The basis for earthquake prediction

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Summary. Recent advances in understanding the behaviour of shear waves propagating in the crust make the routine prediction of earthquakes seem practicable. Accumulating evidence suggests that most of the Earth's crust is pervaded by distributions of fluid-filled cracks and microcracks that are aligned by the contemporary stress-field so that the cracked rockmass is effectively anisotropic to seismic waves. This causes shear-waves to split, and shear-wave splitting is observed whenever shear-waves propagating along suitable raypaths in the crust are recorded by three-component instruments. These distributions of cracks are known as extensive-dilatancy anisotropy or EDA. Many characteristics of the crack- and stress-geometry can be monitored by analyzing shear-waves propagating through the cracked rockmass. Observations of temporal variations of the behaviour of shear-wave splitting in seismic gaps confirm these hypotheses, and suggest that stress changes before earthquakes may be monitored by analyzing shear-waves. In particular, monitoring earthquake preparation zones with three-component shear-wave vertical-seismic-profiles could lead to techniques for the routine prediction of earthquakes.

1 Introduction

Observations of shear-wave splitting above small earthquakes in many parts of the world show that most in situ rocks in the Earth's crust contain distributions of stress-aligned fluid-filled cracks or microcracks. Such distributions of aligned cracks are effectively anisotropic to seismic waves and the phenomenon is called extensive-dilatancy anisotropy or EDA (Crampin et al. 1984; Crampin 1985; Crampin & Atkinson 1985). Similar observations have recently been confirmed elsewhere in the crust by several major oil companies at the Annual Convention of the Society of Exploration Geophysicists in Houston, November 1986 (Alford 1986; Becker & Perelberg 1986; Crampin & Bush 1986; Johnston 1986; Lynn & Thomsen 1987; Willis et al. 1986). Shear-wave splitting was reported from many
(surface-to-surface) reflection surveys and (surface-to-subsurface) vertical-seismic-profiles (VSPs). Shear-wave splitting was also reported at AGU Fall Meetings in San Francisco, December 1985 and 1986, in several VSPs in several locations in California (Majer et al. 1985; Leary & Li 1986; Li et al. 1986). These many observations of shear-wave splitting indicate that aligned EDA-cracks are a common if not universal phenomenon in most rocks in the crust, and that several properties of the crack geometry, and hence of the stress that aligns the cracks, can be estimated from analyzing shear-wave splitting.

Earthquakes are the sudden release of stress accumulated over a period of time in a volume of rock related to the size of the eventual earthquake. A wide variety of earthquake precursors have been occasionally and sporadically observed before some earthquakes, and a very few earthquakes have actually been predicted by empirical correlations. Such precursors are believed to be indirect effects of changes in the stress field acting on the earthquake preparation zone before the stress release is triggered. These phenomena were conceptually linked together by the hypothesis of dilatancy diffusion (Scholz et al. 1973), suggesting the (high-stress) dilatancy of Brace et al. (1966) occurred in the source zone. This was before the presence of EDA-cracks throughout the rockmass had been recognized and the anisotropic nature of the effects fully appreciated.

Analyzing shear-wave splitting is the most direct way to monitor the effect of in situ stress on the rockmass and, in particular, analyzing temporal changes in splitting is the most direct way to monitor changes in stress throughout the rockmass before an earthquake. Thus, analyzing shear-wave splitting, preferably in shear-wave VSPs, is likely to be a way, possibly the only practicable way, to monitor detailed stress changes before earthquakes routinely and predict the time, place, and magnitude of impending earthquake. Analyzing shear-wave splitting also has the advantage that it recognizes and makes use of the essentially anisotropic nature (the variation with direction) of the build-up of stress before earthquakes, which is likely to be one of the principal causes of the sporadic nature of most precursory phenomena observed previously.

Observations of temporal changes in the character of the shear-wave splitting in the Anza seismic gap in California, and less regular changes in a seismic gap on the North Anatolian fault in Turkey, confirm these hypotheses and provide real hope that monitoring high risk areas with shear-wave VSPs could lead to robust techniques for earthquake prediction.

2 Shear-wave splitting in the crust

The behaviour of shear-waves propagating through rock containing aligned
cracks can be simulated by modelling propagation through a homogeneous purely-elastic anisotropic solid which has the same variations with direction of velocity and attenuation as the cracked rock (Crampin 1978, 1984). Fig. 1(a) shows the variation of velocity of body waves propagating through thin parallel liquid-filled cracks with a crack density (0.04), giving delays between split shear-waves typical of the observed anisotropy in some metamorphic (Crampin and Booth 1985) and sedimentary (Crampin et al. 1986b) regions of the crust. A crack density of 0.04 is equivalent to a crack with a diameter of approximately 0.7 in each unit cube. The principal phenomena distinguishing propagation in anisotropic (cracked) rock from propagation in isotropic (uncracked) rock are that in the cracked rock the velocity of the waves varies with direction, and that there are usually two nearly orthogonally polarized shear-waves. The small variation with direction of P-wave velocity [2% in Fig. 1(a)] would be difficult to recognize in the usually complicated structure of the crust. The velocity anisotropy of shear-waves is also small [4% in Fig. 1(a)], but the two polarizations of shear-waves cause shear-wave splitting (similar to the optical phenomenon, bi-refringence) with very distinctive effects on the three-dimensional behaviour of the

On entering a region of aligned cracks, a shear-wave splits into two (or more) components with different polarizations and different velocities. These components separate in time and insert distinctive and easily recognizable signatures into the three-dimensional particle motion when displayed in mutually-orthogonal cross sections of the particle displacements called polarization diagrams or PDs (Crampin 1978). Fig. 2 gives a schematic illustration of the phenomenon and suggests why shear-waves split on propagating through aligned cracks. Thomsen (1986) gives a good heuristic demonstration of the effect of cracks on seismic waves.

One of the most distinctive features of shear-wave splitting is that the polarization of the leading (faster) split shear-wave is controlled by the symmetry of crack geometry along the wave path (Crampin 1981). This leads to fixed patterns of variation of the behaviour of split shear-waves in three-dimensions that are characteristic of the geometry and orientation of the cracks. Fig. 3 shows equal-area projections (polar maps) of the theoretical variations of the polarizations and delays between split shear-waves propagating through parallel vertical liquid-filled cracks. The projections show that the horizontal polarizations of

![Figure 2. Schematic illustration of shear-wave splitting in cracked rock. When a shear-wave enters a cracked rock, the component of motion with displacement normal to the crack face encounters an effectively lower shear modulus and consequently travels slower and is more attenuated than the component with displacement parallel to the cracks.](https://www.oup.com/academic/9780199684788/article-abstract/91231174315/biogem-abstract)
Figure 3. Equal-area projections (with respect to phase velocity) of the horizontal polarizations of the leading (faster) split shear-waves (lefthand side) and the delays between the split shear-waves (righthand side) through the cracks of Fig. 1 aligned vertically and striking in an East-West direction. The delays are contoured in hundredths of seconds for path lengths of 10 km. To the left of the delays are North-South sections of the contours. (a), (b), and (c) correspond to the cracks in Figs. 1(a), (b), and (c), respectively. The inner circle in the projections is the shear-wave window at the free surface for an incidence angle of 35.3°.

The leading split shear-waves are parallel to the strike of the vertical cracks in a broad band across the centre of the projection. The delays between the split shear-waves are largest in the same broad band across the centre of the projection.

Shear-waves displaying splitting and having characteristic patterns of polarization were first observed above a swarm of small earthquakes near the North Anatolian Fault in Turkey in a series of experiments specifically designed to search for shear-wave splitting [Turkish Dilatancy Projects: TDP1 in 1979 (Crampin et al. 1980); TDP2 in 1980 (Crampin et al. 1985); and a more comprehensive experiment TDP3 in 1984 (Chen et al. 1987), currently being analyzed]. Similar phenomena have been observed above poorly consolidated sediments in the Peter the First
Figure 4. Equal-area rose diagrams of the polarizations of the leading split shear-waves above small earthquakes: (a) near the North Anatolian Fault in Turkey (after Chen et al. 1987), (b) in the Peter the First Range, Tadzhikistan USSR (after Crampin et al. 1986a), (c) in the Kinki District of Japan (vector azimuths) (after Kaneshima et al. 1987a), and (d) in the Anza seismic gap, California (following Peacock et al. 1987). The heavy arrows show estimated directions of regional compression.

Fig. 4 shows rose diagrams of polarizations of the leading shear-waves in four such areas. Most earthquakes are in disturbed tectonic regions, and the observations in Fig. 4 are all from mountainous areas, but despite shear-waves having severe interactions with irregular surface topography (Evans 1984), the rose diagrams indicate approximately parallel polarizations. The stations showing particularly irregular rose diagrams are those from sites surrounded by particularly abrupt local topography [stations (a) KD, (b) 33, (c) WTJ, and (d) RDM and CRY], and sites over slate [(c) YGI, and possibly WTJ], where the pronounced cleavage anisotropy (Christensen 1966) dominates the effects of the aligned EDA-cracks. The anisotropic effects of EDA-cracks are also seen in a
comprehensive P-wave refraction survey (Crampin et al. 1986c) and above acoustic events in geothermal reservoirs (Roberts & Crampin 1986; Kaneshima et al. 1987).

Although surface recordings of earthquakes clearly display shear-wave splitting and preferentially oriented polarizations, there are two principal difficulties in interpreting observations from seismometer networks recording earthquakes at the surface. Shear-waves undergo such severe interactions at a free surface that, unless the effective angle of incidence is within the shear-wave window (angles of incidence less than $\sin^{-1}\frac{Vs}{Vp}$: approximately 35° for a Poisson’s ratio of 0.25), incident waveforms are severely disturbed and incident polarizations irretrievably lost (Evans 1984). (Note that the edge of the shear-wave window is determined by the angle of incidence with respect to the local surface immediately surrounding the recording site, so that in areas of steep topography the aperture of the window may be severely distorted.) These constraints mean that appropriate networks to record shear-wave splitting above small earthquakes require three-component instrumentation and sufficiently closely-spaced seismometers to record several arrivals within the shear-wave window above each earthquake. There have been few suitable networks. The other major difficulty is that small earthquakes are a very unreliable and irregular source of shear-waves. These various phenomena combine to make it impossible to model shear-wave splitting with synthetic seismograms (except in unusually simple geological formations) and difficult to monitor small changes in behaviour with uncontrollable sources of signals.

Shear-waves in reflection surveys also display shear-wave splitting. At the recent SEG meeting, AMOCO reported shear-wave splitting in reflection surveys gathered for exploration and production purposes at 12 out of 13 sites across North America (Alford 1986; Lynn & Thomsen 1986; Willis et al. 1986). These demonstrate crack-induced anisotropy, but the complications of shear-wave interaction with the free surface again make the detailed interpretation, required for monitoring changes in stress before earthquakes, either difficult or impossible from reflection surveys. EXXON reported shear-wave splitting in a VSP in the Austin Chalk in Texas (Becker & Perelberg 1986; Johnston 1986), and VSPs, recording a controlled source subsurface, offer excellent prospects of modelling with synthetic seismograms. A multi-offset VSP in the Paris Basin, recorded by the French VSP Consortium, was modelled in detail by synthetic seismograms propagating through a simple structure of aligned cracks (Crampin et al. 1986b). These Paris Basin seismograms are probably the first time that the detailed three-dimensional waveforms of short-period shear-waves
in the top 2 km of the crust have been well-matched by synthetic seismograms. They indicate that repeated shear-wave VSPs recording a controlled source subsurface can be interpreted in sufficient detail, in terms of the internal structure of EDA-cracks, to monitor small changes in crack geometry and hence stress geometry.

It is found that almost all shear-wave seismograms recorded subsurface or within the shear-wave window at the surface display shear-wave splitting. The only such data set claimed not to display shear-wave splitting is one (out of 13) of the industry-generated reflection surveys in North America (Willis et al. 1986). Thus, it appears that effective crack-induced anisotropy is an almost universal property of at least the upper 10 to 20 km of the crust (Crampin 1987).

New observations confirming these results are reports of temporal changes in the characteristics of shear-wave splitting in the Anza seismic gap in Southern California (Peacock et al. 1987), shown in Fig. 5, and, less reliably, in the Izmit gap in Turkey (Chen et al. 1987).

3 Extensive-dilatancy anisotropy (EDA)

Some combination of fluid-filled microcracks, cracks, and pores with preferred orientations (EDA-cracks) aligned by the contemporary stress fields necessarily exist in most rocks in the Earth's crust (Crampin et al. 1984; Crampin 1985). Prograde metamorphic processes release chemically bound water from most mineral grains within the rockmass (Fyfe et al. 1978) and the only way that such water can be released into an intact rock is by hydraulic fracture at high pore pressures into initially-isolated inter- and intra-granular microcracks. Such microfractures are aligned by the same processes that align large industry-generated hydraulic fractures which, below the top few hundred metres, usually take up near-parallel near-vertical orientations perpendicular to the minimum horizontal compressional stress. Prolonged metamorphism may lead to the development of large water-filled fractures, as was found down to 12 km in the Kola Deep Hole where abundant heavily-mineralized water-filled fractures were found at levels (8 km) where the maximum horizontal compressional stress was greatest (Crampin 1985). The orthogonal minimum horizontal stress at 8 km depth would be much less than the vertical stress, and the fractures would be aligned parallel and vertical.

Similarly, sedimentary rocks contain water-filled pore-space after deposition, and consistent patterns of regional stress acting for very long periods of time will tend to align the pore-space by such processes as subcritical crack-growth (Atkinson 1984). All these processes will tend to align cracks and pores perpendicular to the contemporary minimum
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Figure 5. Polarizations and delays at station KNW in the Anza seismic gap for raypaths making angles with the crack normals of (a) more than 75.5°; and (b) less than 75.5°. Lower diagrams are equal-area projections of (lefthand side) horizontal shear-wave polarizations, and (righthand side) delays between the split shear-waves contoured in hundredths of a second and normalized for a path length of 10 km. The polarizations do not show a significant variation in time. The delays in (a) show a negligible increase, whereas the delays in (b) approximately double in the three years of records (after Peacock et al. 1987).

Seismic wavelengths are usually longer than a hundred metres, so that the dimensions of EDA-cracks ranging, from microns (in otherwise intact igneous and metamorphic rocks), to submillimetre pores (in sedimentary rocks), and a few metres (in fractured beds), will have similar effects on shear-wave velocities. We use the generic term "EDA-cracks" to cover this wide range of possible inclusion size. The attenuation of seismic waves is likely to be more sensitive to crack dimensions than the velocity variations but attenuation is usually difficult to measure quantitatively except in controlled experiments such as shear-wave VSPs.
The processes acting on in situ cracks and pores are complicated and not well understood. There are at least 20 phenomena controlling the behaviour of cracks in the crust and most of these phenomena are dependent on stress (Crampin 1987). This means that it is impossible to examine EDA-cracks physically. As soon as we approach in situ cracks by drilling, mining or excavating, the surrounding rock is partially de-stressed and a new stress anomaly imposed on the cracks, so that the original crack geometry is lost. Since the interaction of the various phenomena is extremely complicated with reaction times varying from immediate elastic effects to reactions with time constants of possibly millions of years, extrapolation from the conditions observed in well logs or in the rock physics laboratory to in situ conditions is very difficult. It requires a multivariable extrapolation over, in some cases, many orders of magnitude. Clearly our knowledge of in situ cracks is very limited.

4 The effects of temporal changes of stress on EDA-cracks

It has been recognized since EDA was first suggested (Crampin et al. 1984) that observations of temporal changes in the behaviour of shear-wave splitting would be critical. Such changes confirm the existence of EDA (since all other possible causes of anisotropy could not change in a short space of time), indicate changes of in situ crack geometry, and demonstrate that stress can be monitored by analysis of shear-wave splitting. In principle, all the parameters of EDA-crack geometry may be modified by appropriate changes in the stress field acting on the rockmass:

Crack orientation may be modified by a variety of processes such as differential opening and closing, differential healing, and subcritical crack-growth. Orientation is the easiest crack parameter to monitor as the polarization of the leading split shear-wave is controlled by the symmetry (orientation) of the crack geometry along the raypath, and the orientation is readily estimated from the polarization of the leading split shear-wave in PDs. However, although there may be exceptions, it is not expected that the directions of the principal axes of stress (the regional stress) in an earthquake preparation zone are likely to change significantly before an earthquake, and no temporal variations in polarization have yet been observed.

Crack density may be modified by changes in the number, or changes in the dimensions, of cracks. Both the number and dimensions of cracks may increase by conventional (high-stress) dilatancy (stress greater than half
the eventual fracture strength, Brace et al. 1966], or by continued prograde metamorphism releasing chemically bound water into new or existing cracks. Neither process is likely to be active before typical crustal earthquakes, except perhaps at stress concentrations in the immediate vicinity of the source where the volume is likely to be too small to substantially affect the shear-wave splitting. Similarly, cracks may decrease in number and decrease in dimensions by elastic closure and by healing, but liquid-filled microcracks in impermeable rock can neither easily close nor heal without channels to drain the liquid from the pore space, and re-absorption of pore fluids by retrograde metamorphism is usually not complete. Since the majority of EDA-cracks in (low-porosity) igneous and metamorphic rocks are probably isolated (unconnected) microcracks without channels for drainage (Simmons & Richter 1976), it is not expected that, in general, crack density will change rapidly in earthquake preparation zones. Comparison of Figs. 1(a) and 1(b) shows the effects of different crack densities on seismic velocities: the differential shear-wave velocity anisotropy and the delay between the split shear-waves are changed. Overall changes in delay at Anza (Peacock et al. 1987) are not significant, Fig. 5, although there may be more significant changes over a longer period of time in Turkey (Chen et al. 1987). However, it must be noted that measuring the time intervals between split shear-waves from earthquake sources is a very subjective estimate and accurate determinations require controlled-source VSPs.

Aspect-ratio (least dimension divided by greatest) may be modified by the direct elastic effect of changing the magnitude of the stress on the rockmass. Rock specimens subjected to uniaxial stress dilate as new dry cracks open (usually along internal flaws) and "bow" (increase in aspect ratio) under sufficiently strong applied stress. It is expected that existing liquid-filled cracks would bow in the same way as newly opened dry cracks, but at much lower levels of stress over much longer periods of time. The effect of increasing aspect ratio on shear-waves can be seen by comparing Fig. 1(a) for thin cracks and Fig. 1(c) for cracks with a larger aspect ratio (fatter cracks). The average time delay between shear-waves propagating at between 50^0 and 75^0 to the crack normals approximately doubles in Fig. 1, whereas the average delay between 75^0 and 90^0 to the crack normals remains essentially the same. This is exactly what was observed at one of the Anza stations, KNW, north of the Hot Springs Fault, where the delays between 50^0 and 75.5^0 (optimized value) were observed to double in the two and a half years of recordings presently available in Figure 5(b). This increase is significant at the 99% level, and could be
interpreted as bowing induced by a steady increase in the horizontal stress over two and a half years preparatory to the expected larger earthquake. Note that KNW is the only station of the Anza network which has enough arrivals within the shear-wave window to show such time variations.

Pore-fluid. The dilatancy instability hypothesis for earthquake precursors (Scholz et al. 1973; Aggarwal et al. 1973) suggested that changes of stress could cause fluids to drain from the dilated cracks and modify the wave propagation through the cracked rock. It is suggested here that this is unlikely to occur as, in general, isolated EDA-cracks do not have the necessary channels for drainage. Another important difference is that in the previous model (Aggarwal et al. 1973), the time-frame is determined by the fluid-flow, which may change non-linearly with slowly increasing stress. In contrast, in the present model, the time-frame is determined by the rate of change of the stress itself.

Pore-fluid pressure. In the very long term, the only sustainable pore-fluid pressure is lithostatic, since any other pressure would lead to stress anomalies which would be accommodated over long periods of time by elastic opening and closing, and bowing, and by anelastic healing, and subcritical crack growth. (The large range of pore pressures measured downwell in the field are probably more indicative of permeability than pore-fluid pressure.) Increases of aspect ratio as suggested above could lead to undersaturation and the introduction of vapour-filled space within the pore-space. Such mixed pore-fluids, where the percentage of vapour is likely to be small, would have little effect on shear-wave velocities and patterns of particle displacements, but would have a major effect on wave attenuation (Mavko & Nur 1979). Such changes in attenuation could be easily measured in controlled source VSPs.

We conclude that the most likely change of crack geometry in an earthquake preparation zone would be a change in aspect ratio, which would cause changes in a limited range of directions in the spatial pattern of variations of delay with direction. These are exactly the changes that have been observed at station KNW of the Anza network (Peacock et al. 1987).

5 A scheme for earthquake prediction

Although some progress in earthquake prediction research has been made by analyzing shear-wave splitting from networks of surface seismometers
recording shear-waves above small earthquakes, there are two phenomena that preclude detailed earthquake prediction from such studies: the complicated interactions of shear-waves arriving at the free surface; and the unrepeatability (and unreliability) of earthquake sources when detailed differential measurements are required at frequent intervals. These make accurate observations difficult and prevent detailed modelling with synthetic seismograms except in unusually uniform conditions.

The detailed modelling of Crampin et al. (1986b) with synthetic seismograms of the patterns of shear-wave polarizations recorded in the Paris Basin VSPs using a simple two-layered halfspace demonstrates two things: (1) Shear-waves are not seriously disturbed when transmitted from a surface source [the reciprocity principle (Aki & Richards 1980) that source and receiver can be interchanged does not hold when one of the positions is at a free surface]. (2) Shear-wave polarizations can be modelled by synthetic seismograms in the simple horizontal strata of a sedimentary basin. Although detailed modelling of VSPs with synthetic seismograms may not be possible in the more complicated structures expected in earthquake preparation zones, the Paris Basin results indicate that repeated shear-wave VSPs should yield reliable signals for measuring differential changes in the behaviour of split shear-waves.

There are typically many existing boreholes in the vicinity of earthquake prone areas such as along the San Andreas Fault in California or around Tokyo, Japan. The principal axes of stress (and EDA-crack orientations) may rotate as the vertical stress increases with depth which makes it necessary to monitor shear-wave splitting at sufficient depth to observe vertical cracks. The suggested scheme of monitoring would repeat zero-offset and walk-away shear-wave VSPs in selected boreholes in a vulnerable area (along the San Andreas fault, for example) at intervals of perhaps six months. It would be preferable to use an impulsive shear-wave source such as a sliding weight-drop or a bolt-action gun rather than a shear-wave vibrator, which is difficult to interpret visually. If significant changes were noticed at one or more of the holes, a high risk area would be identified, and a concentrated effort would begin repeating shear-wave VSPs at shorter time-intervals in additional holes in the suspect area. It is probable that the preparation time of a large earthquake is at least several years and there should be adequate time to recognize and examine the stress accumulation - as long as the monitoring begins in time. Since at present we do not know how much time we have before any area is damaged by a large earthquake, it would seem prudent to begin routine monitoring of shear-wave VSPs in vulnerable areas as soon as
6 Discussion

There is now evidence from the behaviour of shear-waves in a wide range of geologic and tectonic structures that most rocks in the Earth's crust contain EDA-cracks. Many details of the crack geometry can be estimated by monitoring shear-wave splitting, preferably in shear-wave VSPs. Now that temporal changes in shear-wave splitting have been observed, many previously inexplicable observations of earthquake precursors are seen to be the indirect effects of stress-induced manipulations of EDA-cracks. Moreover it is possible to devise schemes for routine monitoring of EDA-cracks and the controlling stress, consistent with our present knowledge that should allow the routine prediction of large earthquakes. The previous section outlines the most promising scenario.

There are many things we do not yet understand about EDA-cracks and earthquake sources. It is possible, although unlikely, that earthquakes occur in such irregular ways that it is impossible to routinely and objectively predict the time, place, and magnitude. Most earthquakes are the result of sudden release of stress, and the large range of precursory phenomena, that have occasionally been observed and very occasionally used to actually predict earthquakes, are indirect (usually very indirect) manifestations of precursory changes in stress. However, they do suggest that earthquakes can be predicted. If earthquakes are predictable, the behaviour of the stress in the preparation zone must behave in some characteristic manner before the earthquake. The most immediate effect of these changes of stress will be to modify the crack geometry and modify the behaviour of split shear-waves. This suggests that monitoring the behaviour of in situ stress by shear-wave splitting in shear-wave VSPs is the most likely way such precursory behaviour can be recognized and the earthquake predicted.

We do not know how much time we have before the next damaging earthquake in any area. The evidence cited here demonstrates that we know enough about the effects of stress on the rockmass to know what to monitor. It is essential to start to observe and interpret the effects of stress changes on split shear-waves in all areas of high vulnerability in order to begin to build-up the experience required to routinely predict large earthquakes.

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