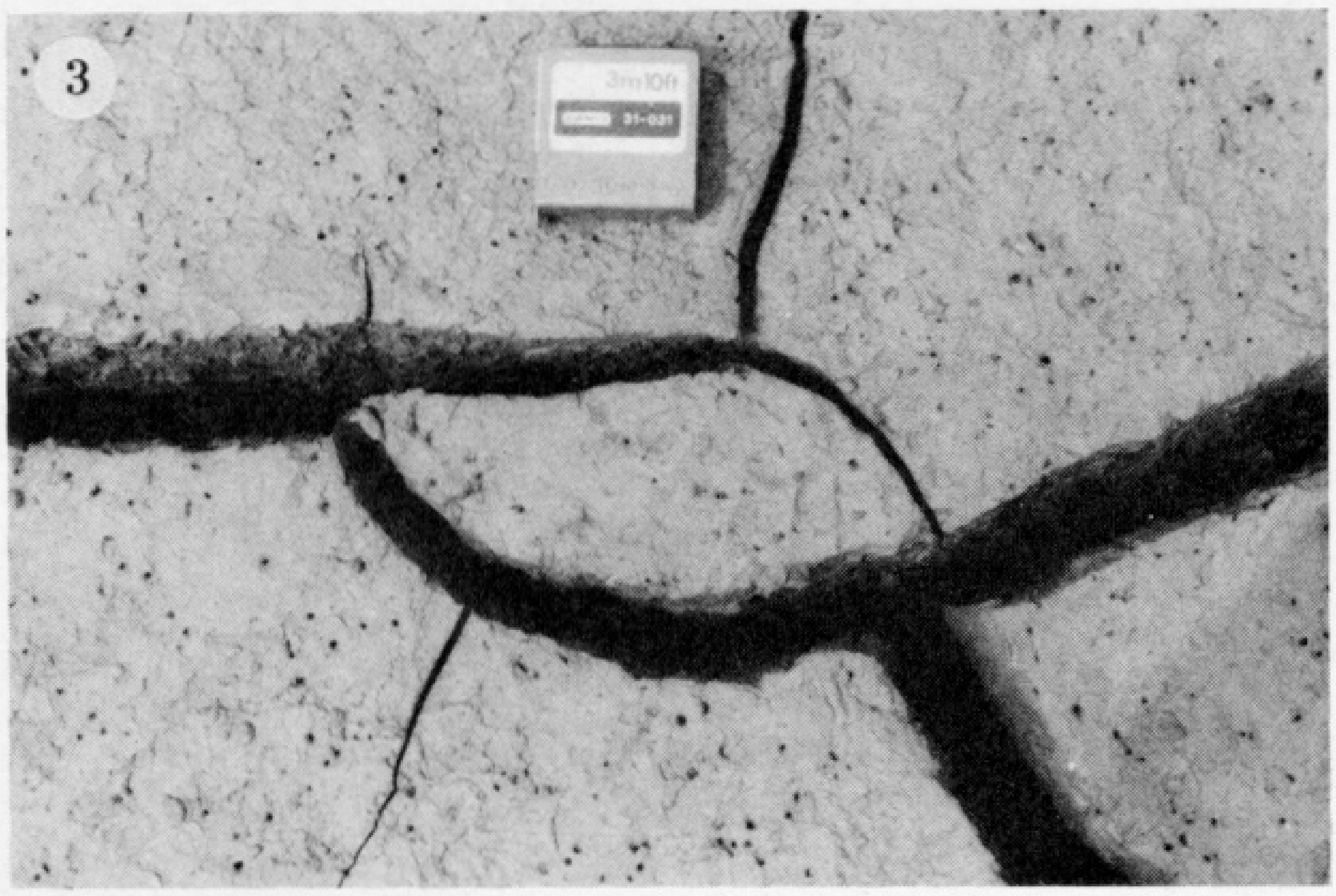

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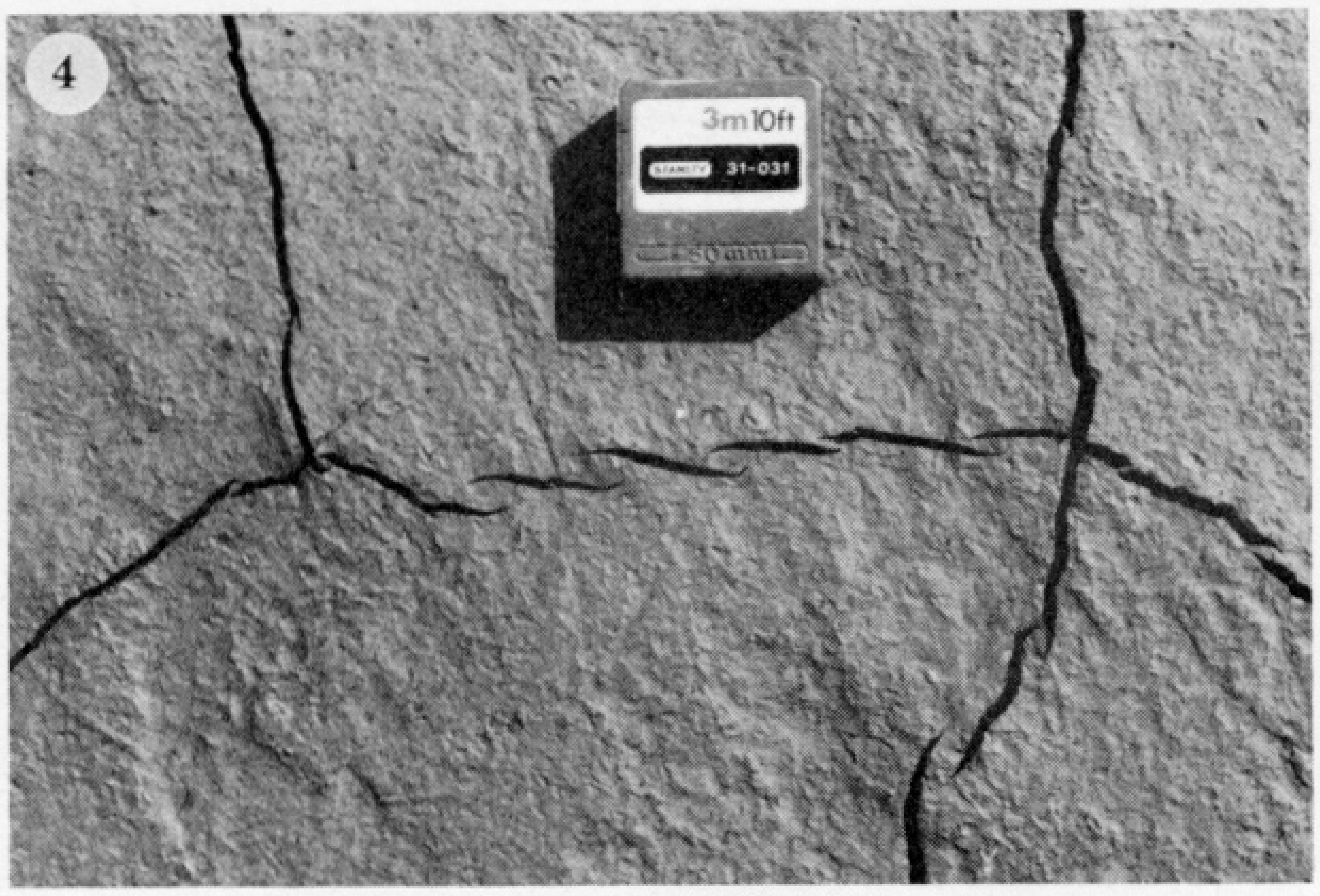

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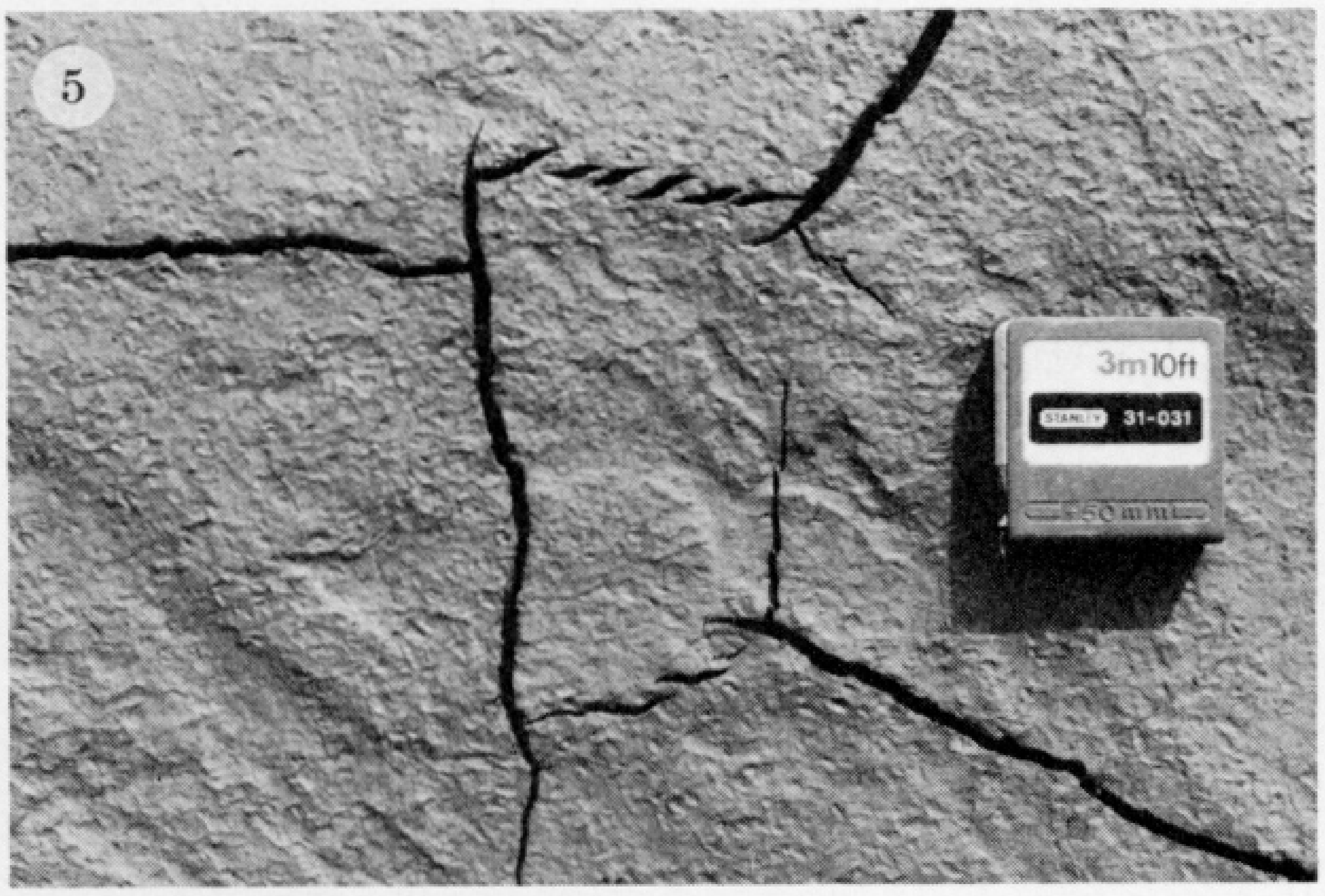

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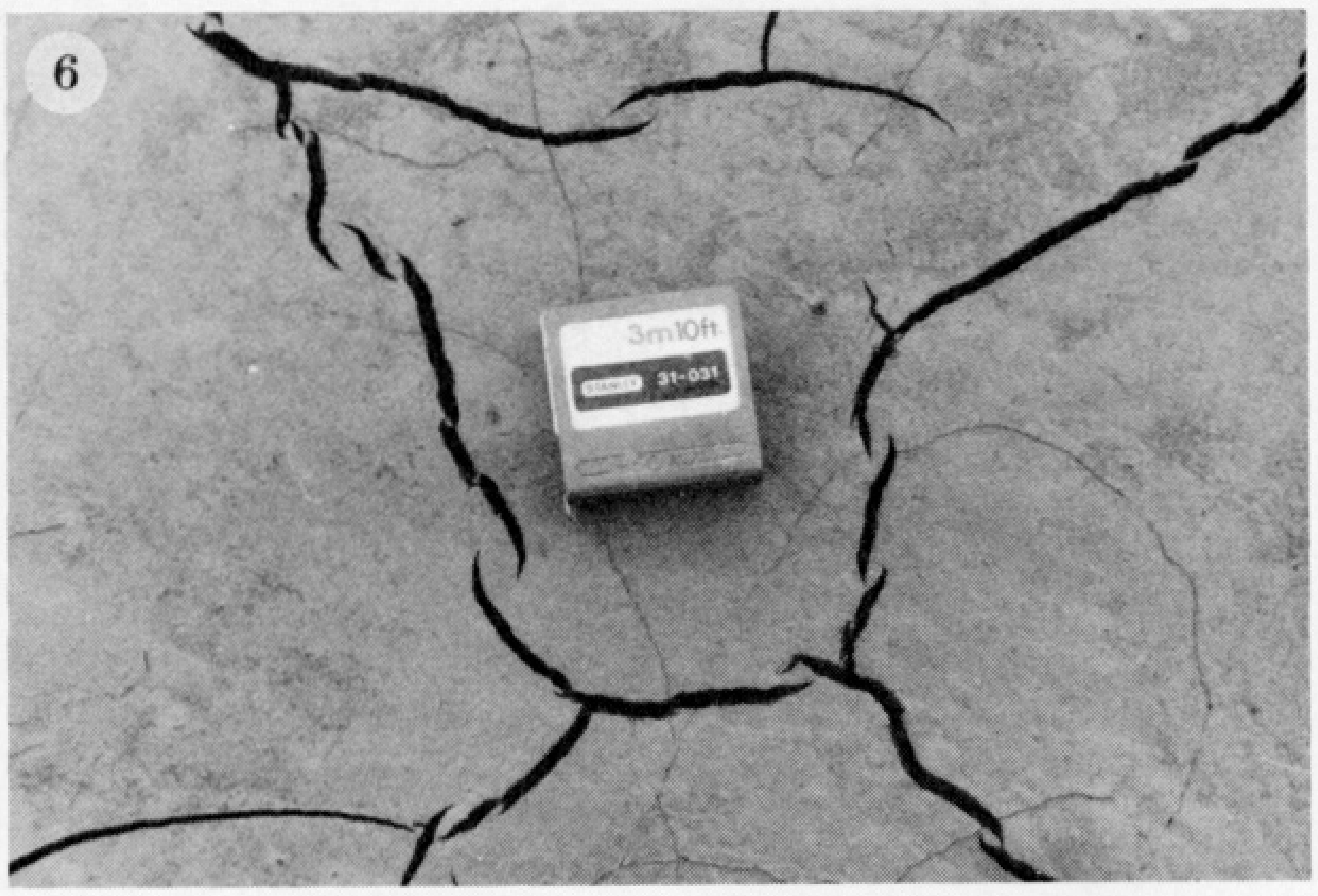

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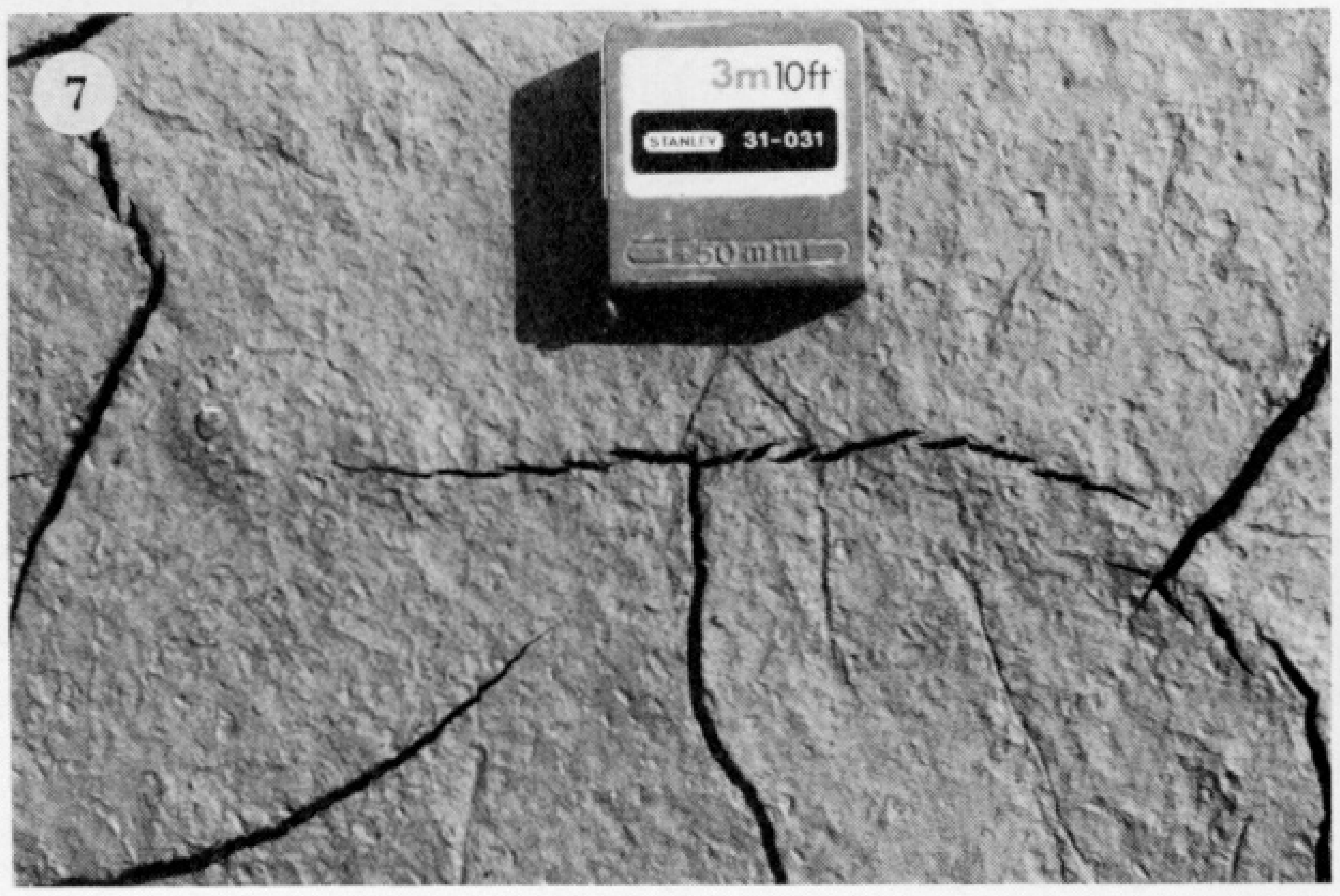

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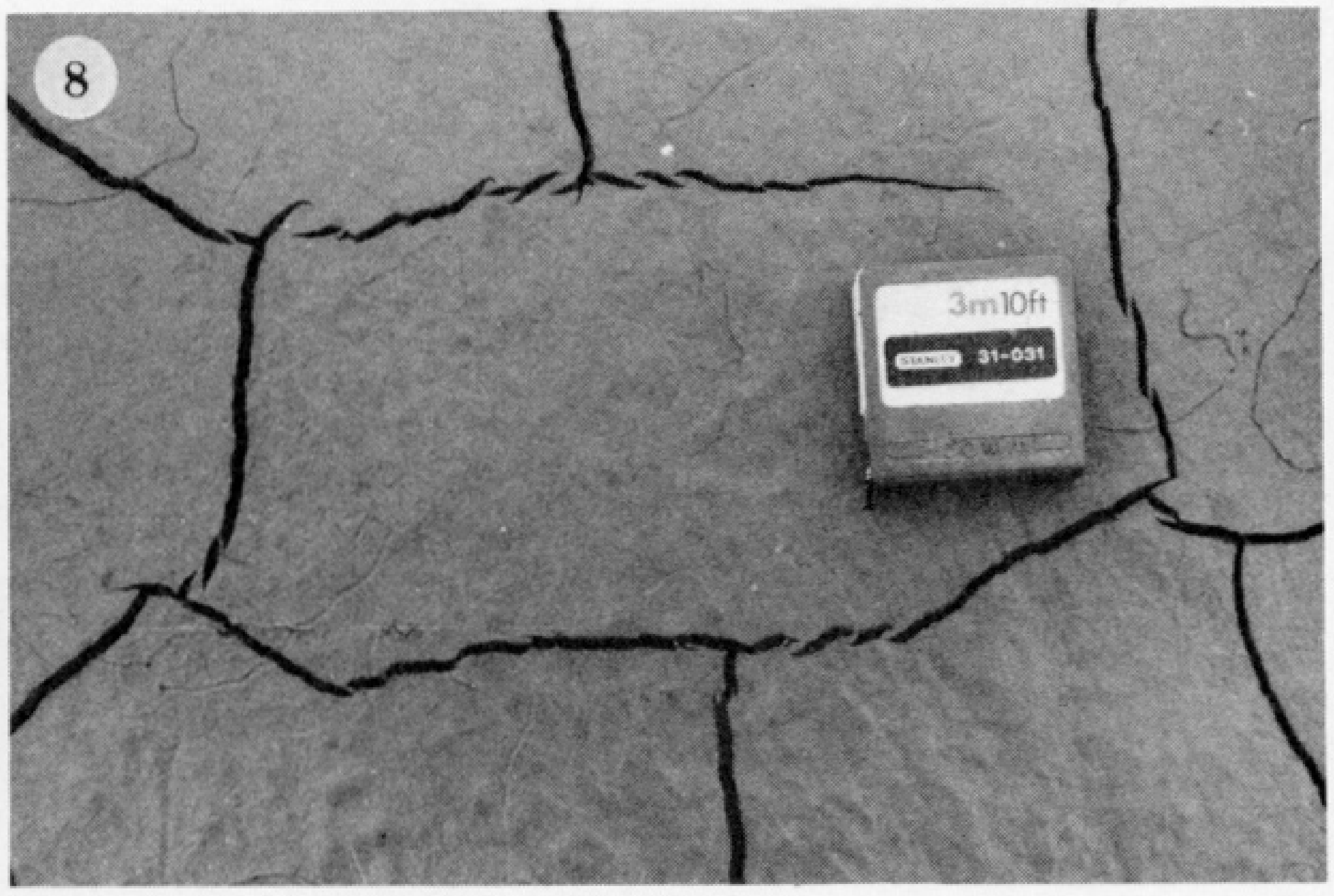

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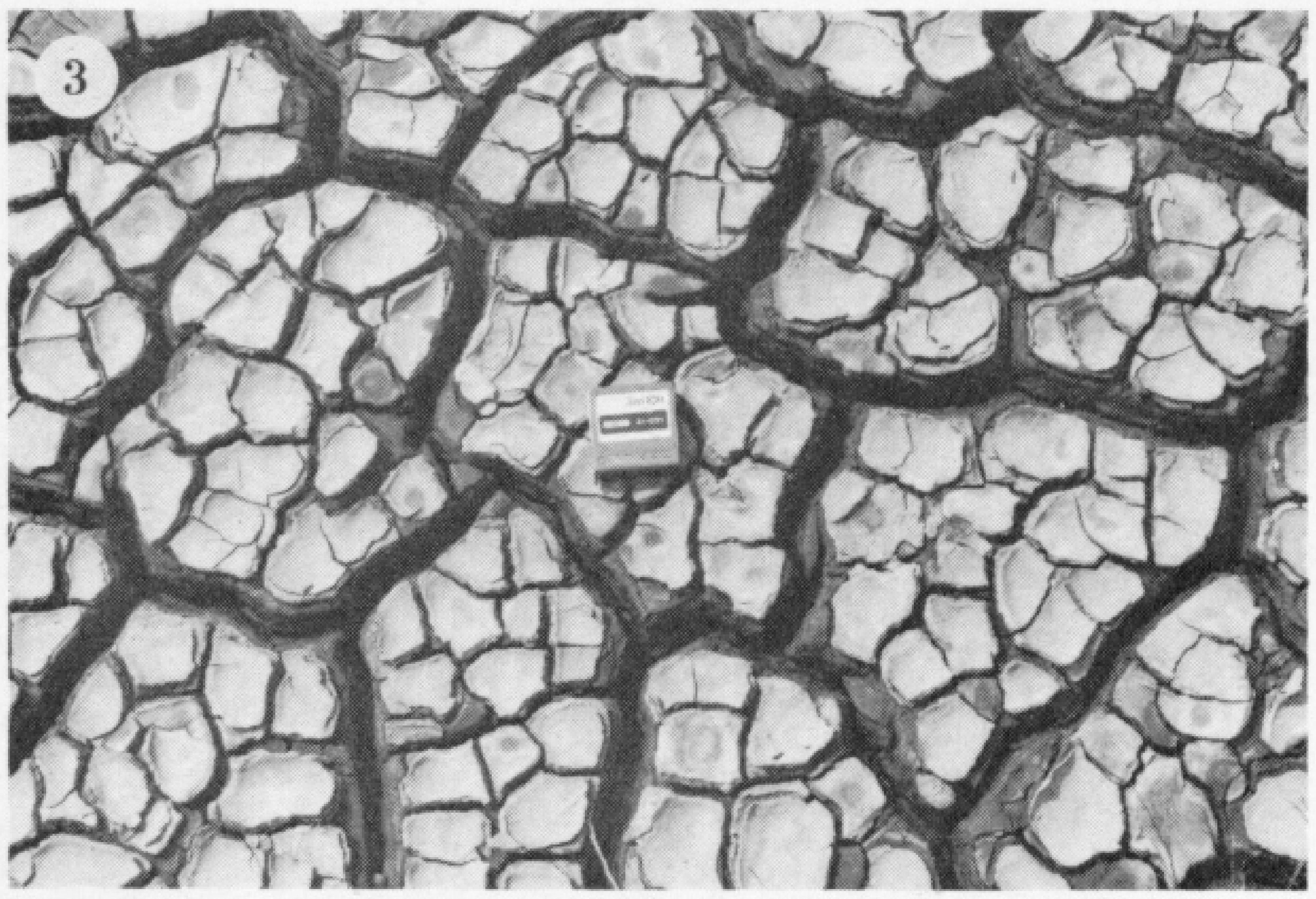

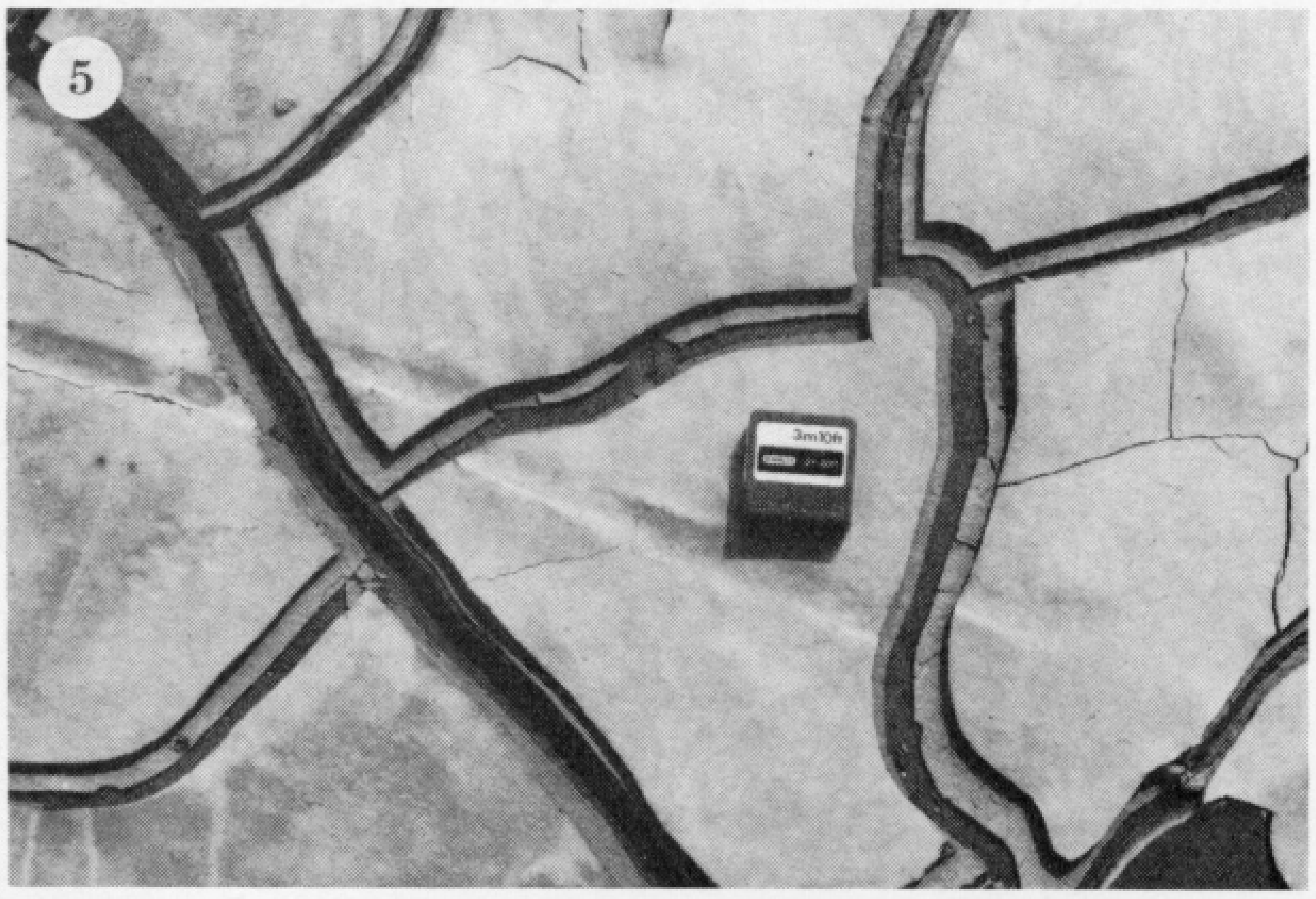

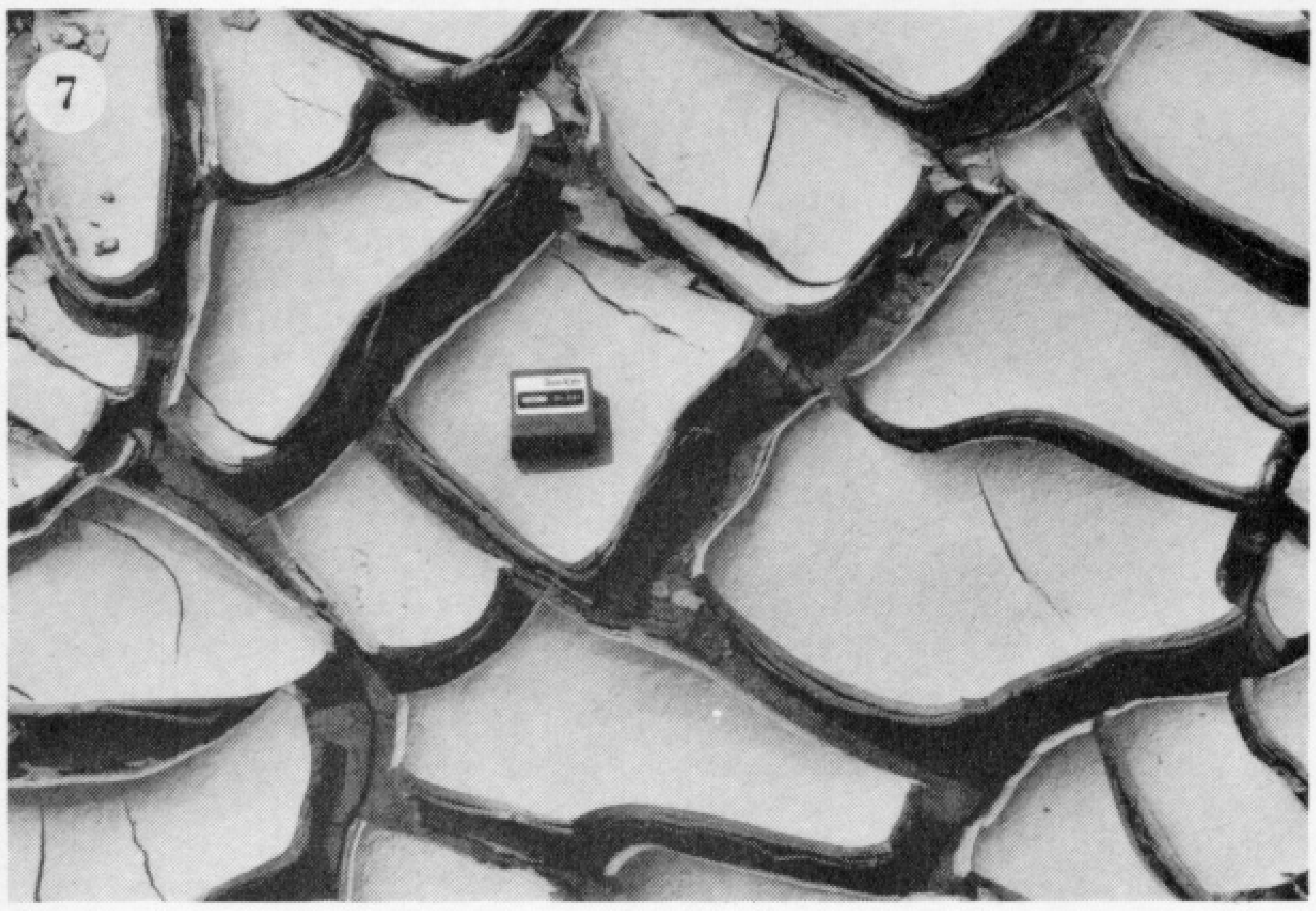

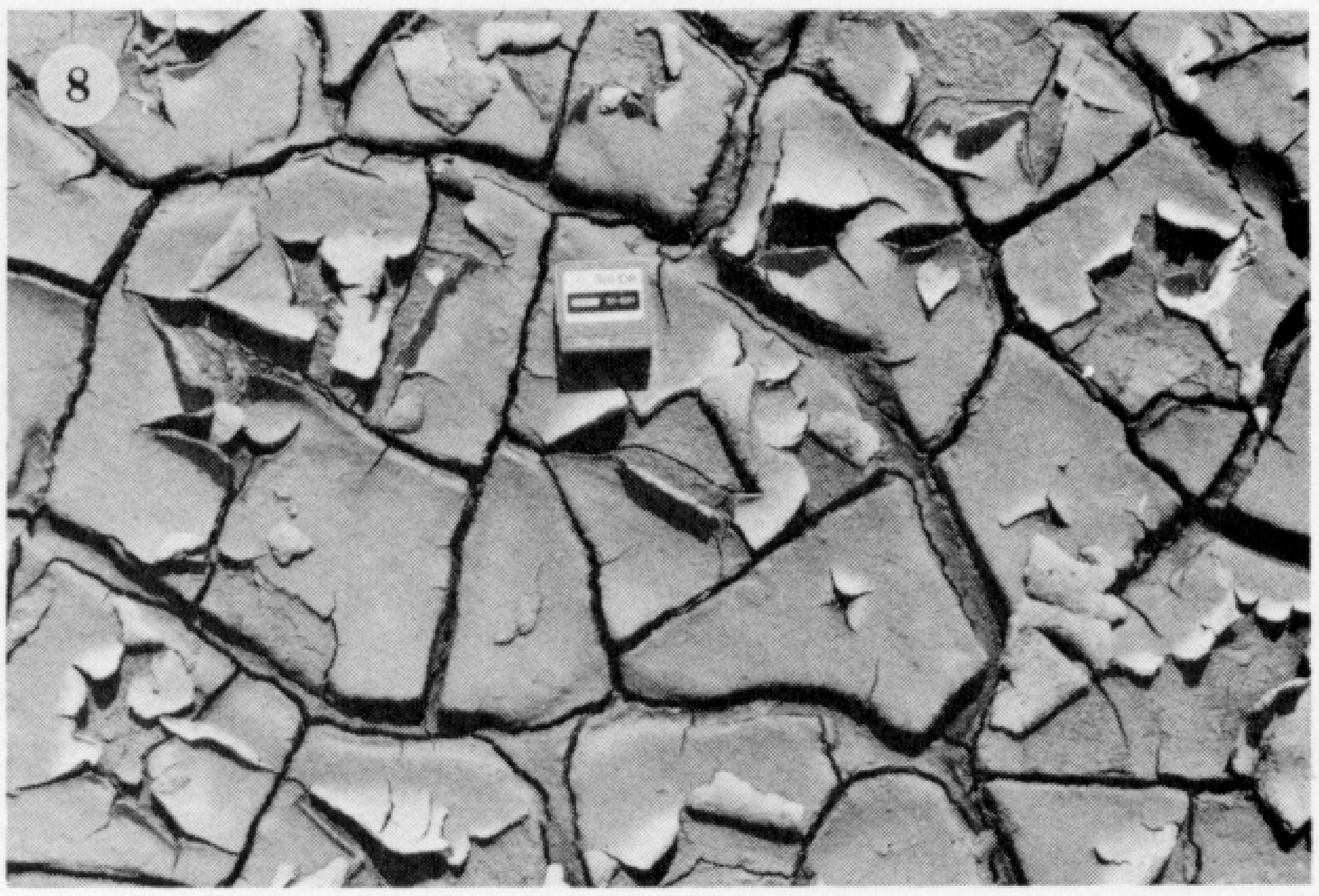

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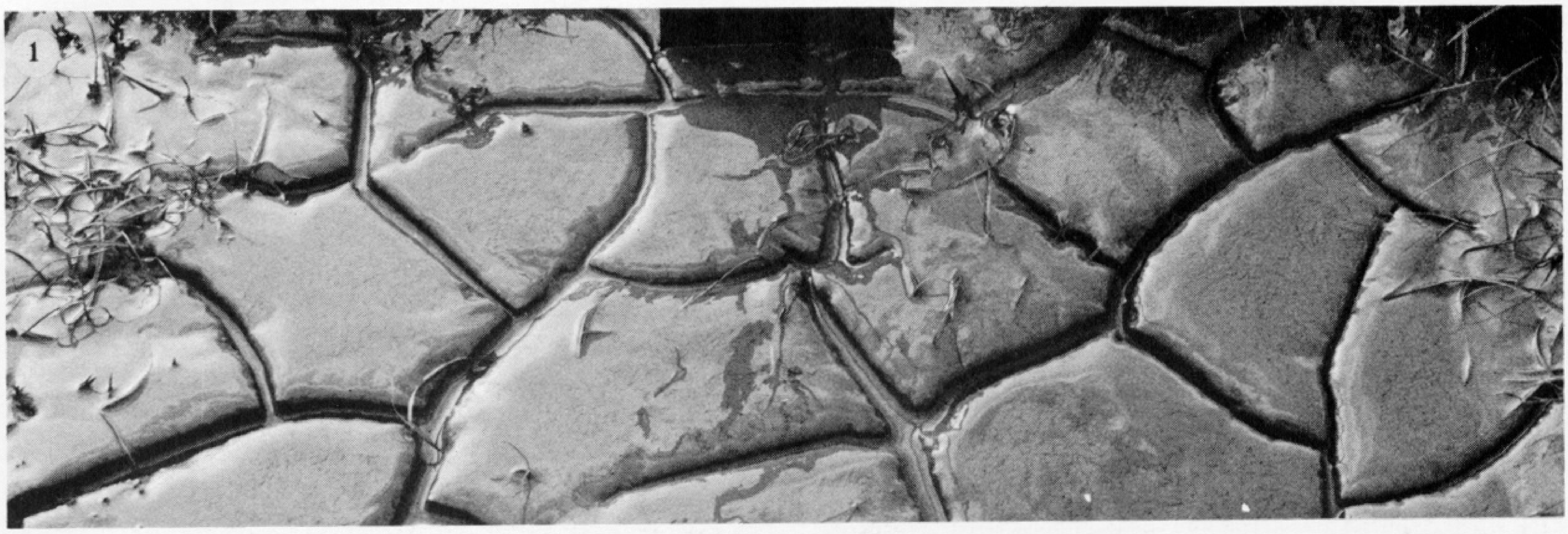
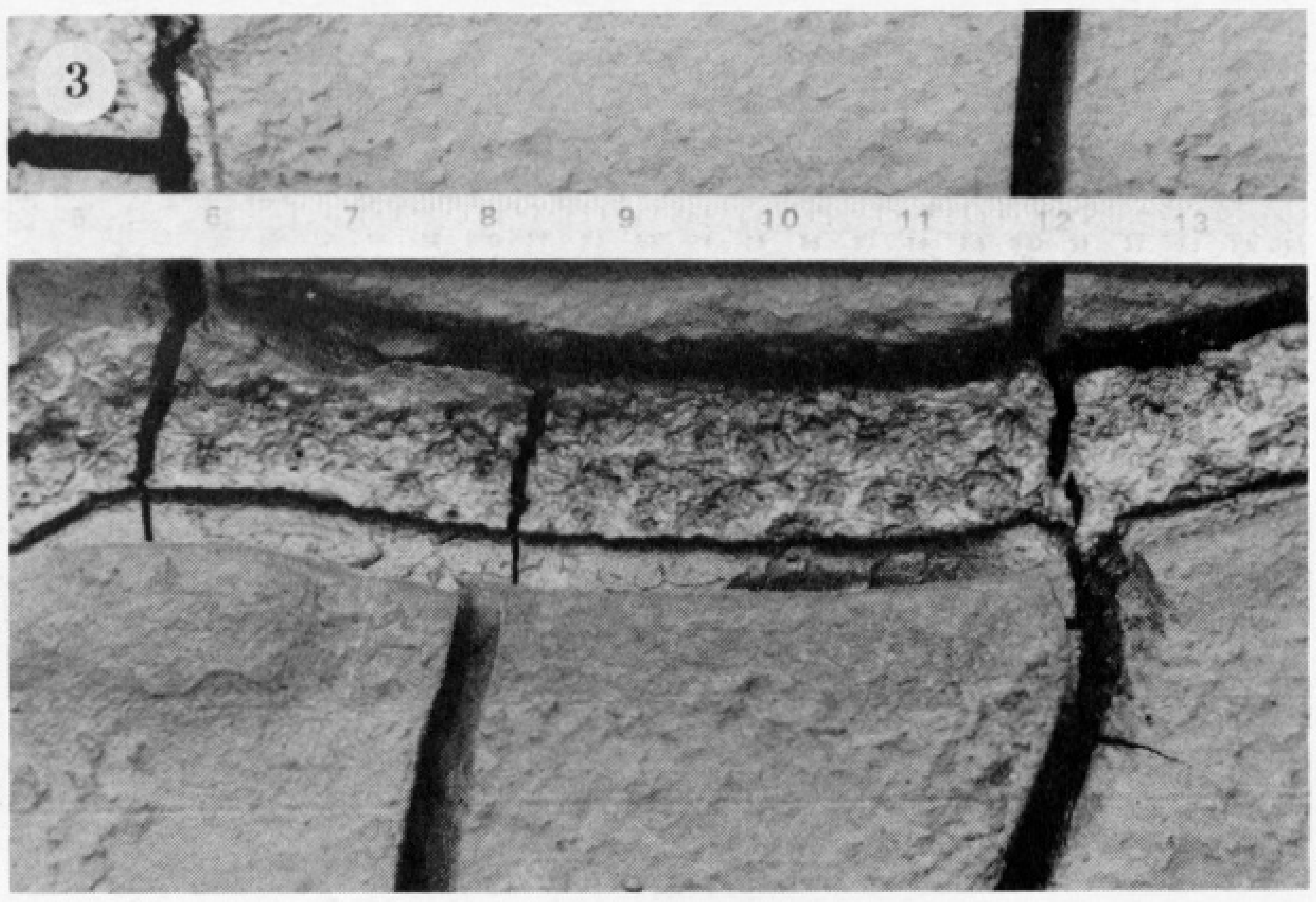
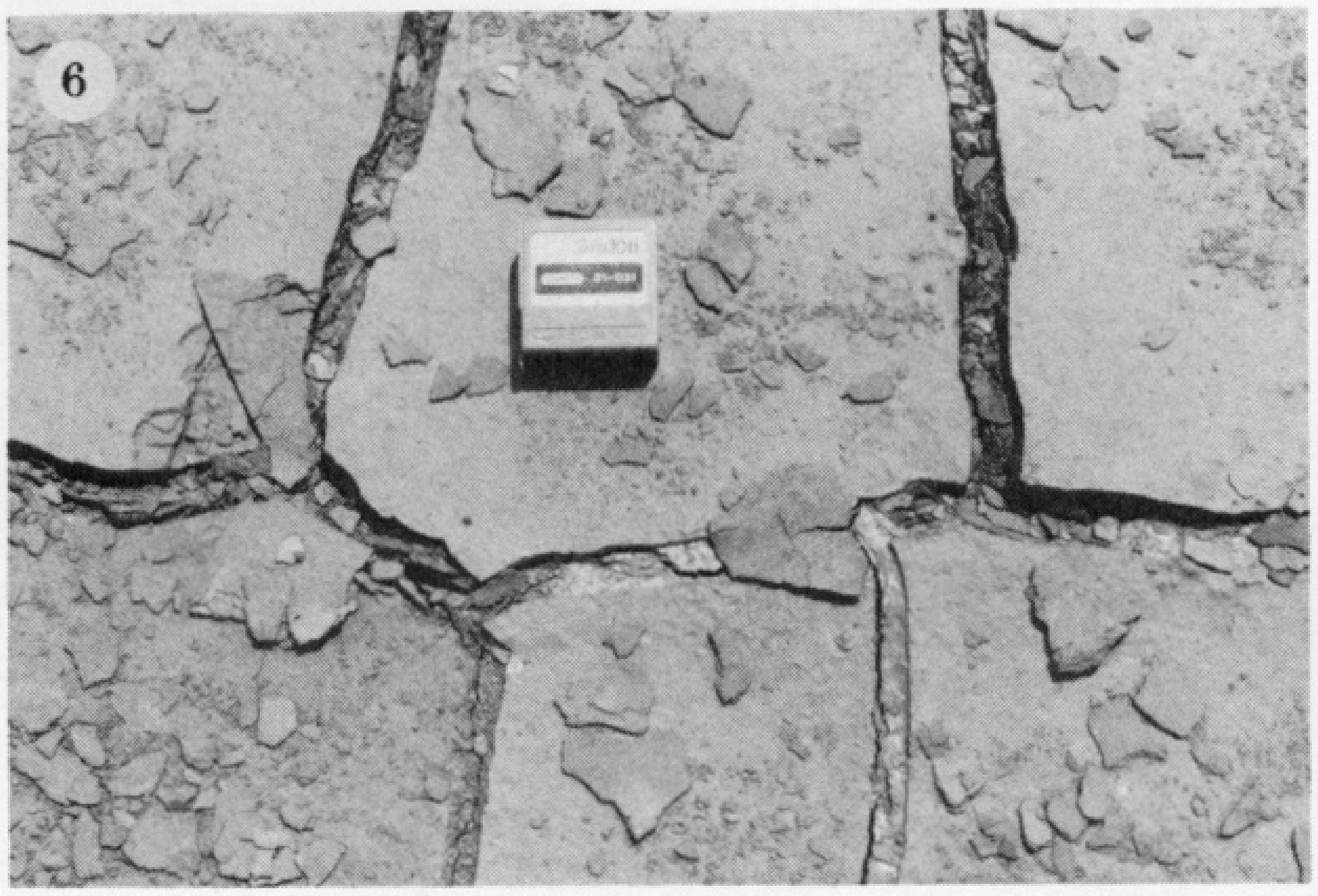
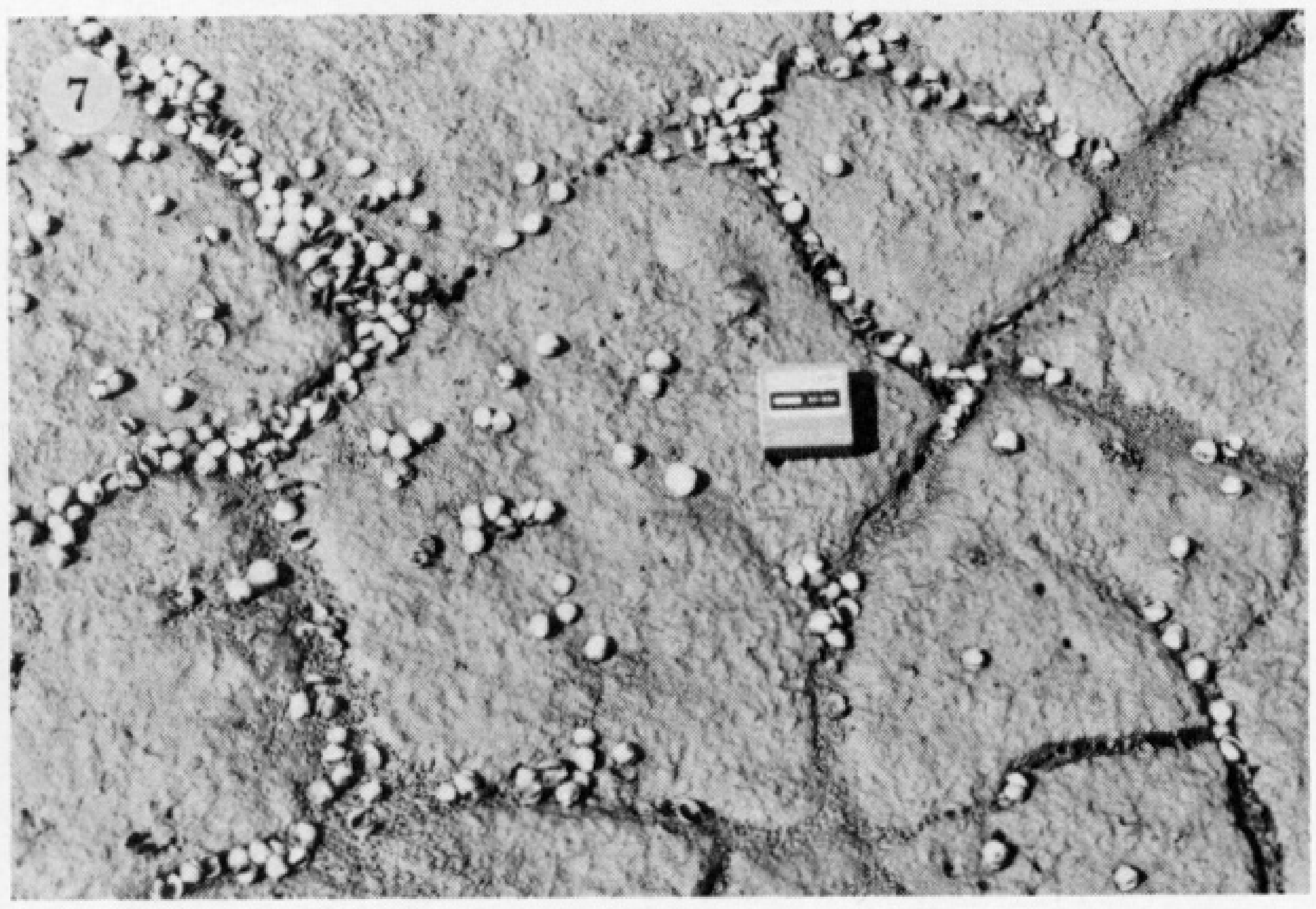


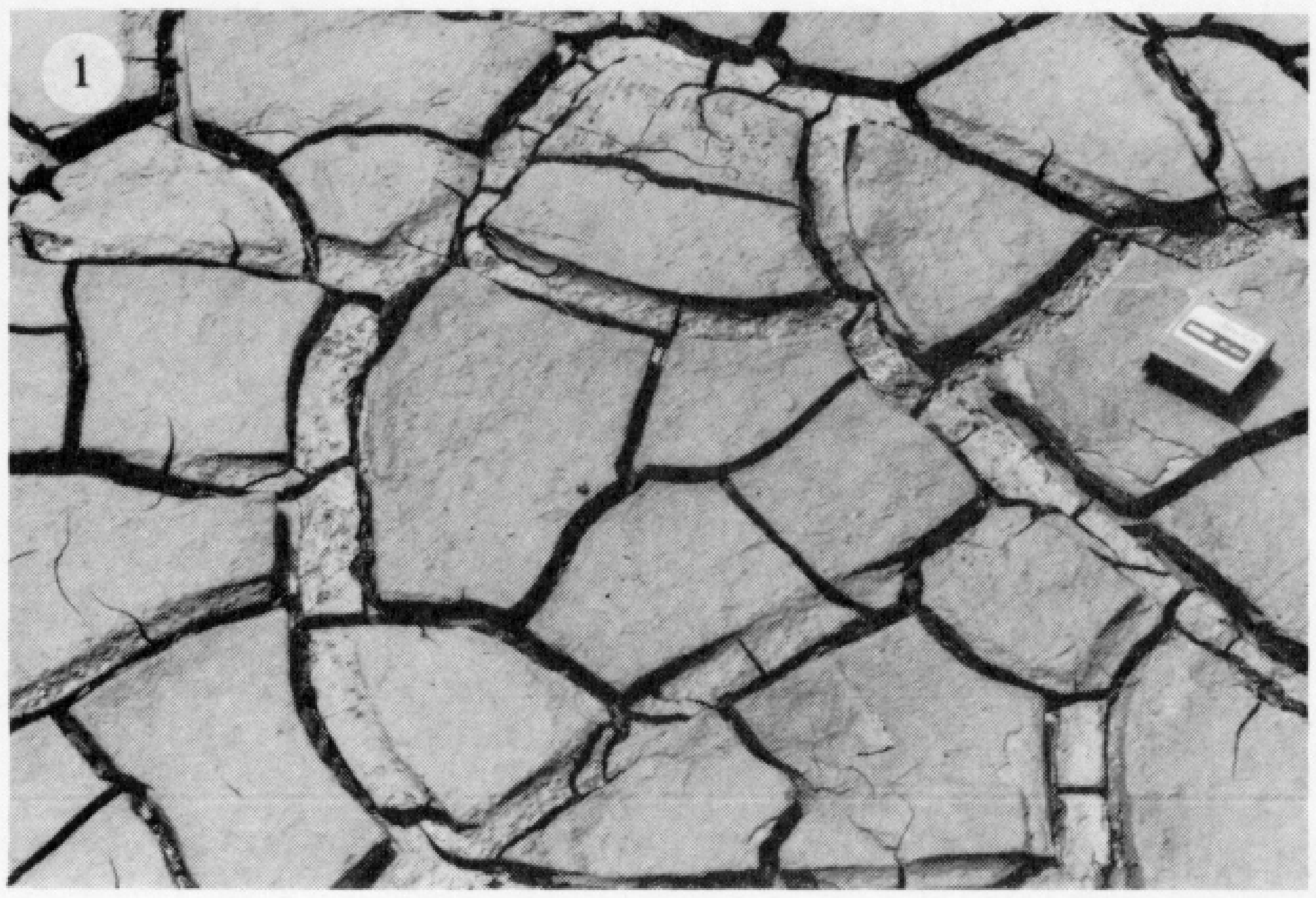






For description see p. 149.

1



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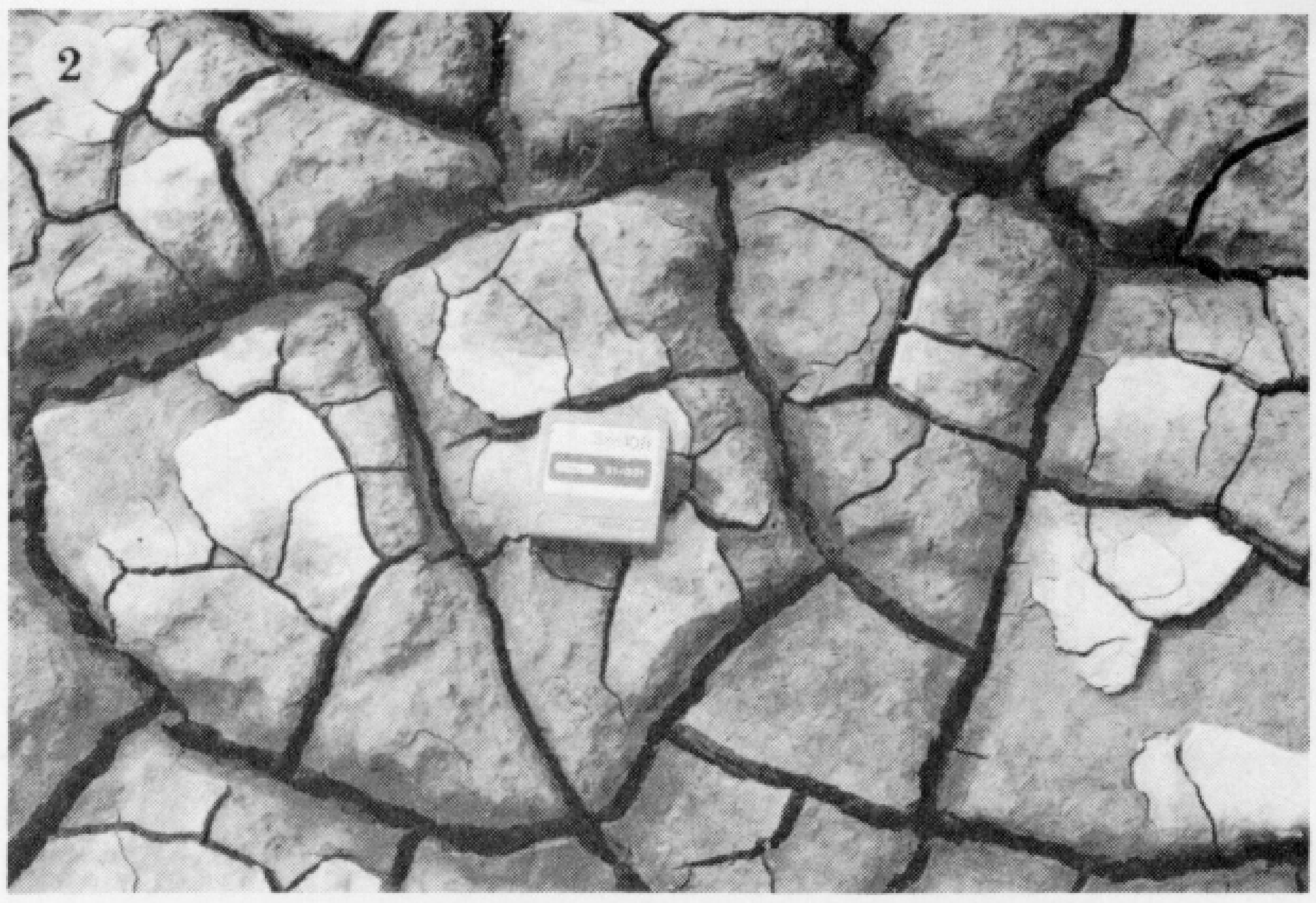

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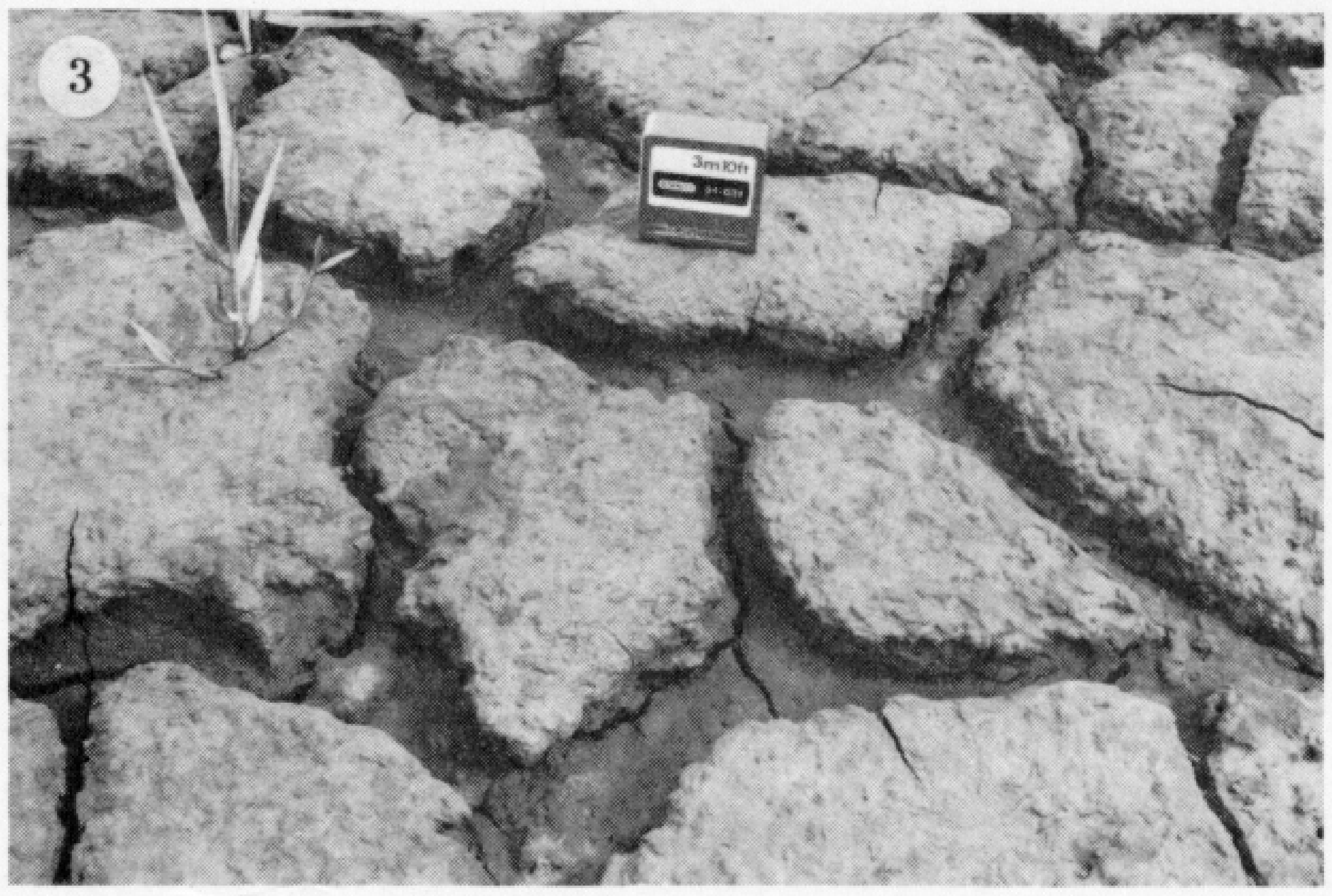

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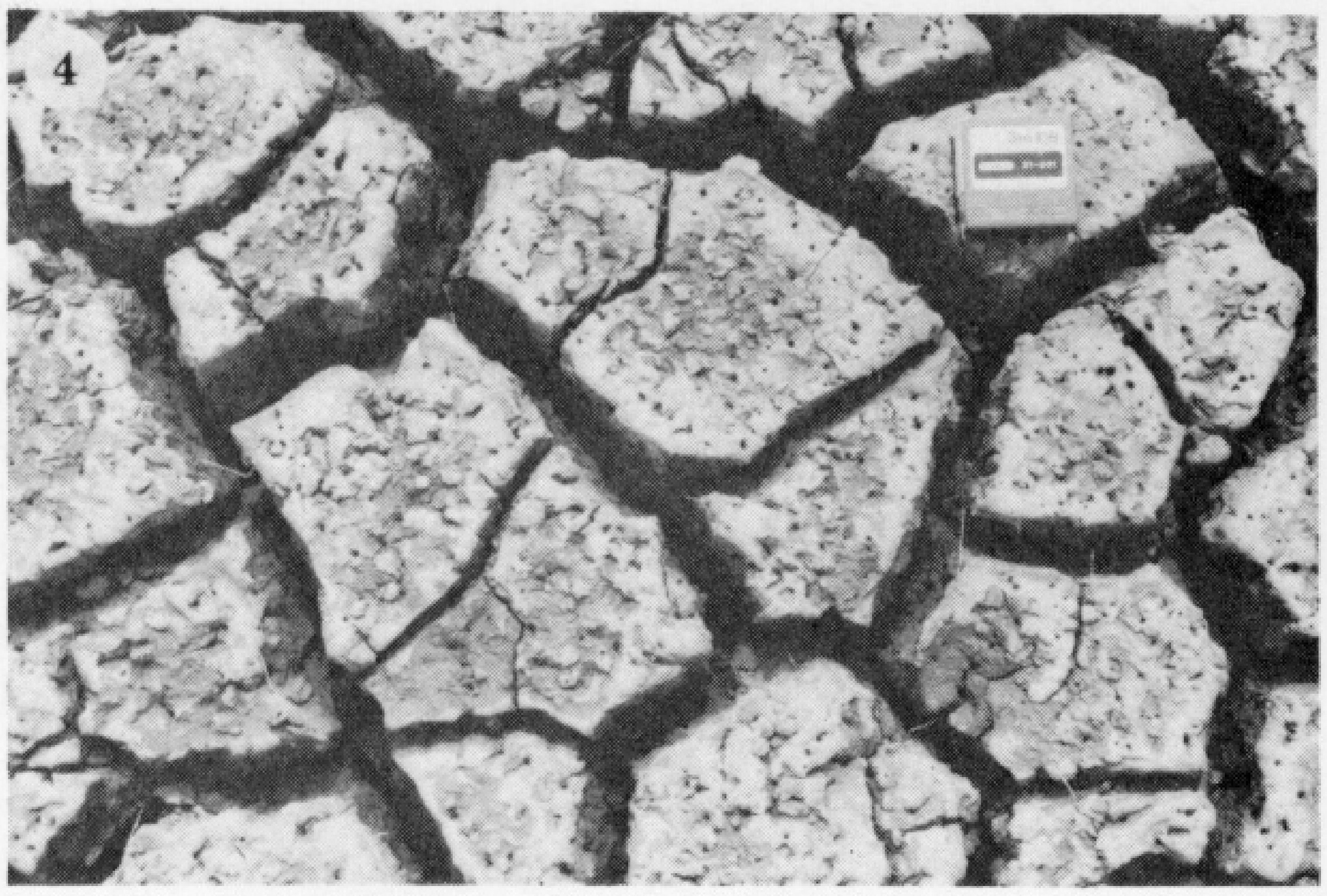

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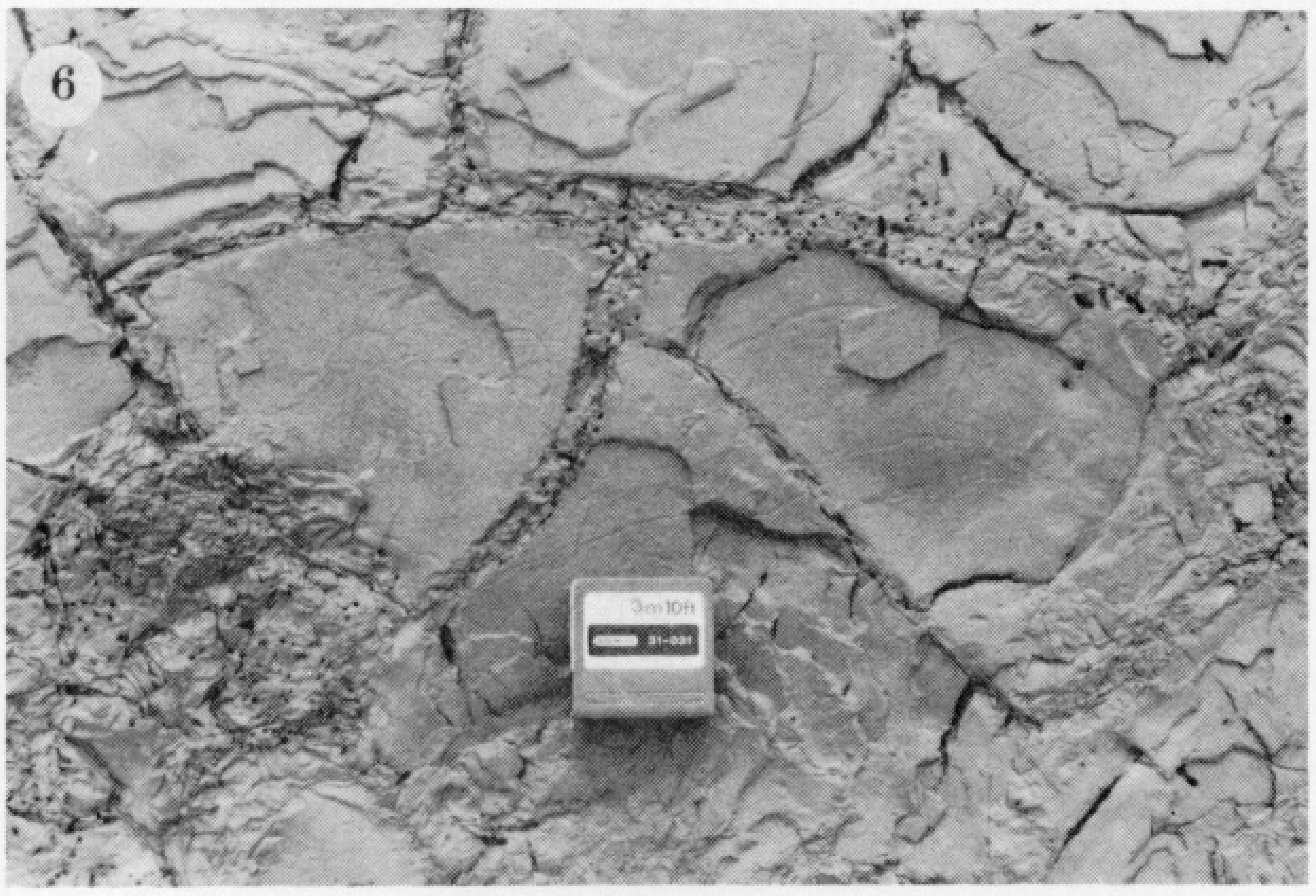
6



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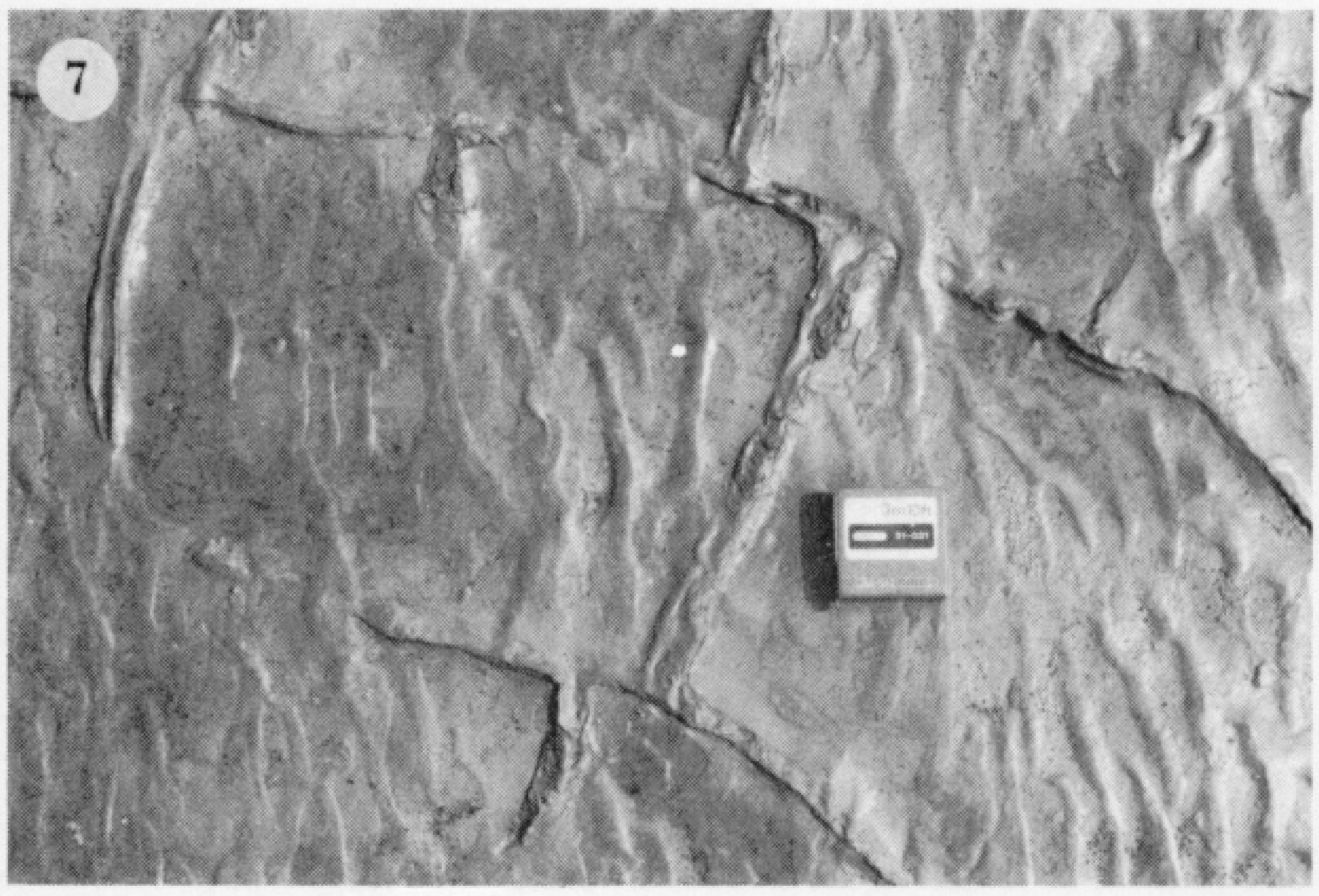

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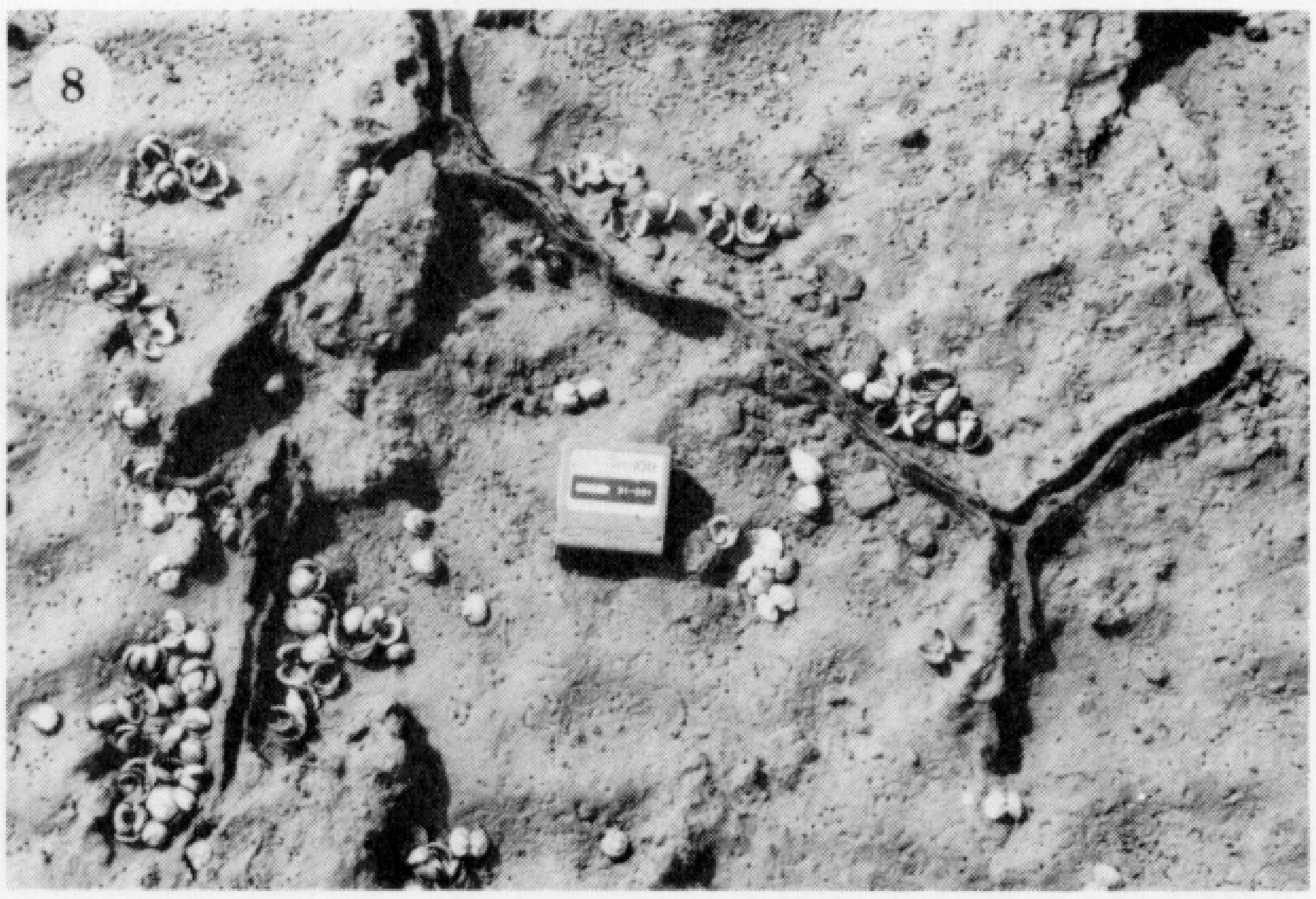

For description see p. 149.

1


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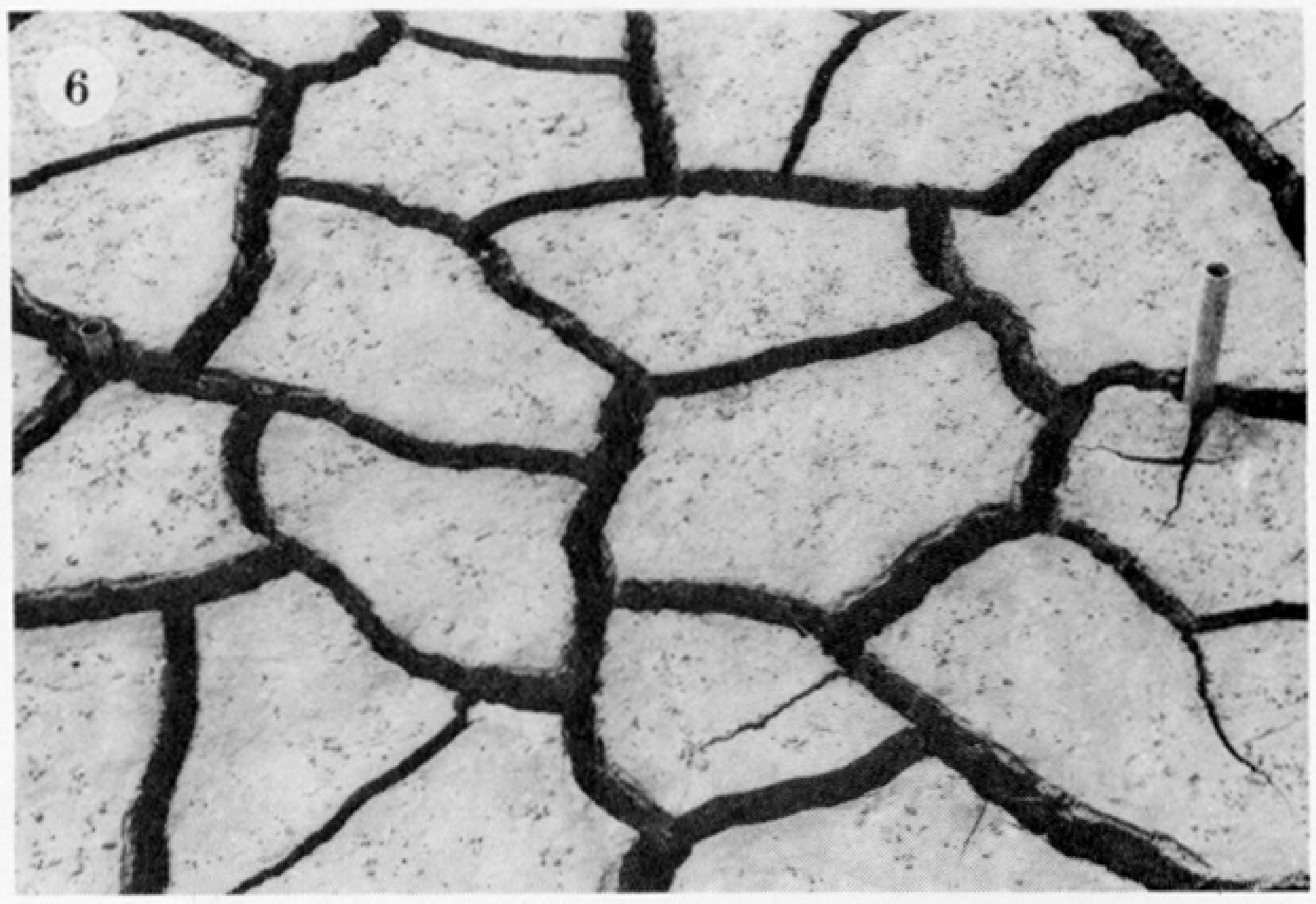
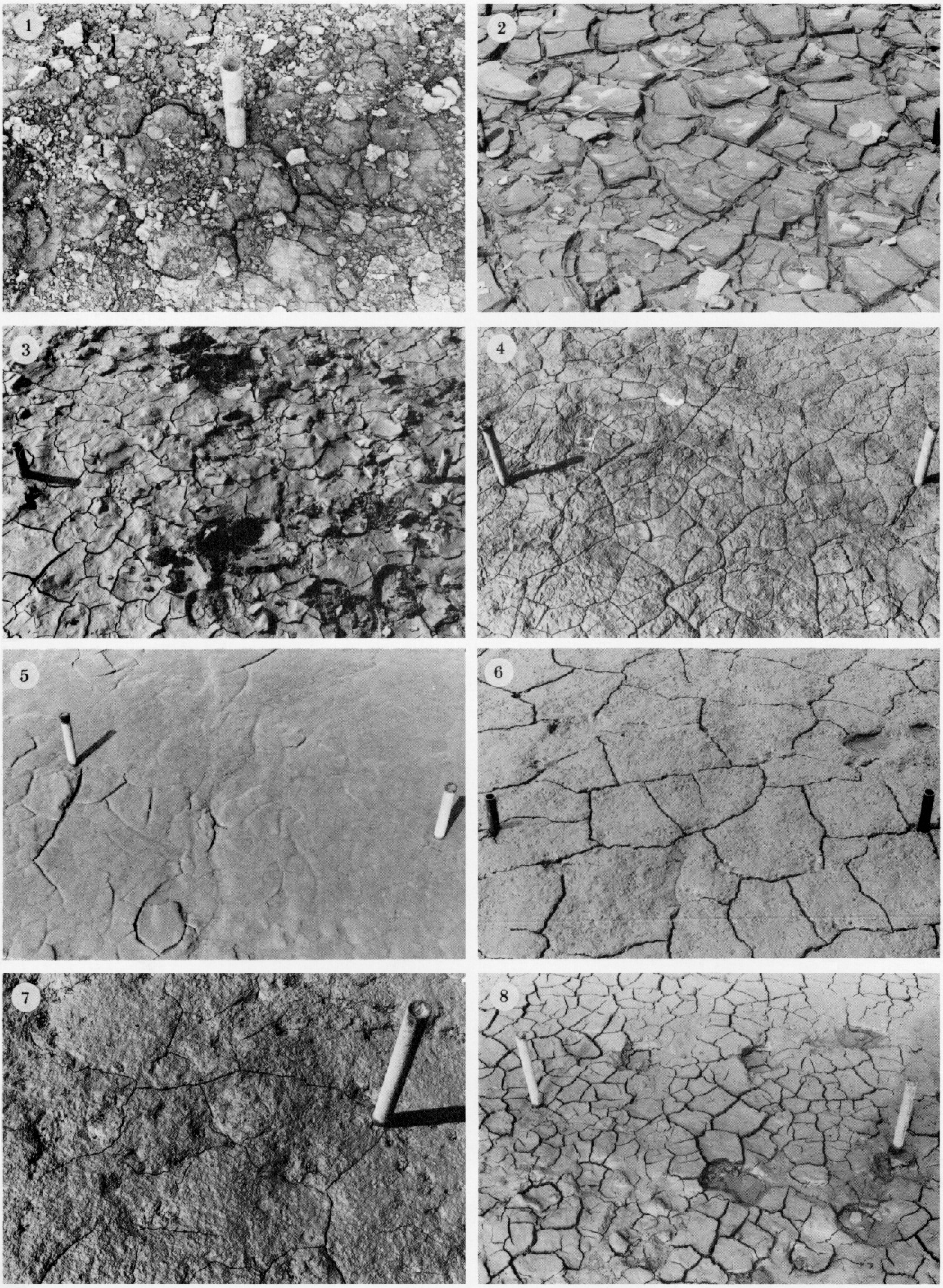
6


7


8


For description see p. 149.



For description see opposite.